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Active Galactic Nuclei at hard X-ray energies: absorption, reflection and the unified model

Ricci, Claudio

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Active Galactic Nuclei at hard X-ray energies: Absorption, Reflection and the Unified Model

THÈSE

présentée à la Faculté des sciences de l'Université de Genève
pour obtenir le grade de Docteur ès sciences,
mention Astronomie et Astrophysique

par

Claudio RICCI

de

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FACULTÉ DES SCIENCES

**Doctorat ès sciences
Mention astronomie et astrophysique**

Thèse de *Monsieur Claudio RICCI*

intitulée :

**" Active Galactic Nuclei at Hard X-ray Energies : Absorption,
Reflection and the Unified Model "**

La Faculté des sciences, sur le préavis de Messieurs Th. COURVOISIER, professeur ordinaire et directeur de thèse (Département d'astronomie), S. PALTANI, docteur (Département d'astronomie), R. WALTER, docteur (Département d'astronomie), D. PFENNIGER, professeur associé (Département d'astronomie), F. FIORE, docteur (Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Roma, Roma, Italia) et V. BECKMANN, docteur (Astroparticule et Cosmologie, François Arago Centre, Université Paris Diderot, Paris, France), autorise l'impression de la présente thèse, sans exprimer d'opinion sur les propositions qui y sont énoncées.

Genève, le 8 décembre 2011

Thèse - 4386 -


Le Doyen, Jean-Marc TRISCONE

N.B. - La thèse doit porter la déclaration précédente et remplir les conditions énumérées dans les "Informations relatives aux thèses de doctorat à l'Université de Genève".

Cette thèse a fait l'objet des publications suivantes:
voir [Appendix A](#)

獻給妳, 我的月亮

To Paolo and Francesca, for their love and support during all these years.

A Paolo e Francesca, per il loro affetto e sostegno durante tutti questi anni.

To the memory of my grandparents, always with me.

Ai miei nonni, sempre con me.

*They laughed at me as "Prof. Moon,"
As a boy in Spoon River, born with the thirst
Of knowing about the stars.
They jeered when I spoke of the lunar mountains,
And the thrilling heat and cold,
And the ebon valleys by silver peaks,
And Spica quadrillions of miles away,
And the littleness of man.
But now that my grave is honored, friends,
Let it not be because I taught
The lore of the stars in Knox College,
But rather for this: that through the stars
I preached the greatness of man,
Who is none the less a part of the scheme of things
For the distance of Spica or the Spiral Nebulae;
Nor any the less a part of the question
Of what drama means.*

Edgar Lee Masters, Spoon River Anthology

mous (0.1–10 keV) d'environ 35 objets pour lesquels aucune information sur la densité de colonne (le paramètre habituellement utilisé pour décrire la quantité d'absorption le long de la ligne de visée) n'était disponible dans la littérature. Cette analyse a été faite en utilisant les données obtenues par *Swift*/XRT et *XMM-Newton*/EPIC. Parmi les sources étudiées, trois montraient des caractéristiques particulières dans les X mous. Ces sources sont les suivantes: les galaxies de Seyfert 1s ESO 140-43 et UGC 3142 et la galaxie de Seyfert 2 ESO 383-18. En étudiant de nouvelles données haute qualité de *XMM-Newton*/EPIC combinées aux données en rayons X durs obtenues par *INTEGRAL* IBIS/ISGRI et *Swift*/BAT (14–195 keV), nous avons contraint les caractéristiques des nuages absorbants. Nous avons trouvé que les spectres X des sources UGC 3142 et ESO 383-18 ne peuvent pas être décrits par un absorbant unique et homogène. Ils nécessitent tous deux au moins deux absorbants neutres qui couvrent partiellement la source. Le spectre X de la source ESO 140-43 faisait apparaître des signes d'un système d'absorption très complexe composé de trois différentes couches de matière ionisée avec des états d'ionisation, des densités et des facteurs de couverture différents. Une des caractéristiques les plus frappantes d'ESO 140-43 est sa variabilité. La source montre une forte variation de flux sur une échelle de temps de six mois entre les deux observations réalisées par *XMM-Newton* avec un changement remarquable des caractéristiques physiques et du facteur de couverture des trois absorbants. Sur des délais plus courts, la source présente également une certaine variabilité que nous supposons liée aux changements des facteurs de couverture de l'un des absorbants. Alors que les absorbants dans ESO 383-18 et UGC 3142 sont probablement liés à la présence de bandes de poussière, les absorbants ionisés font certainement partie d'un vent. L'étude des vents dans les galaxies de Seyfert est cruciale pour la compréhension des rétroactions entre l'AGN et la galaxie hôte.

Les rayons X durs représentent une bande d'énergie unique pour tester le modèle unifié des AGN. Le rayonnement dans cette gamme d'énergie n'est en fait pas affecté par la matière absorbante le long de la ligne de visée, ce qui permet à l'observateur de voir la source centrale. Ainsi, si le modèle unifié des AGN est correct et la seule différence entre les classes est l'absorption, on pourrait s'attendre à voir la même émission X en moyenne des différentes classes d'objets. A partir de toutes les données publiques disponibles réalisées par *INTEGRAL* IBIS/ISGRI sur les 170 galaxies de Seyfert environ, situées à des redshifts $z < 0.2$ et détectées dans les X durs, nous avons mené l'étude la plus complète du spectre moyen des AGN dans les X durs jamais réalisée. Notre échantillon consistait en 44 Seyfert 1s, 29 Seyfert 1.5s, 78 Seyfert 2s et 14 NLS1s. Afin d'éviter tout effet lié à la présence de gaz obscurcissant, nous avons divisé les Seyfert 2s de notre échantillon en deux groupes: Seyfert 2s Compton-thin ($N_H < 10^{24} \text{ cm}^{-2}$) et Seyfert 2s Compton-thick ($N_H \geq 10^{24} \text{ cm}^{-2}$). Le premier regroupe 68 objets et le second en compte seulement 10. Nous avons produit les spectres moyens des différentes classes d'AGN, incluant toutes les données disponibles pour chacune des sources de l'échantillon. A partir d'une analyse spectrale à la fois dépendante et indépendante du modèle, nous avons trouvé que les spectres moyens des Seyfert 1s et Seyfert 1.5s sont conformes, comme prévu par le modèle unifié. Par ailleurs, le spectre X durs moyen des Seyfert 2s montre une plus forte composante de réflexion que celle des Seyfert 1s et Seyfert 1.5s. Nous avons constaté que cette différence est due à la présence de Seyfert 2s que nous avons définies comme "mildly obscured" (MOB, $10^{23} \leq N_H < 10^{24} \text{ cm}^{-2}$) alors que les Seyfert 2s qualifiées de "lightly obscured" (LOB, $N_H < 10^{23} \text{ cm}^{-2}$) ont des caractéristiques plus proches de celles des Seyfert 1s et des Seyfert 1.5s. La réflexion la plus importante que nous avons trouvé dans les Seyfert 2s ne peut être facilement expliquée par le modèle unifié mais pourrait impliquer un plus grand facteur de couverture de la matière environnante ou l'existence de grumeaux denses dans la ligne de visée. Cependant, une fois que l'on a pris en compte une plus importante réflexion pour les Seyfert 2s MOB, les paramètres de l'émission primaire (l'indice de la loi de puissance

et l'énergie de coupure) sont compatibles, ce qui confirme l'idée générale que le moteur central est le même pour tous les types d'objets.

Le télescope LAT (Large Area Telescope) à bord du satellite *Fermi* (une mission de la NASA) est un détecteur de rayons gamma sensible à la bande d'énergie 20 MeV–300 GeV. Le ciel observé dans le domaine des rayons gamma est connu pour être principalement peuplé de blazars et de quelques radio-galaxies très proches, ainsi l'une des découvertes inattendues du *Fermi*/LAT depuis son lancement en Juin 2008 a été la détection du rayonnement gamma émis par les NLS1s. Motivés par cela, nous avons analysé environ 1.6 année de données et avons cherché l'émission à haute énergie provenant des plus brillantes galaxies de Seyfert. Nous avons trouvé la première preuve de l'émission gamma (avec une détection significative d'environ 8σ) provenant de la Seyfert 2 Compton-thick NGC 1068, et nous avons étudié les nouvelles données de la galaxie à sursaut stellaire NGC 4945 dont la détection a déjà été reportée dans le catalogue de 11 mois. Nous avons étudié et modélisé la distribution spectrale en énergie multi longueur d'onde (du domaine radio aux rayons gamma) de ces deux sources et nous avons conclu que les responsables de l'émission gamma sont différents pour les deux objets. Dans le cas de NGC 4945, l'émission est dominée par l'activité stellaire, de violents processus de formation d'étoiles qui accélèrent les particules à de très hautes énergies. Les particules interagissent ensuite avec le milieu interstellaire, produisant des photons gamma. Dans le cas de NGC 1068, la luminosité gamma est trop élevée pour être expliquée par l'activité stellaire. Nous avons proposé un modèle dans lequel les photons gamma seraient produits par des processus Compton inverse dans le jet.

INTEGRAL a pu apporter d'importantes informations pour la compréhension de la géométrie et des mécanismes physiques des AGN. Les résultats obtenus dans ma thèse, en particulier la découverte d'une plus forte composante de réflexion dans les Seyfert 2s, sont important notamment dans l'optique de la prochaine génération de télescopes à rayons X (*Astro-H*, *NuSTAR*, *Athena*), qui permettra de mieux comprendre la structure des AGN, et leur contribution au fond cosmique X.

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Starting to write this section has proved to be one of the most difficult things during the last months of my PhD. Not because I wouldn't know who to acknowledge, but rather because words are a reductive way to present my thanks to all the people who have helped me during my path.

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Active Galactic Nuclei

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1.1 An historical introduction

The history of Active Galactic Nuclei (AGN) starts at the beginning of the last century. In 1909 [Fath](#) undertook a series of observations aimed at understanding the nature of "spiral nebulae", some of the most enigmatic sources at the time. Scientists were in fact struggling to understand whether these objects were nearby gaseous objects similar to the Orion nebula, or very distant collections of unresolved stars. For most objects [Fath](#) found continuous spectra with stellar absorption lines, which indicated emission from unresolved solar-type stars. However, for one object, NGC 1068, he found a peculiar spectrum, showing both bright emission and absorption lines, similar to what had been observed in gaseous nebulae. This result was later confirmed by [Slipher \(1917\)](#) and by [Hubble \(1926\)](#), who found evidence of this behavior also in the spectra of NGC 4051 and NGC 4151. The first systematic study of galaxies showing nuclear emission lines was performed by [Seyfert](#) in 1943, who studied the spectra of NGC 1068, NGC 1275, NGC 3516, NGC 4051, NGC 4151 and NGC 7469. He found that while objects like NGC 1068 had forbidden and permitted lines with roughly similar

profiles and widths of $\sim 3000 \text{ km s}^{-1}$, objects like NGC 4151 showed narrow forbidden lines and very broad ($\sim 7500 \text{ km s}^{-1}$) hydrogen lines. In the following years the study of AGN developed mostly in the radio, an energy band that had started to be explored by astronomers thanks to the pioneering work of Jansky, and to the technological development of radio instruments. As often happens, it was for military reasons that the radio technology was boosted in the early 1940's. Thus at the end of the World War II several groups of radio engineers turned their efforts to radio astronomy. This led to the discovery of emission from a discrete source in Cygnus, which was then called Cygnus A (Hey et al. 1946), and later from several other sources (Bolton & Stanley 1948). In the following years many more radio sources were discovered and their positions accurately estimated, thanks to surveys like the third Cambridge survey at 159 MHz (Edge et al. 1959). The breakthrough came a few years later from observations of the very bright quasar 3C 273. Thanks to radio observations performed during a lunar occultation, Hazard et al. (1963) were able to define the position of the source with an accuracy of about 1 arcsec. In the same year, based on optical observations Schmidt (1963) discovered the presence of redshifted emission lines, which were almost immediately attributed as being due to Hubble expansion (Greenstein & Schmidt 1964). The luminosity obtained and the cosmological distance excluded the possibility that these peculiar objects were very variable stars. Few years later Sandage et al. (1965) reported the discovery of a large number of radio quiet objects that resembled quasars. These objects had been found as a characteristic population examining color-color (U–B, B–V) diagrams of stars. They showed in fact a strong "ultraviolet excess", which is now well known to be one of the most important characteristics of AGN. Since then a large number of AGN were discovered and classified according to their main properties. Today we know that many galaxies harbor AGN, radio-quiet objects, as the galaxies discovered by Carl Seyfert (and today called Seyfert galaxies) can usually be found in spiral galaxies, while radio-loud objects (as 3C 273) are usually hosted in elliptical galaxies.

In the following I will first illustrate the several components that constitute an AGN (Sect. 1.2), then I will introduce the classification (Sect. 1.3) and the unified model (Sect. 1.4) for both radio-loud and radio-quiet objects, and I will present how AGN look at different wavelengths (Sect. 1.5).

1.2 Anatomy of an AGN

AGN are thought to be constituted by several components, all of them very likely intrinsically related to the supermassive black hole lying at their center, and driving their growth and evolution. In the following I will discuss the most important components normally found in AGN: the supermassive black hole (Sect. 1.2.1), the accretion disk (Sect. 1.2.2), the broad line region (Sect. 1.2.3), the narrow line region (Sect. 1.2.4), the corona (Sect. 1.2.5) and the jets (Sect. 1.2.6).

1.2.1 The Supermassive Black Hole

The existence of black holes was predicted by Einstein in his formulation of General Relativity in 1916. Already a century before first Mitchell and then Laplace considered the idea of objects so dense that light cannot escape them. Although much theoretical work was done in the years following Einstein's work, it was not until 1972 that observational evidence for the existence of black holes was found through observations of Cyg X-1 (Bolton 1972, Webster & Murdin 1972).

The presence of supermassive black holes (SMBHs) in the center of AGN was first predicted by Lynden-Bell (1969), and later largely confirmed by several observational evidences. From the short time scales variations ($\lesssim 1$ hour) observed in AGN it is possible to obtain an upper limit on the size

of the central source, which together with mass estimates point towards very high densities, of the order of magnitude of those expected in black holes. A rapidly rotating disk of ionized gas has been detected by HST observations of M87, the velocities measured are in agreement with a disk being Keplerian rotating around a black hole (Ford et al. 1994). Moreover, the luminosities observed in AGN can be easily explained by accretion onto a supermassive black hole (see Sect. 1.2.2), and no serious alternative explanation to this mechanism exist, although theories involving starburst have long been debated (e.g., Terlevich et al. 1992).

The origin of the supermassive black holes hidden at the center of galaxies is still unknown, several scenarios have been proposed (see Dokuchaev et al. 2007 for a review on the topic), amongst which the collapse of supermassive population III stars or the collapse of massive primordial clouds.

Rotating and non-rotating black holes

The role of the surface for a black hole of mass M is played by the sphere with a radius corresponding to the Schwarzschild radius ($r_g = 2GM/c^2$). The Schwarzschild radius is the distance from the singularity at which a body cannot escape anymore from the gravitational attraction and is bound to fall inside the black hole. The metric of space-time around a non-rotating black hole is given by the Schwarzschild solution (1916) to Einstein's general relativity:

$$ds^2 = \left(1 - \frac{2GM}{rc^2}\right) dt^2 - \frac{1}{c^2} \left[\frac{dr^2}{1 - \frac{2GM}{rc^2}} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right].$$

From the metric one can deduce the *last stable circular orbit* around a non-rotating black hole: $r = 3r_g$. So for $r < 3r_g$ no stable orbit exist, and for $r < r_g$ particles rapidly fall in the singularity.

The general solution for a rotating black hole was discovered in 1963 by Kerr. The metric for a black hole with an angular momentum J is

$$ds^2 = \left(1 - \frac{2GMr}{\rho c^2}\right) dt^2 - \frac{1}{c^2} \left[\frac{4GMr a \sin^2\theta}{\rho c} dt d\phi + \frac{\rho}{\Delta} dr^2 \right] - \frac{1}{c^2} \left[\rho d\theta^2 + (r^2 + a^2 + \frac{2GMr a^2 \sin^2\theta}{\rho c^2}) \sin^2\theta d\phi^2 \right]$$

In this formalism a is the angular momentum of the black hole per unit mass ($a = (J/Mc)$) and has the dimension of a distance, $\Delta = r^2 - (2GMr/c^2) + a^2$ and $\rho^2 = r^2 + a^2 \cos^2\theta$. If the black hole is non-rotating, $J = a = 0$, and the Kerr metric reduces to the standard Schwarzschild metric. The radius of the horizon for a rotating black hole is:

$$r_+ = \frac{GM}{c^2} + \left[\left(\frac{GM}{c^2} \right)^2 - \left(\frac{J}{Mc} \right)^2 \right]^{1/2} \quad (1.1)$$

The maximum value of the angular momentum a black hole can have is $J = GM^2/c$, and the radius of the latest circular orbit depends on whether the particle is co-rotating or counter-rotating with respect to the black hole. For a maximally rotating black hole this values is $r = GM/c^2$ for co-rotating particles, and $r = 9GM/c^2$ for counter-rotating ones.

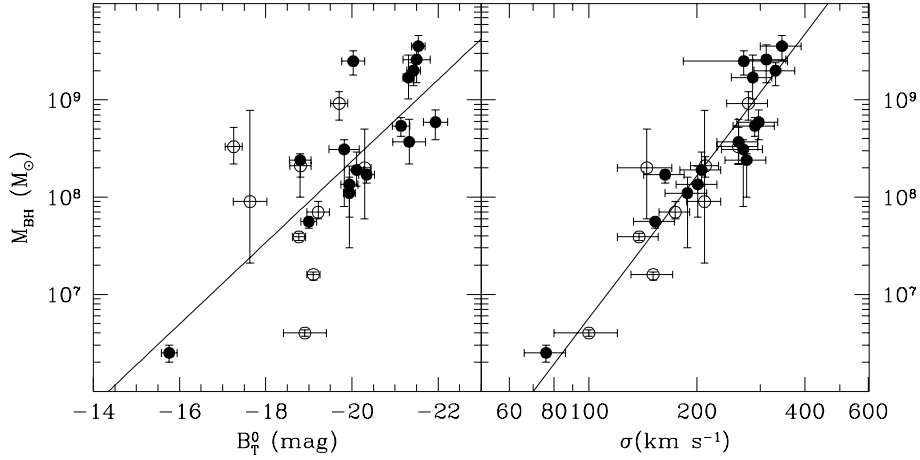


Figure 1.1: *Left panel:* correlation between the black hole mass M_{BH} and the blue luminosity of the galaxy spheroidal component. *Right panel:* correlation between the central velocity dispersion σ of the host galaxy and M_{BH} . Filled symbols show ellipticals galaxies, while open symbols show spiral and lenticular galaxies (Ferrarese & Ford 2005).

Measuring black hole masses

One of the most common ways to measure the mass of the black holes (M_{BH}) in AGN is through the width of their broad emission lines. These lines are emitted from gas orbiting around the central black hole and have normally a velocity broadening of $v \sim 10^4 \text{ km s}^{-1}$. Using the following relation

$$\frac{v^2}{r} = \frac{GM_{\text{BH}}}{r^2},$$

and considering that the emission region has a size of $r \sim 0.01 \text{ pc}$, one obtains a mass of $M_{\text{BH}} \sim 10^8 M_{\odot}$. One of the methods most used to estimate the black hole masses of broad line AGN is the "Reverberation Mapping" (e.g., Kaspi et al. 2000). This technique exploits the fact that emission lines are lagged with respect to the continuum, from which one can calculate r , the distance of the broad emission line region to the central black hole. Vestergaard & Peterson (2006) estimate r from reverberation mapping of the $\text{H}\beta$ line and derive M_{BH} from

$$\frac{M_{\text{BH}}}{10^6 M_{\odot}} = 8.3 \left[\frac{\text{FWHM}(\text{H}\beta)}{10^3 \text{ km s}^{-1}} \right]^2 \left[\frac{\lambda L_{\lambda}(5100)}{10^{44} \text{ erg s}^{-1}} \right].$$

Due to observational limits, this relation can be used only for objects up to $z \sim 0.75$. Above this redshift the line is present in some specific near infrared band. Other emission lines as Mg II and C IV are used to bypass the limits of $\text{H}\beta$.

Several other methods are used to establish the black hole mass. One of the most precise ones is through optical observations of the bulges of the host galaxies (e.g., Magorrian et al. 1998). Water maser emission in circumnuclear disks is often used for obscured AGN. Using the acceleration of masers perpendicular to the line of sight and the distance and speed of masers moving along the line of sight on the outskirts of the disk, it is possible to determine M_{BH} very accurately (e.g., Moran et al. 1995). Many more indirect methods are also often found in literature. Most of them are based on the empirical relation between the black hole mass and the stellar velocity dispersion σ_s (see

Fig. 1.1 and Sect. 5.1). These methods use either direct measurements of σ_s (Ferrarese & Merritt 2000), or indirect estimates obtained from the width of the [O III] line (Greene & Ho 2005), or from the morphological parameters of the bulge (e.g., O'Dowd et al. 2002). Some estimates use instead the bulge luminosity (Wandel 2002), the K-band stellar magnitude (assuming that it is dominated by the bulge, Novak et al. 2006), the X-ray variability time scales (Gierliński et al. 2008), or the properties of outflowing warm absorber clouds (Morales & Fabian 2002). As we will see in Sect. 4, a precise measurements is extremely important to understand the role played by the Eddington ratio (see below for the definition) on the X-ray emission of AGN.

1.2.2 The Accretion Disk

Before the 1970s the importance of accretion in astrophysics was only marginally understood. With the discovery of the first X-ray binaries it was soon realized that the only mechanism that could produce the luminosities observed in many of these sources was accretion onto compact objects.

To have a qualitative idea of the amount of energy produced by accretion processes, one can consider the gravitational potential energy released by the free fall of a mass m on a body of mass M and radius R :

$$\Delta E_{\text{acc}} = \frac{GMm}{R}$$

where G is the gravitational constant. To compare it with nuclear processes, the maximum amount of energy per gram released by nuclear fusion of hydrogen is

$$\Delta E_{\text{nucl}} = 0.007mc^2$$

where c is the speed of light. Considering for example the values typical for a neutron star (radius of $R \sim 10$ km and $M \sim M_\odot$), the quantity of energy released by accretion would be larger than that of nuclear fusion. The energy released ΔE_{acc} depends on how compact the accreting object is ($\Delta E_{\text{acc}} \propto M/R$), thus one can expect that black holes are the sources that exploit best this source of energy. The luminosity of an accreting black hole can be expressed as

$$L_{\text{acc}} \propto \eta \dot{m} c^2$$

where η is the efficiency of the conversion of rest mass energy of the accreting matter into radiation.

The maximum binding energy of a particle rotating around a black hole is the amount of energy which has to be lost in order that the material attains the last bound stable circular orbit. In the case of a non-rotating spherically symmetric black hole, the last stable orbit is $r_I = 3r_g = 6GM/c^2$, which results in a binding energy that is $\sim 6\%$ of the mass energy of the particle. In the case of rotating black holes, for corotating particles the last stable orbit is $r_I = GM/c^2$, while for counter-rotating particles is $r_I = 9GM/c^2$. The maximum binding energies of these orbits is $(1 - 1/\sqrt{3})$ of the rest mass energy of the orbiting material in the corotating case and $(1 - \sqrt{25/27})$ in the counter-rotating case. The corotating case is of the greatest interest because it implies that up to 42.3% of the rest mass energy of the material can be released as it spirals into the black hole through a sequence of almost circular equatorial orbits.

Eddington luminosity

Accretion is limited by the radiation pressure. At high accretion rates the luminosity increases and so does the outward force exerted by the radiation (F_{rad}). On a free electron this force is

$$F_{rad} = \frac{L_{acc}\sigma_T}{4\pi r^2 c},$$

where $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$ is the Thomson cross-section. The radiation pressure balances the gravitational force ($F_G = GMm_p/r^2$, where m_p is the mass of the proton) at the so called Eddington luminosity. For a fully ionized medium in a spherically symmetric geometry such a luminosity is

$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T} \simeq 1.3 \times 10^{38} \frac{M}{M_\odot} \frac{\text{ergs}}{\text{s}}.$$

The Eddington luminosity can be written, in terms of accretion rate as $L_{\text{Edd}} = \eta \dot{M}_{\text{Edd}} c^2$. Thus, the accretion rate of a disk radiating at the Eddington luminosity is

$$\dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2} = \frac{4\pi GMm_p c}{\eta c \sigma_T} \approx 1.3 \times 10^{-8} \left(\frac{M}{M_\odot} \right) \left[\frac{M_\odot}{\text{yr}} \right].$$

The ratio between the bolometric luminosity of an object (see Sect. 1.5.4) and its Eddington limit is called the Eddington ratio:

$$\lambda_{\text{Edd}} = \frac{L_{\text{Bol}}}{L_{\text{Edd}}}.$$

Objects with $\lambda_{\text{Edd}} < 1$ are accreting in the sub-Eddington regime, while those with $\lambda_{\text{Edd}} > 1$ in the super-Eddington one. Although this derivation of the Eddington luminosity is limited by the spherical symmetry approximation, which clearly does not represent the physical situation of an accreting disk, it still provides an useful approximation of the limit luminosity for an accreting system. Another factor affecting the effective Eddington luminosity is the composition of the gas. The discussion above is valid for a fully ionized medium, and it has been shown (e.g., [Murray et al. 2005](#)) that L_{Edd} can be much lower for dusty gas (see also Sect. 4.5).

Bondi accretion

Bondi accretion ([Bondi 1952](#)) considers spherical accretion of interstellar gas onto a compact object, considering the maximum possible rate of gravitational capture. The Bondi accretion rate is calculated using the distance from the accreting object (here we consider a black hole) at which its gravitational influence equals the thermal velocity of the gas:

$$\dot{M}_{\text{Bondi}} = 4\pi R_A^2 \rho_A c_s,$$

where ρ_A is the density of the gas at $R_A \sim GM/c_s^2$, and c_s the sound speed. Assuming that the hot X-ray emitting gas is the supply for the central black hole, it has been possible, thanks to high resolution observations performed by *Chandra*, to resolve the Bondi accretion radius in nearby AGN. A very recent example is NGC 3115, for which [Wong et al. \(2011\)](#) claim to have resolved the accretion flow within the Bondi radius (Fig. 1.2).

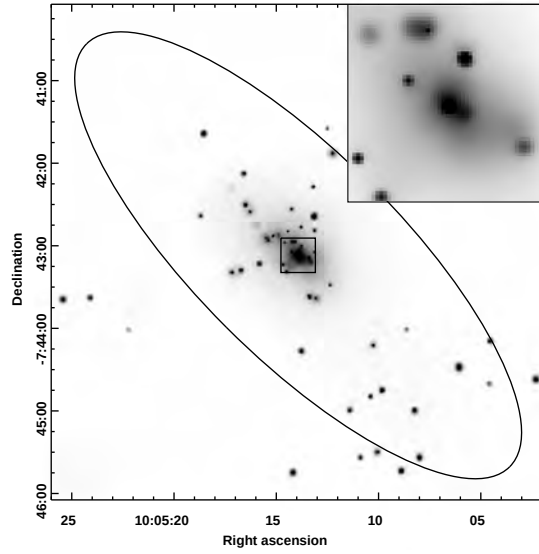


Figure 1.2: Smoothed 0.3–6.0 keV *Chandra* image of NGC 3115 (Wong et al. 2011). No point source is detected at the center, but rather a plateau in the diffuse X-ray surface brightness.

Shakura-Sunyaev accretion disks

Matter falling onto a compact object from infinity acquires kinetic energy as its gravitational potential energy decreases. In order to conserve the angular momentum the matter cannot fall directly into the compact object, but it is commonly believed to form an accretion disk. The simplest case of accretion disks are the thin accretion disks described by Shakura & Sunyaev (1973). In this picture, the matter is supposed to form a geometrically thin and optically thick disk, and follows Keplerian orbits at any radius ($v \sim (M_{\text{BH}}/R)^{1/2}$). Angular momentum is transported outwards due to viscosity produced by turbulent effects and magnetic instabilities (Frank et al. 1992). The heat energy produced in the disk is then radiated in the form of multi-temperature blackbodies, each of them having a temperature

$$T(R) = T_* \left(\frac{R}{R_*} \right)^{-3/4},$$

where R is the radius at which is emitted, R_* is the radius of a body of mass M_* accreting at a rate $\dot{M}$, and T_* is given by

$$T_* \propto \left(\frac{M_* \dot{M}}{R_*^3} \right)^{1/4}.$$

Between frequencies corresponding to the minimum (r_I) and maximum (r_{max}) distance from the accreting object, the spectrum of the accretion disk is given by:

$$I(\nu) \propto \nu^{1/3}.$$

At frequencies less than that corresponding to the temperature of the disc at r_{max} , the spectrum tends towards a Rayleigh-Jeans spectrum, $I_\nu \propto \nu^2$, while it shows a cutoff in the inner parts, $I_\nu \propto \exp(-\frac{h\nu}{kT_{\text{in}}})$, where T_{in} is the temperature of the innermost layers of the thin accretion disc. An example of the spectrum expected from an accretion disk (for different values of T_{in}) is shown in

Fig. 1.3.

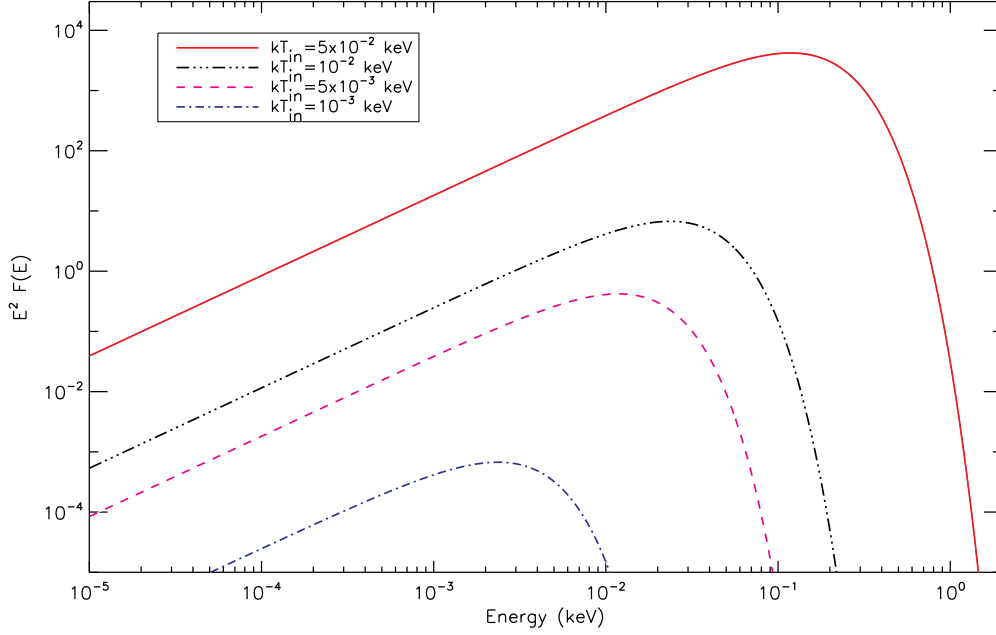


Figure 1.3: Multicolor blackbody emission from geometrically thin optically thick Shakura-Sunyaev accretion disks with different values of the temperature of the inner layer T_{in} .

The maximum temperature of a thin accretion disk around a Schwarzschild black hole occurs at $r = \frac{49}{36}r_g$, and is:

$$T_{\text{max}} = 1.4 \times 10^5 \left(\frac{\dot{M}}{0.1 \dot{M}_{\text{Edd}}} \right)^{1/4} \left(\frac{\eta}{0.08} \right)^{-1/4} \left(\frac{M}{10^7 M_{\odot}} \right)^{-1/4} \text{ K}.$$

For parameters typical of a Seyfert 1 galaxy, one obtains an energy of $kT_{\text{max}} = 12 \text{ eV}$, where k is Boltzmann's constant. From this value one can already see that the disk alone cannot account for the X-ray emission observed in AGN. Recently, [Davis & Laor \(2011\)](#) proposed a way to measure the accretion rate in AGN based on the optical luminosity $L_{\text{opt}} \equiv \nu L_{\nu}$ at $4686 \text{ \AA}$,

$$\dot{M} = 3.5 M_{\odot} \text{ yr}^{-1} (L_{\text{opt},45})^{3/2} M_8^{-0.89},$$

where $M_8 = M_{\text{BH}}/10^8$, and $L_{\text{opt},45} = L_{\text{opt}}/10^{45} \text{ erg s}^{-1}$. Using a sample of ~ 80 PG Quasars, they also found a possible correlation between the efficiency and the black hole mass,s

$$\eta \simeq 0.089 M_8^{0.52}.$$

However, it has been argued by [Raimundo et al. \(2011\)](#) that this correlation between η and M_{BH} might not be intrinsic, but due to a bias in the sample used.

Alternative accretion scenarios

Besides thin accretion disks, three other solutions to the hydrodynamic equations of viscous rotating flows exist.

- The Shapiro, Lightman, & Eardley solution (1976, SLE) considers an accreting gas forming a two temperature plasma, with the ion temperature being greater than that of the electrons ($T_i \sim 10^{11}$ K, $T_e \sim 10^{8-9}$ K). The gas is optically thin and would produce a power-law spectrum in the X-rays and in the soft γ -rays. This solution is however known to be thermally unstable (Piran 1978), and it is not thought to be realistic.
- The optically thick advection-dominated accretion flow (or optically thick ADAF) solution was found for objects accreting at super-Eddington accretion rates (Katz 1977, Abramowicz et al. 1988). In this scenario, the large optical depth of the inflowing gas traps most of the radiation, advecting it into the central black hole.
- The optically thin ADAF (two-temperature ADAF) solution is found for objects accreting at sub-Eddington accretion rates (Narayan & Yi 1994). In this scenario, the accreting gas has a very low density, and is unable to cool efficiently within an accretion time. The viscous energy is therefore stored in the gas as thermal energy instead of being radiated, and is advected into the central object. The gas is optically thin, and has a two-temperature configuration, as for the SLE solution.

An alternative scenario to the accretion disk models, involves accretion of matter in clumps (Courvoisier & Türler 2005, Ishibashi & Courvoisier 2009). The interaction of these clumps at ~ 100 Schwarzschild radii generates optically thick shocks that produce optical-UV photons, whereas the X-rays are generated in optically thin shocks closer to the central black hole.

1.2.3 The Broad-Line Region

Broad emission lines are one of the dominant characteristics of AGN spectra. These lines are assumed to be Doppler-broadened, and are thought to be produced in a region close to the black hole, normally referred to as broad-line region (BLR). The broad emission lines of AGN are an useful probe of the central engine. In fact the bulk motions in the BLR are regulated by gravity (due to the black hole) and radiation pressure (from the accretion disk), although the influence of outflows (see Chapter 5) should probably also be taken into account. The widths of AGN broad lines span over two order of magnitudes, and range from a minimum of $\Delta v_{FWHM} \simeq 500 \text{ km s}^{-1}$ (not so much larger than the narrow lines) to $\Delta v_{FWHM} \gtrsim 10^4 \text{ km s}^{-1}$, with typical values of $\Delta v_{FWHM} \simeq 5000 \text{ km s}^{-1}$. The strongest lines observed in the typical spectrum of an AGN are the hydrogen Balmer-series lines ($H\alpha$, $H\beta$ and $H\gamma$), the hydrogen $\text{Ly}\alpha$, and lines from abundant ions (Mg II , C III , and C IV), for an example see Fig. 1.4. Details on these lines are reported in Table 1.1. In addition to these lines, there are several which are blended because of their large Doppler widths. A list of these lines is reported in Table 1.2.

The broadening of the emission lines is not due to thermal motion. In fact from the lines relative intensities one can calculate that the gas temperature is $T \sim 10^4$ K. The velocity dispersion for a gas with such a temperature would be $v \sim (kT/m_p)^{1/2} \sim 10 \text{ km s}^{-1}$, which is much less than the typical width observed in AGN. If the broadening is purely thermal, then from the typical widths of broad emission lines, one would have an unrealistic temperature of $T \gtrsim 10^9$ K. Most of the broadening is thus attributed to bulk motions of individual line-emitting clouds. The absence of forbidden lines as

[O III] $\lambda 5007$ gives a lower limit to the ion density of $\sim 10^8 \text{ cm}^{-3}$ (Netzer 1990), although the strong Ly α and C IV are probably produced in environments with higher densities of $\sim 10^{11} \text{ cm}^{-3}$. The equivalent width of the Ly α line allows to estimate the fraction of the continuum absorbed by the BLR, and its covering factor ($f = \Sigma/4\pi$), which results to be $\sim 10\%$.

The mass of the BLR can be calculated from the luminosity of C IV ($M_{\text{BLR}} \sim 10^{-3} L_{42}(\text{C IV}) M_{\odot}$) and is negligible compared to that of the central black hole. In fact, even for the most luminous AGN one obtains $M_{\text{BLR}} \simeq 10 M_{\odot}$. The distance of the BLR from the central black hole can be inferred studying the delay of the broad emission lines with respect to the continuum, and it is found to vary with the luminosity ($R_{\text{BLR}} \propto L^{0.7}$, Kaspi et al. 2000). The average values found are of 0.01-0.1 pc for Seyfert 1s, and up to ~ 1 pc for bright quasars.

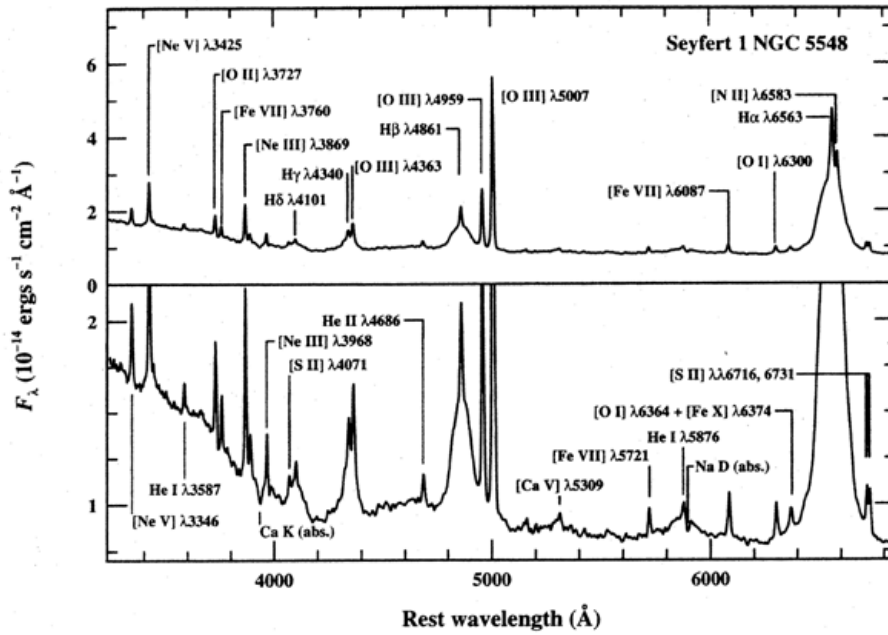


Figure 1.4: Ultraviolet spectrum of the Seyfert 1 NGC 5548. The spectrum highlights some of the most important features produced in the BLR. Figure from Peterson (1997)

1.2.4 The Narrow-Line Region

The narrow-line region (NLR) is the most extensive component of AGN, and the only one which can be resolved by optical observations. Unlike the BLR, in the NLR the electron density is low enough that many forbidden transitions are not collisionally suppressed. Some of the most prominent narrow lines are Ly α $\lambda 1216$, C IV $\lambda 1549$, C III] $\lambda 1909$, [O III] $\lambda 4959$, [O III] $\lambda 5007$, [N II] $\lambda 6584$ and [S II] $\lambda 6717$. The full width at half maximum for narrow emission lines lies in the range $200 \lesssim \Delta v_{\text{FWHM}} \lesssim 900 \text{ km s}^{-1}$, with most of the lines having values of $350 - 500 \text{ km s}^{-1}$. Analogously to the BLR, the distance of the NLR to the central engine also scales with luminosity ($R_{\text{NLR}} \propto L^{0.5}$), and in Seyfert galaxies has sizes of $\sim 100 - 300$ pc, while it might reach diameters of up to few kpc for bright quasars.

The mass of the NLR can be calculated from the luminosity of H β ($M_{\text{NLR}} \simeq 7 \times 10^5 L_{41}(\text{H}\beta) / n_3 M_{\odot}$, where n_3 is the electron density in units of 10^3 cm^{-3}). The mass of the NLR is several orders of magnitude larger than that of the BLR, although the amount of line mission produced is often comparable

Table 1.1: Typical emission lines observed in AGN, table adapted from [Peterson \(1997\)](#).

Line	Relative flux*	Equivalent width ($\text{\AA}$)
$\text{Ly}\alpha \lambda 1216 + \text{N V } \lambda 1240$	100	75
$\text{C IV } \lambda 1549$	40	35
$\text{C III] } \lambda 1909$	20	20
$\text{Mg II } \lambda 2798$	20	30
$\text{H}\gamma \lambda 4340$	4	30
$\text{H}\beta \lambda 4861$	8	60

* Normalized in such a way that $\text{Ly}\alpha + \text{N V} = 100$

for the two regions. This is due to the fact that the emissivity of recombination lines is proportional to the ion density, which makes the BLR more efficient than the NLR.

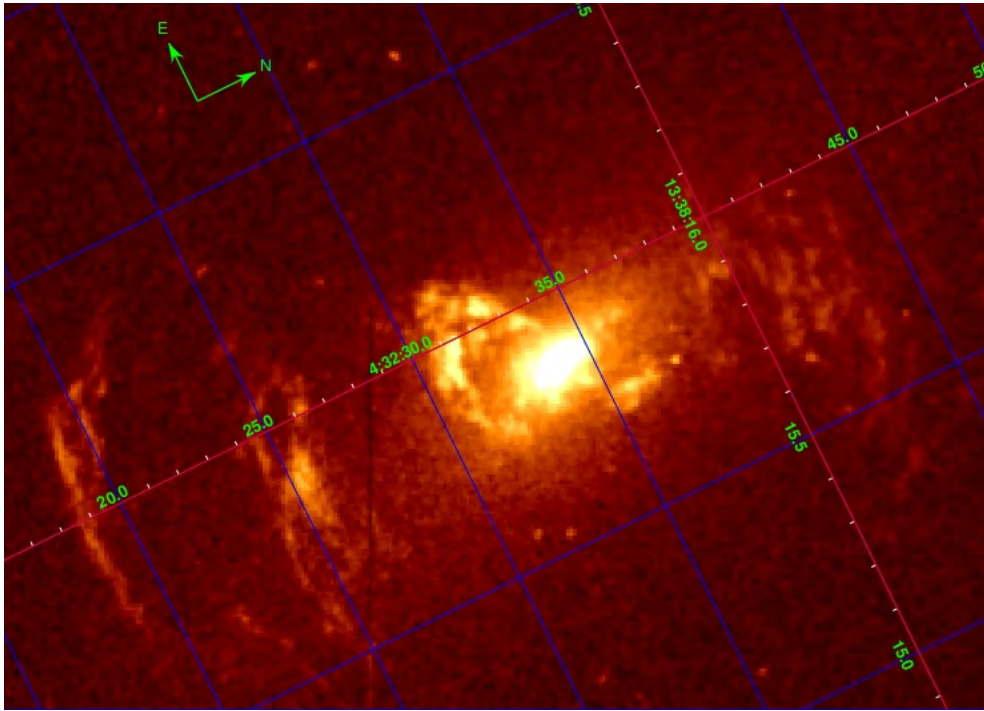


Figure 1.5: $[\text{O III}]$ ionization cone of NGC 5252 observed by the Wide Field Camera on board of the Hubble Space Telescope ([Dadina et al. 2010](#)).

The NLR is normally found to be axisymmetric rather than spherically symmetric. One of the most interesting features of AGN are the "ionization cones" (e.g., [Pogge 1988](#)) which are clearly detected in maps of high-excitation lines as $[\text{O III}] \lambda 5007$ (see Fig. 1.5). These cones have a $[\text{O III}] \lambda 5007 / \text{H}\alpha$ flux ratio higher than one, which is characteristics of low-density gas ionized by the AGN continuum. Outside the cone the ratio is instead lower than the unity, which implies that the gas is mostly ionized by starlight.

Table 1.2: List of blended broad lines, table adapted from [Peterson \(1997\)](#).

Feature	Contributing Lines
Ly β + O VI λ 1035	Ly β λ 1026; O VII $\lambda\lambda$ 1032, 1038
Ly α + N V	Ly α λ 1216; N V $\lambda\lambda$ 1239, 1243
Si IV + O IV]	Si IV $\lambda\lambda$ 1394, 1403; O IV] λ 1402
C IV λ 1549	C IV $\lambda\lambda$ 1548, 1551
He II + O III]	He II λ 1640; O III] λ 1663
C III] + Si III]	Al III λ 1857; Si III] λ 1892; C III] λ 1909
Small blue bump	Balmer continuum ($\lambda < 3646 \text{ \AA}$); Fe II (many lines)
Mg II λ 2798	Mg II $\lambda\lambda$ 2796, 2803
Fe II λ 4570 + He II	Fe II (multiplets 37, 38, & 43); He II λ 4686
H β	H β λ 4861; Fe II $\lambda\lambda$ 4924, 5018 (multiplet 42)
Fe II $\lambda\lambda$ 5190, 5320	Fe II (multiplets 42, 48, 49, and 55)

1.2.5 The Corona

X-ray variability time scales indicate that the X-rays in AGN are produced in a small region located close to the black hole. The possibility that the disk is responsible for the X-ray emission can be discarded on the basis that even very warm disks are not supposed to exceed few hundreds eV (see Sect. 1.2.2). It is now widely accepted that the X-ray emission of AGN is produced by Comptonization of optical-UV photons produced in the accretion disk by a corona of hot electrons. Inverse Compton upscatters to higher energies photons when their mean energy ($\langle E \rangle$) is smaller than the thermal energy of the electrons (of temperature T_e): $\frac{\langle E \rangle}{mc^2} < \frac{4kT_e}{mc^2}$. For $h\nu \ll m_e c^2$ the gain rate of the photon field is given by

$$\frac{dE}{dt} = \frac{4}{3} \sigma_T c U_{\text{rad}} (v^2/c^2) \gamma^2,$$

where σ_T is the Thomson cross-section, U_{rad} the energy density of the photon field, and $\gamma = \sqrt{1 - v^2/c^2}$. The spectrum created by this process depends on the Compton parameter y , given by

$$y = \frac{kT_e}{m_e c^2} \max(\tau_e, \tau_e^2),$$

where τ_e is the optical depth of the corona. The Compton parameter is basically the product of the average energy gain per scatter and the total number of scatterings. If the electron gas is optically thin, it can be shown ([Shapiro et al. 1976](#)) that the spectrum is a power-law with a photon index given by

$$\Gamma = -\frac{1}{2} + \sqrt{\frac{9}{4} + \frac{4}{y}}.$$

As the energy of the photons becomes comparable to the thermal energy of the electrons, the power law emission declines in a cutoff at $E_C \simeq 3kT_e$.

The origin and the geometry (see Fig. 1.6) of the hot corona is still debated, several hypothesis

have been put forward in the last years. In the following I describe three of them: magnetic flares, clumpy discs and aborted jets.

- **Magnetic flares.** A popular explanation for the heating of the electrons in the corona is related to the presence of flares above the accretion disc, similarly to what is observed in the solar corona. Although the physical details are rather unclear, magnetic flares are a reasonably working hypothesis to model X-ray spectra and variability of AGN (e.g., [Haardt et al. 1994](#), [Goosmann et al. 2006](#)). The possible evidence for hot spots corotating with the disk may support this scenario (e.g., [Iwasawa et al. 2004](#)). In this scenario the magnetic flares heat the electrons, which then Comptonize the UV photons from the disk, upscattering them into the X-rays.
- **Clumpy disks.** The hypothesis that the accretion flow breaks up in two phases due to disk instabilities was originally proposed by [Guilbert & Rees \(1988\)](#). In this model one part of the disk is hot and optically thin, while the other is cold and optically thick. The hot phase is responsible for the primary X-ray emission, while the cold phase provides the seed photons for the Comptonization and it reprocesses the primary continuum.
- **Aborted jets.** The idea that the primary X-ray emission of AGN comes from an aborted jet (a jet that stops in the proximity of the supermassive black hole) was introduced by [Henri & Petrucci \(1997\)](#). [Ghisellini et al. \(2004\)](#) proposed a lack of momentum to explain the jet failure. If the matter is launched (at the expense of the angular momentum of the black hole) on the black hole axis in form of blobs, and the velocity of these blobs is lower than the escape velocity, then the blob comes back and collides with the blobs that are being ejected. Kinetic energy is then converted into internal energy, providing the hot electrons necessary to Comptonize the UV photons from the disk.

An alternative model for the production of X-rays has been proposed by [Ishibashi & Courvoisier \(2009\)](#), who pointed out that shocks in a clumpy accretion flow might also produce the observed X-ray luminosities.

1.2.6 The Jets

After the first observations of radio lobes in galaxies in the early 50's ([Jennison & Das Gupta 1953](#)), it was thought that these structures were ejected and completely detached from the host galaxy. It was not until the late 1960's that it was realized ([Rees 1966](#)) that they could actually be powered through jets emitted from the center of galaxies. In the last few decades, in particular thanks to the development of radio interferometry techniques, it has been possible to detect jets in many sources and to resolve even their inner parts (e.g., [Chang et al. 2010](#)). Jets are now known to extend on scales from parsec to hundreds of kpc, are highly collimated and can have continuous appearance or can present knots. Luminous objects sometimes show two jets with very different intensities. This, together with the observation of apparent superluminal motions in the jet of some objects ([Whitney et al. 1971](#)), is interpreted as an effect of orientation and Doppler boosting. The production, acceleration and collimation of jets is still poorly understood. Some of the most popular models are based on magnetohydrodynamics (e.g., [Blandford 2001](#)), and involve the presence of strong electromagnetic fields that convert the rotational kinetic energy of a rotating black hole into an outflow through coupling with differential rotation.

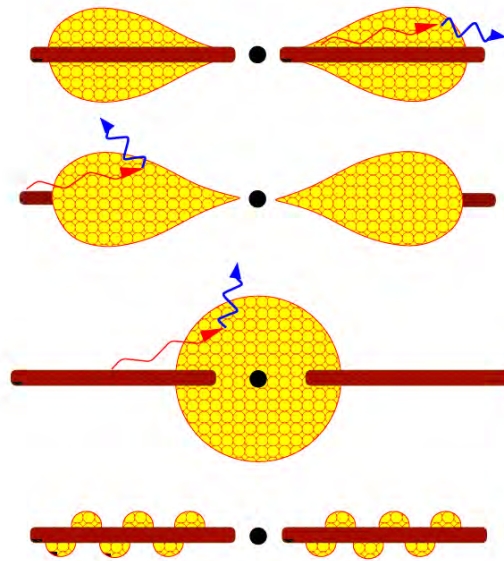


Figure 1.6: Some of the possible geometries for the accretion disk and the Comptonizing corona of AGN. The top panel shows a *slab* or *sandwich* geometry. The remaining three show photon starved geometries, namely geometries in which the corona is less effectively cooled by soft photons from the disk. The two geometries in the middle panels are often referred to as *sphere+disk* geometries, while the bottom geometry is often referred to as a *patchy corona* or *pill box* (Reynolds & Nowak 2003).

1.3 AGN classification

AGN can be distinguished from normal non-active galaxies in several different ways. One of the most commonly used diagnostics are the so called BPT diagrams (Baldwin et al. 1981), which show the ratios of several lines (e.g., [O III]/H β vs [N II]/H α , [O III]/H β vs [S II]/H α , and [O III]/H β vs [O I]/H α , see Fig. 1.7). Comparing these ratios to theoretical values, one can easily spot the objects that cannot be photo-ionized by pure stellar emission, but need other mechanisms, such as AGN or shocks. Similarly, one can distinguish AGN from starburst galaxies or pure stellar emission.

Probably the best way to recognize AGN is thanks to X-ray surveys, X-ray emission in AGN being practically ubiquitous. Other techniques involve radio selection, which was also the first method used to find AGN, or the study of IR colors. For a complete review on the subject one can consult Mushotzky (2004).

AGN come in many flavors. A first division between different types of AGN is based on the relative strength of their radio emission, which is normally associated to the presence or the absence of a jet. AGN with a strong radio emission are called radio-loud, while those weak in the radio band are called radio-quiet. The distinction between radio-loud and radio-quiet objects is usually based on the radio loudness parameter, $R = F_R/F_o$, which is defined as the ratio of monochromatic luminosities at 5 GHz and optical B band at 4400 Å. Kellermann et al. (1989), studying the distribution of the R parameter in the Palomar Bright Quasar Survey, were the first to find evidence of bimodal distribution, which implied the existence of two distinct classes: radio-quiet ($R \sim 0.1 - 1$) and radio-loud ($R \sim 10 - 1000$). The classical boundary between the two populations is set at $R \sim 10$ (Kellermann et al. 1994). An alternative way to quantify the radio loudness of a source is to weight the emission in the radio intensity with that in the X-rays. Terashima & Wilson (2003) introduced

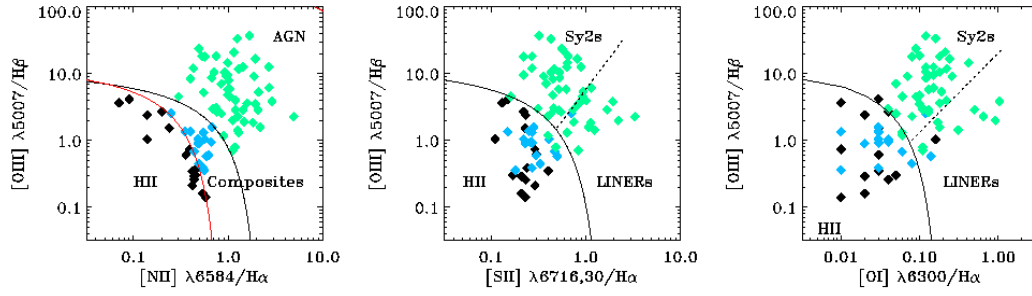


Figure 1.7: BPT diagrams for a large number of IR-selected objects. HII galaxies are in black, Seyfert 2s in blue, and LINERs green (Brightman & Nandra 2011b).

the parameter $R_X = \nu L_\nu(5GHz)/L_X$, where L_X is the luminosity in the 2 – 10 keV energy band. The threshold of this parameter, above which the object is considered radio-loud, is commonly set to $\log R_X = -4.5$.

1.3.1 Radio-quiet AGN

Radio-quiet AGN are divided into low luminosity Seyfert galaxies (Sy) and high luminosity quasars. The division between the two classes is usually set to $M_B = -23$ mag, where M_B is the absolute magnitude in the B band. Seyfert galaxies are the most common AGN in the local universe, and are classified according to their emission lines into Seyfert 1 (showing broad and narrow emission lines), and Seyfert 2s (showing only narrow lines). Many Seyfert galaxies exhibit permitted line profiles with both very broad and relatively narrow components (Osterbrock & Koski 1976, Osterbrock 1981a, Cohen 1983). These objects have been classified as type 1.2, 1.5, 1.8 or 1.9 Seyfert galaxies, depending on the relative contributions of the two components to the total permitted line profiles (see Table 1.3). A parameter often used to distinguish one class from the other is R_s , the ratio of the broad H β flux to that of [OIII] $\lambda 5007$ (e.g., Véron-Cetty & Véron 2010). For Sy1s one has $R_s > 5.0$, for Sy1.2s $2 < R_s < 5$, for Sy1.5s $0.33 < R_s < 2.0$ and for Sy1.8s $R_s < 0.33$. In Sy1.9s and Sy2s H β is not detected, thus one cannot use the R_s parameter.

Narrow line Seyfert 1s (NLS1s) are a particular class of Sy1s, characterized in the optical by permitted lines only slightly broader than the forbidden ones. The first of this class to be noticed for the strange properties of its optical spectrum was Mrk 359 (Davidson & Kinman 1978). In the following years many more sources showing similar characteristics were found, which led Osterbrock & Pogge (1985) to classify them as part of a new class. In the optical, NLS1s have $\text{FWHM}(H\beta) < 2000 \text{ km s}^{-1}$, they often show a strong emission from FeII multiplets, and they have a weak [OIII] emission, with a ratio $[OIII]/H\beta < 3$. It has been suggested that NLS1 are AGN in their early phase (Grupe et al. 1999), characterized by relatively small black hole masses (e.g., Grupe & Mathur 2004) and very high accretion rates in terms of Eddington units (e.g., Grupe et al. 2010). In this scheme the small black hole mass would be responsible for the narrow optical lines, the matter in the broad line region (BLR) having lower velocities than in broad line Seyfert 1s (BLS1s).

The optical spectra around the H β region of a Sy1, a Sy2 and a NLS1 are shown in Fig. 1.9, from which it is possible to see the main differences amongst these three different classes.

Low-ionization nuclear emission-line regions (LINERs) are a peculiar type of AGN (Heckman 1980). Their spectra typically include line emission from weakly ionized or neutral atoms, such as

Table 1.3: Characteristics of the optical spectra of different types of Seyfert galaxies. Table adapted from Véron-Cetty & Véron (2010).

Class	Characteristics
Seyfert 1	Narrow and broad emission lines
Seyfert 1.2	Weaker $H\beta$ component than Seyfert 1s
Seyfert 1.5	Strengths of the broad and narrow components in $H\beta$ are comparable
Seyfert 1.8	Broad components are very weak, but detectable in $H\beta$ as well as $H\alpha$
Seyfert 1.9	Broad component is detected only in the $H\alpha$ line, and not in the higher order Balmer lines
Seyfert 2	Narrow emission lines only

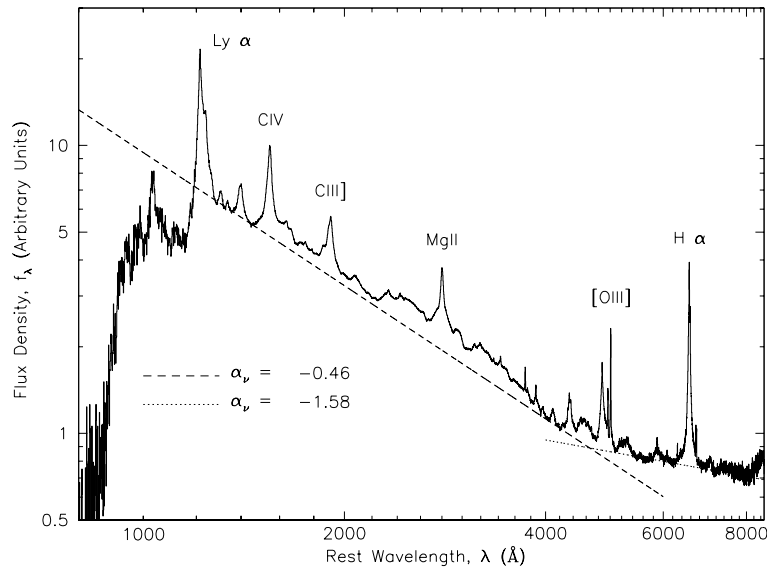


Figure 1.8: Composite spectrum of Type-1 AGN taken from the SDSS (Vanden Berk et al. 2001). The continuum is fitted with a broken power law.

O, O^+ , N^+ , and S^+ , while emission from strongly ionized atoms, such as O^{++} , Ne^{++} , and He^+ , is relatively weak. Spectroscopically, the LINERs might resemble Seyfert 2 galaxies, although some differences are evident (see also Fig. 1.10): the $[OIII]/H\beta$ flux ratio is much larger in Seyfert 2s, and low-ionization lines are more prominent. LINERs are also classified, analogously to Seyfert galaxies, in type 1 and type 2, depending to the presence or absence of broad-line emission (Ho et al. 1997a). LINERs are very common: approximately one-third of all nearby galaxies (within approximately 20-40 Mpc) may be classified as LINER.

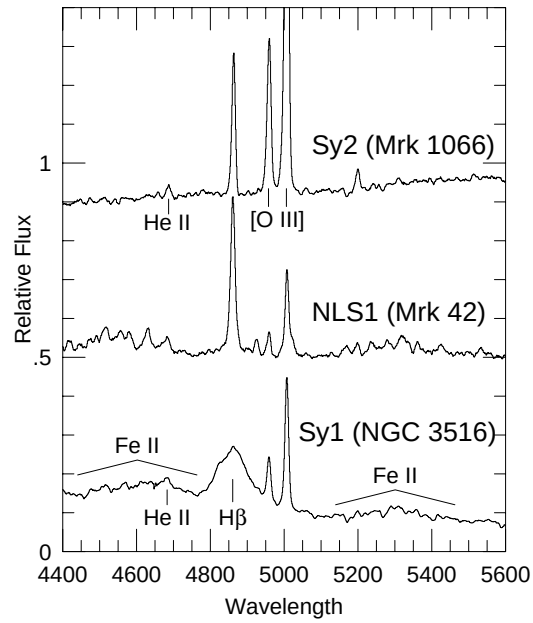


Figure 1.9: Optical spectrum around the H β region of the Sy2 Mrk1066, the Sy1 Mrk42 and the NLS1 NGC 3516 (Pogge 2000).

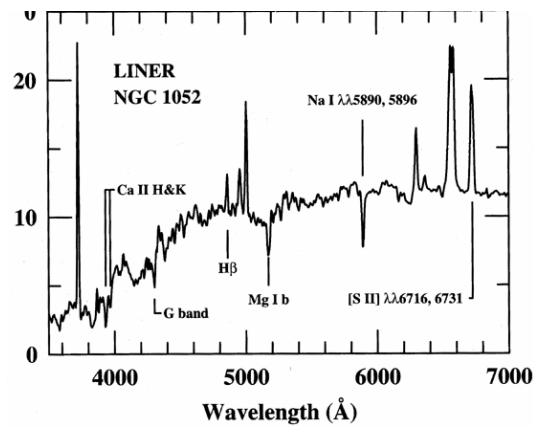


Figure 1.10: Optical spectrum of the LINER NGC 1052 (Ho et al. 1993), figure adapted by Peterson (1997). The image shows the most important emission lines, along with some strong absorption lines from the host galaxy.

1.3.2 Radio-loud AGN

Radio-loud AGN can be classified as radio galaxies (the radio-loud equivalent of Seyfert galaxies), radio quasars and blazars

Analogously to Seyfert galaxies, radio galaxies are divided into narrow line radio galaxies (NLRG) and broad line radio galaxies (BLRG), depending to whether their optical spectra show only narrow lines, or both broad and narrow lines, respectively. According to their morphology they are then classified in Fanaroff-Riley Type I (FRI) or Type II (FRII) (Fanaroff & Riley 1974), the former appearing edge-darkened, and the latter edge-brightened. The formal division between the two classes is normally at 178 MhZ, where FRI radio galaxies have a power $P \lesssim 2 \times 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1}$, while for FRII $P \gtrsim 2 \times 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1}$.

The blazar class includes BL Lac objects and Optically Violent Variable (OVV) quasars. They are characterized by a non-thermal, highly variable, beamed continuum emission. BL Lac objects have lower luminosities and much weaker, if any, emission lines than OVV. Radio quasars are divided, according to the value of their radio spectral index, in flat-spectrum radio quasars (FSRQ) and steep-spectrum radio quasars (SSRQ). This classification reflects the different extension of the radio emitting region in the two classes: a flat spectrum indicates a self-absorbed synchrotron emission from a compact region, whereas a steeper spectrum reflects the dominance of the emission from the radio lobes over the nuclear emission.

1.4 The Unified Model

The weakest form of AGN unification, namely the hypothesis that all AGN are powered by accretion onto SMBHs, is nowadays completely accepted. Going beyond this basic point things become more controversial. The basic idea of unified models is that radio-loud AGN can be unified through an orientation based scheme where jet direction plays a key role (Urry & Padovani 1995), and that radio-quiet AGN can be unified through an orientation based scheme where an obscuring torus (or something similar) plays a key role (Antonucci 1993). A grand unified model, able to explain the reason for the radio-quiet/radio-loud dichotomy, has not been found yet. Several models have been proposed over the years to account for the presence of radio activity. A possible explanation is that in radio-quiet AGN the jets are disrupted and cannot escape the host galaxies, as observed in the Seyfert galaxy NGC 4151 (Mundell et al. 2003). Another model interprets the observed radio dichotomy in terms of the spin of the black hole: objects with a higher spin-rate have a higher probability of producing radio jets (Begelman et al. 1984). In Fig. 1.11 a schematic representation of the unified model of (radio-loud and radio-quiet) AGNs is shown.

1.4.1 Radio-quiet unification

The presence of intermediate objects between Seyfert 1s and Seyfert 2s was firstly explained by differences due to varying amounts of absorbing material along the line of sight. This led to the introduction of a dust shell having any possible geometry, from a 4π shell with varying thickness to an angle-dependent axisymmetric structure or a patchy distribution of dust. The discovery of polarized broad lines in the spectrum of the Seyfert 2 galaxy NGC 1068 (Antonucci & Miller 1985) led to the idea that AGN are surrounded by a torus-like distribution of matter. In this scheme the broad lines observed in the polarized spectrum of NGC 1068 are produced by reflection of the radiation emitted in the BLR. According to the unified model of radio-quiet AGN, all the objects have a dusty torus extending from 1 to 100 pc from the center, and in this frame Seyfert 1s are observed

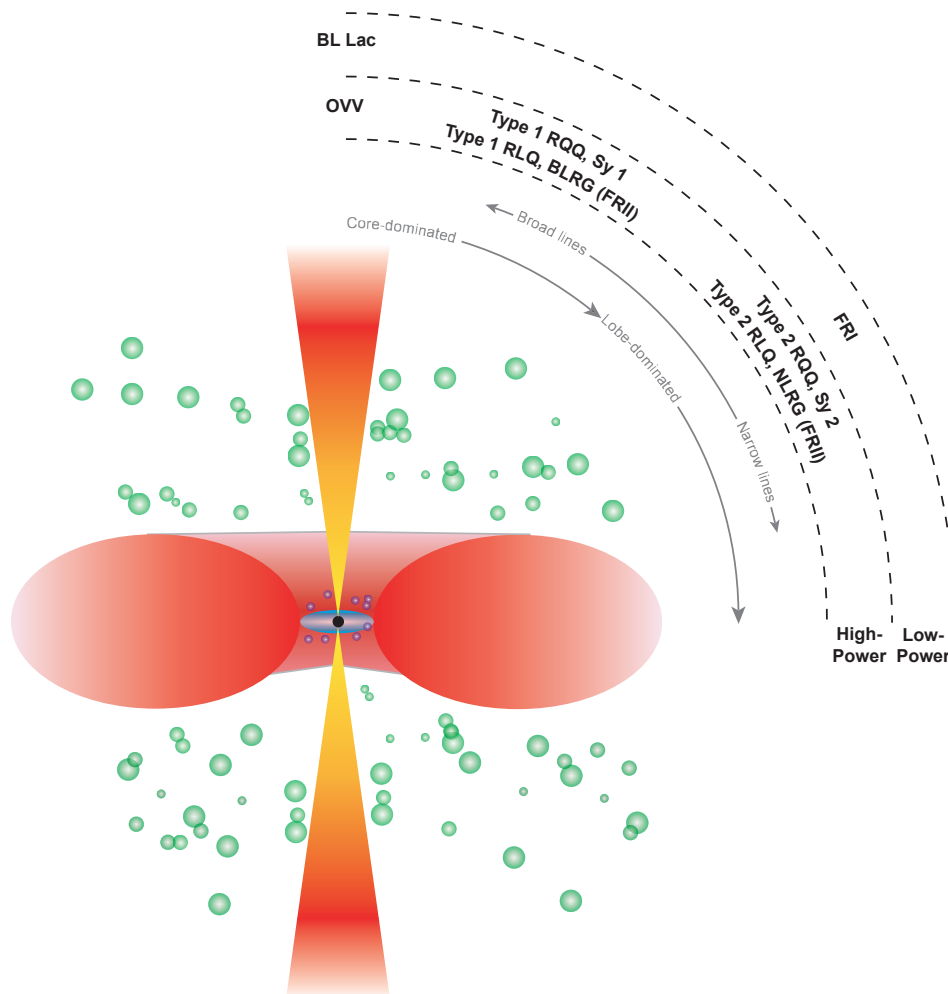


Figure 1.11: Unification model of radio-loud and radio-quiet AGN (Evans 2005).

pole on (see Fig. 1.11) thus that the observer can look at both the BLR and the NLR at the same time, whereas Seyfert 2s are observed edge on, so that the BLR is obscured and one can see only the NLR. The observations of cone-shaped ionized matter in Seyfert 2 galaxies (e.g., NGC 5728, Wilson et al. 1993) strengthened the idea that the absorber has a toroidal shape. The radio-quiet unification will be discussed more in detail in Chapter 8.

1.4.2 Radio-loud unification

Radio-loud AGN are more difficult to understand in the frame of unified schemes, because besides the obscuring material, they have an extra degree of freedom, which is given by the presence of relativistic jets. Differences between broad and narrow line radio galaxies are in rough accord with the idea that the obscuring tori also exist in radio-loud AGN, but this is one of the least well established aspects of the unification scenario.

At low AGN power, the BL Lacs are now commonly interpreted to be the Doppler boosted counterparts of the FR I radio galaxies. The statistics of these populations as seen at different radio frequencies are nicely explained if the BL Lacs are really FR I radio galaxies viewed within a narrow

angle of $\sim 10^\circ$ to the line-of-sight (Urry & Padovani 1995). If this is the case, the BL Lacs are actually intrinsically weaker than other AGN classes, but their observed emission is dramatically boosted by special relativistic effects. At high energy power, it has been proposed by Barthel (1989) that FRII radio galaxies are the misaligned parent population of radio loud quasars, while the core dominated, strongly variable quasars (OVV, FSRQ) are objects for which the jet and the line-of-sight are almost completely aligned.

A poorly understood aspect of the nature of radio-loud AGN is the reason for the differences between FR I and FR II classes. The power of the jet compared with the nature of the ambient medium through which it propagates might play a major role (Bicknell 1994), or there might be an intrinsic difference in the engine of different classes. In this frame, Reynolds et al. (1996) proposed a model in which FRII radio galaxies have a standard accretion disk, while FRI radio galaxies have ADAF.

1.5 A panchromatic view of an AGN

In the following I will report some of the most salient characteristics of AGN, in particular of the radio-quiet ones, in the radio, IR, optical and UV. The X-ray energy band will be broadly discussed in the next chapter (Chapter 2). The spectral energy distribution (SED) of a typical radio-loud and a typical radio-quiet AGN are shown in Fig. 1.12.

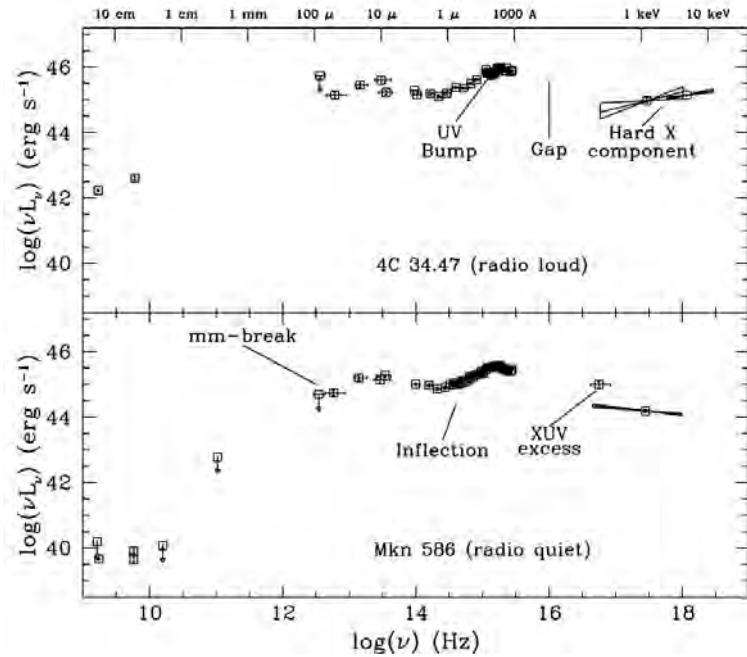


Figure 1.12: Radio to X-ray spectral energy distribution of a typical radio-loud (*upper panel*) and radio-quiet (*lower panel*) AGN (Elvis et al. 1994).

1.5.1 Radio emission

In Seyfert galaxies the radio emission contributes only marginally to the total bolometric luminosity, being the radio flux normally 5 to 6 orders of magnitude lower than the UV/optical one. While in radio-loud AGN the radio emission is clearly connected to the jets, in radio-quiet sources it is mostly unresolved on large scales, and high-resolution imaging shows compact radio emission. Radio variability of radio-quiet AGN, together with their flat radio spectra, indicates the presence of a compact non thermal source. In these objects radio emission is thought to originate in low power jets that do not extend much further from the core, which would explain why no resolved emission is observed.

1.5.2 Infrared emission

Observations performed by *IRAS* and *ISO* revealed that Seyfert galaxies are strong far-infrared (FIR) and mid-infrared (MIR) sources, this emission being of thermal origin, and due to a combination of a warm, a cold, and a very cold dust component. This infrared emission is generally thought to arise from the reprocessing of the primary radiation in the dusty torus surrounding the central engine. The different components are thought to be produced by dust heated by different mechanisms. The warm

($T_W \sim 120 - 170$ K) component is produced by dust heated by either the AGN or a circumnuclear starburst, the cold component ($T_C \sim 30 - 70$ K) by dust is heated by stars located in the host galaxy disk, and the very cold component ($T_{VC} \sim 15 - 25$ K) by dust is heated by the interstellar radiation field. Observations at the end of the far-infrared band show a sub-millimeter break, which is normally attributed to the rapid loss of efficiency of dust grains at longer wavelengths. Infrared variability is also consistent with dust emission, and from the observed delays between infrared and UV continuum one can infer the position of the emitting dust from the nucleus. For the Seyfert galaxy Fairall 9, for instance, this distance is calculated to be ~ 0.3 pc (Clavel et al. 1989). The mid-infrared spectra of Sy1s and Sy2s present some differences. In this energy band ($2.5-11\mu\text{m}$) the spectrum of Sy1s is characterized by a strong continuum, with only weak emission features from the polycyclic aromatic hydrocarbons (PAH) bands, while most Sy2s display a weak continuum but very strong emission in the PAH bands (Clavel et al. 2000). The depleted continuum in Seyfert 2s is attributed to obscuration by dust. Both Sy1s and Sy2s have similar PAH luminosities. This component is thought to be unrelated to the nuclear activity, and to arise in the interstellar medium of the host galaxy bulge.

1.5.3 Optical-UV emission

The main characteristics of the optical-UV spectrum of most AGN is the so-called *big blue bump*. The exact shape of the big blue bump is confused by the large amount of broad and blended lines emitted in the BLR, but its origin is normally attributed to the thermal emission of the accretion disk, and modeled as a multi-color blackbody spectrum. The optical/UV emission of AGN, above all obscured objects, is affected by contamination from the host galaxy and intrinsic reddening caused by dust. In Seyfert 2 galaxies the main component of the optical continuum is the starlight from the host galaxy, although a featureless emission is also found to contribute significantly to the spectrum. Scattered light can explain only $\sim 20\%$ of this emission, and other solutions have been proposed, such as starburst emission (Heckman et al. 1995).

1.5.4 Indicators of bolometric luminosity

Determining the intrinsic luminosity of AGN is not an easy task. To have an estimate of the luminosity which is unbiased by absorption one needs to find an isotropic indicator of the intrinsic AGN luminosity. The NLR extends hundreds of parsecs away from the central engine and is believed to be affected by very low reddening, thus the lines formed in this region can be used to estimate the bolometric luminosity of the AGN. The flux of the [O III] $\lambda 5007$ line is commonly used as such a diagnostic (e.g., Bassani et al. 1999), being one of the most prominent lines emitted in the NLR and suffering a little contamination from star formation processes in the host galaxy. The [O III] $\lambda 5007$ line can however be affected by extinction caused by dust in the host galaxy. This problem is normally solved by applying a reddening correction obtained using the observed Balmer decrement (i.e., the observed ratio of the narrow $\text{H}\alpha/\text{H}\beta$ emission lines compared to the intrinsic ratio) and the extinction curve for galactic dust. However, recently it has been shown that other indicators are better suited to estimate the bolometric luminosity of AGN than the [O III] line. One of them is the infrared [O IV] $25.89\mu\text{m}$ emission line, also produced in the NLR but less affected by dust extinction than the [O III] line, and not significantly influenced by starburst emission (e.g., Meléndez et al. 2008). About 20% of the AGN bolometric flux is re-emitted in the mid-infrared (MIR) band by the dusty torus. This band energy band has also been proposed as a possible indicator, although it suffers from contamination by emission from dust (e.g., Deo et al. 2009) and possible anisotropies

in the torus emission (e.g., [Elitzur & Shlosman 2006](#)). The 2–10 keV emission can also be used as a proxy for the bolometric luminosity of AGN (e.g., [Marconi et al. 2004](#)). Seyfert 1s and Seyfert 2s have been shown to have consistent radio emission (e.g., [Diamond-Stanic et al. 2009](#)), thus radio emission, although not omnipresent, might be an indicator of the intrinsic AGN power. Hard X-rays can also be a very good proxy of the bolometric luminosity of AGN, as they are not significantly affected by absorption, at least up to $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$ (see Sect. 2.2).

The X-ray emission of AGN

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X-ray emission has been found to be an universal characteristic of AGN (Elvis et al. 1978), with their luminosity spanning at these frequencies the range $10^{42} - 10^{48}$ erg sec $^{-1}$, and representing a considerable fraction of their bolometric luminosity ($\sim 5 - 40\%$, Ward et al. 1987). Besides being one of the hallmarks of AGN, the X-ray emission also allows to probe the physical conditions very close to the central black hole and the accretion disk, something which is impossible to do at other wavelength.

In Fig. 2.1 the main features of the X-ray spectra of a type-1 AGN are shown. In the following I will introduce the different components observed in the spectrum of Seyfert galaxies: in Sect. 2.1 the primary power-law, in Sect. 2.2 the role of absorption in the X-rays, in Sect. 2.3 the reprocessed emission and in Sect. 2.4 the soft excess. The X-ray spectrum of absorbed AGN will be discussed in Sect. 2.5, and that of radio-loud AGN in Sect 2.6.

2.1 The primary emission

We have seen in Section 1.2.5 that the Comptonization of low energy seed photons in a hot plasma produces a power-law continuum. The seed photons are supposed to come either from the disk (for radio-quiet objects) or from synchrotron processes (for radio-loud objects). A power-law continuum that extends from the lowest observable X-ray energies to a cutoff energy that is somewhere after ~ 100 keV is consistent with X-ray observations of Seyfert galaxies.

The flux as a function of energy of the power-law continuum is given by:

$$F(E) = kE^{-\Gamma} \text{ photons} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{keV}^{-1} \quad (2.1)$$

$$f(E) = AE^{-\alpha} \text{ keV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{keV}^{-1} \quad (2.2)$$

where k and A are the normalizations of the power-law at 1 keV, Γ is the photon index, related to the spectral index α by $\Gamma = \alpha + 1$.

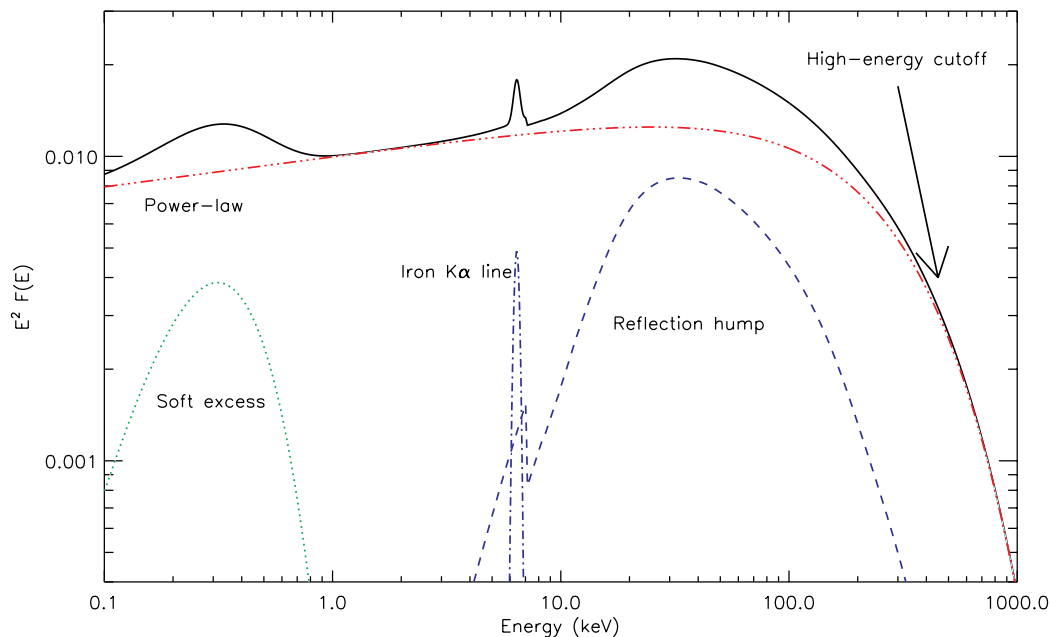


Figure 2.1: Typical X-ray spectrum of an unabsorbed Seyfert galaxies. The figure highlights the different components: the power-law continuum ($\Gamma = 1.9$) extending up to the cutoff energy ($E_C = 300$ keV), the soft excess below few keV, and the iron $K\alpha$ line and the reflection hump ($R = 1$), both signatures of reprocessing of the primary emission.

The power-law shape of the X-ray continuum of AGN was evident since the first observations performed by *Ariel V* (Elvis et al. 1978). The first spectral surveys, carried out by *HEAO-I* and *EXOSAT* found that Seyfert galaxies had photon indices of $\Gamma \sim 1.7 - 1.8$ (Mushotzky et al. 1980; Turner & Pounds 1989). Following observations found a larger scatter in the values of the photon indices. Recent studies of large samples of radio quiet AGN have found that the average value of the photon index ranges between $\Gamma = 1.8$ (Dadina 2008) and $\Gamma = 2.0$ (Beckmann et al. 2009). A recent study of the X-ray spectra of a very large sample of optically selected type-1 AGN (Scott et al. 2011, see Fig. 2.2) found an average value for radio-quiet objects of $\Gamma = 2.01 \pm 0.01$. Using instead an IR-selected sample, Brightman & Nandra (2011a), in the same energy band (0.3–10 keV) found an average value of $\Gamma = 1.83^{+0.06}_{-0.06}$ for type 1 AGN, and of $\Gamma = 1.90^{+0.16}_{-0.17}$ for type-2 AGN.

The existence of a correlation between the luminosity and the photon index is still debated, and several contradictory results have been presented in the last years. While Dai et al. (2004) reported the existence of a positive correlation, other works found none (e.g., Winter et al. 2009) or a negative correlation (e.g., Corral et al. 2011). Also the existence of a possible evolution of the photon index with the redshift is still unclear, while several works found no correlation between Γ and z (e.g., Green et al. 2009), the recent work of Scott et al. (2011) found possible evidence of a flattening at high z . However, the possible influence of selection biases (flatter sources being easier to detect) makes difficult the understanding of whether this correlation is real or not.

Possibly, the most important correlation found so far is between the photon index and the Eddington accretion rate (e.g., Shemmer et al. 2006): objects accreting at higher Eddington rates tend to be steeper. This would imply (for similar values of M_{BH}) also a correlation between Γ and the luminosity. However, Scott et al. (2011) recently found that the correlation between Γ and λ_{Edd} is

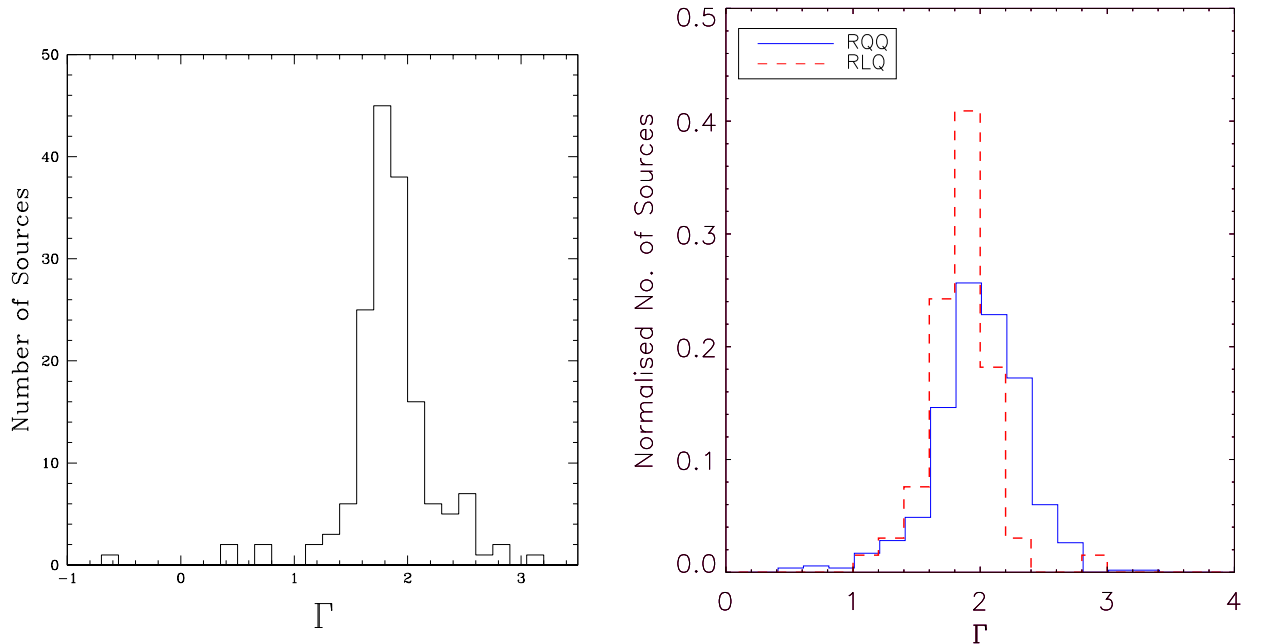


Figure 2.2: Photon index distribution of the Seyfert galaxies (*left panel*, Dadina 2008) observed by *BeppoSAX* in the 2–100 keV energy range, and of a large sample of radio quiet (solid blue) and radio loud (dashed red) type 1 AGN observed by *XMM-Newton* in the 0.3–10 keV energy band (*right panel*, Scott et al. 2011).

confirmed only when using $H\beta$ to measure M_{BH} , different results are obtained when using C IV or Mg II.

2.2 Absorption in the X-rays

Absorption manifests itself through two processes in the X-rays: photoelectric absorption (bound-bound and bound-free transitions), and Compton scattering (free-free transitions), and it can play an important role in the X-ray spectrum of AGN. To model the effect of absorption on the X-ray spectra of AGN, one has to take into account both effects. The photoelectric cross section σ_{ph} has a strong dependence on the energy, and can be approximated according to the analytic formulae of Morrison & McCammon (1983):

$$\sigma_{ph}(E) = (C_0 + C_1 E + C_2 E^2) E^{-3} \times 10^{-24} \text{ cm}^{-2}, \quad (2.3)$$

where C_0 , C_1 and C_2 are constant.

Compton scattering depends on the Klein-Nishina cross section (σ_{KN}), which in the X-rays is equal to the Thomson cross section (σ_{T}), and does not vary with the energy. The ratio between Klein-Nishina and Thomson cross sections $\sigma_{\text{KN}}/\sigma_{\text{T}}$ starts to diverge from the unity at $E \simeq 20$ keV (see Fig. 2.3), and it is of $\simeq 0.6$ at 200 keV. At higher energies σ_{KN} declines steeply. In the following we will ignore relativistic effects, and we will assume $\sigma_{\text{KN}} = \sigma_{\text{T}}$. Compton scattering becomes significant for column densities higher than $\sigma_{\text{T}}^{-1} \simeq 1 \times 10^{24} \text{ cm}^{-2}$, and sources with $N_{\text{H}} \gtrsim \sigma_{\text{T}}^{-1}$ are normally referred to as Compton-thick.

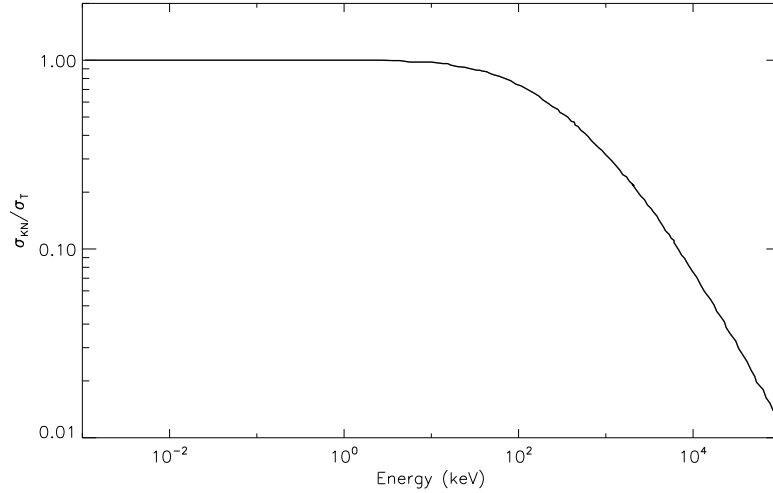


Figure 2.3: Dependence on the energy of the ratio of the total Klein-Nishina Compton-scattering cross section to the Thomson cross section.

Below few hundreds keV the cumulative effect of the two cross sections is given by:

$$M(E) = e^{-\sigma_{ph}(E)N_H} \times e^{-\sigma_T N_H}. \quad (2.4)$$

In Fig. 2.4 is shown the effect of absorption (considering both photoelectric absorption and Compton scattering, as reported in Eq. 2.4) on a power law model with a photon index of $\Gamma = 1.95$ in the 0.1–300 keV energy range, for different values of the column density N_H . For a column density of $N_H = 1.5 \times 10^{24} \text{ cm}^{-2}$, at $\sim 20 \text{ keV}$ only $\simeq 18\%$ of the flux is photoelectrically absorbed, while considering also Compton scattering, only $\simeq 30\%$ of the flux escapes. This value decreases steeply for larger column densities.¹

The absorbers can also be ionized, in which case they are normally referred to as *warm absorbers*. Their effect on the continuum emission is quite different from that of the neutral absorbers showed in Fig. 2.4. Warm absorbers will be presented in detail in Chapter 5.

While, in agreement the unified model, a large number of Seyfert 2s present large column densities ($N_H > 10^{23} \text{ cm}^{-2}$) that can be due to the presence of the torus in the line of sight, many Seyfert 1s (and Seyfert 2s) show Compton-thin absorption ($N_H \sim 10^{22} \text{ cm}^{-2}$). This absorption component is thought to have a different origin than the molecular torus, and several hypothesis have been put forward to explain it. [Matt \(2000\)](#) proposed that the dust lanes in the host galaxies of AGN found by the *Hubble Space Telescope* survey ([Malkan et al. 1998](#)) might have an important role. Other possible culprits might be the BLR, the host galaxy disk ([Maiolino & Rieke 1995](#)), or starburst regions (e.g., [Weaver et al. 2002](#)).

¹It is interesting to notice that, although a column density of the order of $\sim 10^{24} \text{ cm}^{-2}$ might seem very large (and indeed is in extragalactic terms), it represents the average value of N_H of a man's chest ([Brandt 2007](#)).

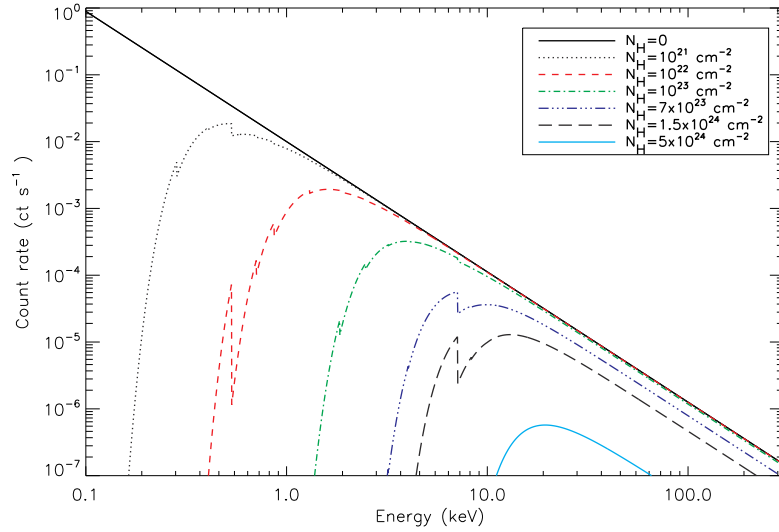


Figure 2.4: Effect of photoelectric absorption and Compton scattering on a power law with a photon index of $\Gamma = 1.95$ in the X-rays for different values of the column density N_H .

2.3 The reprocessed emission

One of the most important features observed in the X-ray spectra of AGN is the reflection component, produced by Compton scattering of the primary emission in some Compton thick material close to the X-ray source. The shape of the reflection component changes depending on the ionization state of the reprocessing material. In Fig. 2.5 the reflected emission from an ionized and a neutral material is shown. In the following I will introduce separately the two situations. In Sect. 2.3.1 I will describe the features arising from neutral reflection, in Sect. 2.3.2 the broad iron $K\alpha$ line will be described, and in Sect. 2.3.3 I will introduce reflection from ionized matter.

2.3.1 Neutral reflection

Reprocessed emission from neutral material is commonly observed in AGN through two features: the iron $K\alpha$ emission line and a reflection hump peaking at ~ 30 keV. However, if the reflecting material is Compton-thin, but still has a significant column density ($N_H \sim 10^{23} \text{ cm}^{-2}$), no Compton hump is produced, and one would observe only the iron $K\alpha$ line (Matt et al. 2003).

The spectrum of the reflection component is determined by the competition between photoelectric absorption and Compton scattering. For neutral matter, photoelectric absorption dominates below 10 keV, while Compton scattering has a stronger influence above this energy. This, together with Compton down-scattering, leads to the creation of a characteristic Compton hump around 30 keV.

The fluorescent iron $K\alpha$ line is produced when one of the 2 K-shell (i.e. $n = 1$) electrons of an iron atom is ejected following photoelectric absorption of an X-ray photon. After the photoelectric event, the excited state can decay in two ways.

- An L-shell ($n = 2$) electron can drop into the K-shell releasing a photon with an energy of 6.4 keV (34% probability). The $K\alpha$ fluorescence produced is made of two components, $K\alpha_1$ ($E=6.404$ keV) and $K\alpha_2$ ($E=6.391$ keV).

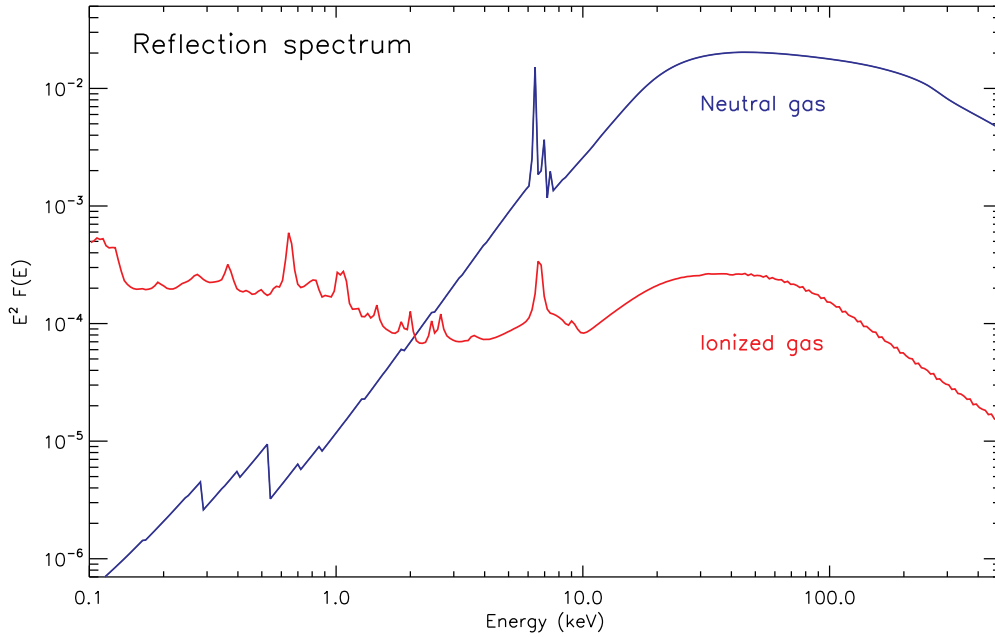


Figure 2.5: Reflection spectrum from ionized and neutral Compton thick matter. The power-law primary continuum in both cases has a photon index of $\Gamma = 1.8$, the ionization parameter is $\xi = 300$ for the ionized gas. The normalizations used are arbitrary.

- The excess energy is carried away through the ejection of an L-shell electron (Auger effect, 66% probability). The Auger effect is equivalent to the photon produced in the $n = 2$ to $n = 1$ transition being internally absorbed by another electron, which is then ejected.

The fluorescent yield determines the probability that an excited ion will de-excite via fluorescence versus the Auger effect. Amongst the lines produced from the reprocessing of the primary continuum, the iron line is the strongest because of the Fe relative abundance, and because the fluorescent yield is proportional to the fourth power of atomic number ($\propto Z^4$). Amongst the other lines normally observed in a reflection spectrum from neutral matter the strongest are the iron $K\beta$ line at 7.06 keV ($\sim 13.5\%$ of the flux of the Fe $K\alpha$, [Palmeri et al. 2003](#)), and the nickel $K\alpha$ line at 7.5 keV.

The first theoretical prediction of the possible detection of emission from neutral iron in the 2–10 keV spectrum of Seyfert galaxies was done by [Guilbert & Rees \(1988\)](#) and [Lightman & White \(1988\)](#). Following this [Nandra et al. \(1989\)](#) carefully analyzed the *EXOSAT* spectrum of MCG–6 – 30 – 15, finding the first evidence of emission at $E \sim 6$ keV. In the same year, using a larger sample [Pounds et al. \(1989\)](#) found significant iron $K\alpha$ emission lines in the spectra of 3 more Seyfert 1 galaxies: NGC 5548, NGC 5506, and NGC 3227. The first evidence of the existence of a reflection hump in the X-ray spectrum of AGN was found combining 12 observations of Seyfert galaxies performed by the Japanese satellite *Ginga* ([Pounds et al. 1990](#)). The first object found to present an excess above 8 keV was MCG–6 – 30 – 15 ([Matsuoka et al. 1990](#)), followed shortly after by NGC 7469 and IC 4329A ([Piro et al. 1990](#)). The nature of the reflecting material is still not completely understood, it might be the accretion disk (e.g., [Zdziarski et al. 1990](#)), the inner edge of the absorbing gas ([Ghisellini et al. 1994](#)), or a disk wind ([Elvis 2000](#)).

According to [Krolik & Kallman \(1987\)](#), the luminosity of the iron $K\alpha$ line can be approximated

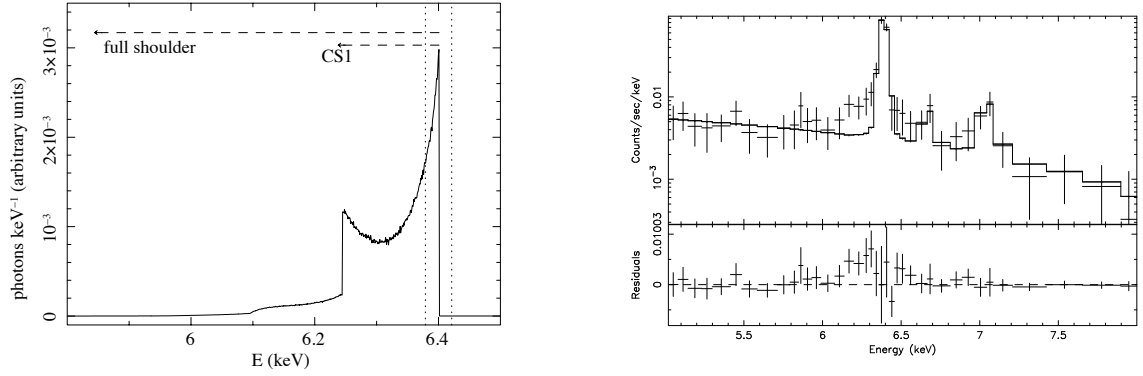


Figure 2.6: Iron $K\alpha$ Compton shoulder, not considering velocity broadening (*left panel*, [Yaqoob et al. 2010](#)). Compton shoulder in the *Chandra*/HEG spectrum of the Circinus Galaxy (*right panel*, [Bianchi et al. 2002](#)).

(neglecting scattering and re-absorption) by

$$L_{K\alpha} \simeq \frac{E_{K\alpha}}{2 + \Gamma} \langle Y \rangle \frac{\Delta\Omega}{4\pi} L_0 \langle \tau_0 \rangle,$$

assuming an illuminating power-law continuum of photon index Γ . In the relation above $E_{K\alpha}$ is the energy of the line, $\langle Y \rangle$ is the fluorescence yield averaged over the ionization states, L_0 is the continuum luminosity per unit energy interval at the K edge, and $\langle \tau_0 \rangle$ is the photoionization optical depth at the K edge averaged over the solid angle subtended by the absorber at the source.

Compton scattering can significantly affect the shape of the observed iron $K\alpha$ line. A single Compton scattering can indeed change the photon energy by an average of about 80 eV, creating a *Compton shoulder* at energies < 6.4 keV.

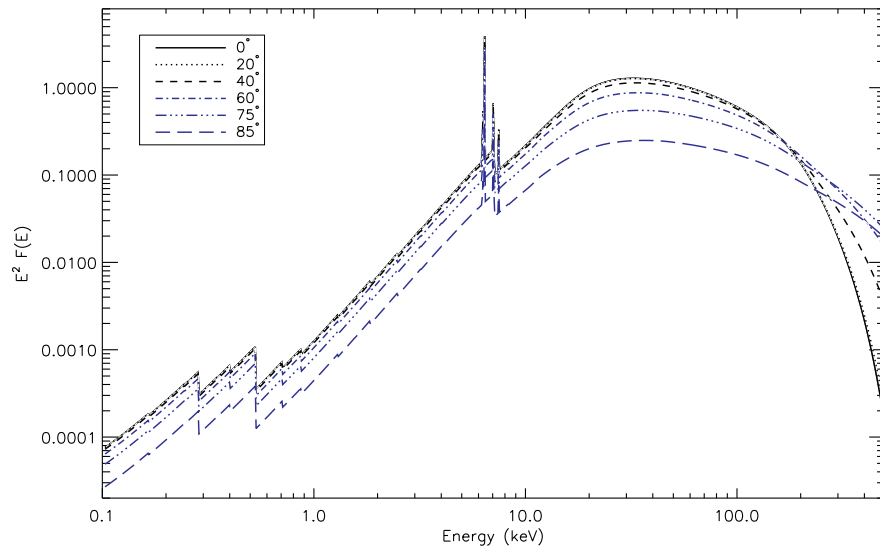


Figure 2.7: Reflection component (of a cutoff power-law with $\Gamma = 1.9$ and $E_C = 300$ keV) from neutral matter for different values of the inclination angle i between the normal to the reflecting surface and the line of sight.

The reflection amplitude is normally parametrized with the R parameter (Magdziarz & Zdziarski 1995). If the X-ray source is isotropic, R represents the solid angle subtended by the reflecting material Ω :

$$R = \frac{\Omega}{2\pi}$$

The value of R depends also on the inclination angle i between the perpendicular to the reflector and the line of sight (see Fig. 2.7): the smaller the value of the inclination angle, the larger the resulting reflection component.

Observations performed by *BeppoSAX* first, and by *INTEGRAL*, *Swift* and *Suzaku*, later have confirmed the presence of a reflection hump in many Seyfert galaxies. Using *BeppoSAX* observations of a large number of objects, Dadina (2008) found that the average value of the reflection parameter is of $R = 1.23 \pm 0.11$ for Seyfert 1s, and of $R = 0.87 \pm 0.14$ for Seyfert 2s.

The existence of a strong correlation between the reflection parameter R and the photon index has been found by Zdziarski et al. (1999), and then confirmed by Zdziarski et al. (2003) and several other successive works (Fig. 2.8). Dadina (2008) found that the correlation could be interpolated as

$$R = (4.54 \pm 1.15) \times \Gamma - 7.41 \pm 4.51.$$

The physical interpretation of this correlation is still not fully understood. Zdziarski et al. (1999) argued that the correlation might be evidence that the X-rays are produced by thermal Comptonization, and reprocessed by the material responsible for the seed photons. In fact, the cooling rate of the hot corona is related to the angle subtended by the reflector (assuming this component is also providing the cooling photons), and is directly connected to the slope of the power law.

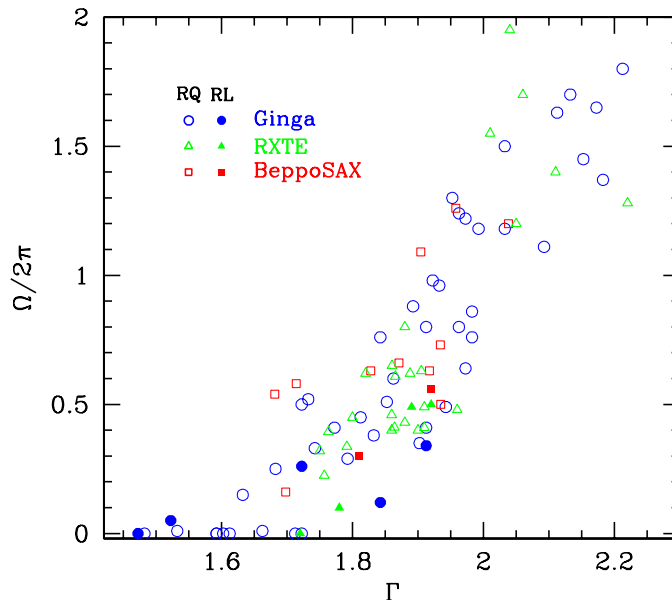


Figure 2.8: Correlation between the reflection parameter $R = \Omega/2\pi$ and the 3–20 keV photon index (Zdziarski et al. 2003).

An anti-correlation between the equivalent width (EW) of the iron $K\alpha$ line and the X-ray luminosity was found by Iwasawa & Taniguchi (1993) using *Ginga* data, and takes the name of *X-ray Baldwin effect* (Fig. 2.9). Although the spectral resolution of *Ginga* did not allow to resolve the

broad and the narrow component of iron $K\alpha$ line, the effect has been confirmed by recent studies performed using *XMM-Newton* (Bianchi et al. 2007). A possible explanation to this effect is related to variability (Jiang et al. 2006): if the line is constant, or less variable than the primary continuum (because produced in a distant material), flux variability of the nuclear emission creates the observed correlation. Another possibility is that the covering factor of the torus decreases with the increasing luminosity, as predicted by the receding torus model (Lawrence 1991).

The iron $K\alpha$ line is now known to be often constituted by two components a narrow and a broad one. The widths of the narrow line core component are normally of the order of a few thousands km s^{-1} , values which are consistent with the line originating in the BLR (e.g., Yaqoob et al. 2001, Kaspi et al. 2001). However, the lack of a correlation between the width of the narrow Fe $K\alpha$ line and the $H\beta$ width or the black hole mass (Nandra 2006) suggests that a significant fraction of the narrow Fe $K\alpha$ line is produced in some other region. A possible explanation is that the line is created in the outer part of the accretion disk. This would explain the rapid (tens of ks) variability observed in some objects (e.g., Petrucci et al. 2002). Part of the line is also thought to be produced by more distant matter (e.g., Reeves et al. 2007), likely in the obscuring torus (e.g., Bianchi et al. 2004). Some objects have shown evidence of Doppler-shifted iron $K\alpha$ lines, called *transient iron lines*, originated in the disk or in an outflow (e.g., Turner et al. 2002, Yaqoob et al. 2003). Currently, most of the reflected emission is believed to originate in the accretion disk, where the broad component is thought to arise (e.g., Nandra et al. 2007).

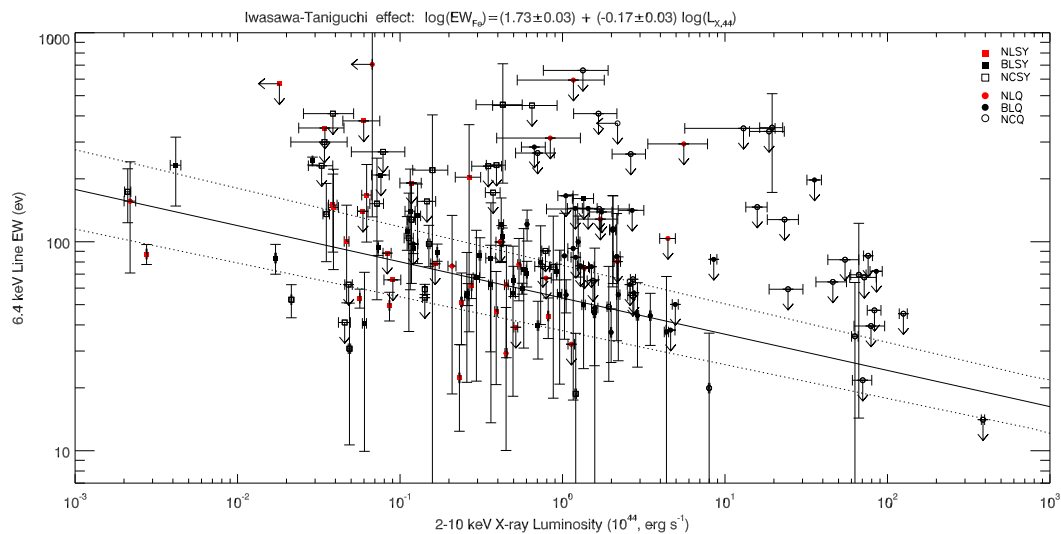


Figure 2.9: The X-ray Baldwin (or Iwasawa-Taniguchi) effect. The plot shows the EW of the neutral iron $K\alpha$ line versus the 2–10 keV luminosity (Bianchi et al. 2007).

2.3.2 Broad iron $K\alpha$ lines

The first detection of a broad iron line was done by Fabian et al. (1994). Thanks to *ASCA* observations, they found a line with a FWHM of 400 eV (or $20,000 \text{ km s}^{-1}$) in the spectrum of MCG–6–30–15. A year later, Mushotzky et al. (1995) found broadened iron lines for two more Seyfert 1s: IC 4329A and NGC 5548. The two objects showed widths much larger than those of their optical and UV lines, and their line centroids were not centered at 6.4 keV, but at $\sim 6.15 - 6.2$. These line profiles were explained using models for relativistic rotating accretion disks (e.g., Laor 1991),

which consider the effects of gravitational redshift, Doppler shift and boosting. These models predict asymmetric lines with a steep blue wing and an extended red wing. The line peak is blue-shifted in most cases, although it can be redshifted by $\sim 5\%$ for nearly face-on disks. A breakthrough was achieved with the 4-day *ASCA* observation of MCG-6-30-15 (Tanaka et al. 1995). Thanks to the high signal to noise the line was found to be broad and asymmetric, with the profile showing a narrow peak at 6.4 keV with an equivalent width of 120 eV, and a skewed reddened wing with an equivalent width of 200 eV. The line is very likely produced in an accretion disk rotating around a Kerr black hole. The broad red tail of the line profile is mainly produced in the innermost region of the accretion disk, between $0.62-3r_g$, in a region where even the blue wing of the emitted line profile is redshifted due to the enormous gravitational potential. The narrow line component (also called blue horn) is mostly produced in a region farther outward, typically at $3-5r_g$. In Fig. 2.10 a recent observation of the broad iron $K\alpha$ line of MCG-6-30-15 is shown (from Fabian & Vaughan 2003). Observations have shown the presence of broad iron lines in several more objects (e.g., Piconcelli

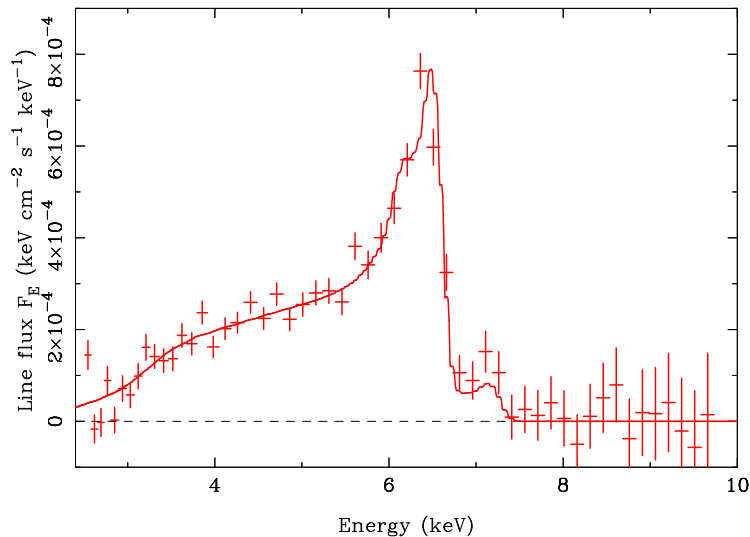


Figure 2.10: The broad iron $K\alpha$ line of MCG-6-30-15 as observed by the long (325 ks) look of *XMM-Newton* (Fabian & Vaughan 2003). The skewed line profile is thought to be the key signature of the innermost region of the accretion disk in the presence of strong gravity.

et al. 2006). However, studies of large samples of Seyfert galaxies found that broadened iron $K\alpha$ lines are not ubiquitous, but they are found in only $\sim 30-40\%$ of the objects (Guainazzi et al. 2006, Nandra et al. 2007). Stacking the spectra of several sources, after dividing them in luminosity bins, Guainazzi et al. (2006) found that a broad red wing is clearly present only in the lower luminosity bin ($L_{2-10\text{keV}} < 10^{43} \text{ erg s}^{-1}$). They also found that the relativistic lines appear to be more intense in Sy1s than in Sy2s, which could be explained by different orientation angles, assuming that the torus and the disk lie in the same plane.

The reason why broad iron $K\alpha$ lines are not present in all AGN is still debated, and several hypothesis have been put forward.

- **Ionized disk.** A certain degree of ionization is expected in accretion disks, above all for high accretion rates (see Ross et al. 1999). A strong reduction of the line flux is expected for moderate (due to resonant trapping) and very large (due to full ionization) degrees of ionization (Matt et al. 1996).

- **Truncated disk.** The disk might be truncated before the last stable orbit, thus producing less intense broad iron $K\alpha$ lines. Accretion disks are believed to be truncated in Galactic black holes, of which AGN are thought to be a scaled-up version. Possible evidence of truncated disk in AGN has been found in the last years (e.g., [Matt et al. 2005](#), [Lobban et al. 2010](#), [Lubiński et al. 2010](#)).
- **Line so broad to be hardly recognizable.** This might happen if the line emission is confined to the inner part of the accretion disk rotating around the Kerr black hole.

Recently, [Fabian et al. \(2009b\)](#) have claimed the first detection of a strong, blurred iron L line in the spectrum of the NLS1 1H 0707-495. However, several works have shown that the broad iron $K\alpha$ lines might be also be created by outflows (e.g., [Turner & Miller 2009](#)). In Sect. 5.3 we will discuss more in details the characteristics of the broad iron lines, and the alternative model proposed to explain it.

2.3.3 Ionized reflection

If the material responsible for the reprocessed emission is ionized, photoelectric absorption has a lower influence on the re-emitted photons, and the albedo below 10 keV increases. The first calculations on the influence of the ionization state on the reflection component were done by [Ross & Fabian \(1993\)](#). Further works on this subjects were done by [Zycki et al. \(1994\)](#), [Ross et al. \(1999\)](#), and [Ballantyne et al. \(2001b\)](#).

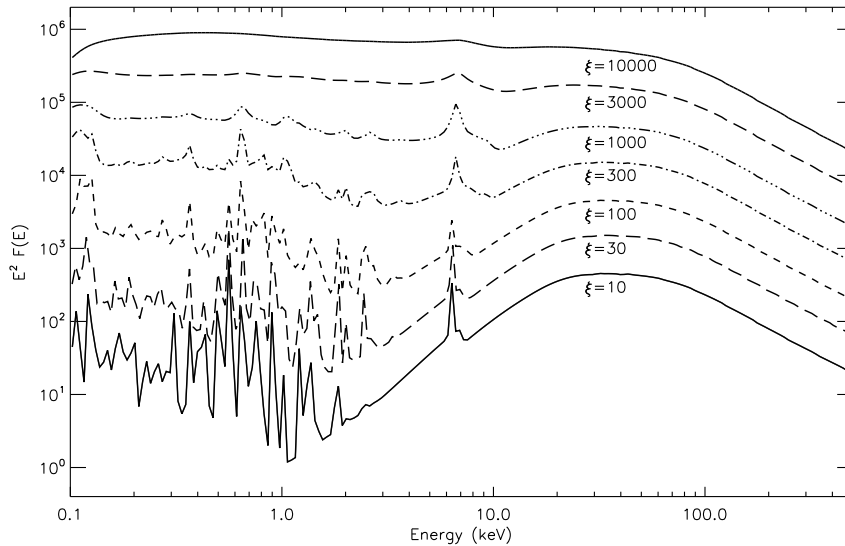


Figure 2.11: Reflection spectra (of a power-law with $\Gamma = 1.9$) from an ionized constant density slab for different values of the ionization parameter ξ .

The ionization parameter ξ is often used to describe the degree to which gas (assumed to have constant density) is ionized. This parameter is defined as

$$\xi = \frac{4\pi F_X}{n_H}, \quad (2.5)$$

where F_X is the illuminating X-ray flux, normally taken in the 0.01 – 100 keV energy band, and n_H is the hydrogen number density of the reflecting material. When the value of ξ increases, due to either an increase of the flux F_X or a decrease of the density n_H , the gas becomes more ionized. As can be seen in Fig. 2.11, the value of ξ greatly affects the spectrum of the reprocessed emission. In the following I will report some of the processes that concur for different values of ξ to modify the emitted spectrum.

- $\xi < 100 \text{ erg cm s}^{-1}$. For low values of the ionization parameter the gas is very weakly ionized, and most of the X-ray emission is absorbed below $\sim 10 \text{ keV}$. Although quantitatively the spectrum is similar to that obtained for a neutral slab, below 1 keV one can see recombination lines from ionized oxygen and carbon. The strongest spectral feature is the iron $K\alpha$ line at 6.4 keV, which has an equivalent width of $\sim 150 \text{ eV}$.
- $100 < \xi < 700 \text{ erg cm s}^{-1}$. As the gas starts to become more ionized, the metals are able to absorb a smaller fraction of the incident X-ray photons, and the albedo of the reflector increases. This produces an apparent deepening of the iron absorption edge and a very weak iron $K\alpha$ line. This happens because the photons of the fluorescent iron line are trapped and destroyed before escaping the disk. For this values of ξ , Fe XVII-XXIII are the most abundant ions of iron, and having an L-shell vacant, they can resonantly absorb the $K\alpha$ line, re-emitting then the photons in a random direction, or losing it because of the Auger effect.
- $700 < \xi < 7000 \text{ erg cm s}^{-1}$. For these values of the ionization parameter the gas is so ionized that all the metals apart from iron are fully ionized. Thus the soft X-ray spectrum has only weak spectral features, which are significantly broadened by Compton scattering. On the other hand, the iron emission line is very strong, and its centroid is at $\sim 6.7 \text{ keV}$. This line is produced by recombination onto He-like iron, and because there are no electrons in the L-shell, the effect of resonant trapping and Auger destruction is no longer significant. The iron absorption edge is shifted to $\sim 9 \text{ keV}$. As ξ increases, the gas becomes so hot that Compton scattering starts to significantly blur the iron $K\alpha$ line and the edge.
- $\xi > 7000 \text{ erg cm s}^{-1}$. For very large values of ξ the last electrons leave the iron nucleus. The hydrogen-like iron Ly- α line at 6.97 keV is suppressed because of resonant trapping in the optically thick gas, which results in a very weak and Compton broadened iron line. The albedo of the reflector is close to unity at all energies, except above 50 keV, at energies where the effects of electron recoil are significative.

2.4 The soft excess

The first indication of spectral complexity below few keV in the spectra of AGN came at the beginning of the 1980's, from *HEAO-I* and *EXOSAT* observations. The first clue was found by Pravdo et al. (1981), who observed an unusual soft X-ray emission in H1613+06. Few years later, Singh et al. (1985) analyzing the *HEAO-1* spectrum of Mrk 509, and Arnaud et al. (1985) working on *EXOSAT* observations of the Seyfert 1 Mrk 841, found evidence of a very strong excess over the power-law continuum emission below 1 keV. Since then this feature has been called *soft excess*, and it is now known to be present in the spectrum of about $\sim 50\%$ Seyfert 1s (e.g., Turner & Pounds 1989, see Fig. 2.12), although higher fractions have been found in soft X-ray selected samples (e.g., Walter & Fink 1993). The soft excess component has been modeled for long time using a simple blackbody spectrum (with temperatures of $\sim 0.1 - 0.2 \text{ keV}$), and it was thought to arise from the hottest part of

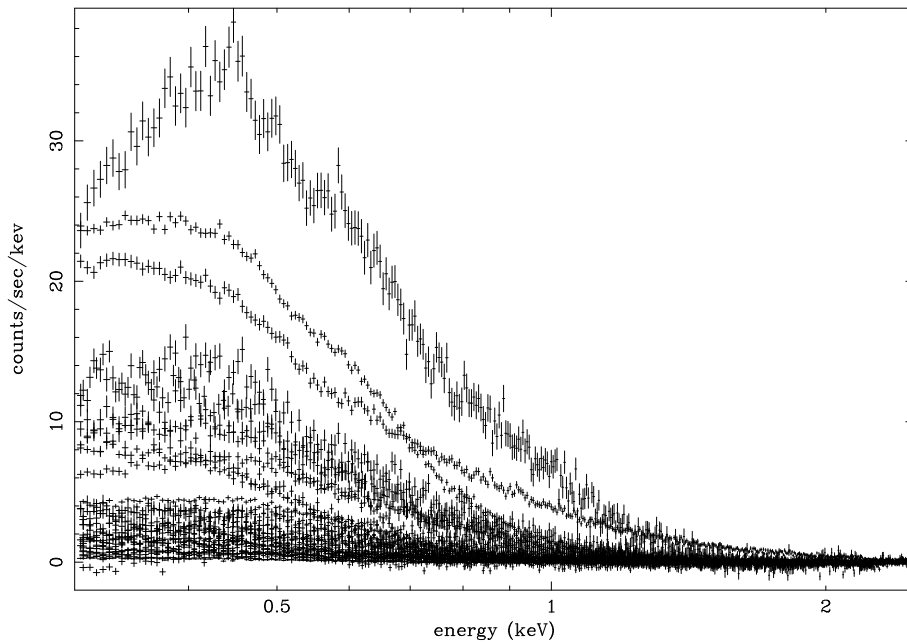


Figure 2.12: Ratio between a power law and the X-ray emission of PG quasars below ~ 2 keV (Crummy et al. 2006). The soft excess component is clearly evident in most of the sources.

the accretion disk (as seen in Galactic black holes), being thus related to the Wien tail of the big blue bump. However, as shown in Sect. 1.2.2, the disk in Seyfert galaxies is supposed to have much lower temperature, unless it is accreting at a super-Eddington ratio. Moreover it has been demonstrated (Gierliński & Done 2004) that the temperature of the thermal component associated to the soft excess does not vary with M_{BH} , which is at odds with the standard models of accretion disks. A possible alternative is that a second cooler Comptonizing region exists, which would upscatter the disk photons to soft X-ray energies. However, also this solution cannot explain the lack of variation of the amplitude of the soft excess with the black hole mass. Alternative models related to atomic processes (and so independent of M_{BH}) have been proposed in the last years. Ballantyne et al. (2001a); Crummy et al. (2006) proposed a model in which the ionized reflection from the disk is blurred by the strong gravity of the black hole, while Gierliński & Done (2004) explained the soft excess as relativistically blurred absorption from a disc wind. The problem for both models is that they need quite extreme values of their parameters to account for the observed soft excesses. The possible origin of the soft excess remains still veiled in mystery, and it will be discussed more in detail in Chapter 5.

2.5 The X-ray spectrum of absorbed AGN

The X-ray spectrum of Seyfert 2s is different from that of their unobscured counterparts, due to the role played by the matter in the line of sight. Absorption in fact depletes part of the continuum, permitting to observe features which would be too weak to be detected in the spectra of Seyfert 1s. In Fig. 2.13 the typical X-ray spectrum of a Seyfert 2, with a column density of $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$ is shown. Above the transmitted power law one can see the reprocessed radiation (i.e. Compton hump and iron $K\alpha$ line) starting to emerge. The presence of obscuration highlights features that are otherwise invisible in Seyfert 1s, due to the dominant contribution of the primary power-law nuclear

continuum. The photoelectric cutoff at low energies ($\lesssim 2$ keV) allows for instance to observe a soft excess which has a very different origin from that observed in Seyfert 1s, although its nature is still debated. It might be related to the emission of very hot gas created in shocks induced by AGN outflows, or to episodes of intense star formation. An alternative scenario is that the AGN photo-ionizes the circumnuclear gas, which is then the responsible of the strong emission at soft X-rays (e.g., Guainazzi & Bianchi 2007). The scattering gas has been identified with the NLR, at least in some objects thanks to the comparison of *Chandra* X-ray observation to [O III] maps obtained by the *Hubble Space Telescope* (Bianchi et al. 2006). The normalization of this scattered component is a few percents that of the primary emission (e.g. Cappi et al. 2006), and its importance in understanding the geometry of AGN will be discussed in detail in Chapter 8.

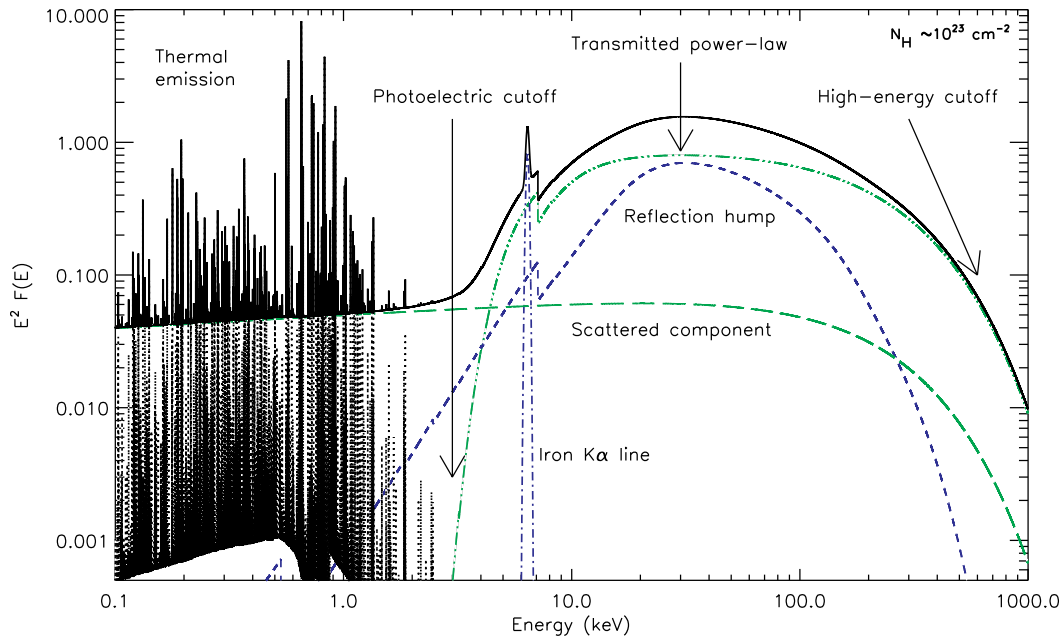


Figure 2.13: X-ray spectrum of a Compton-thin Seyfert 2 galaxy with a column density of $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$. The continuum has a photon index of $\Gamma = 1.9$ and a cutoff at $E_{\text{C}} = 300$ keV.

In Fig. 2.14 the spectrum of a Compton thick Seyfert 2 is shown. For values of $N_{\text{H}} > 10^{24} \text{ cm}^{-2}$ the photoelectric cutoff reaches energies of ~ 10 keV, and the direct emission is almost completely absorbed, so that only the reprocessed and transmitted components are observed. Although much dimmer than less obscured Seyfert 2s, this class of Compton-thick objects is thought to have fundamental role in shaping the Cosmic X-ray background (see Chapter 4).

2.6 The X-ray spectrum of Radio-loud AGN

The X-ray spectra of radio-loud AGN can be very different from that of their radio-quiet counterparts. In radio galaxies the X-ray emission is still thought have a thermal origin, although it might be contaminated by a jet component. This is suspected to produce a flattening of the X-ray continuum and a dilution of the reprocessed features (e.g., Grandi et al. 2006). Radio-loud AGN (excluding blazars, which have different characteristics) have been found to have flatter photon indices than

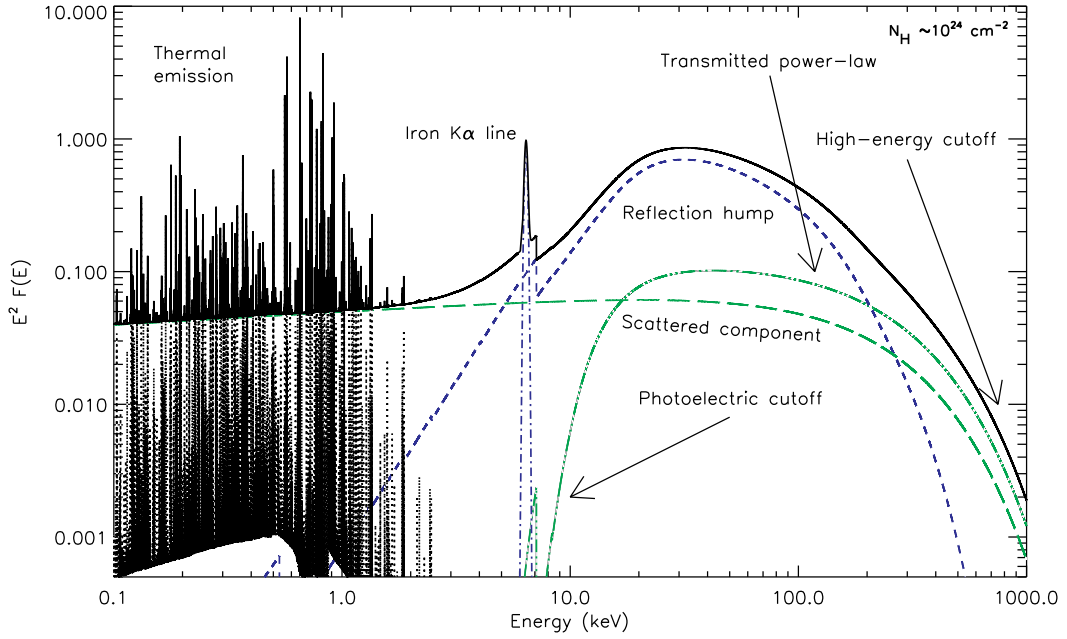


Figure 2.14: X-ray spectrum of a Compton-thick Seyfert 2 galaxy ($N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$). Most of the primary emission is depleted by the strong absorption, and scattered and reprocessed radiation dominate the spectrum.

their radio-quiet counterparts (e.g., [Reeves & Turner 2000](#)). It has been proposed that this difference is due to the contamination of Self Synchrotron Comptonization from the jet. [Scott et al. \(2011\)](#) found that the photon index of radio-loud AGN is $\Gamma = 1.86 \pm 0.02$, significantly different from that of radio-quiet objects (see Fig. 2.2) Values of R and of the equivalent width of the iron $K\alpha$ lines are in fact lower in radio-loud than in radio-quiet objects. In blazars, on the other hand, the thermal features are completely washed out by the dominant non-thermal emission from the jet (e.g., [Grandi et al. 2006](#)). The jet emission dominates the properties of radio loud AGN. The SED of these objects is in fact normally characterized by two peaks, one related to synchrotron emission from the jet, and the other one from the Comptonization (probably in the jet itself) of either the photons from the accretion disk or of the synchrotron photons.

X-ray missions

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This last decade has represented a real golden age for X-ray astronomy, with several different missions operating at the same time in different but often overlapping energy ranges. In the following I will introduce the high-energy missions that played an important role in my thesis: *INTEGRAL* (Sect. 3.1), *XMM-Newton* (Sect. 3.2), *Swift* (Sect. 3.3), *Chandra* (Sect. 3.4) and *Suzaku* (Sect. 3.5).

3.1 INTEGRAL

The INTErnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*, Winkler et al. 2003) is the latest hard X-Ray/soft γ -Ray mission of the European Space Agency (ESA), fruit of a collaboration with the Russian Space Institute (IKI) and the National Aeronautics and Space Administration (NASA). *INTEGRAL* was proposed to ESA in 1989 as a response to a call for new missions proposals in the framework of the "*Horizon 2000*" longterm plan, and it was selected in June 1993. The *INTEGRAL* spacecraft was successfully launched on October 17th 2002 by a four-stage PROTON launcher from Baikonur/Kazakhstan and inserted in a highly eccentric geosynchronous (synchronized with earth rotation, for ground-station coverage) orbit, with a high perigee (9000 km), in order to maximize the time in a stable radiation environment, outside the Earth's radiation belts. Thanks to this particular orbit *INTEGRAL* can observe the sky for $\sim 90\%$ of the time during its ~ 3 -day-long

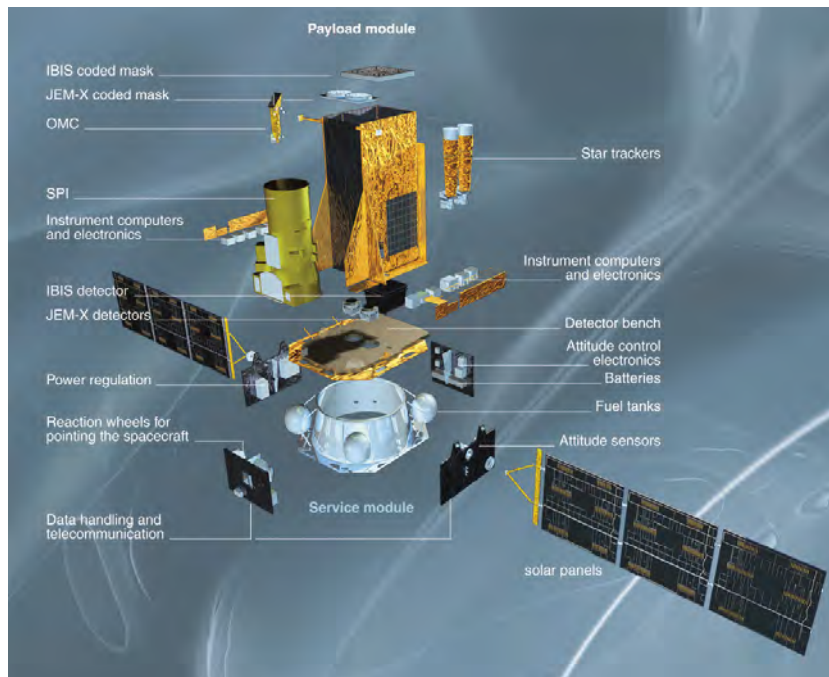


Figure 3.1: The *INTEGRAL* spacecraft and its component. Image from the website of ESA.

orbit. The overall size of the *INTEGRAL* satellite is $5 \times 2.8 \times 3.2$ m, while the solar panels, when they are deployed, are 16 m long. The total mass of the payload is of ~ 4 t, of which ~ 2 t are the scientific instruments. The *INTEGRAL* spacecraft and its components are shown in Fig. 3.1. Recently ESA's Science Program Committee has extended the operations of *INTEGRAL* until at least December 2014, provided no major degradation of its instruments.

INTEGRAL is designed for imaging and spectroscopy with high angular and spectral resolution in the energy range of ~ 15 keV to 10 MeV through its two main instruments: the hard X-ray and gamma-ray imager IBIS (operating in the 15 keV–10 MeV energy band, see Sect. 3.1.2), and the high-resolution spectrometer SPI (20 keV–8 MeV, Sect. 3.1.3). These two instruments are supported by an X-ray telescope JEM-X (3 – 35 keV, Sect. 3.1.4) for a continuous spectral coverage at lower energies, and an optical transient camera, OMC (Sect. 3.1.4), which observes the sky in the Johnson-V band (5400 Å). A detailed list of the parameters of the four instruments is reported in Table 3.1.

Thanks to its high spectral resolution, its fine imaging and its large field of view, *INTEGRAL* has been designed to study both point sources and diffuse emission. *INTEGRAL* has proved to be an invaluable tool for the analysis and monitoring of high-energy transient sources (see Chapter 9), for the study of many high-energy phenomena, as compact objects like Galactic black holes (e.g., Cadolle Bel et al. 2006), X-ray binaries (e.g., Paizis et al. 2006) and cataclysmic variables (e.g., Revnivtsev et al. 2008). *INTEGRAL* has also played an important role in the study of stellar nucleosynthesis (e.g., Diehl et al. 2006), gamma-ray bursts (e.g., Foley et al. 2008), and extragalactic sources, as cluster of galaxies (e.g., Eckert et al. 2008) and AGN (e.g., Beckmann et al. 2006a; Paltani et al. 2008, this thesis).

In the following the coded-mask technique (Sect. 3.1.1) and the four instruments on board *INTEGRAL* (Sects. 3.1.2, 3.1.3, 3.1.4 and 3.1.5) will be discussed in detail, together with the *INTEGRAL* ground segment (Sect. 3.1.6) and the important role of the ISDC (see also Sect. 9.1.1).

Table 3.1: Key parameters of the *INTEGRAL* mission, from Winkler et al. (2003).

Parameter	SPI	IBIS
Energy range	18 keV–8 MeV	15 keV–10 MeV
Detector	19 Ge detectors, each (6×7) cm cooled @ 85 K	16384 CdTe dets, each $(4 \times 4 \times 2)$ mm 4096 CsI dets, each $(8.4 \times 8.4 \times 30)$ mm
Detector area (cm^2)	500	2600 (CdTe), 2890 (CsI)
Spectral resolution (FWHM)	3 keV @ 1.7 MeV	8 keV @ 100 keV
Continuum sensitivity (photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$)	5.5×10^{-6} @ 100 keV 1.2×10^{-6} @ 1 MeV	6×10^{-7} @ 100 keV 5×10^{-7} @ 1 MeV
($\Delta E = E/2, 3\sigma, 10^6 \text{ s}$)		
Line sensitivity (photons $\text{cm}^{-2} \text{s}^{-1}$)	3.3×10^{-5} @ 100 keV 2.4×10^{-5} @ 1 MeV	1.9×10^{-5} @ 100 keV 3.8×10^{-4} @ 1 MeV
($3\sigma, 10^6 \text{ s}$)		
Field of view (fully coded)	16° (corner to corner)	$9^\circ \times 9^\circ$
Angular resolution (FWHM)	2.5° (point source)	$12'$
Source location (radius)	$\leq 1.3^\circ$ (depending on source strength)	$\leq 1'$ (for 10σ source)
Absolute timing accuracy (3σ)	$\leq 200 \mu\text{s}$	$\leq 200 \mu\text{s}$
Mass (kg)	1309	746
Power [max/average] (W)	385/110	240/208
Parameter	JEM–X	OMC
Energy range	4 keV–35 keV	500 nm–600 nm
Detector	Microstrip Xe/CH ₄ –gas detector (1.5 bar)	CCD + V-filter
Detector area (cm^2)	500 for each of the two JEM-X detectors	CCD: (2061×1056) pixels Imaging area (1024×1024) pixels
Spectral resolution (FWHM)	2.0 keV @ 22 keV	–
Continuum sensitivity ^b (photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$)	1.2×10^{-5} @ 6 keV 1.3×10^{-5} @ 30 keV	–
($3\sigma, 10^6 \text{ s}$)		–
Line sensitivity ^b (photons $\text{cm}^{-2} \text{s}^{-1}$)	1.9×10^{-5} @ 6 keV 8.5×10^{-5} @ 30 keV	–
($3\sigma, 10^6 \text{ s}$)		–
Limiting magnitude (mag) ($3\sigma, 5000 \text{ s}$)	–	17.8
Field of view (fully coded)	4.8°	$5^\circ \times 5^\circ$
Angular resolution (FWHM)	$3'$	$25''$
10σ source location (radius)	$\leq 30''$	$6''$
Absolute Timing accuracy (3σ)	$\leq 200 \mu\text{s}$	$\geq 1 \text{ s}$
Mass (kg)	65	17
Power [max/average] (W)	50/37	20/17

Notes. ^a At the moment, both JEM-X detectors are being operated. ^b Assumes operation of both detectors.

3.1.1 The coded-mask technique and the field of view

All the high-energy telescopes on board INTEGRAL use the coded-mask technique (e.g., Caroli et al. 1987), a technique well suited to create hard X and γ -ray images of the sky. In fact, while below $\sim 10 \text{ keV}$ the X-ray photons are focussed using the grazing incidence technique (e.g., *XMM-Newton*, see Sect. 3.2 and Fig. 3.9), at energies above $\sim 10 \text{ keV}$ the grazing incidence angle would have to be very small ($\sim 0.1^\circ$) and the focal lengths very long (up to ~ 10 meters, depending on the energy range). A coded-mask (Fig. 3.2, from ISDC website¹) is an array of elements which are transparent or opaque to the hard X and γ -ray photons. All the sources present in the FOV of the different instruments project a shadow of the mask on the detector plane (called shadowgram), which implies that every source contributes to the background of the others. Choosing a particular pattern in the

¹<http://www.isdc.unige.ch/integral/>

mask helps to facilitate the deconvolution of the signal. The coded-mask of IBIS has a rectangular shape and a size of 1180×1142 mm, is 114 mm thick, and its cells form a coded pattern, called *modified uniformly redundant array* (MURA), of 53×53 elements. About $\sim 50\%$ of the cells are opaque to photons in the IBIS energy range, which provides an opacity of $\sim 70\%$ at 1 MeV. The remaining half of the cells are transparent, with an on-axis transparency of $\sim 60\%$ at 20 keV.

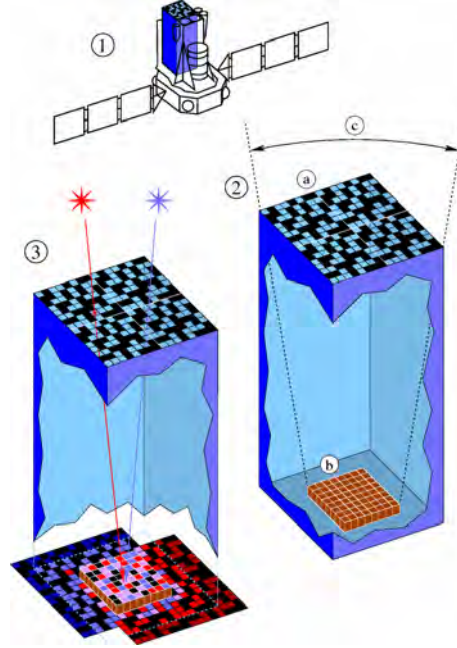


Figure 3.2: Schematic illustration of coded-mask imaging. The image shows the IBIS imager onboard *INTEGRAL*. The coded-mask partially covers the opening of the telescope. The detector (b) records the shadow of the mask created by the hard-X/gamma-ray sources located within the FOV (c). Figure (3) shows, in the case of two sources, the superimposition of the shadows of the mask onto the detector. Figure taken from the ISDC website.

To extract the signal from a source, the original sky image S has to be extrapolated from the overall shadowgram D and the mask geometry M . The encoded information can be described by:

$$D = S * M + B,$$

where D is a matrix representing the two-dimensional shadowgram, and B the real background. If the decoding array G is such that $M * G = \mathbb{1}$, where $\mathbb{1}$ is the identity matrix, then the sky images can be reconstructed using the following relation:

$$S' = D * G = S + B * G,$$

where the term $B * G$ can be measured and removed. The signal-to-noise ratio (S/N) of a source is given by

$$\frac{S}{N} = \frac{C_S}{\sqrt{C_S + C_B}},$$

where C_S and C_B are the count rates of the source and of the background. The reader can refer to [Goldwurm et al. \(2001\)](#) for further details. One of the main advantages of the coded-mask system is that it allows to create images of the hard-X/soft- γ ray sky avoiding confusion even in the crowded

regions of Galactic center and plane. Moreover, coded-mask instruments have very large field of views.

In Fig. 3.3 (*left panel*) the FOVs of the instruments on board *INTEGRAL* are shown. The size of the FOVs depend on the size of the masks and the detectors, and on their distance. In order to obtain large FOVs, the masks are larger than the detectors. This creates two FOVs. The Fully Coded Field of View (FCFOV) is defined as the region of the sky for which the source modulated by the mask illuminates completely the detector plane, while the sources projects a shadow that covers only a part of the detector in the Partially Coded Field of View (PCFOV). The instrument sensitivity is higher in the FCFOV, while it is lower and decreases with the off axis angle in the PCFOV. The four instruments are co-aligned with overlapping FCFOV, so that observations are carried out simultaneously with all the instruments. The spectrometer SPI covers corner to corner the largest FOV, inside the quadratic $9^\circ \times 9^\circ$ FOV of the imager IBIS. The X-ray monitors JEM-X and the optical camera OMC have a much smaller FOV of 4.8° diameter and $5^\circ \times 5^\circ$, respectively. In Fig. 3.3 (*right panel*) a schematic representation of the FOVs of IBIS is shown.

The drawback of using a coded-mask with repeated patterns is that a point source, besides producing a peak at its real position, generates spurious ones, normally referred to as *ghosts*, in positions which are defined by the angular size of the basic pattern. These ghost sources are normally eliminated during the reconstruction process.

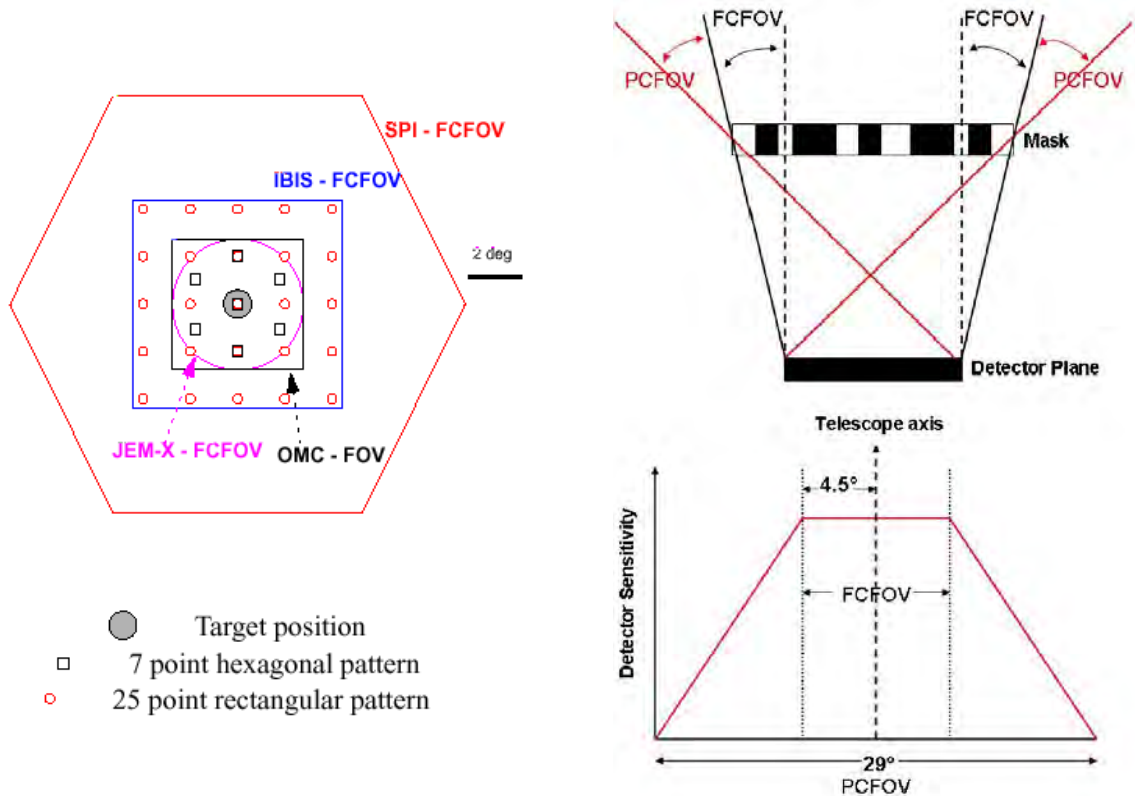


Figure 3.3: The Field of view of the instruments on board *INTEGRAL* (*left panel*, from the ISDC website), and the fully and partially coded field of view of IBIS (*right panel*, from the website of the IBIS group in Southampton).

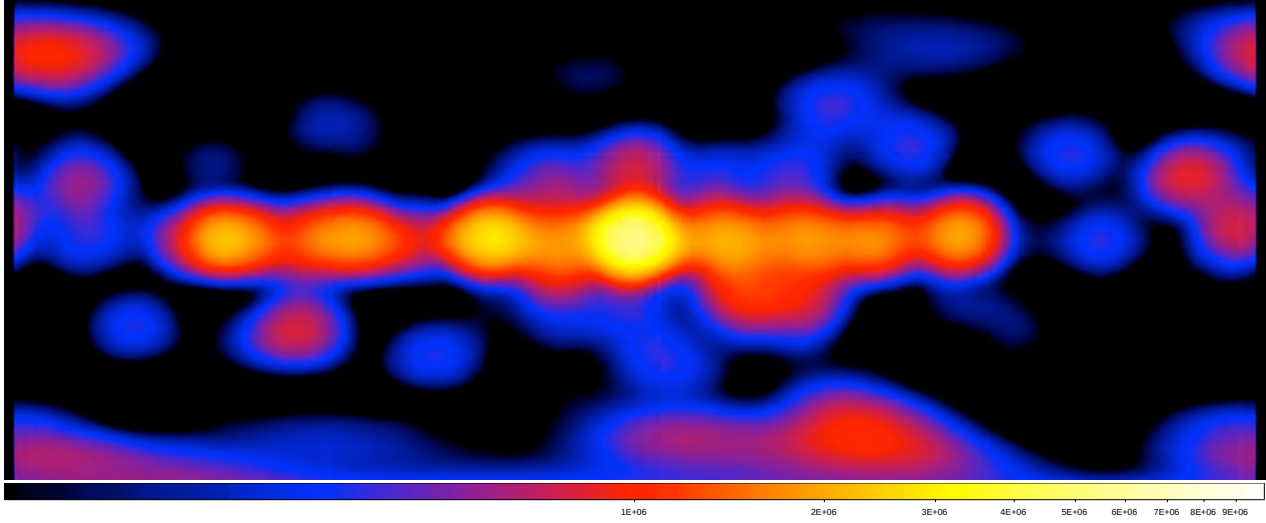


Figure 3.4: *INTEGRAL* IBIS/ISGRI exposure map for the first 900 revolutions.

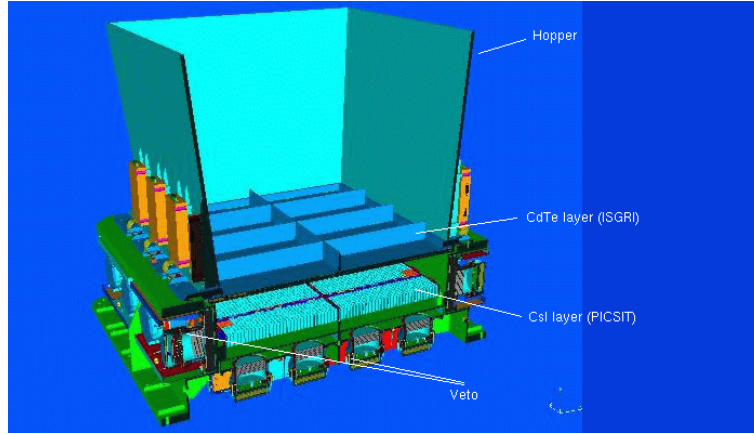


Figure 3.5: Artistic view of the IBIS detector, from the IBIS manual.

3.1.2 IBIS

The Imager on-Board the *INTEGRAL* satellite (IBIS, [Ubertini et al. 2003](#)) is designed to obtain high resolution images and spectral capabilities in the 15 keV to 10 MeV range, with spectral resolution of 9% at 100 keV. It has a large $9^\circ \times 9^\circ$ FCFOV, with a partially coded FOV (PCFOV) extending to $29^\circ \times 29^\circ$. In Fig. 3.4 the exposure map of IBIS/ISGRI during the first 900 revolutions of the spacecraft is shown.

The angular resolution (θ) of coded-mask instruments depends only on the size of the mask elements (H) and on the distance between the mask and the detector plane (L):

$$\theta = \arctan \left(\frac{H}{L} \right).$$

For IBIS this gives angular resolution of ~ 12 arcmin.

IBIS consists of two detector planes (Fig. 3.5). The low energy detector plane *INTEGRAL* Soft Gamma-Ray Instrument (ISGRI, [Lebrun et al. 2003](#)) operates in the 15 keV–1 MeV energy range, and it is an array of 16,384 cadmium telluride (CdTe) pixels, covering 2600 cm², each pixel is 4 × 4 mm side

by side and 2 mm thick. Cadmium telluride is a II-IV semiconductor operating best at temperatures around 0°C. The detector operates in the following way. When the photons hit the solid material, electrons are extracted from the metal atoms, forming electron hole pairs. These electrons are then collected under the action of an external electric field. After correcting for the collection time of the electrons, it is possible to measure the energy of the incident photons. being this quantity roughly proportional to the charge generated. The high-energy detector plane Pixellated Imaging Caesium Iodide Telescope (PICsIT, Labanti et al. 2003) works in the 200 keV – 10 MeV energy band, and is made of 4096 (64×64) caesium iodide CsI(Tl) scintillator crystals ($8.4 \times 8.4 \times 30$ mm) which are sensitive to γ -rays in the energy range from 175 keV to 10 MeV.

The aperture of IBIS is restricted by a lead shielding tube, which carries the coded-mask, and is shielded in all other directions by an active bismuth germanate oxide (BGO) scintillator, called VETO. This anti-coincidence system is used to reject or accept events, recognizing photons from sources in the FOV from background particles or photons propagated or created by the satellite. The anticollimation system of IBIS comprises two mechanically independent subsystems. One is a 55 cm high passive shield made of 1.0 mm tungsten layers, called the *hopper*, and lies on top of the ISGRI detector. The other is called tube, and is made of four walls that link the upper part of the hopper to the four sides of the coded-mask. Tube and hopper define the detectors FOV geometry and reduce the celestial diffuse background component as much as possible.

3.1.3 SPI

The spectrometer on board *INTEGRAL* (SPI, Vedrenne et al. 2003) is an instrument optimized to perform high resolution spectroscopy in an energy band that ranges from 20 keV to 8 MeV. The heart of the spectrometer (Fig. 3.6) is the γ -ray detector plane, made of 19 high-purity germanium detectors. The energy resolution is determined by the width of the band-gap of the semiconductor (0.7 eV for Ge), the energy needed to create an electron-hole pair and the front-end electronics used. For Ge roughly one electron-hole pair per 3 eV is generated, 0.7 eV are needed to overcome the band-gap, and the remaining energy is used up in the creation of lattice phonons. This leads to the energy resolution of 1.8 keV to 3.9 keV in the energy range from 198 keV to 2.7 MeV. The detectors are hexagonal shaped with a side length of 3.2 cm and a height of 6.9 cm, forming a sensitive area of 508 cm². As these detectors have to operate at temperatures of 80 to 95 K, the SPI camera is thermally isolated from the rest of the instrument, and cooled down to 85 K by an active cryostatic system.

Being one of the main purposes of SPI to map the distribution of extended structures like the Al²⁶ or the 511 keV diffuse emission, the FOV needs to be large. Thus, the mask was mounted ~ 1.7 m above the detector, which results in a 16° FCFOV, and a resolution of 2.5°. Sources can be located to about 10 arcmin, depending on the source intensity.

As for IBIS, the instrumental background due to interaction of cosmic-rays with the detector plane has to be minimized. Therefore an active anti-coincidence shield (ACS) of BGO crystals surrounds the detector array, detecting all the events outside the FOV. The ACS is also used for the detection of GRBs outside the FOV, with a timing resolution of ~ 50 ms.

During its first ~ 8 years of life SPI has lost four detectors. The internal background has been much higher than expected, mainly due to activation effects, so source spectroscopy is restricted to strong sources, which provide enough photons, and to diffuse emission.

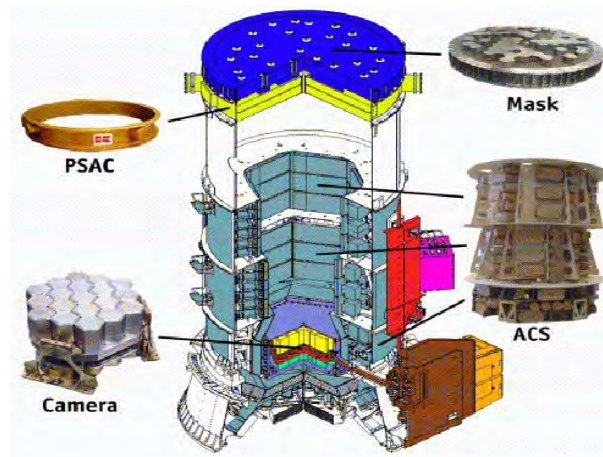


Figure 3.6: The spectrometer SPI, from the ISDC website.

3.1.4 JEM-X

The Joint European Monitor in the X-Rays (JEM-X, [Lund et al. 2003](#)), operating in the 3–35 keV band extends the energy range of *INTEGRAL* to the X-ray band. It contains two identical imaging Microstrip Gas Chambers (JEM-X1 and JEM-X2) with a sensitive area of 500 cm², which use a mixture of xenon and methane (90% and 10%, respectively) at 1.5 bar. As all the other high-energy detectors on *INTEGRAL*, JEM-X uses the coded-mask technology for imaging (Fig. 3.7). The mask pattern for the two JEM-X detectors is identical, but the mask is rotated by 180° to minimize common side loops. The distance between the mask and the detector and the size of the mask elements define an angular resolution of ~ 3.4 arcmin. The mask is cut into a 0.5 mm thick tungsten plate, with an opening fraction of 25%, to achieve better source separation in crowded fields like the Galactic centre.

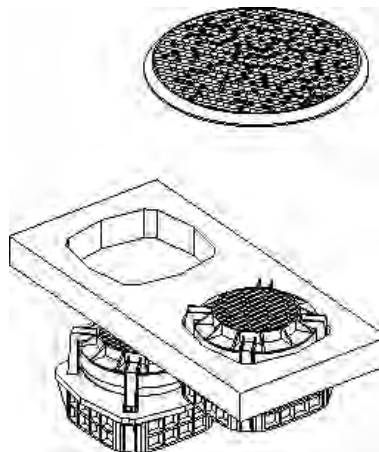


Figure 3.7: Schematic view of Jem-X, from the ISDC website.

Shortly after launch it became evident that the microstrip anodes eroded with an alerting rate of one anode strip per day (out of 256) in JEM-X2. It is suspected that cosmic rays can initiate short-circuits close to the root of the anode strips. To reduce the damage, the gain of both detectors was decreased. The sensitivity of JEM-X is thus much lower than what was expected before the launch.

3.1.5 OMC

The Optical Monitoring Camera (OMC, [Mas-Hesse et al. 2003](#)) consists of an optical system focused on a large format CCD detector (1024×2048 pixel, refractive system: 50 mm entrance pupil, 154 mm focal length) and provides additional data in the optical domain (i.e., Johnson V band). This instrument is co-aligned with the central parts of the large FOV of the other instruments, and has a FOV of $5^\circ \times 5^\circ$. The main scientific objectives of OMC are to monitor the emission of all high-energy targets within its FOV, simultaneously with the γ instruments, and to provide standard Johnson V photometry.

The limiting magnitude for the OMC is mainly defined by its large pixel angular size, due to which a large number of faint stars and zodiacal light will contribute to the background. At the minimum background level (outside the Galactic plane), the limiting magnitude is $m_V = 18.2$ mag (5000 seconds integration), while for the highest expected background level, in Galactic plane observations, it is about $m_V = 14.4$ mag for the same exposure time.

3.1.6 *INTEGRAL* ground segment

The ground segment of *INTEGRAL* consists of two main units: the Operations Ground Segment (OGS) and the Science Ground Segment (SGS).

The OGS includes ESA and NASA's ground station and the Mission Operations Centre (MOC). The telemetry packets from *INTEGRAL* are initially sent to the ground station of ESA in Redu (Belgium) or to that of NASA in Goldstone (California). The data are then sent to the MOC, located at ESOC (Darmstadt, Germany), which performs the standard spacecraft maintenance tasks. MOC also implements the pre-planned timeline received from *INTEGRAL* Science Operations Centre (ISOC).

The SGS includes the ISOC and the Science Data Centre (ISDC). The ISOC is in charge of the planning of the scientific operations, as for instance the instrument configuration for each observation and the observation planning. The *INTEGRAL* Science Data Center ([Courvoisier et al. 2003](#)), located at the ISDC Data Center for Astrophysics, in Versoix (Geneva, Switzerland) represents the key element in the exploitation and analysis of the data. At the ISDC the data are analyzed in near-real time (in order to look for new sources and gamma-ray bursts, see also Chapter 9), formatted and made accessible to the worldwide astronomical community. Such fundamental work guarantees that data can be exploited by a wide community of astronomers, including those who are not familiar with the instrumentation used for gamma-ray observations, and that the scientific community is alerted in the case of new sources or unexpected events.

3.2 XMM-Newton

The X-ray Multi-Mirror Mission Newton (*XMM-Newton*, [Jansen et al. 2001](#)) is an orbiting X-ray observatory. *XMM-Newton* was launched by ESA from Kourou on December 10th 1999 by an Ariane 5 rocket, and placed in a very eccentric 48-hour elliptical orbit, which offers ~ 40 hours of continuous target visibility. The orbit was chosen to allow long continuous observations, and so that the X-ray instruments could be passively cooled to temperatures between -80° and -100° C.

The satellite weighs 3800 kg, is 10 m long and 16 m in span when the solar arrays are deployed. The satellite holds three X-ray telescopes (see Fig. 3.8), each of which contains 58 Wolter-type concentric mirrors, and whose combined collecting area is $4,300 \text{ cm}^2$. *XMM-Newton* has three European Photon Imaging Cameras (EPIC/MOS-1, EPIC/MOS-2 and EPIC/pn, Sect. 3.2.1) operating in the

0.3–12 keV energy band, two reflection grating spectrometers (RGS-1 and RGS-2, Sect. 3.2.2) which are sensitive below ~ 2 keV, and a 30 cm diameter Ritchey-Chretien optical/UV telescope (OM, Sect. 3.2.3). All the instruments on board *XMM-Newton* are independent and can operate simultaneously. The original mission lifetime was two years but it has now been extended for further observations until at least December 2014.

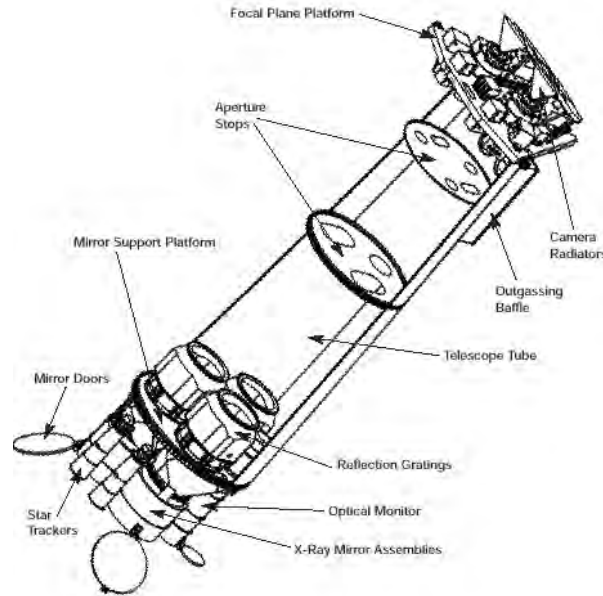


Figure 3.8: Schematic view of *XMM-Newton*, from the ESA website.

3.2.1 EPIC

The main focal plane instrument on *XMM-Newton*, providing imaging and spectroscopy at the same time, is EPIC. The EPIC cameras offer the possibility to perform sensitive imaging observations over the 30 arcmin FOV in the energy range from 0.2 to 12 keV, with a spectral resolution of $E/\Delta E \sim 20 - 50$ and an angular resolution of 6 arcsec FWHM. EPIC consists of three charge-coupled devices (CCD) cameras which register and record the energy of incoming X-ray photons, and a Radiation Monitor to register the dose of radiation seen by the spacecraft as it crosses the radiation belts surrounding the Earth. Two of the cameras employ metal oxide semi-conductors (MOS) CCDs, while the third uses a new type of CCD (pn). The EPIC CCDs operate in photon counting mode, producing an event list which contains every detected photon, its position, its arrival time and its energy.

The EPIC cameras are equipped with three different optical blocking filter with different optical depth (thin, medium, and thick), which shield EPIC CCDs from infrared, visible and UV light, avoiding contamination from sources with a high optical flux.

- **EPIC/MOS**

The MOS detectors (Turner et al. 2001) register photons in the 0.3–10 keV energy band with good energy resolution (slightly better than that of pn). The MOS chip array consists of 7 individual, front illuminated identical CCDs, each of them made of 600×600 pixels. With only a 40-micron sensitive depth of silicon, the detectors are less responsive to high-energy or hard X-rays. This upper part of the spectrum is covered better by the EPIC/pn CCD, which has a 300-micron thickness.

- EPIC/pn

The pn camera (Strüder et al. 2001) is composed of a single silicon wafer with 6×2 integrated CCD chips, each made of 64×189 pixels. The design of pn represents a radical departure from the integrated circuit conception of current MOS CCDs, and whose X-ray detection efficiency is extremely high and homogeneous from the very low to the highest *XMM-Newton* energies (over 90% from 0.5 to 10 keV). In contrast to the MOS camera, the pn-detector has a 400×400 pixel matrix of $6 \text{ cm} \times 6 \text{ cm}$, monolithically fabricated on a four inch high purity silicon wafer. The 36 cm^2 sensitive area makes it the largest X-ray CCD detector ever built.

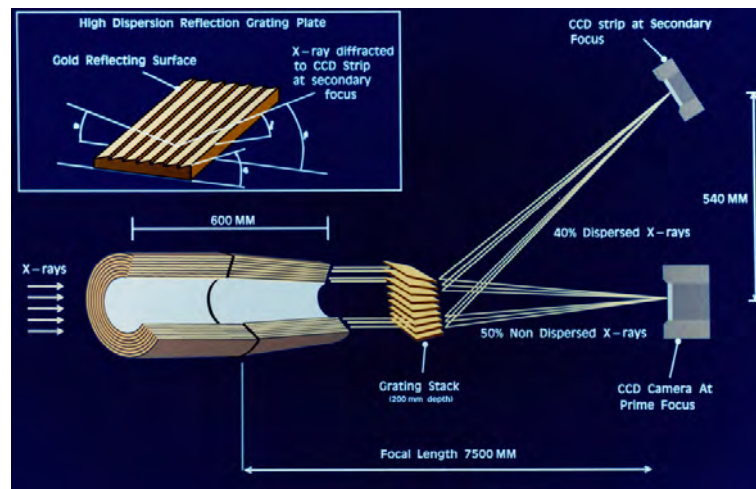


Figure 3.9: Schematic view of the X-ray telescope connected to the RGS on board *XMM-Newton*, from the ESA website.

3.2.2 RGS

The reflection grating spectrometers (RGS, den Herder et al. 2001) on board *XMM-Newton* use the reflection grating technique (Fig. 3.9). A reflection grating is a mirror to which step-like structures have been applied. The X-ray photons reflected off the top and the valley of the grooves interfere with each other, creating spectral image, while photons of different wavelengths are reflected under slightly different angles. In the case of RGS these grooves are 600 per mm. The two grating arrays (measuring $10 \times 20 \text{ cm}$) are composed of 182 grating plates each. These plates consist of a silicon carbide substrate, coated with a thin (2000) film of gold, and are integrated onto a beryllium support structure. The two grating arrays disperse $\sim 40\%$ of the incoming light onto the two RGS cameras, while $\sim 50\%$ of the radiation is directed onto the EPIC cameras. The two RGS cameras are composed of a strip of nine MOS CCDs. These back-illuminated CCDs are operated in single-photon counting, and they measure accurately the position and the energy of each photon, from which is possible to separate the contributions from the different overlapping grating orders. This gives a very high spectral resolution of $E/\Delta E \sim 200 - 800$.

3.2.3 OM

The Optical/UV Monitor Telescope (OM, Mason et al. 2001) is an improved Ritchey-Chretien telescope (a telescope design that gives a high-quality image over a relatively wide field of view) with a

30 cm aperture, and it has a sensitivity in the U band for imaging comparable to a 4-meters instrument on Earth. It provides coverage between 170 nm and 650 nm of the central 17 arcminutes square region of the X-ray field of view, allowing multi-wavelength observations of *XMM-Newton* targets simultaneously in the X-ray and ultraviolet/optical bands.

3.3 SWIFT

The *Swift* satellite (Gehrels et al. 2004) is a NASA multi-wavelength observatory. It was launched on November 20, 2004 by a Delta II 7320-10C expendable launch vehicle which placed it in a ~ 90 minutes orbit at an height of 600 km with an inclination of $\sim 20^\circ$. *Swift* (Fig. 3.10) has three instruments on board: the Burst Alert gamma-ray Telescope (BAT, Sect. 3.3.1), the X-ray Telescope (XRT, Sect. 3.3.2) and UV/Optical Telescope (UVOT, Sect. 3.3.3).

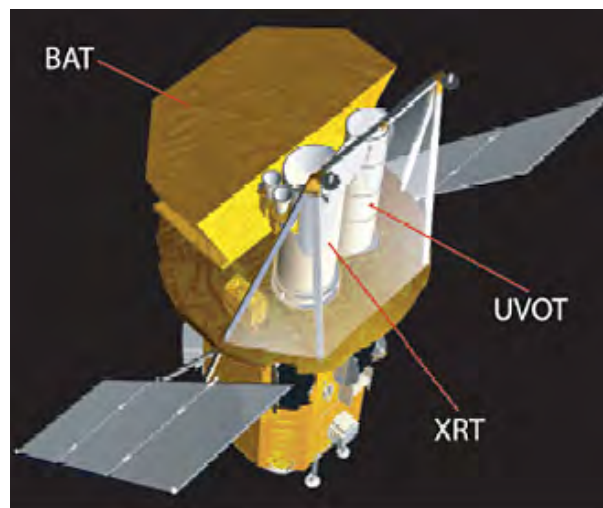


Figure 3.10: Schematic view of *Swift*, from the NASA website.

3.3.1 BAT

The Burst Alert Telescope (BAT, Barthelmy et al. 2005) is a coded-mask instrument operating in the 14–195 keV energy range and designed to provide critical GRB triggers and a few arcminutes positions accuracy. BAT performs continuous surveys of the hard X-ray sky, accumulating sky maps every 5 minutes. These sky images are then analyzed to detect sources and their positions. The coded-mask of BAT is made of $\sim 54,000$ lead tiles (each with a size of $5 \times 5 \times 1$ mm) arranged in a random half-open/half-closed pattern.

3.3.2 XRT

The X-ray Telescope (XRT, Burrows et al. 2004) is equipped with an X-ray CCD imaging spectrometer operating in the 0.2–10 keV energy range, designed to measure the position, spectrum, and brightness of gamma-ray bursts and afterglows. The XRT uses a grazing incidence Wolter I telescope to focus X-rays onto a CCD, providing an instrument with 110 cm² effective area, 23.6 arcmin FOV, 15 arcsec resolution (half-power diameter). The CCD is similar to the *XMM-Newton* EPIC/MOS one, and has an image area of 600×600 pixels.

3.3.3 UVOT

The UV/Optical Telescope (UVOT, [Roming et al. 2004](#)) is a 30 cm modified Ritchey-Chretien UV/optical telescope co-aligned with XRT and mounted on the telescope platform common to all instruments. The telescope is similar to that on board *XMM-Newton*. UVOT provides simultaneous ultraviolet and optical coverage (170–650 nm) in a $17' \times 17'$ field. An 11-position filter wheel allows low-resolution grism spectra of bright GRBs, magnification, and broad-band UV/visible photometry in 6 bands: *V* (5468 Å), *B* (4392 Å), *U* (3465 Å), *UVW1* (2600 Å), *UVM2* (2246 Å), and *UVW2* (1928 Å).

3.4 Chandra

The *Chandra* X-ray observatory (Fig. 3.11) was launched on July 23rd, 1999 in an elliptical high-earth orbit, which allows it to observe the X-ray sky for 48 hours in a row. *Chandra* carries high-resolution optics, which provide an on-axis spatial resolution of 0.5 arcsec, and represents an improvement of about an order of magnitude with respect to the previous X-ray missions.

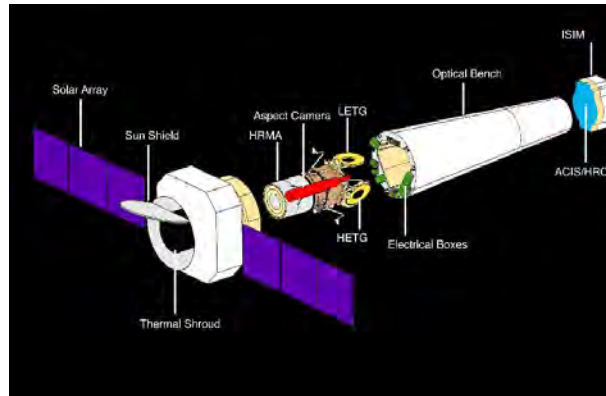


Figure 3.11: Schematic view of the *Chandra* X-ray observatory (Credits NASA/CXC/SAO).

Chandra has two focal plane instruments: the High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS). HRC is used for high resolution imaging, fast timing measurements, and for observations requiring a combination of both. ACIS has two CCD configurations, ACIS-S and ACIS-I, optimized for spectroscopy and imaging, respectively. There are two transmission grating spectrometers, formed by sets of gold gratings which can be placed just behind the mirrors. One set is optimized for low energies (LETG) and the other for high energies (HETG). The HETG is made of two grating assemblies: the High Energy Grating (HEG) and the Medium Energy Grating (MEG). The HEG provides a spectral resolution FWHM $\Delta\lambda = 0.012 \text{ Å}$ in the 0.8–8.5 keV (16–1.5 Å) range, twice as good as that of the MEG ($\Delta\lambda \simeq 0.023 \text{ Å}$, 0.5–7 keV or 25–2 Å). The effective area of the HEG is higher than that of the MEG around 6 keV, and it is the instrument that can provide the best information about the iron $K\alpha$ line (FWHM $\simeq 40 \text{ eV}$, 1900 km s^{-1} at 6.4 keV). LETG is a single grating assembly that complements the HETG by providing grating data ($\Delta\lambda = 0.05 \text{ Å}$) to very soft energies (0.07–6.0 keV or 175–2 Å). The grating spectra can be dispersed onto either of *Chandra* focal plane detectors, but the usual configuration is to use HETG with the ACIS-S, and the LETG with either ACIS or HRC. The HRC is better suited for the very soft energies, being the photons below 0.2 keV dispersed off the edge of the ACIS-S array.

3.5 Suzaku

The Japanese mission *Suzaku* (Mitsuda et al. 2007) was launched on July 10th, 2005. *Suzaku* (Fig. 3.12) carries four X-ray telescopes focusing on to a CCD which is a part of the X-ray Imaging Spectrometer array (XIS) (Koyama et al. 2007). Three CCDs (XIS0, XIS2 and XIS3) are front illuminated (FI), while XIS1 is back illuminated (BI). The three FI CCDs cover an energy range of 0.6–10 keV with an energy resolution of $\text{FWHM} \simeq 120 - 150 \text{ eV}$ at 6 keV. The XIS1 CCD has a lower area at 6 keV, but has an enhanced soft-and response (down to 0.2 keV). To give a broad band spectral coverage *Suzaku* carries also the non-imaging collimator Hard X-ray Detector (HXD, Takahashi et al. 2007) operating in the 15–70 keV, and a GSO well-type Phoswich counter (Fukazawa et al. 2009), which provides data for the brightest sources in the 75–165 keV energy band.

Suzaku also carries the now non-functioning X-ray calorimeter XRS-2, which would have provided a very high resolution ($\lesssim 6 \text{ eV}$). Due to a coolant leak, also XIS2 stopped functioning shortly after the launch.

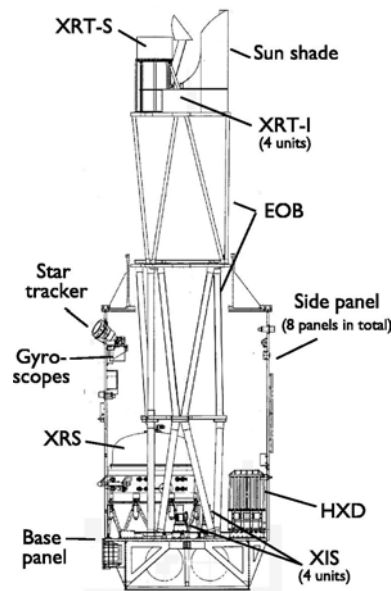


Figure 3.12: Schematic view of *Suzaku* (Mitsuda et al. 2007).

X-ray surveys and population studies

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4.7	The second <i>INTEGRAL</i> AGN catalog	65

Beyond our galaxy, the extragalactic sky shows several prominent features (Fig. 4.1). The most intense one is the cosmic microwave background (CMB), the relic emission from the Big Bang. The second is the infrared (CIB) and optical (COB) emission produced by galaxies. The third one consist of a prominent maximum of emission peaking in the hard X-rays, the Cosmic X-ray Background (CXB). Although it is nowadays quite well assessed that AGN are the main contributors to this X-ray emission, the way different types of objects contribute to it is still not clear, and accurate studies at X-ray energies of the characteristics of AGN populations and of their evolution are necessary. In this Chapter we will first give an historical introduction on the CXB (Sect. 4.1), we will then discuss the actual knowledges on the column density distributions of AGN (Sect. 4.3), a particularly important ingredient in the populations synthesis models of the CXB (Sect. 4.4), and in Sect. 4.5 we will discuss about the influence of the radiation pressure on the absorbers of AGN. In Sect. 4.6 we will introduce the fundamental plane of AGN activity, an extremely elegant way to connect radio-loud and radio-quiet AGN using only three parameters. In Sect. 4.7 we will present our population study at hard X-rays performed using *INTEGRAL* data on all the ~ 200 AGN detected by IBIS/ISGRI during its first ~ 6 years of operations.

4.1 The Cosmic X-ray Background: an historical introduction

The story of the Cosmic X-ray background starts before that of the CMB (Penzias & Wilson 1965), with the first X-ray rocket experiment in the early 60s (Giacconi et al. 1962). The experiment aimed at detecting the fluorescent X-ray emission produced by the lunar surface, but instead it turned out to achieve two extremely important discoveries. The first one was the first detection of an X-ray point-like sources, Sco X-1, which opened the road to the study of X-ray binaries and X-ray sources in general. The second one was the detection of a diffuse isotropic X-ray emission: the CXB. In the following years two explanations were proposed to interpret the CXB: a really diffuse emission like an intergalactic hot gas, or the contributed emission of a large number of isotropically distributed point sources (like AGN). The isotropy of the CXB was confirmed by the first all sky surveys performed by *UHURU* (Giacconi et al. 1974) and *ARIEL V* (McHardy et al. 1981). The results obtained by these

first surveys implied that the number of discrete sources contributing to the CXB needed to be very high ($> 10^6 \text{ sr}^{-1}$, Schwartz & Tucker 1988).

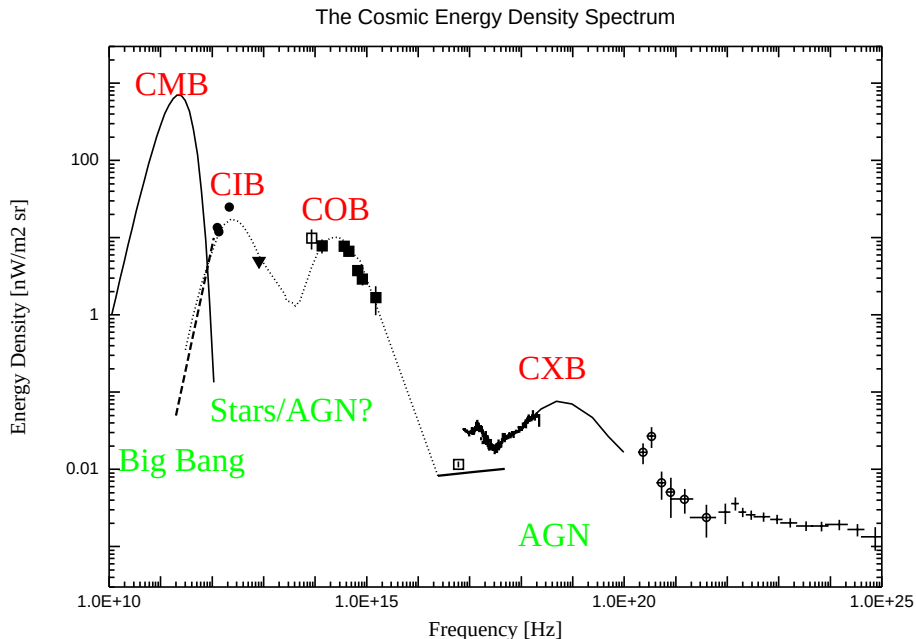


Figure 4.1: The extragalactic background from the radio to the γ -ray band (Hasinger 2000).

At the beginning of the 1980s observations performed by *HEAO-1* showed that in the 3-50 keV energy band the CXB spectrum was well fitted by an isothermal bremsstrahlung model produced by a optically thin hot plasma with a temperature of $\sim 40 \text{ keV}$ (Marshall et al. 1980). This, together with the discovery that all the Seyfert 1 galaxies with reliable 2–20 keV spectra were well fitted by a power-law with an average photon index of $\Gamma \sim 1.65$ (Mushotzky 1984), significantly different from the slope of the CXB in the same energy band, supported the diffuse intergalactic gas hypothesis. On the other hand, the deep survey performed by *Einstein* resolved $\sim 20\%$ of the CXB in the 1–3 keV band into discrete sources at fluxes of $\sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Giacconi et al. 1979), a large fraction of which identified as AGN. The controversy was solved by observations performed by the FIRAS instrument on board *COBE*, which did not detect any significant deviation from a pure black body like emission of the CMB, thus discarding the possible origin of the CXB in a hot diffuse plasma (Mather et al. 1994).

AGN were confirmed to be the dominant contributors to the CXB at energies $< 2 \text{ keV}$ thanks to the very deep look at the Lockman Hole performed by *ROSAT* (Hasinger et al. 1993). This deep observation allowed in fact to resolve $\sim 60\%$ of the CXB emission into discrete sources above $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$, and optical follow ups showed that a fraction as high as $\sim 85\%$ of these objects were AGN (Lehmann et al. 2000). At higher energies, thanks to *BeppoSAX* observations it was possible to resolve $\sim 30\%$ of the CXB in the 5–10 keV range (Fiore et al. 2001), which allowed to identify most of the sources with AGN (e.g., Fiore et al. 1999).

4.2 X-ray surveys and AGN evolution

In the last decade, several extremely deep X-ray surveys performed with *Chandra* and *XMM-Newton*, followed by multi-wavelength campaigns provided very important insights on the evolution of AGN.

Two of the deepest surveys ever performed, the *Chandra* Deep Field North (CDFN, 2 Ms, e.g., [Alexander et al. 2003](#)) and the *Chandra* Deep Field South (CDFS, 4 Ms, e.g., [Fiore et al. 2011](#)), were able to resolve the CXB into single sources at a level of 80 – 90% in the 0.5 – 8 keV energy band ([Hickox & Markevitch 2006](#)). However, it has been argued that this fraction might be lower at hardest energies, in particular above ~ 5 keV it might be only $\sim 50\%$ ([Worsley et al. 2005](#)).

One of the main findings of very deep survey has been the anti-hierarchical behavior of the nuclear activity. [Hasinger et al. \(2005\)](#) found that the space density of the most luminous Seyfert 1s and quasars peaks at a redshift $z \geq 2$, while that of less luminous Seyfert 2s and Seyfert 1s at $z \geq 1$. This implies that high-luminosity AGN can form and are fed very early in the Universe, in a gas- and dust-rich environment, and that half of the total black hole mass density was accumulated at $z < 1$. On the other hand, the lower luminosity population has to wait much longer to grow (or to be activated), possibly due to the lack of large reservoirs of gas. A similar behavior is found in the cosmic star formation history, which is limited to small galaxies at low redshifts, while it is observed also in massive galaxies at $z \geq 2$ (e.g., [Daddi et al. 2004](#)).

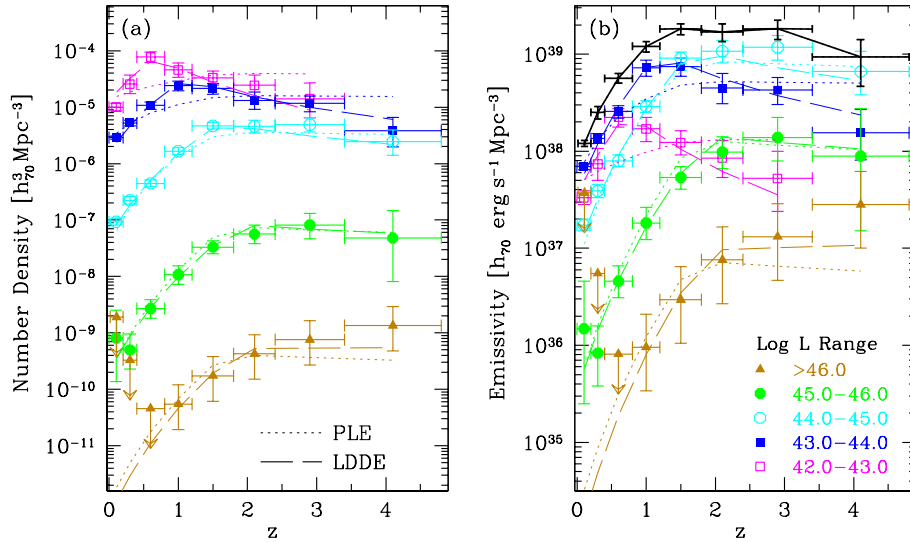


Figure 4.2: The space density (*Left panel*) and the soft X-ray emissivities (*Right panel*) of AGN as a function of the redshift for different luminosities. Densities from the pure luminosity evolution and luminosity-dependent density evolution models are represented by solid lines. Figure taken from [Hasinger et al. \(2005\)](#).

Important insights on the evolution of AGN can be extracted from their X-ray luminosity function (XLF, [Maccacaro et al. 1991](#)), i.e. the function which gives the density of AGN per luminosity bin. Combining several surveys which covered 5 order of magnitudes of flux, [Ueda et al. \(2003\)](#) found that the evolution of the hard XLF (HXLF, 2 – 10 keV band) can be well fitted using a luminosity-dependent density evolution (LDDE) of the form:

$$\frac{d\Phi(L_X, z)}{d \log L_X} = \frac{d\Phi(L_X, 0)}{d \log L_X} e(z, L_X),$$

where

$$e(L_X, z) = \begin{cases} (1+z)^{p_1} & [z < z_c(L_X)] \\ e(z_c) \left[\frac{1+z}{1+z_c(L_X)} \right]^{p_2} & [z \geq z_c(L_X)], \end{cases}$$

and

$$z_c(L_X) \begin{cases} z_c^* & (L_X \geq L_a) \\ z_c^* \left(\frac{L_X}{L_a} \right)^\alpha & (L_X < L_a). \end{cases}$$

In the above equation $\log L_a = 44.6$, and $z_c^* = 1.9$, and α was a free parameter. The term $e(z, L_X)$ represents the evolution. The fact that the cut-off redshift z_c increases with the luminosity, implies that the peak spatial density is located at lower values of z for AGN with luminosities below $\log L_X \simeq 44.5$, consistent with what shown in Fig. 4.2.

In the last few years, thanks to *INTEGRAL* /ISGRI and *Swift* /BAT several deep surveys have been performed above 10 keV (e.g., Beckmann et al. 2006c, Sazonov et al. 2007, Paltani et al. 2008, Ajello et al. 2008c, Tueller et al. 2008). Beckmann et al. (2006c) found that the slope of the number-flux distribution, $\log N - \log S$, is best fitted by a power-law with a slope $\alpha = 1.66 \pm 0.11$, while Paltani et al. (2008) obtained $\alpha = 1.55 \pm 0.13$. Tueller et al. (2008) obtained $\alpha = 1.42 \pm 0.14$, a value similar to what was found by Beckmann et al. (2010) ($\alpha = 1.42 \pm 0.7$). All values of α are consistent with the Euclidean one, expected for homogeneous space distribution. A slope steeper than $\alpha = 1.5$ can be attributed to a positive cosmological evolution: AGN have been either more numerous and/or more luminous at larger distances, and therefore the brightest objects are missing in the local universe (e.g., Gioia et al. 1984). Beckmann et al. (2006c) reaching a limiting flux of $3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, were able to resolve $\sim 1\%$ of the CXB in the 20–40 keV energy band, and found a luminosity function consistent with that observed at lower energies (e.g., Ueda et al. 2003). Paltani et al. (2008) studying very deep *INTEGRAL* observations of the 3C 273/Coma field (2500 deg²) reached a lower flux limit of $6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, and were able to resolve $\sim 2.5\%$ of the CXB in the 20–60 keV band.

4.3 Column density distributions

The first measurements of absorption in the X-rays were performed by *HEAO-1* (Mushotzky 1984), and found column densities of $N_H \sim 10^{21} \text{ cm}^{-2}$ in a few objects. Later studies performed by *EXOSAT* (e.g., Turner & Pounds 1989) showed that absorbing material in the line of sight was present in a large fraction of AGN. In the following, in agreement with what is commonly found in literature, we will refer to absorbed AGN for the objects with $N_H > 10^{22} \text{ cm}^{-2}$, and to unabsorbed for those with $N_H < 10^{22} \text{ cm}^{-2}$, independently of their optical classification.

Constraining the intrinsic column density distribution is a quite complicated task, mostly due to the obvious selection effect that biases the sample towards lower values of N_H . Theoretical predictions on the N_H distribution of AGN are extremely difficult and require a great deal of parameters. As an example, the galaxy evolution model of Hopkins et al. (2006), which takes into account fueling of AGN by mergers of gas-rich galaxies, predicts a distribution peaking around $N_H \sim 10^{22.5} \text{ cm}^{-2}$, which does not correspond to that observed (see Fig. 4.3). Using a sample of [O III] selected nearby AGN Risaliti et al. (1999) found that the ratio of obscured to unobscured AGN is $\sim 4 : 1$, and that about half of the obscured AGN are Compton-thick (CT, $N_H > 10^{24} \text{ cm}^{-2}$, see Sect. 2.2). Similar results were found by Guainazzi et al. (2005) studying a sample of 49 local Seyfert 2s. Deep field observations of Lockman Hole (Mainieri et al. 2002) and the CDFS (Tozzi et al. 2006) have confirmed that 75% of all AGN are obscured. In their recent work, Treister et al. (2009), using *INTEGRAL* and *Swift*/BAT observation found a much lower amount of CT AGN. The column density distribution they found declines in fact quite steeply at $N_H > 10^{24} \text{ cm}^{-2}$. The actual number of CT objects is one of the key issues of synthesis models of the CXB, and it will be discussed in Sect. 4.4.

An extremely important discovery was done by Ueda et al. (2003) (see also previous works, e.g.,

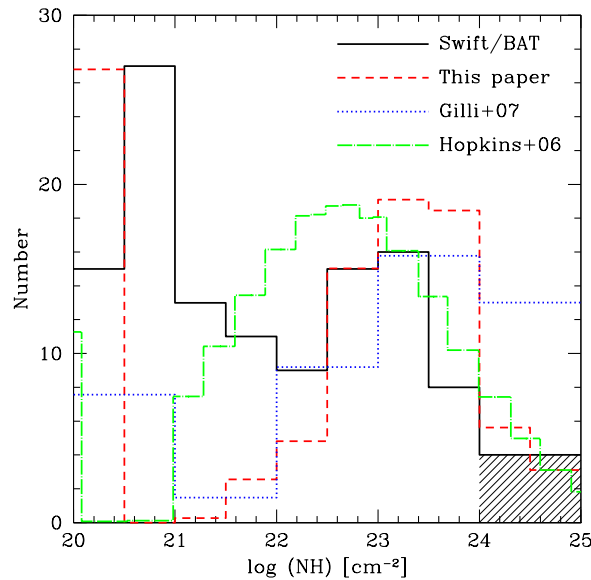


Figure 4.3: Theoretical and observed column density distributions from [Treister et al. \(2009\)](#).

[Lawrence 1991](#)): they found that the fraction of absorbed AGN appears to decrease with the X-ray intrinsic luminosity. This has been later confirmed by several other independent measurements of different samples selected in different energies bands (e.g., [Hasinger 2004](#), [La Franca et al. 2005](#), [Markwardt et al. 2005](#)), although discordant results have been found (e.g, [Dwelly & Page 2006](#) [Wang et al. 2007](#)). The existence of this trend has been also confirmed by the discovery that it is seen also in samples of objects located in the nearby universe, where selection biases are not important ([Barger et al. 2005](#)).

[Gilli et al. \(2007\)](#) approximated the variation of the ratio of absorbed to unabsorbed AGN (f) with the luminosity using the following empirical relation:

$$f(L) = f_S e^{-L/L_c} + f_Q (1 - e^{-L/L_c}),$$

where f_S and f_Q are the asymptotic values of f at low and high luminosity, respectively, and L_C was fixed to $\log L_C = 43.5$.

Discordant results have been found about a possible correlation between f and the redshift. Some works found evidence of an increase of f with z (e.g., [La Franca et al. 2005](#)), while others found no correlation (e.g., [Ueda et al. 2003](#), [Treister & Urry 2005](#)). [Della Ceca et al. \(2008\)](#) found evidence for the existence of significant differences in the luminosity functions of absorbed and unabsorbed objects. This discrepancy between the two luminosity functions has been confirmed by [Burlon et al. \(2011\)](#), and it is strictly related to the anti-correlation the fraction of absorbed objects with the luminosity.

Using *INTEGRAL* data, both [Sazonov et al. \(2007\)](#) and [Beckmann et al. \(2006c\)](#) confirmed the decrease of f with luminosity. [Beckmann et al. \(2006c\)](#) found $f = 0.7$ for $\log L(20 - 60 \text{ keV}) < 43.4$, and $f = 0.5$ for $\log L(20 - 60 \text{ keV}) > 43.4$. [Sazonov et al. \(2007\)](#) obtained similar results: $f = 0.66$ for objects with a luminosity $\log L(20 - 60 \text{ keV}) < 43.6$, and $f = 0.25$ above this value.

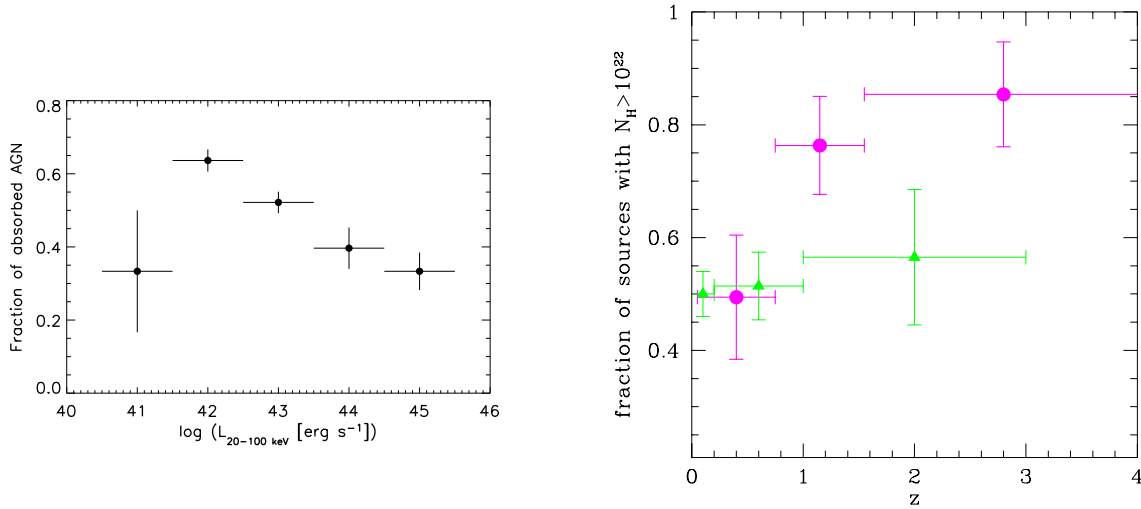


Figure 4.4: Fraction of absorbed ($N_{\text{H}} > 10^{22} \text{ cm}^{-2}$) sources versus the hard X-ray (20–100 keV) luminosity (Beckmann et al. 2009), and versus the redshift (Tozzi et al. 2006).

4.4 Synthesis models of the CXB

The first major problem of fitting the spectrum of the CXB using a combination of AGN spectra was found in the 1990s, and it was defined the *spectral paradox*. In fact, while the X-ray spectra of bright AGN observed with *HEAO1*, *EXOSAT* and *Ginga* had a slope well modeled by a power law with photon indices of $\Gamma \sim 1.7$ (e.g., Mushotzky 1984), in the same band the CXB was found to be much flatter ($\Gamma \simeq 1.4$, e.g., Gendreau et al. 1995). Moreover, the extragalactic source counts in the 0.3–3.5 keV band obtained by the *Einstein* Extended Medium Sensitivity Survey (EMSS, Gioia et al. 1990) was about 2–3 times lower than that in the 2–10 keV band measured by *Ginga* (Butcher et al. 1997), assuming a power law with $\Gamma = 1.7$. This problem was solved with the discovery of the reflection hump and of the existence of a large number of absorbed sources. It was indeed found that integrating over the redshift spectra which tend to flatten with energy, with reasonable assumptions on the cosmological evolution, one could reproduce the observed shape of the CXB below 10 keV (e.g., Fabian & Iwasawa 1999). The first deep surveys performed by *Chandra* and *XMM-Newton* confirmed this, finding a large number of AGN with flat spectra (e.g., Giacconi et al. 2001, Hasinger et al. 2001).

The recipe for building realistic models of the CXB, according to Comastri (2004), consists of three steps.

1. One should assume as a template spectrum for unobscured (type-I) sources the average spectrum of nearby Seyfert 1s above 2 keV. This is normally done assuming a steep ($\Gamma = 1.9$) power-law continuum plus a reflection component from a face-on accretion disk, and a high energy cutoff at $E \sim 300$ keV. In Fig. 4.5 the templates used by Gilli et al. (2007) (for different values of the absorption) are shown.
2. To model the spectra of obscured (type-II) AGN, one should consider a column density distribution, with values of N_{H} ranging between $10^{21-25} \text{ cm}^{-2}$, plus a certain amount of unabsorbed reflection.

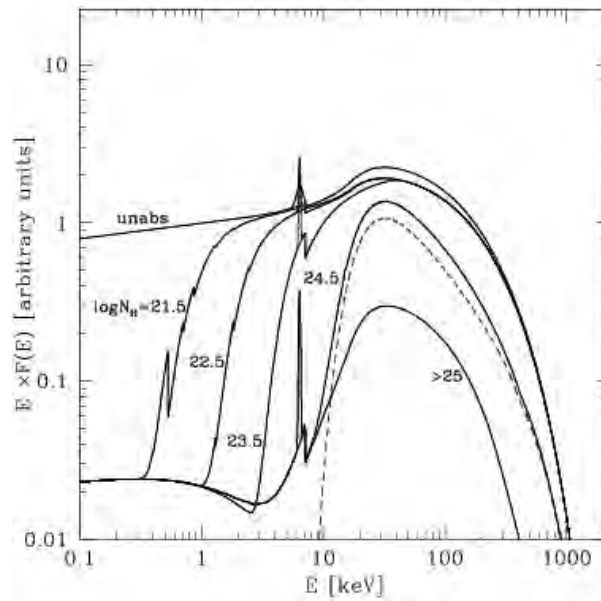


Figure 4.5: Spectral templates for different values of the column density N_H used by [Gilli et al. \(2007\)](#) in their CXB synthesis model.

3. The spectra of both type-I and type-II AGN should be folded with an evolving X-ray luminosity function, whose parameters have been determined by X-ray surveys and are appropriate for obscured and unobscured AGN.

The column density distribution is left free to vary in shape and normalization, until one obtains a good fit of the CXB, of the source counts in different energy bands, and of the redshift distributions at different limiting fluxes.

The latest synthesis model of the CXB was done by [Gilli et al. \(2007\)](#) using the latest observations of the CXB performed by *XMM-Newton* ([Lumb et al. 2002](#), [De Luca & Molendi 2004](#)), *Chandra* ([Hickox & Markevitch 2006](#)) and *RXTE* ([Revnivtsev et al. 2003](#)), and a recent reanalysis of the *HEAO1-A2* data ([Revnivtsev et al. 2005](#)). The main finding of their work was that a large amount of CT AGN, as many as the absorbed Compton-thin ones, are needed to explain the peak at ~ 30 keV of the CXB. The fit to the CXB of [Gilli et al. \(2007\)](#) with (*right panel*) and without (*left panel*) the population of CT AGN is showed in Fig. 4.6. Measurements of the CXB performed by *Swift*/BAT ([Ajello et al. 2008b](#)) have found a difference in the normalization of $8 \pm 3\%$ with respect to those performed by *HEAO-1 A-2*. It has been argued that this might imply the existence of an even larger (of a factor ~ 2) population of CT AGN. However, recent observations performed by *INTEGRAL* ([Türler et al. 2010](#)) contradicted these results, finding a spectrum of the CXB consistent with that of *HEAO-1 A-2*.

CT AGN are not easy to find. One suitable energy band for hunting them is the hard X-ray one. At these energies in fact (see Sect. 2.2) absorption affects less the intrinsic luminosity. However, recent hard X-ray surveys performed by *Swift*/BAT (e.g., [Tueller et al. 2008](#), [Markwardt et al. 2005](#)) and *INTEGRAL* IBIS/ISGRI ([Beckmann et al. 2006a](#), [Malizia et al. 2009](#)) have found only few of these objects. Another possible way to detect CT AGN is in the mid-IR band. At these energies one sees mostly dust-reprocessed (thermal) emission, thus bright mid-IR sources which are faint in the optical and in the near-IR band are good candidate to be heavily obscured (e.g., [Martínez-Sansigre et al. 2005](#)). This technique has been exploited to find CT AGN using *Spitzer* observations of the

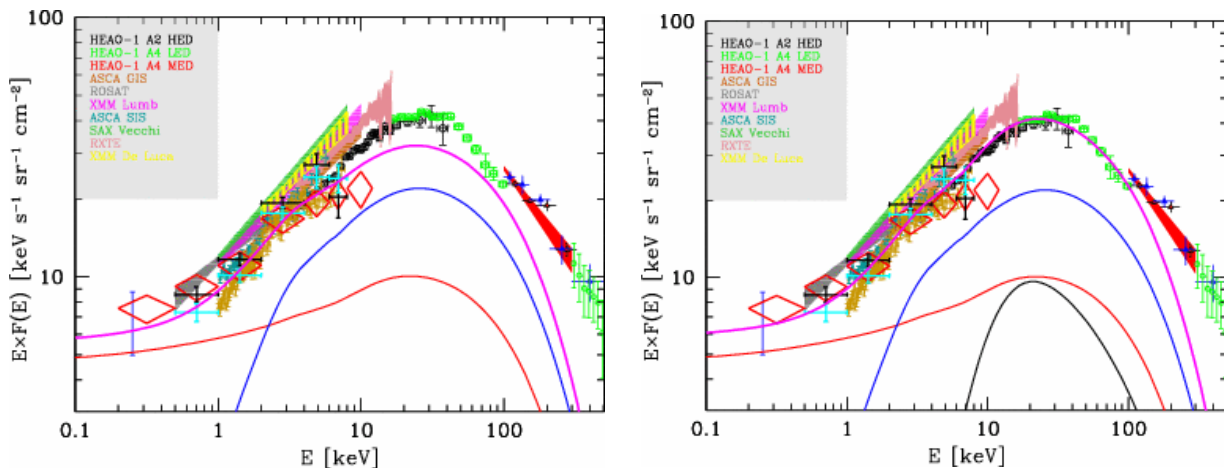


Figure 4.6: Synthesis models of the CXB excluding (*Left panel*) and including (*Right panel*) the population of CT sources (Gilli et al. 2007).

Chandra Deep Fields, and stacking the X-ray spectra of the mid-IR excesses (Daddi et al. 2007; Fiore et al. 2008). The problem of this approach is the possible influence of starburst emission, some of the mid-IR excesses might indeed be powerful starburst galaxies.

Recently, Treister et al. (2009) have shown that the real amount of CT AGN might actually be a factor 3 lower than what found by Gilli et al. (2007). They have in fact showed that the contribution of CT AGN to the CXB has a very strong degeneracy with the reflection normalization R (see Fig. 4.7). In their work, Gilli et al. (2007) used a value of $R = 1.3$ and $R = 0.88$ for unobscured and obscured low luminosities sources, respectively, and of $R = 0$ for high luminosity sources. As can be seen from Fig. 4.7, assuming $R = 1$ the density of CT AGN decreases of a factor ~ 3 .

4.5 Radiation pressure

As we will discuss in Sect. 5.1 the AGN can affect the environment of the host galaxy through two possible phenomena. One of them is related to the pressure exerted by the radiation produced in the central engine, and is normally parametrized in terms of the Eddington ratio λ_{Edd} . The first to hypothesize that radiation pressure might have an important effect of the absorbing medium was Lawrence & Elvis (1982). Since then several proofs to this were found, one of the most important of them probably being the decreasing of the fraction of absorbed objects with the increasing luminosity (Ueda et al. 2003, see also Sect. 4.3).

It has been recently suggested by Fabian et al. (2008) that even if an AGN is in a sub-Eddington regime for ionized gas, it might appear to be in super-Eddington regime for the dusty gas. Thus, due to the radiation pressure, long-lived stable clouds cannot survive in regimes where the radiation pressure is too strong, and AGN can live only in well determined zones of the $N_{\text{H}} - \lambda_{\text{Edd}}$ plane. On the other hand, dust lanes, which are located much further away from the central engine, can survive even to high values of λ_{Edd} (*left panel* of Fig. 4.8). Fabian et al. (2009a) using *Swift* /BAT AGN from the 9-months catalog (Tueller et al. 2008) found that most AGN are actually located outside of the *forbidden zone*, with the only exception of MCG-05-23-16 (*right panel* of Fig. 4.8). This object is well known to have warm absorbers, so it is not necessarily absorbed by dusty gas.

Table 4.1: Observed fraction of absorbed and CT AGN from different X-ray surveys. The table has been adapted from [Ajello \(2009\)](#) and [Burlon et al. \(2011\)](#).

Reference	Energy band (keV)	Completeness	% Absorbed	% CT	Instrument
Mainieri et al. (2002)	0.5–7	100%	~ 75%	0	<i>XMM-Newton</i>
Ueda et al. (2003)¹	–	96%	< 55%	~ 25%	Merged
Markwardt et al. (2005)	15–200	95%	~ 64%	10%	<i>Swift</i> /BAT
Tozzi et al. (2006)	0.5–7	99%	~ 75%	5%	<i>Chandra</i>
Beckmann et al. (2006a)	20–40	100%	~ 64%	10%	<i>INTEGRAL</i> /ISGRI
Bassani et al. (2006)	20–100	77%	~ 65%	~ 14%	<i>INTEGRAL</i> /ISGRI
Sazonov et al. (2007)	17–60	90%	~ 50%	~ 1%	<i>INTEGRAL</i> /ISGRI
Ajello et al. (2008a)	14–170	100%	~ 55%	< 20%	<i>Swift</i> /BAT
Tueller et al. (2008)	14–195	100%	~ 50%	~ 5%	<i>Swift</i> /BAT
Paltani et al. (2008)	20–60	100%	~ 60%	< 24%	<i>INTEGRAL</i> /ISGRI
Della Ceca et al. (2008)	4.5–7.5	97%	~ 57%	0	<i>XMM-Newton</i>
Malizia et al. (2009)	20–40	100%	~ 43%	7%	<i>INTEGRAL</i> /ISGRI
Beckmann et al. (2009)	18–60	~ 97%	~ 44%	~ 4%	<i>INTEGRAL</i> /ISGRI
Burlon et al. (2011)	15–195	100%	~ 53%	~ 5%	<i>Swift</i> /BAT

Notes ¹ Sample obtained merging different catalogs.

4.6 The fundamental plane of black hole activity

[Corbel et al. \(2000, 2003\)](#) found a clear non-linear relation between the luminosity in the radio and X-ray band in the black hole binary GX 339-4 of the form

$$L_R \propto L_X^{0.7}$$

Using a larger sample of black hole binaries, [Gallo et al. \(2003\)](#) found that this relation appears to be universal, although recent studies (e.g., [Gallo et al. 2007](#)) have shown that this might not always be the case for sources at a relatively high luminosity ($L_X > 10^{-3} L_{\text{Edd}}$).

Shortly after the finding of [Corbel et al. \(2000, 2003\)](#), two works of two independent groups ([Merloni et al. 2003](#); [Falcke et al. 2004](#)) established the existence of a plane linking L_R (at 5 GHz), L_X (in the 2–10 keV band) and M_{BH} , for all the accreting black holes, from X-ray binaries to AGN, including *Sgr A** (Fig. 4.9). This relation, defined by [Merloni et al. \(2003\)](#) the *fundamental plane of black hole activity*, is given by:

$$\log L_R = (0.60^{+0.11}_{-0.11}) \log L_X + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.05}_{-4.07}.$$

In a successive work [Merloni et al. \(2006\)](#) showed that this relation is not an artifact due to biases introduced by the sample selection, but an intrinsic characteristic of accreting black holes.

Of the three parameters of the fundamental plane, only M_{BH} is really fundamental, while L_X is an indicator of the radiative output of the system, and L_R is an indicator of the jet emission. The correlation found between L_X and L_R implies a certain stability and regularity in the jet formation. A possible explanation to the fundamental plane is the following. If, as demonstrated by [Körding et al. \(2006\)](#), $L_R \propto \dot{m}^{1.4}$, and if one considers the approximate solution for radiatively inefficient accretion $L_X/L_{\text{Edd}} \propto (\dot{m}/\dot{m}_{\text{Edd}})^2$, then it is straightforward to obtain $L_R \propto L_X^{0.7} M_{\text{BH}}^{0.7}$. This is within 0.1 from what has been obtained by [Merloni et al. \(2003\)](#) and [Falcke et al. \(2004\)](#), and it might imply that the fundamental plane is dominated by radiatively inefficient sources.

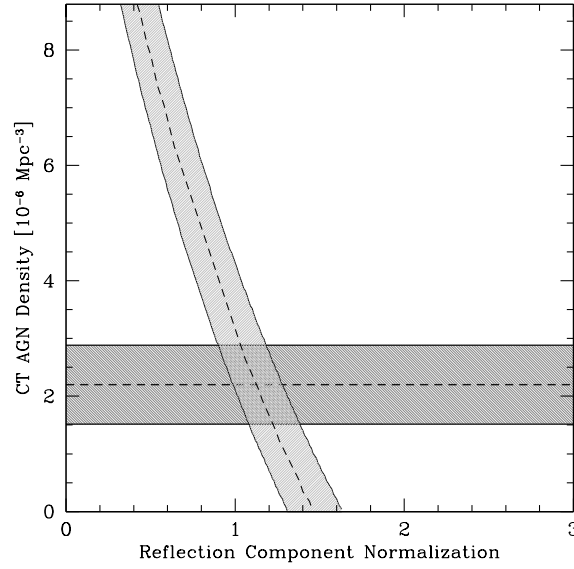


Figure 4.7: Degeneracy of the local density of CT AGN and the normalization of the reflection parameter R subject to the constraint of either the XRB intensity or the number of CT AGN in hard X-ray surveys (Treister et al. 2009). The dark gray region shows the space density obtained by Treister et al. (2009), while the light gray region shows the constraints to these parameters given by the intensity of the XRB in the 20-40 keV band.

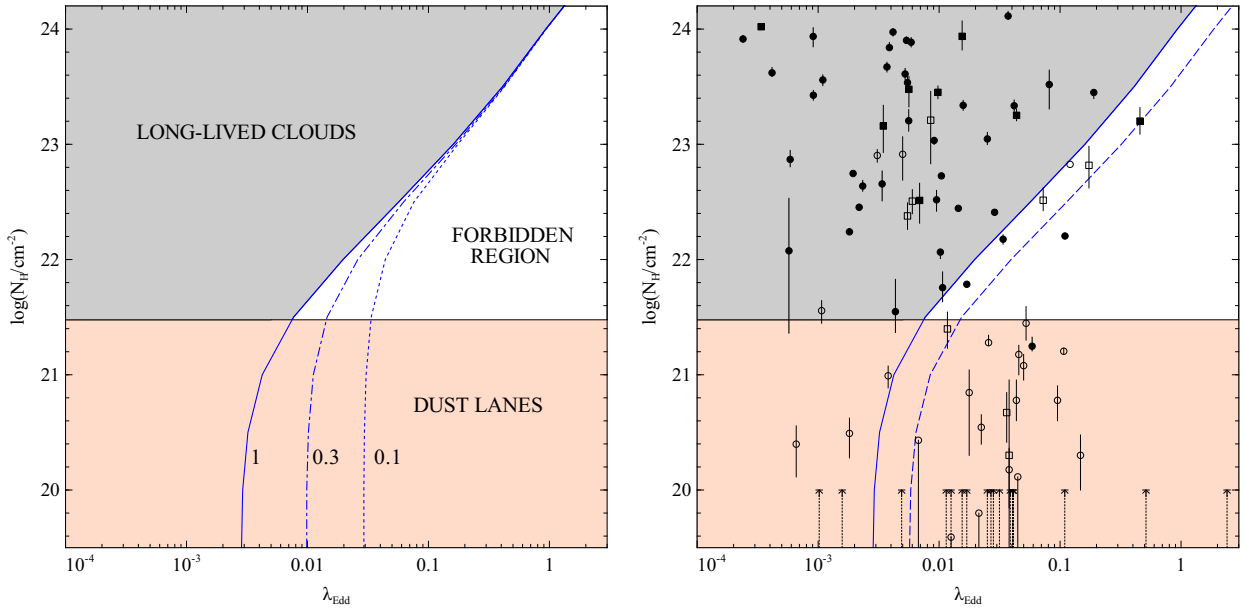


Figure 4.8: Different zones of the $N_{\text{H}} - \lambda_{\text{Edd}}$ plane, the lines represent different values of the grain abundances (*left panel*). AGN from the BAT 9-months catalog in the $N_{\text{H}} - \lambda_{\text{Edd}}$ plane (*right panel*). Both figures are taken from Fabian et al. (2009a).

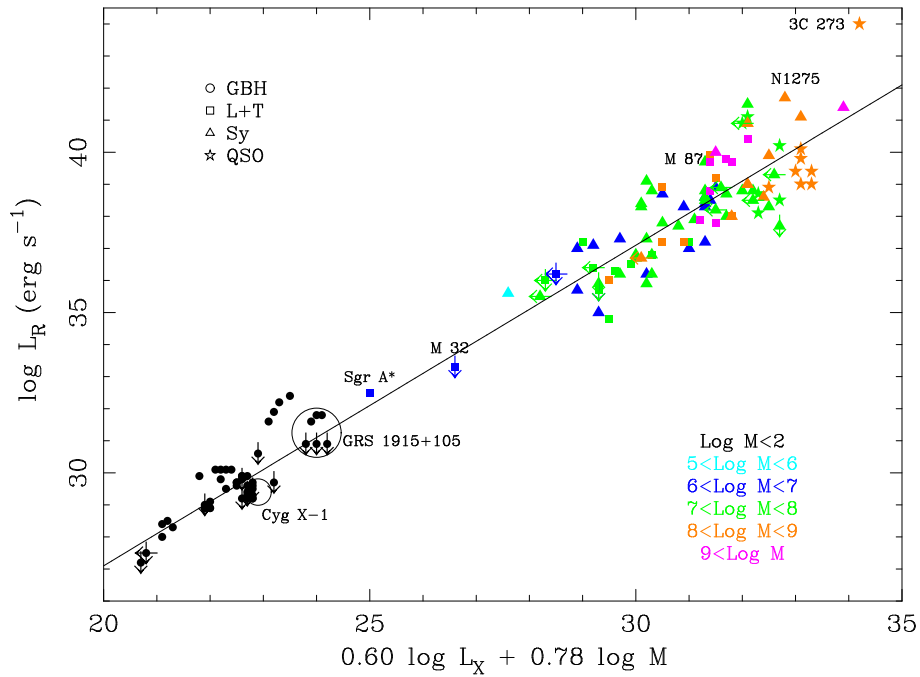


Figure 4.9: The fundamental plane of black hole activity (Merloni et al. 2005).

4.7 The second *INTEGRAL* AGN catalog

Hard X-ray surveys, being the less biased by absorption, are extremely important to fully understand the characteristics of different populations of AGN. This makes *INTEGRAL* a very powerful tool to study the AGN phenomenon.

The first *INTEGRAL* AGN catalog (Beckmann et al. 2006c) was released after 14 months of observations, and contained 42 AGN (*left panel* of Fig. 4.10), most of them radio-quiet. Of the AGN detected, 10 were Seyfert 1s, 9 Seyfert 1.5s, 16 Seyfert 2s, 5 blazars, 1 radio galaxy and 1 unidentified AGN. Excluding the blazars, the average redshift of the sample is $\langle z \rangle = 0.020 \pm 0.004$, and the average luminosity in the 20–100 keV band $\langle \log L \rangle = 43.3 \text{ erg s}^{-1}$. Due to the low quality of the spectra, most of them were fit using a single power-law model. Only for six of them a more complex model (i.e. a power law with a high energy cutoff) is needed. The average values of the photon indices found were $\Gamma_1 = 2.11 \pm 0.05$ and $\Gamma_{1.5} = 2.10 \pm 0.02$ for Seyfert 1s and Seyfert 1.5, while Seyfert 2s are on average harder, $\Gamma_2 = 1.95 \pm 0.01$.

After the first AGN catalog, *INTEGRAL* detected many more extragalactic sources (e.g., Beckmann et al. 2008, Molina et al. 2009), which led us to release a second catalog (Beckmann et al. 2009), which contained about 5 times as many AGN as the first one (*right panel* of Fig. 4.10). Of the 187 AGN reported in our work 162 were identified as Seyfert galaxies, 18 as blazars, and 7 objects as generic AGN. Amongst the Seyfert galaxies, 67 were type 1/1.2, 29 type 1.5, and 66 type 1.9/2. About 44% of the sources in the sample are absorbed, and the CT AGN represent only a $\sim 4\%$ of the whole population. The decrease in the fraction of absorbed sources for increasing luminosities is confirmed also in this hard X-ray selected sample (see Sect. 4.3), with $f = 0.65$ at $\log L_{20-100 \text{ keV}} = 42 \text{ erg s}^{-1}$ and $f = 0.35$ at $\log L_{20-100 \text{ keV}} = 45 \text{ erg s}^{-1}$.

Fitting the hard X-ray spectra of the Seyfert galaxies with a simple power-law model we found consistent average photon indices for Seyfert 1s ($\Gamma = 1.92 \pm 0.02$) and Seyfert 2s ($\Gamma = 1.88 \pm 0.02$), whereas Seyfert 1.5s are slightly steeper, and their value is consistent only with that of Seyfert 1s

($\Gamma = 2.02 \pm 0.03$). Both Seyfert 1.5s and Seyfert 2s have a lower average luminosity in the 20–100 keV band ($\langle \log L_{1.5} = 43.3 \text{ erg s}^{-1} \rangle$ and $\langle \log L_2 = 43.4 \text{ erg s}^{-1} \rangle$, respectively) than Seyfert 1s ($\langle \log L_1 = 44.0 \text{ erg s}^{-1} \rangle$). Being the black hole masses of the two classes consistent, the average Eddington ratio is lower for Sy1.5s and Sy2s ($\lambda_{\text{Edd}}^{1.5} = 0.015$ and $\lambda_{\text{Edd}}^2 = 0.02$, respectively) than for Sy1s ($\lambda_{\text{Edd}}^1 = 0.064$).

We did not find any correlation between the Eddington ratio and the photon index, although it might actually be hidden by the large uncertainties on the values of both parameters. The sources are distributed in the $N_{\text{H}} - \lambda_{\text{Edd}}$ plane mostly outside the forbidden zone defined by [Fabian et al. \(2008\)](#) (see Sect. 4.5). Besides MCG-05-23-16, four sources of the sample are in the forbidden area: IGR J00335+6126, Mrk 766, IC 4329A and NGC 5506.

The sample shows a strong intrinsic correlation between the optical (L_{V}) and the hard X-ray luminosity (L_{X}), as expected by the two-phase disk scenario (see Sect. 1.2.5). The distribution of $\alpha_{\text{OX}} = -\frac{\log(f_{\text{O}}/f_{\text{X}})}{\nu_{\text{O}}/\nu_{\text{X}}}$, where f_{O} and f_{X} are the monochromatic fluxes at 5500 Å and at 20 keV, respectively, are quite similar. However, both Sy 2s and Sy 1.5s show extended wings towards high values, possibly related to the higher absorption.

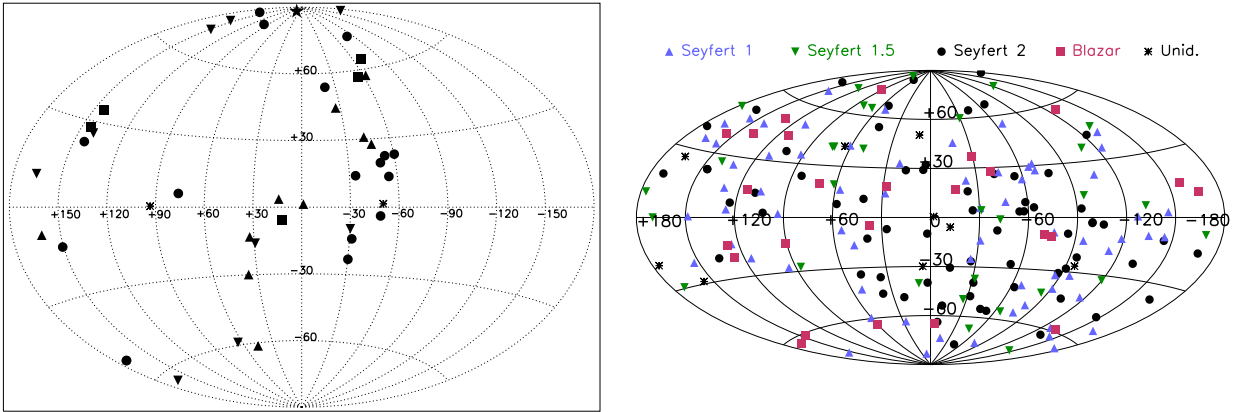


Figure 4.10: Distribution in the sky (in Galactic coordinates) of the 42 sources contained in the first *INTEGRAL* AGN catalog (*left panel*, [Beckmann et al. 2006b](#)), and of the 187 sources of the second *INTEGRAL* AGN catalog (*right panel*, [Beckmann et al. 2009](#)).

The second INTEGRAL AGN catalogue★

V. Beckmann^{1,2,3}, S. Soldi⁴, C. Ricci^{1,2}, J. Alfonso-Garzón⁵, T. J.-L. Courvoisier^{1,2}, A. Domingo⁵, N. Gehrels⁶,
 P. Lubiński^{7,1}, J. M. Mas-Hesse⁵, and A. A. Zdziarski⁷

¹ ISDC Data Centre for Astrophysics, Chemin d'Écogia 16, 1290 Versoix, Switzerland
 e-mail: beckmann@apc.univ-paris7.fr

² Observatoire Astronomique de l'Université de Genève, Chemin des Maillettes 51, 1290 Sauverny, Switzerland

³ APC Laboratory, Université Paris Diderot, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France

⁴ Laboratoire AIM – CNRS – CEA/DSM – Université Paris Diderot (UMR 7158), CEA Saclay, DSM/IRFU/Sap, 91191 Gif-sur-Yvette, France

⁵ Centro de Astrobiología LAEX (CSIC-INTA), POB 78, 28691 Villanueva de la Cañada, Madrid, Spain

⁶ Astrophysics Science Division, NASA Goddard Space Flight Center, Code 661, MD 20771, USA

⁷ Centrum Astronomiczne im. M. Kopernika, Bartycka 18, 00-716 Warszawa, Poland

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ABSTRACT

Aims. The INTEGRAL mission provides a large data set for studying the hard X-ray properties of AGN and allows testing of the unified scheme for AGN.

Methods. We present analysis of INTEGRAL IBIS/ISGRI, JEM-X, and OMC data for 199 AGN supposedly detected by INTEGRAL above 20 keV.

Results. The data analysed here allow significant spectral extraction on 148 objects and an optical variability study of 57 AGN. The slopes of the hard X-ray spectra of Seyfert 1 and Seyfert 2 galaxies are found to be consistent within the uncertainties, whereas higher cut-off energies and lower luminosities we measured for the more absorbed/type 2 AGN. The intermediate Seyfert 1.5 objects exhibit hard X-ray spectra consistent with those of Seyfert 1. When applying a Compton reflection model, the underlying continua appear the same in Seyfert 1 and 2 with $\Gamma \approx 2$, and the reflection strength is about $R \approx 1$, when assuming different inclination angles. A significant correlation is found between the hard X-ray and optical luminosity and the mass of the central black hole in the sense that the more luminous objects appear to be more massive. There is also a general trend toward the absorbed sources and type 2 AGN having lower Eddington ratios. The black hole mass appears to form a fundamental plane together with the optical and X-ray luminosity of the form $L_V \propto L_X^{0.6} M_{\text{BH}}^{0.2}$, similar to what is found between L_R , L_X , and M_{BH} .

Conclusions. The transition from the type 1 to type 2 AGN appears to be smooth. The type 2 AGN are less luminous and have less accreting super massive black holes. The unified model for Seyfert galaxies seems to hold, showing in hard X-rays that the central engine is the same in Seyfert 1 and 2, but seen under different inclination angles and absorption. The fundamental plane links the accretion mechanism with the bulge of the host galaxy and with the mass of the central engine in the same way in all types of Seyfert galaxies.

Key words. galaxies: active – galaxies: Seyfert – X-rays: galaxies – surveys – catalogs

1. Introduction

The extragalactic X-ray sky is dominated by active galactic nuclei (AGN), which are commonly assumed to host an accreting supermassive black hole in the centres of galaxies. X-ray spectroscopy has been vital in the study of the AGN phenomenon, because it probes the condition of matter in the vicinity of the black hole. One model for the X-ray emission is that of a hot corona lingering on top of the inner accretion disc of the black hole and emitting inverse Compton radiation from disc photons that have been upscattered by energetic electrons. Another model assumes a disc with a hot inner advection-dominated accretion flow (ADAF; e.g. Abramowicz et al. 1996). An alternative model for the accretion process onto black holes is that of clumpy accretion flows (e.g. Guilbert & Rees 1988). Courvoisier & Türler (2005) assume that the different elements (clumps) of the

accretion flow have velocities that may differ substantially. As a consequence, collisions between these clumps will appear when the clumps are close to the central object, resulting in radiation.

Because optical spectroscopy distinguishes between two main types of low-luminosity AGN, the broad-line Seyfert 1 and narrow-line Seyfert 2 objects, a similar distinction is apparent between unabsorbed sources with on-average softer X-ray spectra and the flatter spectra of absorbed sources. This has been noticed by Zdziarski et al. (1995), based on *Ginga* and *CGRO/OSSE* data and later confirmed e.g. by Gondek et al. (1996) using combined *EXOSAT*, *Ginga*, *HEAO-1*, and *CGRO/OSSE* spectra, and by Beckmann et al. (2006) using *INTEGRAL* IBIS/ISGRI data of AGN above 20 keV. A study of *BeppoSAX* PDS spectra of 45 Seyfert galaxies has come to a similar conclusion, although the spectra of Seyfert 2 appeared steeper when considering a possible cut-off in the spectra of Seyfert 1 galaxies (Deluit & Courvoisier 2003). X-ray data already show that most, but not all, AGN unabsorbed in the X-rays are Seyfert 1 type, and most, but not all, AGN that are absorbed belong to the Seyfert 2 group (e.g. Awaki et al. 1991).

★ All tables of this paper are also available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/505/417>

Thus a longstanding discussion has been, whether these two groups indeed represent physically different types of objects, or whether they can be unified under the assumption that they are intrinsically the same but seen from a different viewing angle with respect to absorbing material in the vicinity of the central engine (e.g. Antonucci 1993), and that the difference in X-ray spectral slope can be explained solely by the absorption and reflection components. This *unified model* naturally explains the different Seyfert types in a way that the broad-line region is either visible (Seyfert 1) or hidden (Seyfert 2) possibly by the same material in the line of sight as is responsible for the absorption detectable at soft X-rays (e.g. Lawrence & Elvis 1982). On the other hand, the model has some problems explaining other aspects of AGN, for example, that some Seyfert galaxies change their type from 1 to 2 and back, but also the observation that Seyfert 2 objects exhibit flatter hard X-ray spectra than Seyfert 1 even in the energy range >20 keV, where absorption should not play a major role unless $N_H \gg 10^{24} \text{ cm}^{-2}$. Also, the existence of Seyfert 2 galaxies that show no absorption in the soft X-rays, like NGC 3147 and NGC 4698 (Pappa et al. 2001) cannot be explained by the unified model.

Lately, two hard X-ray missions have provided surveys at >20 keV with enough sky coverage to be suitable for population studies of AGN. One is the NASA-led *Swift* mission (Gehrels et al. 2004) launched in 2004, the other one the ESA-led *INTEGRAL* satellite (Winkler et al. 2004), launched in October 2002. Due to its observation strategy of following-up gamma-ray bursts, *Swift*/BAT (Barthelmy et al. 2005) provides a more homogeneous sky coverage in the 15–195 keV energy range, while the hard X-ray imager IBIS/ISGRI on-board *INTEGRAL* is more sensitive and extends up to several hundred keV with better spectral resolution. *INTEGRAL* provides broad-band coverage through the additional X-ray monitor JEM-X in the 3–30 keV range (Lund et al. 2003) and provides photometry with the optical camera OMC in the V-band (Mas-Hesse et al. 2003).

The AGN surveys provided by *Swift*/BAT (Tueller et al. 2008) and *INTEGRAL* IBIS/ISGRI (Beckmann et al. 2006b; Bassani et al. 2007) have already led to the discovery that the fraction of absorbed and Compton thick sources is less than expected from cosmic X-ray background synthesis models (e.g. Treister & Urry 2005; Gilli et al. 2007). With the ongoing *INTEGRAL* mission, it is now possible to compile a large sample of AGN for spectroscopic and correlation studies and to probe the unified model for AGN. The data analysis is described in Sect. 2, the average properties of the AGN in the sample in Sect. 3, the discussion of the properties in the view of unified models in Sect. 4, and we end with the conclusions in Sect. 5. Notes on individual sources can be found in the Appendix (Sect. A).

2. Data analysis

The list of AGN presented here is based on all *INTEGRAL* detections of AGN reported in the literature, therefore enter into the *INTEGRAL* general reference catalogue¹ (Ebisawa et al. 2003; Bodaghee et al. 2007). It has to be pointed out that for many sources, we present the first *INTEGRAL* spectral analysis, because Bodaghee et al. (2007), Sazonov et al. (2007), and Bassani et al. (2006) did not include spectral analysis, and Beckmann et al. (2006) discussed a sample of 38 AGN based only on

¹ For the latest version of the catalogue see <http://isdc.unige.ch/index.cgi?Data+catalogs>

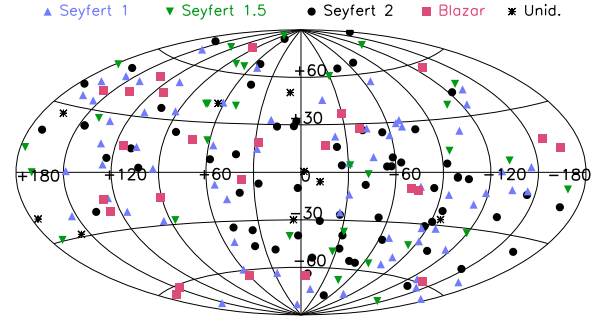


Fig. 1. *INTEGRAL*-detected AGN during the first 5 years of the mission. As unidentified we mark those sources where the AGN type has not been determined yet.

1.3 years of *INTEGRAL* data. With the *INTEGRAL* mission continuing smoothly, most of the sky has been observed in the first 5 years of operations, leading to a rather uniform sky distribution of detected AGN, as shown in Fig. 1. For each extragalactic source, we analysed the IBIS/ISGRI, JEM-X, and OMC data from the early mission (revolution 26 starting on 30 December 2002) up to spacecraft revolution 530 (ending on 17 February 2007), covering more than 4 years of data. To include only high-quality data, the selection considers ISGRI data taken at an off-axis angle smaller than 10° and includes only those observations that lasted for at least 500 s. Analysis software used in this work is version 7 of the Offline Standard Analysis Software (OSA) provided by the ISDC Data Centre for Astrophysics (Courvoisier et al. 2003). For each source, imaging analysis was performed to determine the significant sources in the field around the AGN. Taking their fluxes into account is important when analysing data from coded-mask instruments, because all sources in the field add to the background of the source of interest. Then standard spectral extraction was used, considering all significant sources in the field.

For the X-ray monitor JEM-X, a similar selection of data was performed, using a maximum off-axis angle of 3° due to the smaller field of view compared to IBIS. The much lower effective exposure time when compared to IBIS/ISGRI (Table 1) results in only 23 detections of AGN by JEM-X with a significance $>5\sigma$. For JEM-X, spectra were extracted from the mosaic images, since this procedure is more reliable for faint sources than the standard spectral extraction in OSA 7.

Naturally, some sources reported in the literature do not show up significantly in the data analysed here, because they were observed after February 2007, or they are, like the blazar class, highly variable and therefore do not give a significant detection in the combined data set. The 199 AGN reported to be found in *INTEGRAL* data are listed in Table 1, together with their redshift, position (J2000.0), and their effective exposure time in IBIS/ISGRI and JEM-X for the data set used here. Twelve sources, which were reported in the literature but gave a detection significance $<3\sigma$ in the data presented here are listed in Table 1 and marked by an x. These objects are not considered in the following analysis. All errors given in this paper are at the 1σ level.

2.1. Black hole masses

We also include in Table 1 the black hole masses of the central engine and the method used to determine them, as found in the literature. Different methods can be used to estimate the mass of

Table 1. *INTEGRAL* AGN catalogue. The column *Method* indicates the method used to determine the black hole mass, see Sect. 2.1 for details.

Name	Type	z	RA [deg]	Dec [deg]	ISGRI [ks]	JEM-X [ks]	$\log M_{\text{BH}}$ [$M_{\odot}$]	Method
IGR J00040+7020 ^x	Sy2	0.096	1.00638	70.32125	1947.3	20.9		
IGR J00254+6822	Sy2	0.012	6.38092	68.36147	2534.6	178.9		
IGR J00335+6126	Sy1	0.105	8.3265	61.46178	3338.7	356.5	8.5 ± 0.5^a	LL/CL
1ES 0033+59.5	BLLac	0.086	8.96929	59.83461	3338.7	356.4		
Mrk 348	Sy2	0.0151	12.19642	31.95697	150.7	21.1	7.2 ± 0.7^b	SO
NGC 418 [*]	AGN	0.0190	17.64842	-30.22128	38.5	–		
NGC 526A	Sy1.5	0.0191	20.97583	-35.06528	73.7	–	8.1 ± 0.7^c	S
ESO 297-18	Sy2	0.0252	24.65492	-40.01131	59.5	–	9.7 ± 0.5^n	KM
IGR J01528-0326	Sy2	0.0167	28.20375	-3.44749	837.1	79.6		
NGC 788	Sy2	0.0136	30.27687	-6.81553	926.6	117.9	7.5 ± 0.7^b	SO
Mrk 590	Sy1.2	0.0264	33.63984	-0.76669	936.0	266.6	$7.14^{+0.1}_{-0.09}^d$	R
IGR J02097+5222	Sy1	0.0492	32.40700	52.44543	698.4	2.0		
SWIFT J0216.3+5128	Sy2	0.0288	34.11292	51.42375	481.9	2.0		
Mrk 1040	Sy1.5	0.0167	37.06079	31.31094	42.8	–	7.6 ± 0.3^e	S
IGR J02343+3229	Sy2	0.0162	38.57500	32.48333	70.5	–		
NGC 985	Sy1	0.0431	38.65738	-8.78761	808.1	48.3	8.9 ± 0.5^n	KM
NGC 1052	Sy2	0.0050	40.27000	-8.25578	707.0	31.1	8.2 ± 0.3^e	S
RBS 345	Sy1	0.0690	40.56667	5.53000	443.2	–		
NGC 1068	Sy2	0.0288	40.67012	-0.01344	914.4	44.8	7.2 ± 0.1^e	M
QSO B0241+62	Sy1	0.0446	41.24042	62.46847	711.9	35.2		
IGR J02466-4222	AGN	0.0695	41.65375	-42.36600	191.4	21.9		
IGR J02501+5440	Sy2	0.015	42.67417	54.70419	773.8	13.5		
MCG-02-08-014	Sy2	0.0168	43.09750	-8.51042	528.1	4.7		
NGC 1142	Sy2	0.0288	43.80133	-0.18381	634.1	–	9.4 ± 0.5^n	KM
QSO B0309+411	Sy1	0.136	48.25817	41.33366	488.4	303.1		
IGR J03184-0014 ^x	QSO	–	49.60000	-0.22889	–	–		
NGC 1275	Sy2	0.0176	49.95067	41.51170	506.8	282.0	8.5 ± 0.7^e	S
1H 0323+342	Sy1	0.0629	51.17150	34.17941	431.6	0.9		
IGR J03334+3718	Sy1.5	0.0547	53.32833	37.30305	463.4	5.6		
NGC 1365	Sy1.5	0.0055	53.40208	-36.13806	143.3	3.0	7.7 ± 0.3^f	S
IGR J03532-6829	BLLac	0.0870	58.30833	-68.48306	740.8	9.4		
3C 111	Sy1	0.0485	64.58867	38.02661	160.1	–	9.6 ± 0.8^c	B
3C 120	Sy1	0.0330	68.29623	5.35434	365.9	79.3	7.7 ± 0.2^g	R
UGC 3142	Sy1	0.0217	70.94537	28.97194	449.6	39.9		
LEDA 168563	Sy1	0.0290	73.01958	49.54583	112.5	–		
ESO 33-2	Sy2	0.0181	73.99834	-75.54056	1110.4	–		
4U 0517+17	Sy1.5	0.0179	77.68958	16.49861	1145.4	19.8		
Ark 120	Sy1	0.0327	79.04784	-0.15017	571.9	63.1	$8.18^{+0.05}_{-0.06}^g$	R
IGR J05270-6631 ^x	QSO	0.978	81.56021	-66.5125	631.7	323.4	8.4 ± 0.5^a	LL/CL
PKS 0528+134 ^x	blazar	2.060	82.73507	13.53199	917.6	157.3		
NGC 2110	Sy2	0.0078	88.04742	-7.45622	20.5	–	8.3 ± 0.3^e	S
MCG+08-11-011	Sy1.5	0.0205	88.72338	46.43934	50.8	–	8.1 ± 0.6^c	SO
IRAS 05589+2828	Sy1	0.0330	90.54042	28.47139	1689.9	29.0		
SWIFT J0601.9-8636	Sy2	0.0064	91.41292	-86.63111	177.8	31.9	7.9 ± 0.5^n	KM
IGR J06117-6625	Sy1.5	0.230	92.95208	-66.40847	1122.2	97.2		
Mrk 3	Sy2	0.0135	93.90129	71.03748	814.9	55.4	8.7 ± 0.3^e	S
IGR J06239-6052	Sy2	0.0405	95.94004	-60.97927	598.0	–		
IGR J06292+4858 ^x	BLLac	0.097	97.300	48.97389	–	–		
PKS 0637-752	Sy1	0.651	98.94379	-75.27133	1066.6	22.7	9.4 ± 0.5^e	CL
Mrk 6	Sy1.5	0.0188	103.0513	74.42689	819.4	109.7	8.2 ± 0.5^n	KM
QSO B0716+714	BLLac	0.3	110.4727	71.34343	863.8	162.8		
LEDA 96373	Sy2	0.0294	111.6096	-35.90583	180.9	5.6		
IGR J07437-5137	Sy2	0.025	115.9208	-51.61694	947.3	–		
IGR J07565-4139	Sy2	0.021	119.0817	-41.62836	1703.0	50.6		
IGR J07597-3842	Sy1	0.040	119.9242	-38.73223	1288.1	31.8	8.3 ± 0.5^p	LL
ESO 209-12	Sy1.5	0.0405	120.4900	-49.77833	2288.6	117.7		
PG 0804+761	Sy1	0.10	122.7444	76.04514	694.9	44.9	$8.84^{+0.05}_{-0.06}^g$	R
Fairall 1146	Sy1.5	0.0316	129.6279	-35.99306	1689.9	26.2		
QSO B0836+710	BLLac	2.1720	130.3515	70.89506	754.4	29.7		
IGR J09026-4812 ^m	Sy1	0.039	135.6555	-48.22608	3773.3	470.1		
SWIFT J0917.2-6221	Sy1	0.0573	139.0392	-62.32486	669.0	16.1		
IGR J09253+6929	Sy1	0.039	141.321	69.488	324.1	–	7.6 ± 0.5^a	LL/CL
Mrk 110	NLS1	0.0353	141.3036	52.28625	54.2	–	$7.42^{+0.09}_{-0.1}^g$	R
IGR J09446-2636	Sy1.5	0.1425	146.1500	-26.60000	157.1	–		
NGC 2992	Sy1	0.0077	146.4252	-14.32639	383.3	66.7	7.7 ± 0.3^e	S

Table 1. continued.

Name	Type	z	RA [deg]	Dec [deg]	ISGRI [ks]	JEM-X [ks]	$\log M_{\text{BH}}$ [$M_{\odot}$]	Method
MCG-05-23-016	Sy2	0.0085	146.9173	-30.94886	130.2	—	6.3 ± 0.5^c	SO
IGR J09523-6231	Sy1.5	0.252	148.0854	-62.54333	1059.1	111.1	—	—
NGC 3081	Sy2	0.0080	149.8731	-22.82628	255.3	—	7.4 ± 0.3^b	S
SWIFT J1009.3-4250	Sy2	0.033	152.4512	-42.81222	437.4	—	—	—
IGR J10147-6354	Sy1.2	0.202	153.6750	-63.89194	1182.9	104.6	8.6 ± 0.5^a	LL/CL
NGC 3227	Sy1.5	0.0039	155.8776	19.86492	142.0	—	$7.3^{+0.2}_{-0.1}^h$	K
NGC 3281	Sy2	0.0107	157.9669	-34.85369	211.3	41.9	8.0 ± 0.5^n	KM
SWIFT J1038.8-4942	Sy1.5	0.060	159.6875	-49.78194	908.6	10.2	—	—
IGR J10404-4625	Sy2	0.0237	160.0928	-46.42353	673.6	—	—	—
Mrk 421	BLLac	0.0300	166.1138	38.20883	826.1	482.4	8.3 ± 0.3^e	S
IGR J11366-6002	Sy2	0.014	174.1754	-60.05217	2196.0	315.7	—	—
NGC 3783	Sy1	0.0097	174.7574	-37.73853	22.9	—	$7.47^{+0.07}_{-0.09}^g$	R
IGR J12026-5349	Sy2	0.028	180.6985	-53.83547	1535.9	116.6	—	—
NGC 4051	Sy1.5	0.0023	180.7901	44.53144	793.2	—	6.3 ± 0.2^g	R
NGC 4138	Sy1.5	0.0030	182.3745	43.68500	798.4	31.4	6.8 ± 0.5^n	KM
NGC 4151	Sy1.5	0.0033	182.6364	39.40545	820.3	548.3	$7.5^{+0.1}_{-0.6}^h$	K
NGC 4180	AGN	0.0070	183.2627	7.03881	1016.8	72.1	—	—
Was 49	Sy2	0.0610	183.5742	29.52872	931.4	—	—	—
Mrk 766	Sy1.5	0.0129	184.6110	29.81267	994.6	—	6.5 ± 0.3^i	S
NGC 4258	Sy1.5	0.0015	184.7397	47.30397	816.2	4.6	7.59 ± 0.01^i	M
4C 04.42	BLLac	0.9650	185.5940	4.22106	1277.5	232.6	—	—
Mrk 50	Sy1	0.0234	185.8506	2.67911	1320.8	264.8	—	—
NGC 4388	Sy2	0.0084	186.4455	12.66203	869.2	146.8	7.2 ± 0.6^b	SO
NGC 4395	Sy1.5	0.0011	186.4539	33.54661	1103.5	—	$4.7^{+0.3}_{-0.7}^i$	V
3C 273	QSO	0.1583	187.2779	2.05239	2004.6	299.2	$9.81^{+0.1}_{-0.07}^k$	R
NGC 4507	Sy2	0.0118	188.9023	-39.90925	389.3	—	7.6 ± 0.6^c	SO
SWIFT J1238.9-2720	Sy2	0.0250	189.7271	-27.30778	71.3	—	8.6 ± 0.5^n	KM
IGR J12391-1612	Sy2	0.0367	189.7762	-16.17975	618.7	39.4	8.9 ± 0.5^n	KM
NGC 4593	Sy1	0.0090	189.9143	-5.34425	1466.5	213.5	$6.99^{+0.08}_{-0.1}^h$	R
IGR J12415-5750	Sy1.5	0.0242	190.3575	-57.83417	1653.1	101.6	8.0 ± 0.5^a	LL/CL
PKS 1241-399	QSO	0.1910	191.1223	-40.21289	551.3	—	—	—
ESO 323-32	Sy1	0.0160	193.3348	-41.63717	744.4	23.9	—	—
3C 279	BLLac	0.5362	194.0465	-5.78931	1144.1	185.0	8.4 ± 0.5^e	CL
IGR J13000+2529 ^x	AGN	—	195.0000	25.48333	937.1	241.0	—	—
Mrk 783	Sy1.5	0.0672	195.7452	16.40763	728.2	11.2	—	—
IGR J13038+5348	Sy1	0.0302	195.9975	53.79172	366.3	16.5	7.5 ± 0.5^n	KM
NGC 4945	Sy2	0.0019	196.3587	-49.47083	1100.0	141.8	6.2 ± 0.3^l	M
IGR J13057+2036	AGN	—	196.4273	20.58103	853.1	12.0	—	—
ESO 323-77	Sy1	0.0150	196.6108	-40.41389	920.1	65.3	7.4 ± 0.6^c	LL
IGR J13091+1137	Sy2	0.025	197.2733	11.63414	391.1	8.2	8.6 ± 0.5^n	KM
IGR J13109-5552	Sy1	0.104	197.6795	-55.86991	1506.6	26.6	—	—
NGC 5033	Sy1.5	0.0029	198.3650	36.59358	743.2	6.2	—	—
IGR J13149+4422	Sy2	0.0366	198.8155	44.40750	421.4	56.8	—	—
Cen A	Sy2	0.0018	201.3651	-43.01911	1268.0	149.5	8.0 ± 0.6^c	K
ESO 383-18	Sy2	0.0124	203.3596	-34.01631	756.8	191.6	—	—
MCG-06-30-015	Sy1.2	0.0077	203.9741	-34.29558	767.2	213.0	$6.7^{+0.1}_{-0.2}^i$	S
NGC 5252	Sy2	0.0230	204.5667	4.54236	58.9	—	$9.03^{+0.4}_{-0.02}^l$	K
Mrk 268	Sy2	0.0399	205.2964	30.37811	728.7	—	—	—
4U 1344-60	Sy1.5	0.0129	206.8833	-60.61000	1537.7	231.2	—	—
IC 4329A	Sy1	0.0161	207.3304	-30.30956	381.9	52.6	$\sim 7^g$	R
Circinus Galaxy	Sy2	0.0014	213.2871	-65.34084	2272.1	201.3	$6.04^{+0.07}_{-0.09}^l$	M
NGC 5506	Sy1.9	0.0062	213.3120	-3.20750	102.9	88.5	6.7 ± 0.7^b	SO
IGR J14175-4641	Sy2	0.076	214.2664	-46.69419	1268.8	21.4	—	—
NGC 5548	Sy1.5	0.0172	214.4985	25.13706	200.9	42.4	7.82 ± 0.02^h	R
RHS 39	Sy1	0.0222	214.8425	-26.64472	454.4	8.1	8.7 ± 0.5^n	KM
H 1426+428	BLLac	0.1291	217.1358	42.67472	499.5	224.7	9.1 ± 0.7^e	SB
IGR J14471-6414	Sy1	0.053	221.6158	-64.27319	1797.1	171.8	—	—
IGR J14471-6319	Sy2	0.038	221.8120	-63.28868	1842.9	230.3	—	—
IGR J14492-5535	AGN	—	222.3038	-55.60578	1886.0	142.4	—	—
IGR J14515-5542	Sy2	0.018	222.8880	-55.67733	1869.2	144.0	—	—
IGR J14552-5133	NLS1	0.016	223.8223	-51.57102	2007.3	7.9	6.3 ± 0.5^p	LL
IGR J14561-3738	Sy2	0.024	224.0342	-37.64803	2185.9	340.8	—	—

Table 1. continued.

Name	Type	z	RA [deg]	Dec [deg]	ISGRI [ks]	JEM-X [ks]	$\log M_{\text{BH}}$ [$M_{\odot}$]	Method
IGR J14579-4308	Sy2	0.016	224.4296	-43.13000	2012.9	333.4		
Mrk 841	Sy1.5	0.0364	226.0050	10.43782	131.3	6.7	8.5 ± 0.7^c	R
ESO 328-36	Sy1	0.0237	228.6958	-40.35861	2200.9	384.8		
IGR J15161-3827	Sy2	0.0365	229.0375	-38.44806	2181.2	372.1		
NGC 5995	Sy2	0.0252	237.1040	-13.75778	1129.2	28.6		
IGR J15539-6142	Sy2	0.015	238.3967	-61.68206	1754.0	101.0		
IGR J16024-6107	Sy2	0.0114	240.4517	-61.14822	1792.4	84.3		
IGR J16056-6110	Sy1.5	0.052	241.4643	-61.19525	1727.2	64.4		
IGR J16119-6036	Sy1	0.016	242.9642	-60.63194	1789.6	60.9		
IGR J16185-5928	NLS1	0.035	244.6518	-59.45482	2066.0	44.6	7.4 ± 0.5^p	LL
IGR J16351-5806	Sy2	0.009	248.8071	-58.08047	2230.3	39.3		
IGR J16385-2057	NLS1	0.0269	249.6250	-20.94389	1505.9	80.4		
IGR J16426+6536	NLS1	0.323	250.7670	65.54747	56.0	—	7.0 ± 0.5^c	LL/CL
IGR J16482-3036	Sy1	0.0313	252.0623	-30.58502	2450.9	53.7		
ESO 138-1	Sy2	0.0091	252.8333	-59.23389	1509.2	21.4		
NGC 6221	Sy2	0.0050	253.1942	-59.21639	1481.0	21.4		
NGC 6240	Sy2	0.0245	253.2457	2.40047	300.5	67.7		
Mrk 501	BLLac	0.0337	253.4676	39.76017	476.3	70.6	9.2 ± 0.3^e	S
IGR J16558-5203	Sy1	0.054	254.0234	-52.06135	3065.7	249.6	7.9 ± 0.5^p	LL
IGR J16562-3301	BLLac	—	254.0701	-33.03680	3669.2	111.4		
NGC 6300	Sy2	0.0037	259.2467	-62.81972	237.9	8.9	5.5 ± 0.4^c	X
IGR J17204-3554	AGN	—	260.1042	-35.90000	6318.5	292.3		
QSO B1730-130 [*]	QSO	0.9020	263.2613	-13.08042	1080.1	33.1		
GRS 1734-292	Sy1	0.0214	264.3681	-29.13403	9122.1	665.7	8.9 ± 0.7^q	SO
IGR J17418-1212	Sy1	0.0372	265.4625	-12.19611	1300.1	45.5		
IGR J17488-3253	Sy1	0.020	267.2297	-32.91449	6159.4	410.4		
IGR J17513-2011	Sy2	0.047	267.8068	-20.20405	6220.1	268.7	6.0 ± 0.5^p	LL
IGR J18027-1455	Sy1	0.0034	270.6974	-14.91522	2463.8	173.0		
IGR J18244-5622	Sy2	0.0169	276.0812	-56.36909	103.3	4.4		
IGR J18249-3243	Sy1	0.355	276.2361	-32.71661	5126.8	208.7		
IGR J18259-0706	Sy1?	—	276.48958	-7.17264	2009.5	226.1		
PKS 1830-211	BLLac	2.5070	278.4162	-21.06106	2775.4	111.2		
3C 382	Sy1	0.0579	278.7641	32.69635	15.2	0.7	9.2 ± 0.5^n	KM
ESO 103-35	Sy2	0.0133	279.5846	-65.42805	28.5	—	7.1 ± 0.6^c	X
3C 390.3	Sy1	0.0561	280.5374	79.77142	448.0	33.2	$8.46^{+0.09}_{-0.1}^g$	R
ESO 140-43 [*]	Sy1	0.0141	281.2917	-62.35583	378.0	27.7		
IGR J18559+1535	Sy1	0.084	284.0000	15.63694	2594.9	24.7		
ESO 141-55 [*]	Sy1	0.0366	290.3092	-58.67083	378.0	79.9	7.1 ± 0.6^c	SO
1RXS J192450.8-29143	BLLac	0.3520	291.2127	-29.24170	955.7	28.6		
1H 1934-063	Sy1	0.0106	294.3879	-6.21806	654.2	2.1	7.9 ± 0.6^c	SO
IGR J19405-3016	Sy1	0.052	295.0631	-30.26347	930.3	22.3		
NGC 6814	Sy1.5	0.0052	295.6683	-10.32333	438.5	7.4	7.1 ± 0.2^h	CL
IGR J19473+4452	Sy2	0.0539	296.8307	44.82845	1194.3	1.0		
3C 403	Sy2	0.0590	298.0617	2.50778	490.2	—		
QSO B1957+405	Sy2	0.0561	299.8682	40.73386	2258.1	69.5	9.4 ± 0.1^l	K
1ES 1959+650 [*]	BLLac	0.048	299.9994	65.14851	11.2	—	8.1 ± 0.3^e	S
ESO 399-20	NLS1	0.0250	301.7383	-34.54833	857.2	24.7		
IGR J20187+4041	Sy2	0.0144 ^r	304.6606	40.68344	2851.0	442.7		
IGR J20286+2544	Sy2	0.013	307.1462	25.73361	840.2	4.1		
4C 74.26 ^x	QSO	0.1040	310.6549	75.13403	77.1	—	9.6 ± 0.5^e	CL
Mrk 509	Sy1.2	0.0344	311.0406	-10.72348	71.7	57.3	$8.16^{+0.03}_{-0.04}^g$	R
S5 2116+81	Sy1	0.086	318.5021	82.07975	176.5	—	8.8 ± 0.5^n	KM
IGR J21178+5139	AGN	—	319.4468	51.64823	1261.9	171.3		
IGR J21247+5058	Sy1	0.020	321.1640	50.97329	1392.7	174.7		
IGR J21272+4241 ^x	Sy1.5	0.316	321.7917	42.69194	836.3	189.8		
IGR J21277+5656	Sy1	0.0144	321.9373	56.94436	984.5	166.6		
RX J2135.9+4728	Sy1	0.0252	323.9766	47.47453	1213.4	136.3		
PKS 2149-306	FSRQ	2.345	327.9813	-30.46492	258.6	47.1		
NGC 7172	Sy2	0.0086	330.5071	-31.87167	346.5	68.8	7.7 ± 0.6^c	SO
BL Lac	BLLac	0.0686	330.6804	42.27778	738.1	—	8.2 ± 0.7^e	SB
IGR J22292+6647	Sy1 ^o	0.113 ^o	337.3062	66.78106	1678.9	9.3		
NGC 7314	Sy1	0.0048	338.9419	-26.05047	546.8	1.7	6.0 ± 0.5^c	S
Mrk 915	Sy1	0.0241	339.1938	-12.54517	609.0	12.8		
IGR J22517+2217	BLLac	3.668	342.9280	22.29900	251.3	5.8		
3C 454.3	BLLac	0.8590	343.4906	16.14822	207.1	36.3	9.2 ± 0.7^e	CL

Table 1. continued.

Name	Type	z	RA [deg]	Dec [deg]	ISGRI [ks]	JEM-X [ks]	$\log M_{\text{BH}}$ [$M_{\odot}$]	Method
1H 2251-179	Sy1	0.0640	343.5245	-17.58203	579.2	314.6	< 6.9 ^c	W
NGC 7469	Sy1	0.0163	345.8156	8.87386	139.2	–	7.09 ± 0.05^g	R
MCG-02-58-022	Sy1.5	0.0469	346.1812	-8.68572	624.5	28.2	7.1 ± 0.6^c	SO
NGC 7603 ^x	Sy1.5	0.0295	349.7359	0.24347	104.5	–	8.1 ± 0.3^e	S
IGR J23206+6431	Sy1	0.0732	350.15	64.52	3888.2	349.8	–	–
IGR J23308+7120	Sy2	0.037	352.6552	71.37911	1965.1	–	–	–
IGR J23524+5842	Sy2	0.164	358.0917	58.75908	4076.7	361.1	–	–

* Beckmann et al. (2007b); ^a Masetti et al. (2009); ^b Bian & Gu (2007); ^c Middleton et al. (2008); ^d Kaspi et al. (2000); ^e Woo & Urry (2002); ^f Merloni et al. (2003); ^g Peterson et al. (2004); ^h Hicks & Malkan (2008); ⁱ Uttley & McHardy (2005); ^k Paltani & Türler (2005); ^l Graham (2008); ^m Zurita-Heras et al. (2009); ⁿ Winter et al. (2009); ^o Butler et al. (2009); ^p Masetti et al. (2006); ^q see Appendix A; ^r Gonçalves et al. (2009); ^x not detected in the data set presented here.

the central black hole M_{BH} in an AGN or a normal galaxy, most of them still carrying fairly large uncertainties. Nevertheless, considering the importance of the black hole mass in studying the properties of these objects, we decided to include a compilation of the mass estimates from the literature as the best guess that can be provided at present for each object in this catalogue.

We have included masses estimated from gas and/or stellar kinematics in the nuclear region of the galaxy, in the presence (method “M”, see e.g. Greenhill 1997) or not (“K”, Hicks & Malkan 2008) of a water maser, from assuming virialized motions of the broad line region (BLR) clouds, either using the reverberation-mapping technique (“R”, Kaspi et al. 2000) or estimating the size of the BLR from the emission line luminosity (of the $H\beta$ line usually; “LL”, Wu et al. 2004) or from the optical continuum luminosity (usually measured at 5100 Å; “CL”, Kaspi et al. 2000). Other methods are based on the empirical relation between the black hole mass and the stellar velocity dispersion σ_s , using either direct measurements of the latter (“S”, Ferrarese & Merritt 2000) or indirect estimates of σ_s from the width of the [O III] line (“SO”, Greene & Ho 2005) or from the morphological parameters of the bulge (“SB”, O’Dowd et al. 2002). Some estimates use the bulge luminosity (“B”, Wandel 2002), the K-band stellar magnitude (assuming that it is dominated by the bulge; “KM”, Novak et al. 2006), the X-ray variability time scales (“X”, Gierliński et al. 2008), or the properties of outflowing warm absorber clouds (“W”, Morales & Fabian 2002). Whenever the uncertainty on the estimate of the black hole mass is not available in the reference paper, we assumed a conservative one following the typical uncertainties of the method used for the mass measurement.

The most reliable methods are those involving direct measurements of gas and stellar kinematics, with average uncertainties in the range 0.15–0.3 dex, reaching 0.1 dex or less when water maser emission is detected (see Vestergaard 2004, for more details). Also the reverberation mapping technique provides black hole masses with accuracy around 0.15–0.3 dex, which drops to values of 0.4–0.5 dex and even to 1 dex when the radius of the BLR is estimated from the emission line or the continuum luminosity. Masses estimated from the stellar velocity dispersion can have uncertainties around 0.3 dex when σ_s is directly measured, while indirect measurements of σ_s result in much less precise estimates (≥ 0.7 dex). Larger uncertainties are provided by the other methods mentioned above, 0.5–0.6 dex for method “B”, 0.5–1 dex for “X” (Awaki et al. 2005), 0.5 dex for “KM” (Winter et al. 2009), and only upper limits can be derived with the method based on outflowing warm absorber clouds.

2.2. X-ray spectral fitting

For all 187 objects with a detection significance above 3σ in the IBIS/ISGRI 18–60 keV energy band, spectral analysis was performed using an absorbed power law with N_{H} fixed to the value reported in the literature (Table 2) and adopting XSPEC version 11.3.2 (Arnaud 1996). When the significance was below 5σ , the photon index was fixed to $\Gamma = 2$. The N_{H} value used for the fitting is the intrinsic absorption plus the Galactic hydrogen column density, whereas in Table 2 only the intrinsic absorption is reported. In cases where no absorption information was found, *Swift/XRT* and *XMM-Newton* data were analysed to determine the level of absorption. For those objects detected only at a low significance level (i.e. between 3 and 5σ), the photon index was fixed to $\Gamma = 2.0$ in order to extract a flux value. Table 2 gives the fit results to the IBIS/ISGRI data. Fluxes are model fluxes according to the best-fit result. In the cases where a cut-off power law model gave a significantly better fit to the ISGRI data we set the Γ column to “C”. For these 12 objects, the fluxes reported are based on the best-fit model reported in Table 3. These 12 sources and all sources that gave a high IBIS/ISGRI detection significance of $>30\sigma$ are also discussed in more detail in Appendix A.

The JEM-X spectra of the 23 AGN detected by the X-ray monitor were fit with the IBIS/ISGRI data and results reported in Table 4. As for the ISGRI spectra alone, we also did not fit the absorption values in the case of the combined JEM-X/ISGRI spectra, because the JEM-X data starting at 3 keV did not allow a significant constraint on N_{H} in most cases. In cases where the flux of the source varied significantly, so no combined fit could be performed resulting in $\chi^2_{\nu} < 2$, only simultaneous data were used (e.g. in the case of NGC 4388). For two AGN, NGC 1275 and IGR J17488–3253, a more complex model than an absorbed cut-off power law was required to represent the combined JEM-X and IBIS/ISGRI data (see Appendix A).

2.3. Optical data

Optical data in the V band are provided by the optical monitoring camera (OMC). Data were extracted from the OMC Archive² getting one photometric point per shot. The photometric apertures were centred on the source position, as listed in version 5 of the OMC Input Catalogue (Domingo et al. 2003). The fluxes and magnitudes were derived from a photometric aperture of 3×3 pixels (1 pixel = 17.504 arcsec), slightly circularized,

² <http://sdc.laefi.inta.es/omc/>

Table 2. Spectral fit results for IBIS/ISGRI data.

Name	ISGRI 18–60 keV [σ]	N_{H} [10^{22} cm^{-2}]	$f_{20-40 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	$f_{40-100 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	Γ_{ISGRI}^+	$\log L_{20-100 \text{ keV}}$ [erg s^{-1}]
IGR J00254+6822	7.5	40 ^c	0.6	0.8	2.1 ± 0.5	42.67
IGR J00335+6126	5.9	0.5 [*]	0.3	0.9	1.1 ± 0.2	44.50
1ES 0033+59.5	12.6	0.36 ^a	0.8	0.3	$3.6^{+0.4}_{-0.3}$	44.36
Mrk 348	14.6	30 ^b	4.2	6.6	C	43.74
NGC 526A	4.3	1.6 ^b	2.2	2.9	2	43.62
ESO 297-18	5.2	42 ⁱ	3.1	6.8	1.5 ± 0.3	44.10
IGR J01528-0326	8.5	14 ^c	0.9	2.3	$1.2^{+0.2}_{-0.5}$	43.30
NGC 788	23.4	<0.02 ^a	2.5	3.9	1.8 ± 0.1	43.42
Mrk 590	4.5	0.03	0.5	0.6	2	43.23
IGR J02097+5222	7.7	0.03 ⁱ	1.2	2.0	$1.7^{+0.3}_{-0.2}$	44.25
SWIFT J0216.3+5128	5.1	1.27 ^f	0.8	0.8	$2.3^{+1.2}_{-1.0}$	43.48
Mrk 1040	3.4	0.067 ^b	2.3	3.0	2	43.52
IGR J02343+3229	3.5	2.2 ^d	1.4	1.8	2	43.27
NGC 985	5.8	0.6 ^b	0.9	1.3	$2.0^{+0.4}_{-0.3}$	43.99
NGC 1052	5.6	0.041 ^b	0.8	1.5	$1.6^{+0.4}_{-0.6}$	42.11
RBS 345	5.0	–	0.9	1.9	$1.3^{+0.6}_{-0.4}$	44.49
NGC 1068	7.3	>150 ^a	1.2	1.3	$2.3^{+0.4}_{-0.3}$	43.68
QSO B0241+62	16.3	1.5 ^a	2.0	3.0	1.8 ± 0.1	44.37
IGR J02466-4222	3.3	1	1.0	1.4	2	44.45
IGR J02501+5440	5.1	–	0.6	1.5	1.2 ± 0.3	43.03
MCG-02-08-014	6.3	–	1.3	0.9	$2.7^{+0.6}_{-0.5}$	43.15
NGC 1142	16.2	45 ^b	2.7	4.2	1.8 ± 0.1	44.11
QSO B0309+411	4.0	<0.1 [*]	3.0	3.9	2	45.53
NGC 1275	15.7	3.75 ^a	2.2	0.4	$3.7^{+0.3}_{-0.2}$	43.18
1H 0323+342	5.1	0.1 ^b	0.7	2.4	$1.0^{+0.4}_{-0.7}$	44.43
IGR J03334+3718	6.9	–	1.0	1.5	1.9 ± 0.3	44.25
NGC 1365	5.1	44 ^b	1.5	2.2	1.8 ± 0.6	42.38
IGR J03532-6829	7.3	0.05 [*]	1.4	0.6	$3.5^{+0.7}_{-0.6}$	44.63
3C 111	13.7	0.63 ^a	5.3	6.9	2.0 ± 0.2	44.83
3C 120	22.0	0.2 ⁱ	3.0	4.4	1.8 ± 0.1	44.27
UGC 3142	17.3	1.4 ^x	2.8	3.7	2.0 ± 0.1	44.84
LEDA 168563	5.4	<0.22 ⁱ	2.2	3.1	$1.9^{+0.5}_{-0.4}$	44.00
ESO 33-2	15.5	0.1 ^b	1.3	2.0	1.8 ± 0.2	43.38
4U 0517+17	24.5	0.1 ^b	3.0	3.6	$2.13^{+0.09}_{-0.08}$	43.68
Ark 120	15.6	<0.1 [*]	2.7	3.4	2.1 ± 0.1	44.18
NGC 2110	4.9	4.3 [*]	7.0	9.3	2	43.34
MCG+08-11-011	7.8	0.183 ^b	5.2	6.7	2.0 ± 0.4	44.05
IRAS 05589+2828	15.4	<0.04 ⁱ	1.4	2.8	$1.5^{+0.2}_{-0.1}$	44.02
SWIFT J0601.9-8636	6.5	5.6 ⁱ	1.3	1.0	$2.6^{+0.7}_{-0.6}$	42.32
IGR J06117-6625	17.8	0.048 ^b	1.9	2.6	1.96 ± 0.16	45.85
Mrk 3	26.7	110 ^a	3.7	6.4	1.73 ± 0.07	43.61
IGR J06239-6052	3.6	20 ^b	0.5	0.7	2	43.65
PKS 0637-752	5.4	0.035 ^b	0.7	1.1	1.7 ± 0.6	46.45
Mrk 6	15.1	10 ^a	1.9	2.3	2.1 ± 0.2	43.53
QSO B0716+714	4.6	<0.01 ^a	0.3	0.3	2	45.24
LEDA 96373	5.3	–	1.4	2.6	$1.5^{+0.7}_{-0.5}$	43.89
IGR J07437-5137	3.5	–	0.4	0.5	2	43.13
IGR J07565-4139	6.2	1.1 ^b	0.7	0.6	$2.7^{+0.6}_{-0.4}$	43.12
IGR J07597-3842	14.2	0.05 ^b	1.8	1.9	2.3 ± 0.2	44.14
ESO 209-12	12.2	0.1 ^b	0.9	1.4	$1.8^{+0.1}_{-0.2}$	43.93
PG 0804+761	6.3	0.023 ^b	1.1	1.5	2.0 ± 0.5	44.81
Fairall 1146	9.9	0.1 ^b	0.9	1.4	$1.8^{+0.3}_{-0.2}$	43.73
QSO B0836+710	15.4	0.11 ^a	2.1	4.1	$1.5^{+0.2}_{-0.1}$	47.93
IGR J09026-4812	17.8	0.9 ^w	0.9	1.4	1.9 ± 0.1	43.91
SWIFT J0917.2-6221	5.8	0.5 ^f	0.8	1.1	$1.9^{+0.5}_{-0.6}$	44.18
IGR J09253+6929	7.0	8 ^d	1.8	2.6	1.9 ± 0.4	44.19
Mrk 110	3.6	0.019 ^b	2.2	3.0	2	44.18
IGR J09446-2636	3.2	0.1 ^b	1.3	1.7	2	45.60

Table 2. continued.

Name	ISGRI 18–60 keV [σ]	N_{H} [10^{22} cm^{-2}]	$f_{20-40 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	$f_{40-100 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	Γ_{ISGRI}^+	$\log L_{20-100 \text{ keV}}$ [erg s^{-1}]
NGC 2992	15.8	0.1 ^f	2.8	4.1	1.9 ± 0.1	42.95
MCG-05-23-016	14.6	1.6 ^a	5.6	8.1	1.9 ± 0.1	43.34
IGR J09523-6231	5.3	8 ^d	0.6	0.7	$2.2^{+0.6}_{-0.5}$	45.41
NGC 3081	9.7	66 ^m	2.6	4.1	1.8 ± 0.2	42.97
SWIFT J1009.3-4250	6.9	30 ^f	1.5	2.0	2.0 ± 0.4	43.95
IGR J10147-6354	3.0	2 ^d	0.5	0.7	2	45.18
NGC 3227	16.6	6.8 ^b	5.6	7.1	2.0 ± 0.1	42.63
NGC 3281	7.5	151 ^b	1.8	2.7	1.9 ± 0.3	43.06
SWIFT J1038.8-4942	5.3	0.6 ^f	0.6	1.4	1.3 ± 0.4	44.21
IGR J10404-4625	6.9	3 ^f	1.2	1.4	$2.2^{+0.4}_{-0.3}$	43.54
Mrk 421	173.8	0.08 ⁱ	22.4	20.6	$2.45^{+0.03}_{-0.02}$	44.92
IGR J11366-6002	7.6	0.35 ^o	0.6	0.7	$2.2^{+0.5}_{-0.4}$	42.73
NGC 3783	6.1	0.08 [*]	6.0	8.4	1.9 ± 0.4	43.48
IGR J12026-5349	14.8	2.2 ^a	1.6	2.2	2.0 ± 0.1	43.84
NGC 4051	11.7	<0.02 [*]	1.8	1.5	2.1 ± 0.2	41.58
NGC 4138	9.0	8 ^b	1.2	1.9	1.8 ± 0.3	41.79
NGC 4151	205.7	6.9 ^a	24.0	32.3	C	43.13
NGC 4180	9.4	–	0.9	1.8	$1.6^{+0.3}_{-0.2}$	42.46
Was 49	3.8	10 ^b	0.6	0.8	2	44.12
Mrk 766	6.9	0.8 ^a	1.0	1.5	1.8 ± 0.3	42.95
NGC 4258	6.6	8.7 ^b	1.1	1.1	2.3 ± 0.4	41.04
4C 04.42	7.7	0.1 ^b	0.7	1.8	1.2 ± 0.2	46.83
Mrk 50	6.2	0.018 ^b	0.5	0.4	$2.6^{+0.7}_{-0.6}$	43.09
NGC 4388	78.1	27 ^a	9.8	15.2	C	43.59
NGC 4395	8.8	0.15 ^a	1.5	1.6	$2.3^{+0.4}_{-0.3}$	40.85
3C 273	78.0	0.5 ^a	7.5	10.6	1.92 ± 0.03	46.09
NGC 4507	30.9	29 ^a	6.3	10.0	C	43.70
SWIFT J1238.9-2720	6.3	60 ^f	2.7	5.3	$1.6^{+0.4}_{-0.3}$	44.06
IGR J12391-1612	9.9	3 ^f	1.7	2.2	2.0 ± 0.2	44.08
NGC 4593	33.0	0.02 ^a	3.2	4.1	C	43.08
IGR J12415-5750	6.7	<0.11 ^b	0.8	1.4	$1.7^{+0.2}_{-0.3}$	43.45
PKS 1241-399	3.5	–	0.7	0.9	2	45.23
ESO 323-32	5.6	7 ^f	0.8	1.5	$1.6^{+0.4}_{-0.3}$	43.13
3C 279	8.6	$\leq 0.13^a$	0.9	1.7	1.6 ± 0.2	46.40
Mrk 783	4.7	0.046 ^b	0.9	1.2	2	44.36
IGR J13038+5348	4.5	<0.03 [*]	1.0	1.3	2	43.67
NGC 4945	78.7	400 ^a	9.9	18.4	C	42.35
IGR J13057+2036	3.1	–	0.4	0.6	2	
ESO 323-77	9.0	55 ^a	1.1	2.1	$1.5^{+0.3}_{-0.2}$	43.21
IGR J13091+1137	7.5	90 ^a	1.6	2.5	2.1 ± 0.3	43.76
IGR J13109-5552	8.7	<0.1 ^p	0.9	1.2	$2.0^{+0.3}_{-0.2}$	44.78
NGC 5033	4.2	0.03 ^b	0.6	0.8	2	41.43
IGR J13149+4422	4.7	5 ^d	0.8	1.1	2	43.77
Cen A	247.2	12.5 ^a	28.1	43.4	1.82 ± 0.01	42.71
ESO 383-18	6.5	17 ^x	0.9	1.2	$1.9^{+0.4}_{-0.3}$	42.86
MCG-06-30-015	21.1	0.03 ^b	2.3	1.7	2.4 ± 0.1	42.74
NGC 5252	3.0	0.68 ^b	2.0	2.7	2	43.76
Mrk 268	5.7	–	0.9	0.7	2.5 ± 0.6	43.78
4U 1344-60	35.2	5 ^a	3.5	4.6	C	43.48
IC 4329A	58.5	0.42 ^a	8.8	12.3	C	44.09
Circinus Galaxy	120.0	360 ^a	10.9	10.1	C	41.96
NGC 5506	27.8	3.4 ^a	7.0	6.2	2.1 ± 0.1	43.16
IGR J14175-4641	8.0	–	0.8	1.3	1.8 ± 0.3	44.48
NGC 5548	3.1	0.51 ^a	1.0	1.3	2	43.19
RHS 39	7.7	<0.05 ^a	1.6	2.2	2.0 ± 0.3	43.63
H 1426+428	4.6	<0.02 [*]	0.6	0.8	2	44.80
IGR J14471-6414	7.2	<0.1 [*]	0.5	0.8	1.8 ± 0.3	43.95
IGR J14471-6319	6.4	2 ^f	0.6	0.8	$2.0^{+0.5}_{-0.6}$	43.67
IGR J14492-5535	8.6	12 ^q	0.9	1.4	1.7 ± 0.3	

Table 2. continued.

Name	ISGRI 18–60 keV [σ]	N_{H} [10^{22} cm^{-2}]	$\dot{f}_{20-40 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	$\dot{f}_{40-100 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	Γ_{ISGRI}^+	$\log L_{20-100 \text{ keV}}$ [erg s^{-1}]
IGR J14515-5542	9.4	0.4^f	0.8	1.4	1.6 ± 0.2	43.19
IGR J14552-5133	8.5	0.1^b	0.6	1.1	$1.6^{+0.4}_{-0.2}$	42.98
IGR J14561-3738	9.4	$>100^q$	0.6	1.2	$1.7^{+0.2}_{-0.4}$	43.37
IGR J14579-4308	15.4	20^d	1.1	1.4	2.0 ± 0.2	43.16
Mrk 841	3.2	0.21	1.0	1.4	2	43.87
ESO 328-36	5.7	—	0.4	0.4	2.5 ± 0.6	43.00
IGR J15161-3827	12.3	—	1.0	1.7	1.7 ± 0.2	43.90
NGC 5995	16.4	0.7^*	2.2	1.5	2.8 ± 0.2	43.74
IGR J15539-6142	4.6	18^f	0.5	0.7	2	42.78
IGR J16024-6107	3.7	$<0.1^o$	0.3	0.4	2	42.46
IGR J16056-6110	3.8	$<1^c$	0.3	0.5	2	43.72
IGR J16119-6036	9.3	0.1^b	0.9	1.4	$1.8^{+0.3}_{-0.2}$	43.11
IGR J16185-5928	6.1	$<0.1^e$	0.5	0.9	1.6 ± 0.3	43.57
IGR J16351-5806	10.2	$<0.1^s$	0.8	1.6	1.5 ± 0.2	42.64
IGR J16385-2057	7.2	0.21^d	0.8	0.5	3.1 ± 0.4	43.35
IGR J16426+6536	4.4	—	2.6	3.4	2	46.32
IGR J16482-3036	27.5	0.13^f	2.5	3.1	2.1 ± 0.1	44.10
ESO 138-1	3.7	150^b	0.4	0.6	2	42.26
NGC 6221	4.7	1^a	0.5	1.0	2	41.93
NGC 6240	12.1	2^b	2.1	3.6	1.7 ± 0.2	43.89
Mrk 501	12.4	0.013^b	2.5	1.7	2.8 ± 0.3	44.05
IGR J16558-5203	16.5	0.011^b	1.1	1.5	2.0 ± 0.1	44.25
IGR J16562-3301	7.0	0.2^f	1.0	2.3	$1.32^{+0.16}_{-0.07}$	42.30
NGC 6300	10.1	22^a	3.1	3.6	2.2 ± 0.2	42.30
IGR J17204-3554	6.4	12^b	0.3	0.4	2.2 ± 0.5	43.96
GRS 1734-292	106.4	3.7^a	4.3	4.4	C	43.96
IGR J17418-1212	6.6	0.1^b	0.8	1.5	1.5 ± 0.2	43.85
IGR J17488-3253	27.5	0.7^*	1.1	1.6	C	43.39
IGR J17513-2011	16.0	0.6^*	0.8	1.1	1.95 ± 0.12	44.00
IGR J18027-1455	15.2	19.0^a	1.2	1.7	1.9 ± 0.1	41.86
IGR J18244-5622	3.0	14^f	1.3	1.7	2	43.28
IGR J18249-3243	7.5	$<0.1^n$	0.5	0.7	1.9 ± 0.4	45.72
IGR J18259-0706	7.8	0.6^f	0.6	0.8	2.1 ± 0.3	48.19
PKS 1830-211	25.2	$\leq 0.7^a$	1.9	3.7	$1.49^{+0.05}_{-0.07}$	48.19
3C 382	3.0	0.88^b	3.8	5.0	2	44.85
ESO 103-35	4.9	19^a	3.0	4.0	2	43.44
3C 390.3	14.3	$<0.1^a$	2.3	3.9	1.7 ± 0.1	44.67
ESO 140-43	14.0	1.8^x	1.7	2.6	1.7 ± 0.2	43.40
IGR J18559+1535	12.0	0.7^d	0.9	1.3	2.0 ± 0.2	44.59
ESO 141-55	19.0	0.004^t	1.9	2.8	1.9 ± 0.4	44.30
1RXS J192450.8-29143	4.6	0.088^b	0.5	0.7	2	45.70
1H 1934-063	9.2	0.1^b	1.3	0.7	$3.1^{+0.4}_{-0.3}$	42.71
IGR J19405-3016	11.8	$<0.1^a$	1.3	1.9	1.8 ± 0.2	44.30
NGC 6814	16.2	$<0.05^a$	3.0	4.6	1.8 ± 0.1	42.65
IGR J19473+4452	7.1	11^a	1.1	2.0	1.3 ± 0.3	44.33
3C 403	4.5	45^b	0.9	1.2	2	44.23
QSO B1957+405	42.6	20^a	3.7	5.0	1.97 ± 0.05	44.81
ESO 399-20	4.3	0.048^b	0.6	0.9	2	43.33
IGR J20187+4041	12.2	6.1^b	0.9	1.3	$1.9^{+0.1}_{-0.2}$	42.99
IGR J20286+2544	10.4	42^f	1.8	3.3	1.6 ± 0.2	43.28
Mrk 509	11.2	$<0.01^a$	3.8	4.1	2.3 ± 0.3	44.34
S5 2116+81	4.4	$<0.1^a$	1.3	1.8	2	44.76
IGR J21178+5139	7.7	2^f	0.8	1.5	1.5 ± 0.2	44.04
IGR J21247+5058	47.3	0.6^k	4.7	7.3	C	44.04
IGR J21277+5656	13.6	0.1^b	1.6	1.8	2.2 ± 0.2	43.20
RX J2135.9+4728	9.2	0.4^i	0.9	1.6	1.7 ± 0.2	43.55
PKS 2149-306	4.6	0.03	0.9	1.2	2	47.98
NGC 7172	19.4	9.0^a	3.6	4.7	2.0 ± 0.1	43.13
BL Lac	5.5	0.3^b	0.7	1.2	$1.8^{+0.4}_{-0.3}$	44.34

Table 2. continued.

Name	ISGRI 18–60 keV [σ]	N_{H} [10^{22} cm^{-2}]	$f_{20-40 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	$f_{40-100 \text{ keV}}$ [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]	Γ_{ISGRI}^+	$\log L_{20-100 \text{ keV}}$ [erg s^{-1}]
IGR J22292+6647	5.7	0.2*	0.5	0.6	2.3 ± 0.5	44.57
NGC 7314	12.9	0.122 ^b	2.1	2.5	2.2 ± 0.3	42.37
Mrk 915	4.5	<0.1*	0.6	0.8	2	43.28
IGR J22517+2217	6.6	3 ^v	1.6	3.4	1.4 ± 0.4	48.43
3C 454.3	30.8	0.5 ^b	7.1	13.2	1.58 ± 0.06	47.76
1H 2251-179	22.9	<0.19 ^a	3.3	3.8	2.2 ± 0.1	44.85
NGC 7469	6.1	0.061 ^b	1.8	2.3	2.1 ± 0.4	44.39
MCG-02-58-022	15.0	<0.08 ^a	2.0	1.4	2.8 ± 0.2	44.26
IGR J23206+6431	7.7	0.6*	0.4	0.7	$1.5^{+0.5}_{-0.3}$	44.15
IGR J23308+7120	3.7	6 ^o	0.3	0.4	2	43.39
IGR J23524+5842	6.7	6 ^d	0.4	0.5	2.0 ± 0.5	44.79

+ “C” indicates that a more complex model is required to fit the data (see Table 3); * this work; ^a Beckmann et al. (2006), and references therein; ^b Bodagheer et al. (2007), and ref. therein; ^c Landi et al. (2007b); ^d Rodríguez et al. (2008); ^e Malizia et al. (2008); ^f Malizia et al. (2007); ^g Beckmann et al. (2007b); ^h Revnivtsev et al. (2007); ⁱ Winter et al. (2008); ^k Ricci et al. (2009a); ^l Beckmann et al. (2007a); ^m Bassani et al. (1999); ⁿ Landi et al. (2008); ^o Landi et al. (2007c); ^p Molina et al. (2008); ^q Sazonov et al. (2008); ^s Landi et al. (2007a); ^t Gondoin et al. (2003); ^u Landi et al. (2007d); ^v Bassani et al. (2007); ^w Tomsick et al. (2008); ^x Ricci et al. (2009b).

Table 3. Spectral fit of a cut-off power-law model for AGN with more complex IBIS/ISGRI spectra.

Name	N_{H} [10^{22} cm^{-2}]	Γ_{ISGRI}	E_{C} [keV]	χ^2_{ν} (d.o.f.)
Mrk 348	30	$0.9^{+0.4}_{-0.06}$	55^{+56}_{-21}	0.91 (8)
NGC 4151	6.9	$1.60^{+0.06}_{-0.07}$	118^{+25}_{-13}	1.10 (9)
NGC 4388	27	1.3 ± 0.1	95^{+26}_{-17}	0.34 (7)
NGC 4507	29	$1.15^{+0.28}_{-0.13}$	72^{+53}_{-22}	0.54 (8)
NGC 4593	0.02	$1.1^{+0.4}_{-0.2}$	48^{+114}_{-9}	0.87 (7)
NGC 4945	400	$1.43^{+0.16}_{-0.11}$	127^{+56}_{-26}	0.75 (8)
4U 1344-60	5	$1.11^{+0.29}_{-0.09}$	51^{+27}_{-12}	0.76 (7)
IC 4329A	0.42	1.37 ± 0.17	80^{+19}_{-13}	1.50 (9)
Circinus Galaxy	360	$1.29^{+0.18}_{-0.13}$	33^{+6}_{-3}	1.03 (7)
GRS 1734-292	3.7	1.50 ± 0.10	54^{+8}_{-7}	0.88 (8)
IGR J17488-3253	0.2	$0.74^{+0.33}_{-0.13}$	40^{+8}_{-3}	0.98 (7)
IGR J21247+5058	0.6	$1.19^{+0.13}_{-0.19}$	74^{+38}_{-28}	0.75 (8)

i.e. removing $\frac{1}{4}$ pixel from each corner (standard output from OSA). Therefore the computed values include the contributions by any other source inside the photometric aperture. We flagged in Table 5 those sources that might be affected by a nearby star (at less than $1''$), with a potential contamination below 0.2 mag in any case. Other 8 AGN containing a brighter contaminating source within the extraction aperture were not included in this compilation. In addition, for some extended AGN, this 3×3 aperture does not cover the full galaxy size, but just their central region.

To only include high-quality data, some selection criteria were applied to individual photometric points. Shots were checked against saturation, rejecting those with long exposures for the brightest sources, if necessary. For faint sources, a minimum signal-to-noise ratio of 3 was required for the longest integration shots. The shortest shots were only used if the signal-to-noise ratio was greater than 10. Because these sources can show extended structure in the OMC images, anomalous PSF, as well as problems in the centroid determination, were allowed. Finally, to avoid contamination by cosmic rays, we excluded those points whose fluxes deviate more than 5 times the standard

deviation from the median value of their surrounding points, applying three iterations of this filter.

We list in Table 5 the median V magnitude of each AGN, the average of error estimates (1σ level) of each photometric point given by OSA 7, $\langle\sigma_V\rangle$, the luminosity in the Johnson V filter (centred on 5500 Å, effective width 890 Å), the α_{OX} value, the number of photometric points used in the analysis and a flag indicating the potential contamination of the photometric value by a nearby star. The value of α_{OX} is measured as the slope of a power law between the two energy ranges

$$\alpha_{\text{OX}} = -\frac{\log(f_0/f_x)}{\log(\nu_0/\nu_x)}. \quad (1)$$

Here, f_0 and f_x are the monochromatic fluxes at the frequencies ν_0 (at 5500 Å) and ν_x (at 20 keV).

No K correction has been applied to the V luminosities, since the redshifts are relatively low and the optical slope of these objects is not well known. Moreover, depending on the redshift, the V band might be contaminated to different degrees by the OIII and H β emission lines. We did not correct for this effect, either.

2.3.1. Optical variability

Among the 57 AGN for which OMC data are available, 3 show strong variability in the photometric V -band data, with an amplitude larger than 0.5 mag: QSO B0716+714, NGC 4151, and 3C 279.

The BL Lac QSO B0716+714 appears as a point source in a low background field and was monitored by OMC during 2 periods, at IJD³ around 1415 (November 2003) and 1555 (April 2004). This source brightened by a factor ~ 4 during this period, as shown in Fig. 2, ranging from $V = 14.60$ mag to 13.05 mag. Moreover, this blazar also shows a day-scale variability pattern within the two monitoring periods, with an amplitude around 0.3 mag.

NGC 4151 is an extended source, classified as Seyfert 1.5, much larger than the OMC aperture. We detected a clear weakening of its central, dominating region by around 0.5 mag (60% in flux) from 11.15 mag to 11.65 mag between May 2003

³ The INTEGRAL Julian Date is defined as IJD = MJD–51 544.0. The origin of IJD is 2000 January 1 expressed in Terrestrial Time.

Table 4. Spectral fit results for combined JEM-X and IBIS/ISGRI data.

Name	JEM-X [σ]	N_{H}^b [10^{22} cm^{-2}]	f_{3-20}^c keV	f_{20-100}^c keV	Γ	E_C [keV]	$\log L_{3-100} \text{ keV}$ [erg s^{-1}]	χ_r^2 (d.o.f.)
1ES 0033+59.5	10.1	0.36	6.0	1.4	$2.75^{+0.18}_{-0.16}$	—	45.16	0.51 (8)
NGC 1275 ^a	38.6	3.75	22.8	3.0	—	—	43.58	$>5^a$
3C 120	5.5	0.2	5.8	7.5	1.76 ± 0.06	—	44.52	0.67 (15)
Mrk 421	155.7	0.08	61.6	32.5	$2.12^{+0.05}_{-0.04}$	133^{+32}_{-21}	45.29	1.43 (14)
NGC 4151 ^a	91.5	6.9	33.2	40.4	$1.75^{+0.04}_{-0.06}$	170^{+30}_{-32}	43.25	1.36 (14)
NGC 4388 ^a	14.3	27	10.3	26.0	$1.26^{+0.15}_{-0.09}$	78^{+35}_{-20}	43.68	0.41 (15)
NGC 4593 ^a	7.0	0.02	4.4	7.7	$1.46^{+0.09}_{-0.15}$	193^{+12}_{-93}	43.34	1.01 (15)
Cen A ^a	57.2	12.5	28.1	43.4	1.85 ± 0.01	—	42.94	1.49 (17)
MCG-06-30-015	11.2	0.03	7.0	5.0	2.10 ± 0.05	—	42.93	0.79 (10)
4U 1344-60 ^a	8.3	5	5.6	21.0	$1.47^{+0.11}_{-0.16}$	86^{+31}_{-22}	43.70	0.76 (15)
IC 4329A ^a	11.3	0.42	14.5	21.1	1.41 ± 0.08	86^{+18}_{-13}	44.31	1.29 (15)
Circinus Galaxy ^a	5.3	360	3.9	21.0	1.2 ± 0.2	30 ± 3	42.03	1.52 (11)
NGC 5506	16.8	3.4	12.1	8.0	2.20 ± 0.08	—	43.27	0.66 (12)
H 1426+428	7.5	< 0.02	6.1	1.2	$2.83^{+0.25}_{-0.21}$	—	44.90	0.67 (9)
Mrk 501	7.9	0.013	10.2	4.8	2.3 ± 0.1	—	44.60	0.73 (15)
GRS 1734-292 ^a	10.5	3.7	6.7	8.0	$1.25^{+0.10}_{-0.16}$	39^{+5}_{-6}	44.02	1.28 (12)
IGR J17488-3253 ^a	21.8	0.72	1.7	2.9	1.63 ± 0.03	—	43.11	1.10 (119)
QSO B1957+405 ^a	10.5	20	16.2	8.3	$1.9^{+0.1}_{-0.2}$	—	45.26	0.76 (9)
Mrk 509	7.2	< 0.01	7.5	9.3	1.8 ± 0.1	—	44.66	0.69 (8)
IGR J21178+5139	17.1	2	1.5	2.2	1.7 ± 0.1	—	—	1.61 (13)
IGR J21247+5058 ^a	54.1	0.6	9.5	11.1	1.4 ± 0.1	61^{+22}_{-11}	44.27	1.41 (11)
3C 454.3	6.4	0.5	10.7	20.3	1.54 ± 0.05	—	47.93	0.58 (16)
1H 2251-179	10.7	< 0.19	5.7	7.2	1.8 ± 0.1	—	45.10	1.20 (13)

^a see Appendix A; ^b N_{H} values have been fixed during the fit; ^c fluxes are given in [$10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$]

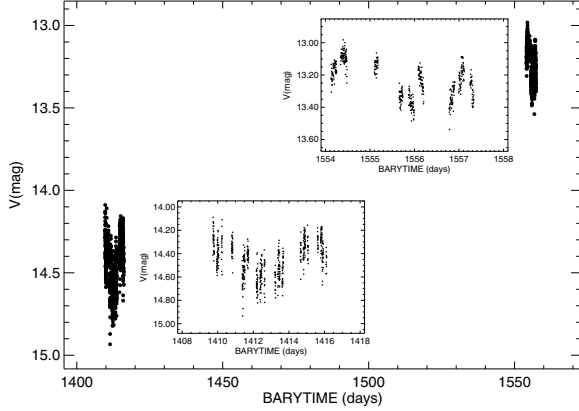


Fig. 2. OMC lightcurve of QSO B0716+714. The insets show a zoom on the lightcurves during the 2 periods when this object was monitored by OMC. The optical luminosity increased by a factor of 4. The photometric accuracy of individual photometric points is $\sigma \sim 0.09$ mag. Barycentric time is given in *INTEGRAL* Julian Date (IJD).

and January 2007. Since the optical photometry is contaminated to some extent by bulge stellar light, the variation in the optical emission from the nucleus itself might have been significantly larger.

The AGN 3C 279 was barely detectable around June 2003, with a 2σ OMC detection at $V = 17.0$. The catalogued value for it in the low state is $V = 17.8$ mag (O’Dell et al. 1978). After May 2005, this blazar was clearly detected with a brightness in the range $V = 14.8$ – 15.8 mag, indicating that it brightened by up to a factor close to 10 (Fig. 3). This is a very active source, with

optical photometry reported in the range $B = 18.3$ to $B = 11.3$ (O’Dell et al. 1978).

Other AGN monitored by OMC also show some hints of variability, such as 3C 273 and 3C 390.3, but at smaller amplitudes (just a few percent over the period considered).

3. Properties of *INTEGRAL* detected AGN

The catalogue of *INTEGRAL*-detected extragalactic objects presented here comprises 187 sources in total. Out of this sample, 162 objects have been identified as Seyfert galaxies (161 with redshift information), 18 blazars (all of them with redshift), and 7 objects have been claimed to be AGN without further specification of the AGN type. Within the Seyfert group, we found 67 Seyfert 1 to 1.2 objects, 29 intermediate Seyfert 1.5, and 66 Seyfert type 1.9 and type 2.

The redshift distribution of the Seyfert type AGN in this sample is shown in Fig. 4. The average redshift is $z = 0.03$. Figure 5 shows the parameter space filled by *INTEGRAL*-detected AGN in redshift and X-ray luminosity, ranging from low-luminous low-redshift Seyfert as close as $z = 0.001$ up to the high-redshift blazar domain.

To investigate the spectra of AGN subtypes, we derived averaged spectral properties and stacked spectra of the Seyfert 1 and 2 types, as well as for the intermediate Seyferts and the blazars, and according to the intrinsic absorption. The nine brightest sources, two blazars and seven Seyfert, with $>50\sigma$ (Cen A, NGC 4151, GRS 1734-292, NGC 4945, NGC 4388, IC 4329A, Circinus Galaxy, 3C 273, and Mrk 421) have been excluded from the statistical spectral analyses because their high signal-to-noise ratio would dominate the averaged spectra, and also all sources with $<5\sigma$ were ignored. In addition, we excluded the

Table 5. Median V magnitude, the average of error estimates $\langle\sigma_V\rangle$, luminosity in the Johnson V filter, α_{OX} , the number of photometric points and contamination flag (“Y” indicates potential contamination by a nearby star up to 0.2 mag; see text for details).

Name	V [mag]	$\langle\sigma_V\rangle$ [mag]	$\log L_V$ [erg s $^{-1}$]	α_{OX}	N	Cont. flag
Mrk 348	13.76	0.05	42.71	1.01	81	Y
NGC 788	12.60	0.04	43.09	1.14	1342	
NGC 985	13.73	0.05	43.66	1.13	644	
NGC 1052	11.38	0.03	42.70	1.31	1004	
NGC 1068	9.99	0.02	44.80	1.38	693	
NGC 1275	12.51	0.04	43.27	1.21	856	
NGC 1365	11.51	0.05	42.72	1.27	35	
3C 120	14.00	0.05	43.31	1.02	216	
UGC 3142	15.12	0.22	43.49	0.93	259	
ESO 33-2	13.99	0.09	42.78	1.09	40	
Mrk 3	12.88	0.04	42.95	1.08	425	Y
Mrk 6	13.68	0.06	42.94	1.07	657	
QSO B0716+714	14.27	0.09	45.26	1.19	1116	
ESO 209-12	14.60	0.21	43.24	1.07	387	
PG 0804+761	14.07	0.08	44.28	1.09	299	
4U 0937-12	12.66	0.03	42.56	1.12	443	
MCG-05-23-016	13.12	0.05	42.47	1.03	1514	
NGC 3227	12.06	0.04	42.21	1.11	12	
NGC 3281	12.67	0.04	42.85	1.16	316	
Mrk 421	13.05	0.06	43.58	0.91	3112	
NGC 4051	12.26	0.04	41.67	1.20	76	
NGC 4138	11.87	0.04	42.06	1.26	585	
NGC 4151	11.52	0.04	42.28	1.03	7461	
Mrk 50	14.47	0.09	42.86	1.11	774	Y
NGC 4388	12.26	0.06	42.80	1.05	509	
NGC 4395	14.09	0.11	40.23	1.05	7	
3C 273	12.58	0.04	45.31	1.05	2010	Y
IGR J12391-1612	14.15	0.06	43.34	1.05	104	
NGC 4593	12.24	0.04	42.83	1.14	1204	
ESO 323-32	13.11	0.07	43.03	1.20	158	Y
3C 279	15.52	0.11	45.29	1.01	294	
Mrk 783	15.39	0.16	43.39	1.01	37	
NGC 4945	12.44	0.17	41.43	1.04	327	
IGR J13091+1137	13.70	0.05	43.18	1.07	15	
NGC 5033	11.57	0.03	42.16	1.33	55	
ESO 383-18	14.33	0.08	42.32	1.09	673	Y
MCG-06-30-015	13.23	0.07	42.36	1.09	1268	Y
Mrk 268	14.30	0.06	43.37	1.08	7	
IC 4329A	13.20	0.05	43.00	0.98	501	
NGC 5506	12.93	0.05	42.38	1.03	701	
NGC 5548	13.14	0.05	43.08	1.17	256	
H 1426+428	16.11	0.25	43.72	0.98	619	
NGC 5995	13.47	0.07	43.29	1.05	118	Y
ESO 138-1	13.59	0.11	42.34	1.20	12	Y
NGC 6221	11.91	0.07	42.49	1.33	16	
Mrk 501	13.21	0.04	43.65	1.07	567	
NGC 6300	11.52	0.05	42.38	1.19	31	
3C 390.3	14.61	0.13	43.54	1.00	482	Y
1H 1934-063	13.35	0.05	42.59	1.10	12	
NGC 6814	12.42	0.04	42.31	1.14	134	
ESO 399-20	13.96	0.08	43.07	1.18	84	
Mrk 509	13.38	0.05	43.60	1.03	400	
NGC 7172	12.66	0.04	42.66	1.10	508	
Mrk 915	14.10	0.09	42.75	1.09	40	
1H 2251-179	14.20	0.09	43.83	0.98	1570	Y
NGC 7469	12.70	0.04	44.21	1.15	22	
MCG-02-58-022	14.13	0.06	43.59	1.01	93	

5 Compton thick objects, i.e. NGC 1068, NGC 3281, NGC 4945, Circinus Galaxy, ESO 138-1.

The average Seyfert 1 (including type 1.2) spectral property was constructed using the mean weighted by the errors on the photon indices of 55 ISGRI power-law fit results, the

Seyfert 2 composite spectrum includes 44 sources, and 20 objects form the intermediate Seyfert 1.5 group where spectral fitting allowed constraining the spectral shape (Table 2). In addition, 11 blazars allowed spectral extraction. When computing the weighted average of the various subclasses, the 11 blazars

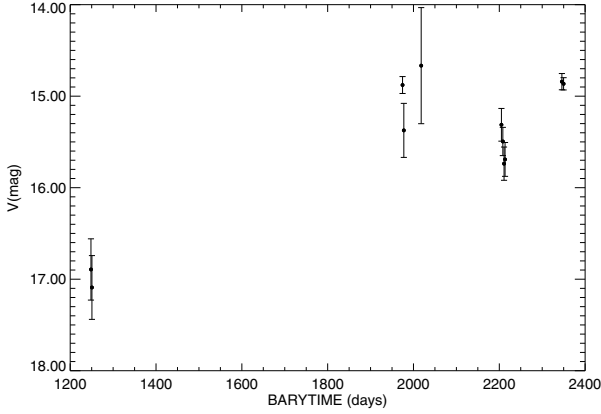


Fig. 3. OMC lightcurve of 3C 279. Barycentric time is given in IJD. Photometric data have been re-binned to obtain one value per revolution (3 days).

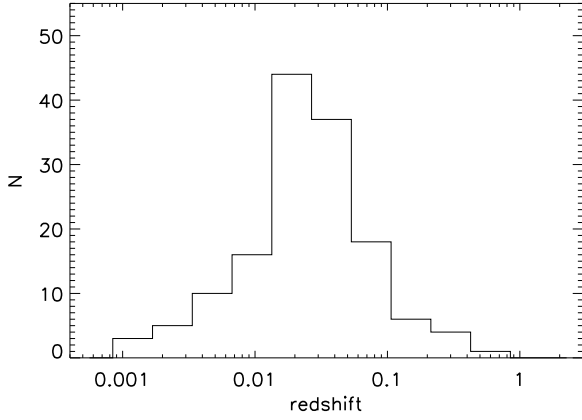


Fig. 4. Redshift distribution of the Seyfert content of 144 *INTEGRAL* detected AGN with detection significance $\geq 4\sigma$. The average redshift is $z = 0.03$.

had a hard X-ray spectrum with $\Gamma = 1.55 \pm 0.04$ when compared to the 119 Seyfert galaxies with $\Gamma = 1.93 \pm 0.01$. The Seyfert 1 ($\Gamma = 1.92 \pm 0.02$) and Seyfert 1.5 ($\Gamma = 2.02 \pm 0.03$) only show slightly steeper hard X-ray spectra than the Seyfert 2 objects ($\Gamma = 1.88 \pm 0.02$). Table 6 gives the properties of the different Seyfert types. All quantities, except for the photon indices, have been averaged in logarithmic space. For 12 objects, a cut-off power law model gave a better representation of the ISGRI spectra (Table 3). The average photon index is in these cases $\langle \Gamma \rangle = 1.3 \pm 0.4$ with a cut-off energy of $\langle E_C \rangle = 86 \pm 25$ keV.

We get a similar result when stacking the IBIS/ISGRI spectra together. Again, only sources above 5σ are considered here. The spectra were renormalised on the 18–30 keV energy bin before stacking them, re-adjusting the errors on the flux so that the significance is taken into account. The significances for the stacked spectra are consistent with what would be expected based on the single spectra significances, i.e. the 18–60 keV significances are 98σ for the Seyfert 1, 61σ (Seyfert 1.5), 94σ (Seyfert 2), and 148σ for all Seyfert spectra stacked together. The results of spectral model fitting to these spectra are summarized in Table 7. A simple power law model gives a photon index of $\Gamma = 1.97 \pm 0.02$ for all Seyfert objects, $\Gamma = 1.96^{+0.03}_{-0.02}$ for the Seyfert 1,

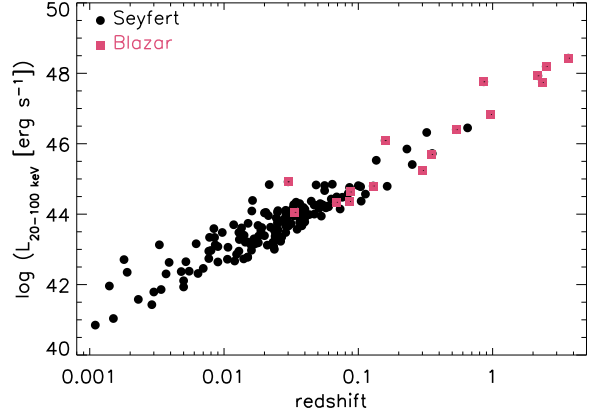


Fig. 5. X-ray luminosity versus redshift of 161 *INTEGRAL* detected AGN with significance $\geq 4\sigma$.

Table 6. Average properties of the *INTEGRAL* AGN. In parentheses, the number of objects used for the given average value is indicated.

	Seyfert 1	Seyfert 1.5	Seyfert 2
$\langle z \rangle$	0.03 (63)	0.014 (24)	0.02 (57)
$\langle \Gamma \rangle^a$	1.92 ± 0.02 (55)	2.02 ± 0.03 (20)	1.88 ± 0.02 (44)
$\langle \log N_H \rangle^b$	21.2 (61)	21.7 (23)	22.9 (51)
$\langle \log L_{20-100 \text{ keV}} \rangle^c$	44.0 (63)	43.3 (24)	43.4 (57)
$\langle \log M_{\text{BH}} \rangle$	7.8 (30)	7.2 (14)	7.7 (27)
$\langle \lambda \rangle^d$	0.064 (30)	0.015 (14)	0.02 (27)
	Unabs	Absorbed	all Sey
$\langle z \rangle$	0.03 (74)	0.014 (60)	0.02 (144)
$\langle \Gamma \rangle^a$	1.94 ± 0.02 (66)	1.91 ± 0.02 (44)	1.93 ± 0.01 (119)
$\langle \log N_H \rangle^b$	21.0 (75)	23.1 (60)	21.9 (135)
$\langle \log L_{20-100 \text{ keV}} \rangle^c$	43.8 (74)	43.4 (60)	43.6 (144)
$\langle \log M_{\text{BH}} \rangle$	7.6 (37)	7.7 (34)	7.6 (71)
$\langle \lambda \rangle^d$	0.06 (37)	0.015 (34)	0.03 (71)

^a Γ is the average photon index derived from the weighted mean on the power law model fits to the single IBIS/ISGRI spectra; ^b absorption is given in cm^{-2} ; ^c luminosities in $[\text{erg s}^{-1}]$; ^d $\lambda = L_{\text{Bol}}/L_{\text{Edd}}$ is the Eddington ratio.

$\Gamma = 2.02 \pm 0.04$ for Seyfert 1.5, and $\Gamma = 1.89^{+0.04}_{-0.02}$ for the Seyfert 2 class. In all cases, a cut-off power law improves the fit result significantly according to an F-test (Table 7). The resulting model is $\Gamma = 1.4 \pm 0.1$ with cut-off at $E_C = 86^{+16}_{-17}$ keV for all Seyfert galaxies, fully consistent with the average from the 12 cut-off power law model fits. For Seyfert 1 we derive $\Gamma = 1.4 \pm 0.1$ and $E_C = 86^{+21}_{-14}$ keV, and $\Gamma = 1.4 \pm 0.2$ with $E_C = 63^{+20}_{-12}$ keV for intermediate Seyfert 1.5, and $\Gamma = 1.65 \pm 0.05$ with $E_C = 184^{+16}_{-52}$ keV Seyfert 2 galaxies. It should be considered that the latter fit still has a poor quality with $\chi^2_\nu = 2.6$.

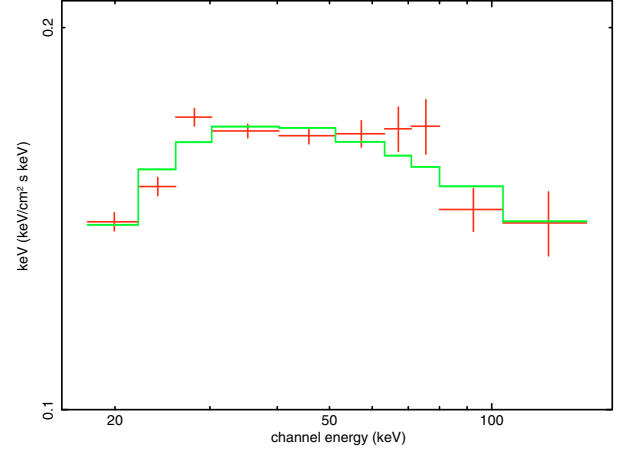
A model that adds a reflection component from cold material to the underlying continuum (the so-called PEXRAV model; Magdziarz & Zdziarski 1995) gives again a better fit in most cases. The underlying continuum shows a similar gradient in the different source classes when not allowing for a high-energy cut-off in the PEXRAV model, so this fit has the same degree of freedom as the one using the cut-off power law. The difference shows up, however, in the inclination angle i and strength R of the reflection component. Here R is defined as the relative amount of reflection compared to the directly viewed primary spectrum.

Table 7. Results from spectral fitting of the stacked IBIS/ISGRI spectra of INTEGRAL AGN

Sample	Γ	E_C [keV]	R	χ^2_ν
Sey 1 ($\geq 5\sigma$)	$1.96^{+0.03}_{-0.02}$	—	—	5.66
	1.44 ± 0.10	86^{+21}_{-14}	—	1.10
($i = 30^\circ$)	1.96 ± 0.02	—	$1.2^{+0.6}_{-0.3}$	1.15
Sey 1.5 ($\geq 5\sigma$)	2.02 ± 0.04	—	—	3.54
	1.36 ± 0.15	63^{+20}_{-12}	—	0.57
($i = 45^\circ$)	2.04 ± 0.04	—	$3.1^{+4.7}_{-1.3}$	0.29
Sey 2 ($\geq 5\sigma$)	$1.89^{+0.04}_{-0.02}$	—	—	3.13
	1.65 ± 0.05	184^{+16}_{-52}	—	2.58
($i = 60^\circ$)	$1.91^{+0.02}_{-0.03}$	—	$1.1^{+0.7}_{-0.4}$	1.67
all Sey ($\geq 5\sigma$)	1.97 ± 0.02	—	—	6.18
	$1.44^{+0.08}_{-0.13}$	86^{+16}_{-17}	—	1.96
($i = 45^\circ$)	1.95 ± 0.02	—	$1.3^{+0.7}_{-0.4}$	1.53
all Sey ($\geq 10\sigma$)	1.98 ± 0.02	—	—	6.04
	$1.41^{+0.10}_{-0.11}$	80^{+17}_{-13}	—	1.23
($i = 45^\circ$)	1.95 ± 0.02	—	$1.3^{+0.7}_{-0.4}$	1.23
Unabs. ($\geq 5\sigma$)	$1.97^{+0.03}_{-0.01}$	—	—	5.64
	$1.53^{+0.09}_{-0.08}$	100^{+25}_{-15}	—	1.82
($i = 45^\circ$)	1.98 ± 0.02	—	$1.3^{+0.6}_{-0.4}$	0.95
Abs. ($\geq 5\sigma$)	$1.91^{+0.04}_{-0.03}$	—	—	1.2
	$1.43^{+0.13}_{-0.08}$	94^{+32}_{-13}	—	1.59
($i = 45^\circ$)	$1.91^{+0.04}_{-0.03}$	—	$1.5^{+1.5}_{-1.4}$	1.03

The value of R depends on the inclination angle i between the normal of the accretion disc and the line of sight. The smaller the inclination angle, the larger the resulting reflection component. As the data are not sufficient to fit R and i simultaneously, the inclination angle was set to $i = 30^\circ$ for Seyfert 1, $i = 45^\circ$ for Seyfert 1.5, and $i = 60^\circ$ for Seyfert 2. It is worth noting that the quality of the fit did not depend on the choice of i . The results are included in Table 7. Using this model, Seyfert 1 and Seyfert 2 show only slightly different underlying continua and a reflection component of the same strength $R \approx 1$ within the statistical errors. Seyfert 1.5 objects appear to have slightly steeper spectra ($\Gamma = 2.0$) and stronger reflection ($R = 3^{+5}_{-1}$). Applying a higher significance level (e.g. $\geq 10\sigma$) for the source selection does not change the results significantly, as shown for all Seyfert galaxies in Table 7. This confirms that the stacked spectra are dominated by the most significant sources. The result of the fit to the whole Seyfert sample with the PEXRAV model is shown in Fig. 6.

The classification according to the Seyfert type of the objects is based on optical observations. An approach to classifying sources due to their properties in the X-rays can be done by separating the sources with high intrinsic absorption ($N_H > 10^{22} \text{ cm}^{-2}$) from those objects that do not show significant absorption in the soft X-rays. Not all objects that show high intrinsic absorption in the X-rays are classified as Seyfert 2 galaxies in the optical, and the same applies to the other AGN sub-types. Nevertheless a similar trend in the spectral slopes can be seen: the 44 absorbed AGN show a hard X-ray spectrum ($\Gamma = 1.91 \pm 0.02$) consistent with that of the 66 unabsorbed sources ($\Gamma = 1.94 \pm 0.02$). Using the stacked spectra, the absorbed sources show a slightly flatter continuum with $\Gamma = 1.91^{+0.04}_{-0.03}$ than unabsorbed Seyfert galaxies, with $\Gamma = 1.97^{+0.03}_{-0.01}$. Also here, a cut-off power law has been tested, but comparing it to the simple power law model improves the fit only for the

**Fig. 6.** Stacked IBIS/ISGRI spectrum for Seyfert objects (excluding Compton thick sources) in EF_E versus energy. The spectrum has been fit by a PEXRAV model with $\Gamma = 1.95$ and reflection $R = 1.3$.

unabsorbed sources. For these sources we derive $\Gamma = 1.5 \pm 0.1$ and $E_C = 100^{+25}_{-15}$ keV, and for the absorbed ones $\Gamma = 1.4 \pm 0.1$ with $E_C = 94^{+32}_{-13}$ keV. Thus, for the different absorption classes we get consistent cut-off values and spectral slopes, although the stacked unabsorbed spectrum is represented better by the simple power-law model with no cut-off. Applying the PEXRAV model shows that the spectra can be represented by reflection models. The fit improves significantly when adding a reflection component with $R \approx 1.5$, while the underlying continuum slope is the same as for the simple power law.

A difference between type 1 and type 2 objects is seen in the average luminosity of these subclasses. For 60 absorbed Seyfert galaxies, the average luminosity is $\langle L_{20-100 \text{ keV}} \rangle = 2.5 \times 10^{43} \text{ erg s}^{-1}$, more than a factor of 2 lower than for the 74 unabsorbed Seyfert with redshift information ($\langle L_{20-100 \text{ keV}} \rangle = 6.3 \times 10^{43} \text{ erg s}^{-1}$). The differences in luminosities are exactly the same when excluding the 5 Compton thick objects. The 16 blazars again appear brighter when assuming an isotropic emission, with $\langle L_{20-100 \text{ keV}} \rangle = 10^{46} \text{ erg s}^{-1}$. The latter value has to be used with caution: because the blazar emission is beamed towards the observer, not isotropic but collimated in a jet, blazars are highly variable and *INTEGRAL* detects them mainly in phases of outbursts.

4. Discussion

4.1. The sample in comparison with previous studies

For the whole population of sources seen by *INTEGRAL* we observe an increase in the fraction of unabsorbed objects compared to the first *INTEGRAL* AGN catalogue. Whereas $\frac{2}{3}$ of the Seyfert population in the first sample showed $N_H > 10^{22} \text{ cm}^{-2}$, there are now more unabsorbed than absorbed sources, i.e. only 44% appear to be absorbed. A similar trend has also been observed in the *Swift*/BAT survey (Tueller et al. 2008), where the fraction is $\frac{1}{2}$. This trend is expected because with ongoing observations, IBIS/ISGRI and BAT perform deeper studies, which is also reflected in the increase in the average redshift and luminosity of the objects that are detectable. Sazonov et al. (2004, 2007) have shown that there is an anticorrelation of the fraction of absorbed sources with the X-ray luminosity. In a sample of 95 AGN detected by *RXTE*, they observed that the fraction

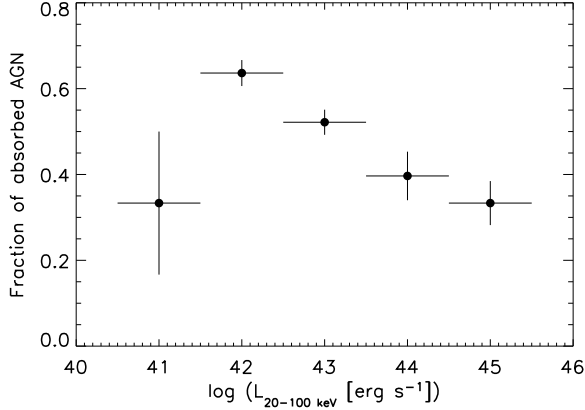


Fig. 7. Fraction of absorbed ($N_{\text{H}} > 10^{22} \text{ cm}^{-2}$) Seyfert galaxies as a function of hard X-ray luminosity for *INTEGRAL* detected AGN ($\geq 4\sigma$). The lowest luminosity bin includes only 3 sources.

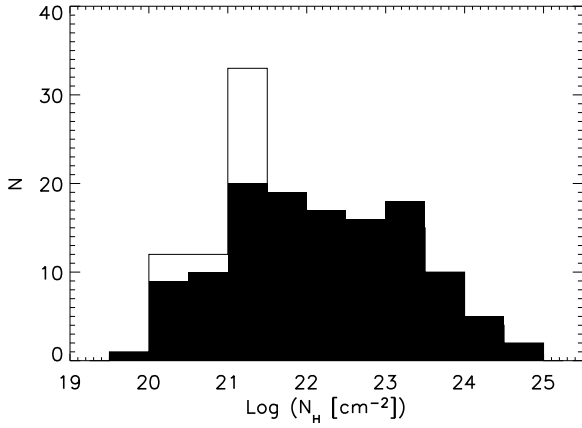


Fig. 8. Distribution of intrinsic absorption of the Seyfert content of *INTEGRAL* detected AGN ($\geq 4\sigma$). The unshaded area indicates objects where the N_{H} value is an upper limit.

of absorbed sources is $\sim 70\%$ for $L_{3-20 \text{ keV}} < 10^{43.5} \text{ erg s}^{-1}$ but only $\sim 20\%$ for objects with $L_{\text{X}} > 10^{43.5} \text{ erg s}^{-1}$. This trend can also be seen in the sample presented here. Determining the fraction of absorbed Seyfert galaxies in logarithmic bins of X-ray luminosity, we see the trend toward a decreasing fraction with luminosity in the range $L_{20-100 \text{ keV}} > 3 \times 10^{41} \text{ erg s}^{-1}$ (Fig. 7). The fraction appears low though in the lowest luminosity bin ($L_{20-100 \text{ keV}} < 3 \times 10^{41} \text{ erg s}^{-1}$), but it has to be considered that this luminosity bin contains only 3 AGN, the Seyfert 1.5 galaxies NGC 4258, NGC 4395, and NGC 5033.

The fraction of Compton thick objects in the sample presented here is only 4% (5 objects out of the 135 Seyfert galaxies with measured intrinsic absorption). Although this sample is not a complete one, this indicates further that the fraction of Compton thick AGN is indeed $\ll 10\%$ as already reported in e.g. Beckmann et al. (2006b) and Bassani et al. (2007). In addition, a recent study based on combined *INTEGRAL* and *Swift*/BAT data puts an upper limit of $\lesssim 9\%$ on the fraction of Compton thick AGN (Treister et al. 2009), and one can thus consider most of the Seyfert population detected by *INTEGRAL* and *Swift* to be Compton thin. The distribution of intrinsic absorption (Fig. 8) shows that the Seyfert galaxies in the *INTEGRAL* sample are evenly distributed between 10^{21} cm^{-2} and $3 \times 10^{23} \text{ cm}^{-2}$, as

Table 8. Correlation matrix for *INTEGRAL* AGN.

	M_{BH}	Γ	L_{X}	Edd. ratio	L_{V}
				λ	
N_{H}	no	no	no	no	no
M_{BH}	–	no	$>99.99\%$	intrinsic	$>99.99\%$
Γ		–	no	no	no
L_{X}			–	intrinsic	$>99.99\%$
λ				–	no

already seen in the first *INTEGRAL* AGN catalogue (Beckmann et al. 2006c) and in the *Swift*/BAT AGN survey (Tueller et al. 2008). A significant amount of sources have reported N_{H} values of $N_{\text{H}} < 10^{21} \text{ cm}^{-2}$. We assigned $N_{\text{H}} = 10^{21} \text{ cm}^{-2}$ to these objects, which causes the peak in the distribution. The claim of two distinct groups resulting in two peaks in the N_{H} distribution as reported by Paltani et al. (2008) appears therefore caused by low number statistics. Although a clear dependency is seen on the intrinsic absorption when dividing the sample in two groups, there is no significant linear correlation with any of the parameters we tested. We summarize the analysis of the correlations in Table 8. Here the correlation probability is given if larger than 90%. The correlations between Eddington ratio and L_{X} and M_{BH} are intrinsic, i.e. caused by the dependence of λ on these two parameters.

For synthesis studies of the cosmic X-ray background one will have to take into account that both, the fraction of Compton thick and of absorbed sources, appears to be lower than assumed in most models published so far (e.g. Treister & Urry 2005; Gilli et al. 2007). Although the average redshift in the *INTEGRAL* sample has increased significantly since the first catalogue from $\langle z \rangle = 0.01$ to now $\langle z \rangle = 0.03$, *INTEGRAL* will not be able to probe evolutionary effects. The only possibility of measuring evolutionary effects would be the combination of *Swift*/BAT data with a deep ($\sim 10 \text{ Ms}$) *INTEGRAL* IBIS/ISGRI field (Paltani et al. 2008).

A systematic analysis of all *BeppoSAX* observations of AGN has been presented by Dadina (2007). Thirty-nine objects from this work are in common with the *INTEGRAL* sample. Four sources show strong differences in flux by more than a factor of 2 between the measurements, i.e. the Seyfert 2 galaxies NGC 4388, NGC 2110, NGC 7172, and the type 1 radio galaxy 3C 111. All these objects are known to be variable at hardest X-rays (e.g. Beckmann et al. 2007). In addition, the average flux in the 20–100 keV band appears to be higher in the *INTEGRAL* data than in the *BeppoSAX* one. This can be caused by the different time coverage: while *BeppoSAX* observations are mostly snapshots of the sources with duration of $\Delta t \ll 100 \text{ ks}$, the *INTEGRAL* observations of the AGN have the average exposure of 1200 ks. Thus the data presented here can include some short-term bright states, which would have been missed in most cases by *BeppoSAX*. In addition, the fluxes presented here are model fluxes, and because more complex modelling is necessary for the *BeppoSAX* spectra, applying a cut-off and a reflection component in most cases, this leads to lower broad-band model fluxes compared to the simple power law model applied here (see also Sect. 4.2). In addition, there is a systematic difference in the calibration of the ISGRI and PDS detectors, with steeper and higher-normalization Crab spectra extracted for ISGRI (Kirsch et al. 2005). This explains also larger spectral slope values fitted to the ISGRI spectra, when compared with the values quoted by Dadina (2007), although the primary reason for these differences is the simpler spectral model applied to the *INTEGRAL* data.

Table 9. OSSE detected AGN not seen by *INTEGRAL*.

Name	Type	Exposure ^a [ks]
CTA 102	blazar	180
H 1517+656	BL Lac	19
III Zw2	Sy1/2	15
Mrk 279	Sy1.5	11
M82	Starburst	127
NGC 253	Starburst	1
NGC 7213	Sy1.5	31
NGC 7582	Sy2	–
PKS 2155-304	BL Lac	347
QSO 1028+313	Sy1.5	556

^a ISGRI exposure time.

CGRO/OSSE (Johnson et al. 1993) covered the energy range of approximately 50–10³ keV. It therefore primarily detected AGN with hard and bright X-ray spectra, which we also expect to be detectable by *INTEGRAL*. While the first *INTEGRAL* AGN catalogue listed 24 OSSE-detected AGN not seen by *INTEGRAL*, this number has now decreased to 10. We list those sources and the IBIS/ISGRI exposure time on the particular AGN in Table 9. It can be expected that the persistent sources in this list, i.e. the Seyfert and starburst galaxies, will be detected once a significant amount of exposure time is available for these objects.

As expected, only a few objects are jointly detected by *INTEGRAL* IBIS/ISGRI and *Fermi*/LAT, according to the bright source list based on three months of LAT data (Abdo et al. 2009). These 13 objects are blazars, except for the two radio galaxies Cen A and NGC 1275. The common blazars between ISGRI and LAT are 1ES 0033+595, PKS 0528+134, QSO B0716+714, Mrk 421, 3C 273, 3C 279, Mrk 501, PKS 1830-211, 1ES 1959+650, BL Lac, and 3C 454.3. The group of sources jointly detected by *Fermi*/LAT and ISGRI is expected to increase significantly through *INTEGRAL* target-of-opportunity (ToO) observations of blazars that show a flare in the LAT data.

4.2. The intrinsic hard X-ray spectrum

The effect that Seyfert 1 and low-absorbed objects appear to have steeper X-ray spectra than the Seyfert 2 and highly absorbed AGN was first noticed by Zdziarski et al. (1995), based on *Ginga* and *CGRO/OSSE* data and later confirmed e.g. by Gondek et al. (1996) using combined *EXOSAT*, *Ginga*, *HEAO-1*, and *CGRO/OSSE* spectra. A study of *BeppoSAX* PDS spectra of 45 Seyfert galaxies came to a similar conclusion, although the spectra of Seyfert 2 appeared steeper when considering a possible cut-off in the spectra of Seyfert 1 galaxies (Deluit & Courvoisier 2003). The difference in the hard X-ray spectral slope between Seyfert 1 and 2 has been a point of discussion ever since its discovery. Zdziarski et al. (2000) considered the anisotropy of Compton scattering in planar geometry and effects of reflection, but came to the conclusion that this cannot be the sole explanation. Beckmann et al. (2006) argued that the difference might be a selection effect, as objects have to have a harder X-ray spectrum to be detectable when strong intrinsic absorption is present. With the growing sample of AGN, this argument does not seem to hold, as the absorption in the energy band >20 keV is negligible for Compton thin objects, and also the ongoing identification effort of newly detected hard X-ray sources did not

reveal a different population than already presented in Beckmann et al. (2006).

A solution might be provided when considering the effects of Compton reflection on the hard X-ray spectrum, as shown in the previous section. Recent analysis of a sample of 105 Seyfert galaxies using the spectra collected with *BeppoSAX* in the 2–200 keV band (Dadina 2008) provided no evidence of any spectral slope difference when applying more complex model fitting including a reflection component (PEXRAV). The mean photon index values found for Seyfert 1 and Seyfert 2 samples were $\Gamma = 1.89 \pm 0.03$ and $\Gamma = 1.80 \pm 0.05$. The difference between types 1 and 2 is seen in this model in the different strength of the reflection component, with $R = 1.2 \pm 0.1$ and $R = 0.9 \pm 0.1$, and different cut-off energies of $E_C = 230 \pm 22$ keV and $E_C = 376 \pm 42$ keV, for Seyfert 1 and Seyfert 2, respectively. It has to be pointed out that spectral slope, reflection strength, and cut-off energy are closely linked. The IBIS/ISGRI data have a disadvantage over broad-band data when studying the spectral shape of the hard X-ray continuum, as we lack information about the spectrum below 18 keV. But on the positive side, using data from only one instrument, the spectra do not suffer from the problem of intercalibration factors, which is apparent in all studies using different instruments, and especially when using data from different epochs. In those cases, where spectra are taken by more than one instrument at different times, the flux variability can mimic a stronger or weaker reflection component or cut-off energy (e.g. Panessa et al. 2008).

The *INTEGRAL* data show consistent slopes for the spectra of unabsorbed/type 1 and absorbed/type 2 objects already when a simple power-law model is used. When applying the model used by Dadina (2007) to the stacked *INTEGRAL* spectrum of Seyfert galaxies, we get similar results: the underlying power-law appears to have consistent (within 2σ) spectral slope for type 1 ($\Gamma = 1.96$) and type 2 ($\Gamma = 1.91$) objects and the same reflection strength $R \approx 1.1$. The data do not allow to determine the cut-off energy or inclination angle when fitting the reflection component (Fig. 6). When fitting a simple cut-off power law, the *INTEGRAL* data show the same trend as the *BeppoSAX* sample, i.e. a lower cut-off energy for Seyfert 1 ($E_C = 86$ keV) than for Seyfert 2 ($E_C = 184$ keV). It has to be taken into account, though, that the fit to the Seyfert 2 data is bad quality, and that fixing the cut-off here to the same value as derived for the Seyfert 1, also leads to the same spectral slope. When fitting a reflection model to the stacked data, one gets a consistent photon index of $\Gamma \approx 1.95$ and reflection strength $R \approx 1.3$ for both absorbed and unabsorbed AGN. These values of Γ and R agree with the correlation $R = (4.54 \pm 1.15) \times \Gamma - (7.41 \pm 4.51)$ Dadina (2008) found for the *BeppoSAX* AGN sample, which, for the *INTEGRAL* sample with $\Gamma = 1.95$, would lead to $R = 1.4$. This $R(\Gamma)$ correlation was first noted based on *Ginga* data for extragalactic and Galactic black holes, leading to $R = (1.4 \pm 1.2) \times 10^{-4} \Gamma^{(12.4 \pm 1.2)}$ (Zdziarski et al. 1999), which in our case would result in a smaller expected reflection component with $R = 0.6$ but within 1σ of the value detected here. Absorbed and unabsorbed show a consistent turnover at about $E_C = 100$ keV when a cut-off power law model is applied.

The observed dichotomy of different spectral slopes for type 1 and type 2 objects might therefore be caused by data with too low significance, which do not allow to fit the reflection component, or in general by a strong dependence of the spectral slope on the choice of the fitted model. One aspect that has to be kept in mind is the dependence of the reflection strength R on the model applied and on the geometry assumed. Murphy & Yaqoob (2009) showed recently that their model of a reflection

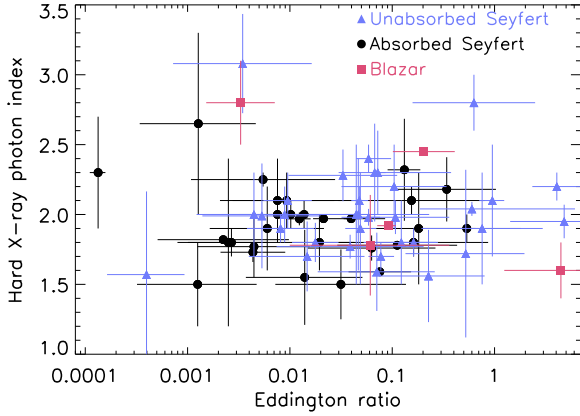


Fig. 9. Photon index of a simple power-law fit to the IBIS/ISGRI data versus Eddington ratio λ .

spectrum from a Compton-thick face-on torus that subtends a solid angle of 2π at the X-ray source is a factor of ~ 6 weaker than that expected from a Compton-thick, face-on disc as modelled in PEXRAV. Therefore, applying a torus model to the data presented here would result in much less reflection strength.

4.3. Eddington ratios and accretion rates in Seyfert galaxies

A different approach to search for differences or similarities in Seyfert galaxies is to study the accretion rates. Middleton et al. (2008) suggest that different accretion states lead to differences in the hardness of hard X-ray ($E > 10$ keV) spectra between types 1 and 2 AGN (type 1 spectra being systematically softer). Using data from *CGRO/OSSE*, *BeppoSAX*, and *INTEGRAL*, they found that the 24 Seyfert 2 galaxies in their sample of hard X-ray selected AGN show an accretion rate (parameterized with the Eddington ratio) in average smaller than that of their 23 Seyfert 1. This effect has also been seen when studying AGN detected by *Swift/BAT* (Winter et al. 2009). This would be consistent with all accreting black holes in general showing harder spectra at low accretion rates (Laor 2000; Remillard & McClintock 2006).

The 20–100 keV luminosities as derived from the IBIS/ISGRI data were used to approximate the bolometric luminosity. Assuming a canonical photon index of 2.0 for a single power law, the total X-ray luminosity is about $L_{(1-200 \text{ keV})} = 3 \times L_{(20-100 \text{ keV})}$. Assuming that the first peak of the spectral energy distribution is as strong as the X-ray luminosity, we derive $L_{\text{Bol}} = 6 \times L_{(20-100 \text{ keV})}$. The Eddington luminosity considering pure hydrogen is given by $L_{\text{Edd}} = 1.26 \times 10^{38} \frac{M}{M_{\odot}} \text{ erg s}^{-1}$, and thus the Eddington ratio is $\lambda = L_{\text{Bol}}/L_{\text{Edd}} = 4.8 \times 10^{-38} L_{(20-100 \text{ keV})} \frac{M_{\odot}}{M} \text{ erg}^{-1} \text{ s}$. The Eddington ratio can be computed for 71 Seyfert objects of the sample presented here. The photon index as determined from IBIS/ISGRI data and the Eddington ratio are compared in Fig. 9. The four AGN on the top left of this figure, with steep spectra and low Eddington ratio ($\lambda < 0.005$), are the Seyfert 1 1H 1934-063, the Seyfert 2 objects SWIFT J0601.9-8636 and NGC 4258, and the blazar Mrk 501. There is no significant correlation detectable, even when excluding these outliers. As observed by Steffen et al. (2003) in *Chandra* data of AGN, it appears that the 2–8 keV luminosity function is dominated by type 1 AGN at high X-ray luminosities and by type 2 at low luminosities. The same effect is seen

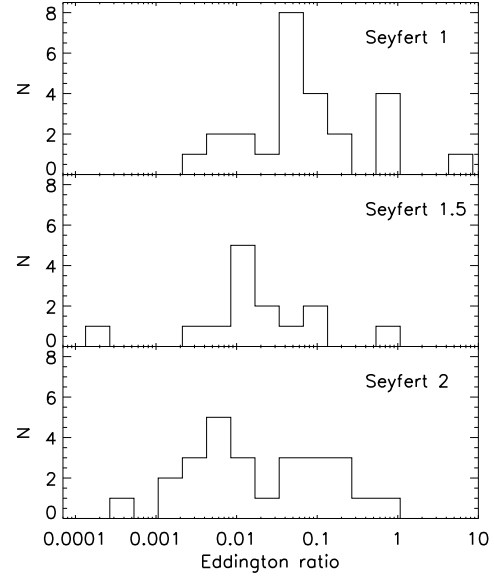


Fig. 10. Distribution of Eddington ratios for Seyfert 1, 1.5, and type 2 AGN in the sample.

also in the *INTEGRAL* luminosity function (Beckmann et al. 2006b). Connected to this, we observe not only that the absorbed sources are less luminous than the unabsorbed ones, but also that absorbed sources have smaller accretion rates as seen in lower Eddington ratios (Fig. 10). In agreement with Middleton et al. (2008) results, we find that the average values of Eddington ratio for Seyfert 1 ($\langle \lambda_{\text{Sy1}} \rangle = 0.064$) are higher than those found for intermediate Seyfert type ($\langle \lambda_{\text{Sy1.5}} \rangle = 0.015$) and Seyfert 2 with $\langle \lambda_{\text{Sy2}} \rangle = 0.02$ (Fig. 10), although we do not observe the differences in the underlying spectra, as seen in their study. The same applies for the separation into unabsorbed ($\langle \lambda_{(N_{\text{H}} < 10^{22} \text{ cm}^{-2})} \rangle = 0.06$) and absorbed sources ($\langle \lambda_{(N_{\text{H}} > 10^{22} \text{ cm}^{-2})} \rangle = 0.015$). To calculate the probability that the Eddington ratios of Sey1/unabsorbed objects and Sey2/absorbed AGN are drawn from the same population, we applied a Kolmogorov-Smirnov test. We can reject the null hypothesis (same population), with a probability of false rejection of 0.1% and 3% for the Seyfert 1 – Seyfert 2 and unabsorbed – absorbed objects, respectively. On the other hand, since we do not find a significant correlation between the hard X-ray photon index and the Eddington ratio, we cannot back up the scenario by Middleton et al. (2008) as a way to explain the different spectral hardness of type 1 and type 2 AGN.

When studying the effect of radiation pressure on dusty absorbing gas around AGN, Fabian et al. (2008) trace a region in the N_{H} -Eddington ratio plane that is forbidden to long-lived clouds in AGN. In fact, even when the AGN is in the sub-Eddington regime for the ionized gas, it can appear to be super-Eddington for the dusty gas, hence ejecting the surrounding absorbing clouds. Objects in this region of the N_{H} -Eddington ratio plane could present outflows or show transient or variable absorption. Fabian et al. (2009) tested the predictions of this model using the *Swift/BAT* AGN sample of Winter et al. (2008) and find a good agreement, with only 1 object lying in the forbidden area, the Seyfert 1.9 object MCG-05-23-016. This object has been shown to exhibit high accretion rates at the Eddington limit (Beckmann et al. 2008). In Fig. 11 we show the regions defined by Fabian et al. (2009) in the N_{H} -Eddington ratio plane and our AGN sample. The forbidden region is on the

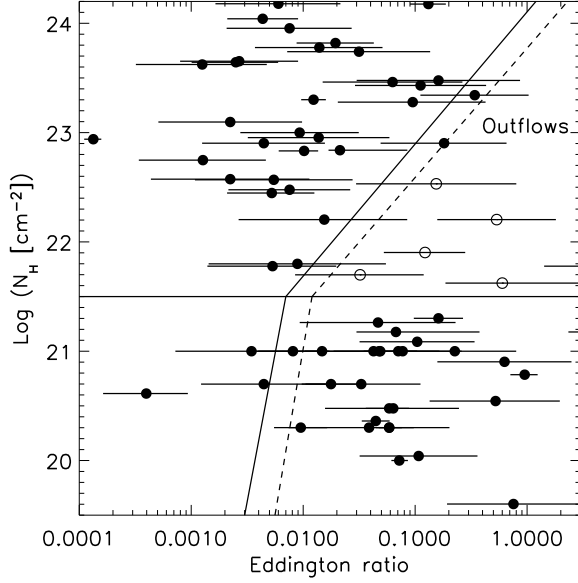


Fig. 11. Intrinsic absorption versus Eddington ratio for the Seyfert galaxies in the *INTEGRAL* sample. The “forbidden zone” described by Fabian et al. (2009) is occupied by 5 *INTEGRAL* AGN (empty circles).

upper-righthand side of the plot and bordered by an upper limit to N_H (for absorption due to dust lanes at few kpc from the AGN centre) and the Eddington limit for the dusty gas when only the black hole mass is considered to be gravitationally important (continuous line) or if also as much mass from intervening stars is included (dashed line). It is important to keep in mind that the bolometric luminosity is a critical parameter in defining the limits of the forbidden area, as different estimates of it can be used. Therefore, using a bolometric correction by a factor of few larger than what we applied here would shift the data points towards higher Eddington ratios, occupying the forbidden region completely. Nevertheless, with the bolometric luminosity we estimate ($L_{\text{Bol}} = 6 \times L_{(20-100 \text{ keV})}$), and find 5 objects with a detection significance $>4\sigma$ in this area: IGR J00335+6126, MCG–05–23–016, Mrk 766, IC 4329A, and NGC 5506. Out of these, only MCG–05–23–016 occupies the forbidden region also in Fabian et al. (2009), whereas IGR J00335+6126 was not included and Mrk 766 lacked absorption information in their study, IC 4329A is located close to the border of the forbidden zone, and NGC 5506 is not within this area. This raises the question of whether this region indeed cannot be occupied persistently by Seyfert type AGN, although the 5 objects do display some peculiarities, as described in the following. IC 4329A and IGR J00335+6126 are just above the upper limit N_H and MCG–05–23–016 has a complex spectrum with warm absorbers, not necessarily related to dusty gas (Fabian et al. 2009). The Seyfert 1.9 NGC 5506 has been identified as an obscured narrow-line Seyfert 1 (Nagar et al. 2002), which might explain the high accretion rate in this object. And the Seyfert 1.5 Mrk 766 with a black hole mass of only $3.5 \times 10^6 M_\odot$ (Uttley & McHardy 2005) might be a similar case to the highly efficient Seyfert MCG–05–23–016 (Beckmann et al. 2008). But the small number of objects and the fact that the uncertainty on the Eddington ratio is still rather large do not allow us to conclusively state that strongly absorbed Seyfert galaxies cannot exhibit high accretion rates over a long phase of their lifetimes.

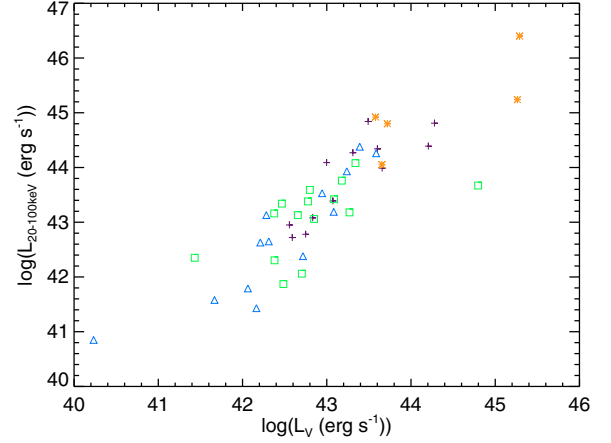


Fig. 12. X-ray luminosity L_X versus V-band luminosity L_V . AGN of different types are located along the same dispersion line, over more than 5 decades in luminosity. Symbols: crosses – Seyfert 1-1.2; triangles – Seyfert 1.5; squares – Seyfert 1.8-2; asterisks – BL Lacs.

4.4. Correlations with optical data and α_{OX}

We show in Fig. 12 the dispersion diagram of L_X vs. L_V , with different symbols for the different classes of objects considered. While the apparent correlation between both luminosities is certainly driven by the distance effect evident in Fig. 5, it is remarkable that the different classes of objects, from Seyfert 2 to blazars, are located on the same correlation line, over more than 5 decades in luminosity. Subtracting the common dependence on redshift through a partial correlation analysis, the correlation between the luminosities is still statistically significant, with a correlation coefficient of 0.74 and the probability of a chance occurrence is $\ll 0.01\%$. To test this correlation further, we made simulations using a bootstrap method (Simpson et al. 1986): to each couple of X-ray flux and redshift we randomly assigned an optical flux, drawn from the real values found for our sample and without excluding multiple choices of the same value (see also Bianchi et al. 2009, for a similar procedure). We then computed the X-ray and optical luminosities and calculated the Spearman and the partial correlation coefficients for the $L_X - L_V$ relation and the Spearman coefficient for the $F_X - F_V$ relation. Repeating this procedure 100 000 times, we were able to build histograms of the correlation coefficients of the simulated samples and found that only 0.001% of the simulated samples have a (Spearman or partial) correlation coefficient greater than measured in the real sample for the $L_X - L_V$ relation. For the $F_X - F_V$ correlation, the probability of chance occurrence is higher but still not significant, $\sim 2\%$. This indicates that the X-ray and optical emissions are indeed correlated, beyond the bias introduced by the common dependence on distance.

To further investigate this relation, we computed the histograms of the α_{OX} values for the different subtypes. We show in Fig. 13 that the peaks of the distributions coincide for the four subsamples, with mean values close to each other (Seyfert 2: 1.14, Seyfert 1.5: 1.13, Seyfert 1-1.2: 1.08, and BL Lac: 1.03). Seyfert 2 and 1.5 nevertheless show an extended wing towards higher α_{OX} ratios. NGC 1068, the prototypical Seyfert 2 galaxy, shows the highest α_{OX} value, 1.38. Because it is a Compton-thick object, this high α_{OX} value can be understood clearly. Other Compton-thick Seyfert galaxies, such as NGC 3165 and ESO138–1, also show α_{OX} values above 1.20. But other objects with high α_{OX} values, such as NGC 1052 and NGC 5033,

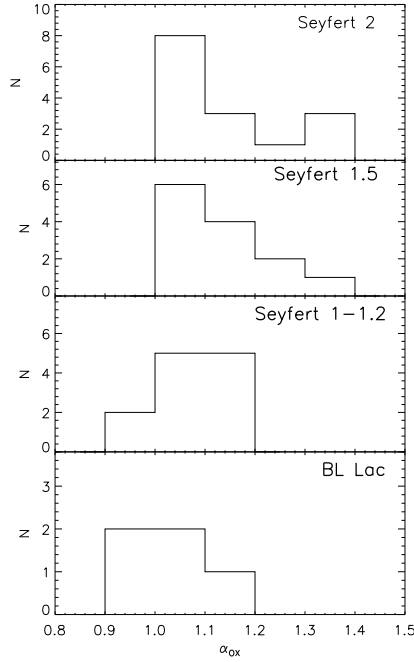


Fig. 13. α_{OX} histograms for 4 subtypes of AGN.

have low hydrogen column densities; in contrast several objects with high neutral columns, like NGC 3281, NGC 4945, and ESO 383–18, show relatively low α_{OX} values.

As discussed in Sect. 2.3.1, only 3 objects in the sample have shown significant optical variability over the period being monitored ($\Delta V > 0.5$ mag). For the blazars QSO B0716+714 and 3C 279, both their L_V and L_X values have to be dominated by the central AGN, with only a minor contribution by stars in V. This is indeed expected for this type of high-luminosity blazars while accretion processes and bulge stars dominate the V band in less active Seyfert galaxies.

That most Seyfert galaxies in the sample look similar when analysed from the point of view of their α_{OX} value indicates that the true nature of these objects is indeed very similar, thus supporting the unified scenario of AGN. The central black hole behaves very similarly with respect to the host galaxy, independent of the type of object. The classification as type 1 or type 2 AGN would mainly derive from observations of parameters dependent on geometrical effects, such as the profile of the emission lines or of the X-ray emission, but would not be tracing systematic differences in the intrinsic nature of these objects.

4.5. A fundamental plane of AGN activity

In the view of unification of different AGN types, it has been pointed out that AGN, spanning black hole masses in the range of $10^5 M_\odot \lesssim M_{\text{BH}} \lesssim 10^9 M_\odot$ and even accreting black holes in X-ray binaries with $M_{\text{BH}} \sim 10 M_\odot$, show similarities in radiative efficiency and jet power versus accretion rate (e.g. Fender et al. 2007). This connection gave rise to the “fundamental plane” of black hole activity. It has been found that indeed there is a close connection between the radio and X-ray luminosity of Galactic and super massive black holes of the form $L_{\text{radio}} \propto L_X^{0.7}$ (Corbel et al. 2000, 2003), linking the jet activity to the total output of the central engine. Later on, a connection of these two

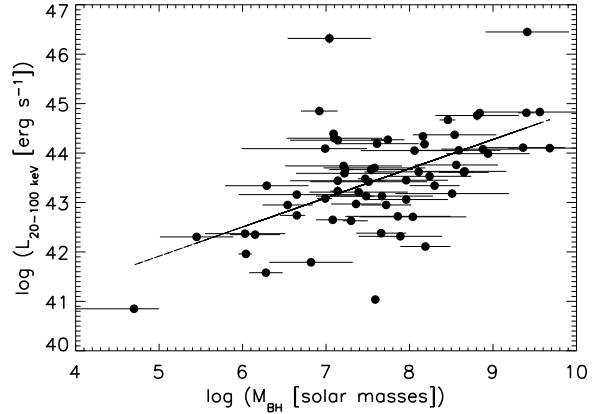


Fig. 14. Hard X-ray luminosity versus black hole masses for Seyfert galaxies. Errors on L_X are smaller than the symbols. More massive AGN appear to be brighter in the hard X-rays with $L_X \sim M_{\text{BH}}^{0.7 \pm 0.1}$. The correlation coefficient is 0.52 with a probability of non-correlation $< 2 \times 10^{-6}$.

parameters with the black hole mass itself was found, establishing the fundamental plane of AGN and Galactic black hole activity in the form of $L_{\text{radio}} \propto L_X^{0.6} M_{\text{BH}}^{0.8}$ (e.g. Merloni et al. 2003).

The correlation between X-ray luminosity and black hole mass is also common to all objects in our sample, showing indeed that more massive AGN are more luminous ($L_X \sim M_{\text{BH}}^{0.7 \pm 0.1}$, as shown in Fig. 14). A similar relation has lately been reported for various X-ray selected AGN samples (e.g. Bianchi et al. 2009; Wang et al. 2009), and also in these cases the slope is lower than 1. This could indicate that more massive black holes either have lower accretion rates than less massive objects, or a smaller fraction of their total power is converted into X-ray luminosity (assuming that the bolometric luminosity scales linearly with black hole mass). As reported in Table 8, a significant correlation is also detected between the black hole mass and the optical luminosity. Only for 8 out of 41 objects might the correlation of L_V versus M_{BH} be induced by the method used to estimate the mass, i.e. when deriving the mass from the K-band magnitudes (assumed to represent the bulge luminosity) or from continuum optical luminosity. However, caution should be used in general when considering a correlation between luminosity and black hole mass, because possible selection effects or different biases could contribute to the observed correlation in non complete samples. Woo & Urry (2002) argue that, when correlating bolometric luminosity with black hole mass, the Eddington luminosity sets a (soft) upper limit to the luminosities and therefore determines the empty region of the diagram in the upper left corner. On the other hand, the lower-right corner should be populated by low-luminosity, massive black holes that are not included or are rare in the high-energy AGN samples, such as normal or radio galaxies.

As discussed in detail in the previous section, there is also a significant correlation between optical and X-ray luminosity. Therefore, as summarised in Table 8, we found three significant correlations in our sample between the luminosities L_X and L_V , and the mass of the central black hole M_{BH} . This leads to the assumption that also these parameters, similar to L_X , L_R , and M_{BH} , form a fundamental plane for AGN. By applying an analysis following Merloni et al. (2003), we fit the data with the function

$$\log L_V = \zeta_{VX} \log L_X + \zeta_{VM} \log M_{\text{BH}} + b_V. \quad (2)$$

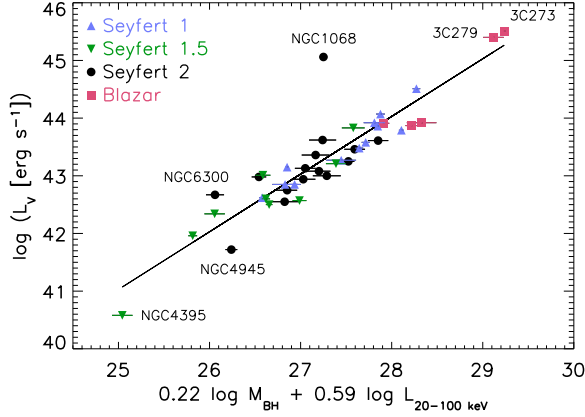


Fig. 15. Fundamental plane of optical luminosity L_V , X-ray luminosity L_X , and mass of the central black hole M_{BH} . Errors on luminosity are smaller than the symbols.

We obtain $\zeta_{VX} = 0.59 \pm 0.07$, $\zeta_{VM} = 0.22 \pm 0.08$, and $b_V = 16.0$, leading to

$$\log L_V = 0.59 \log L_X + 0.22 \log M_{\text{BH}} + 16.0; \quad (3)$$

i.e., $L_V \propto L_X^{0.6} M_{\text{BH}}^{0.2}$. We show this relation in Fig. 15. As already pointed out and discussed here and in Sect. 4.4, we carefully investigated that the effects of distance and selection effect are not causing the correlation observed here.

While the fundamental plane including the radio and X-ray luminosity can be understood as a connection of the jet activity, as visible in the radio, and the accretion flow, as dominating the X-rays, the correlation found here shows a different connection. The optical luminosity is commonly thought to be dominated by the AGN accretion disc (e.g. Siemiginowska et al. 1995) and therefore by the accretion processes onto the supermassive black hole, but there is also a possible contribution by the jet (Soldi et al. 2008) and emission of the bulge, and therefore of the stars in the host galaxy contributing to it. The latter is especially important as the resolution of *INTEGRAL*'s OMC camera does not allow a deconvolution of the core and the bulge. Nevertheless it shows that there is a significant bulge- M_{BH} correlation and that accretion processes are closely linked to the mass of the central black hole. The finding that this fundamental plane holds for all Seyfert types indicates further that these AGN are indeed intrinsically the same.

5. Conclusions

We have presented the second *INTEGRAL* AGN catalogue, including 187 extragalactic objects. The AGN population detected by *INTEGRAL* is dominated by Seyfert galaxies in the local ($\langle z \rangle = 0.03$) universe, with moderate X-ray luminosity ($\langle L_{20-100 \text{ keV}} \rangle = 4 \times 10^{43} \text{ erg s}^{-1}$). Seyfert 1 galaxies appear to have higher luminosities ($\langle L_{20-100 \text{ keV}} \rangle = 10^{44} \text{ erg s}^{-1}$) and Eddington ratio ($\langle \lambda_{\text{Sy1}} \rangle = 0.064$) than the Seyfert 2 galaxies ($\langle L_{20-100 \text{ keV}} \rangle = 2.5 \times 10^{43} \text{ erg s}^{-1}$, $\langle \lambda_{\text{Sy2}} \rangle = 0.02$). Although IBIS/ISGRI spectra alone lack the information about the iron line complex and the continuum shape below 18 keV, they can be used to study the average Seyfert spectra in a statistical way. The underlying continuum of the hard X-ray spectrum appears to be consistent between different Seyfert types, both when a simple power-law model is applied and when considering the effects of Compton reflection. Applying the PEXRAV reflection

model with no high energy cut-off, the Seyfert 1 and 2 galaxies show the same underlying power law with $\Gamma \simeq 1.95$ and a reflection component of $R \simeq 1.1$, when applying different inclination angles of $i \simeq 30^\circ$ and $i \simeq 60^\circ$, respectively. Although, when applying a cut-off power law model to the stacked spectra, the Seyfert 1 show lower cut-off energies ($E_C = 86^{+21}_{-14} \text{ keV}$) than the Seyfert 2 objects ($E_C = 184^{+16}_{-52} \text{ keV}$), the bad quality of the fit in the latter case and that fixing the cut-off to the value of the Seyfert 1 leads to a similar spectral slope might indicate that the spectra are intrinsically indeed the same.

The same differences as for different Seyfert classes are observable when considering the intrinsic absorption: the unabsorbed sources also have higher luminosities ($\langle L_{20-100 \text{ keV}} \rangle = 6.3 \times 10^{43} \text{ erg s}^{-1}$) and Eddington ratio ($\langle \lambda \rangle = 0.06$) than the absorbed AGN ($\langle L_{20-100 \text{ keV}} \rangle = 2.5 \times 10^{43} \text{ erg s}^{-1}$, $\langle \lambda \rangle = 0.015$). Also separating the objects into absorption classes, the underlying continuum appears similar when considering the effects of Compton reflection. The mass of the central black hole is on average the same among the different Seyfert types and absorption classes, with $\langle M_{\text{BH}} \rangle = 4 \times 10^7 M_\odot$. Also comparing optical to hard X-ray emission, the different Seyfert classes show the same ratio ($\alpha_{\text{OX}} = 1.1$). On average, the hard X-ray spectra of Seyfert 1.5 objects are closer to those of the Seyfert 1 class than to Seyfert 2.

The optical data provided by *INTEGRAL*/OMC can be used to monitor variability. Strong variability ($\Delta V \geq 0.5 \text{ mag}$) is only seen in three objects within the optical sample of 57 AGN, i.e. in the blazars QSO B0716+714 and 3C 279, and in NGC 4151.

The overall picture can be interpreted within the scenario of a unified model. The whole hard X-ray detected Seyfert population fills the parameter space of spectral shape, luminosity, and accretion rate smoothly, and only an overall tendency is seen in which more massive objects are more luminous, less absorbed, and accreting at higher Eddington ratio. An explanation for why the absorbed sources have been claimed to show flatter spectra in the hard X-ray domain when fit by a simple power law can be that the slope of the continuum strongly depends on the fitted model and that Compton reflection processes play a major role here. Considering these effects, it appears that the different Seyfert types are indeed intrinsically the same.

More evidence for the unified scheme is that a fundamental plane can be found between the mass of the central object and optical and X-ray luminosity. The correlation takes the form $L_V \propto L_X^{0.6} M_{\text{BH}}^{0.2}$, similar to what is found in previous studies between L_R , L_X , and M_{BH} . This links the accretion mechanism with the bulge of the host galaxy and with the mass of the central engine in the same way in all types of Seyfert galaxies. The connection is also apparent through the same optical-to-hard X-ray ratio measured in all Seyfert classes.

Evolutionary effects are likely to be beyond the AGN population accessible by *INTEGRAL* and *Swift*. Deep hard X-ray surveys by future missions like *NuSTAR*, *Astro-H*, and *EXIST* will be able to answer this question through deep observations of small portions of the sky.

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Appendix A: Notes on individual sources

We include here all Seyfert galaxies above 30σ IBIS/ISGRI detection significance, all sources showing a complex ISGRI spectrum (Table 3), and those for which the results found here differ from previous works.

Mrk 348: the X-ray spectrum of this Seyfert 2 was studied by *RXTE*, showing the same spectral shape as reported here ($\Gamma = 1.8$) and evidence for a reflection component with $R \lesssim 1$ (Smith et al. 2001). Instead of a cut-off power law with $\Gamma = 0.9$ and $E_C = 55$ keV as given in Table 3, the *INTEGRAL* data can be equally well represented by a Compton reflection model (PEXRAV) with $R = 1$ and photon index $\Gamma = 1.8$ and no high-energy cut-off.

NGC 1275 presents a very complex spectrum in *INTEGRAL* data as it includes several components of different physical origin. While the hard X-ray spectrum visible in the IBIS/ISGRI data is dominated by the narrow-line radio galaxy NGC 1275 and its spectrum above 20 keV can be represented by a simple power law model, we observe in JEM-X the Perseus galaxy cluster. An extensive discussion of the *INTEGRAL* spectrum has been presented in Eckert & Paltani (2009).

NGC 4051: this Seyfert 1.5 shows a strong reflection component when fit together with soft X-rays, e.g. $R \approx 7$ for *Suzaku* (Terashima et al. 2009), and $R \approx 6$ for combined *Swift*/XRT and IBIS/ISGRI data (Beckmann et al. 2009), while the data presented here allow only to fit a single power law model with $\Gamma = 2.1 \pm 0.2$. When fitting the *Suzaku* data with a simple power law model, Terashima et al. (2009) derive a photon index of $\Gamma = 1.5^{+0.3}_{-0.2}$ for a low flux state, indicating strong flux and spectral variability.

NGC 4151: this bright AGN allows complex modelling beyond the scope of this paper, and we refer to an early *INTEGRAL* analysis by Beckmann et al. (2005), to an analysis of *BeppoSAX* data by de Rosa et al. (2007), and to a study of the different spectral states by Lubiński et al. (2009).

NGC 4388: the hard X-ray data of this Seyfert 2 galaxy have been studied by Beckmann et al. (2004). Their analysis of *INTEGRAL*, *XMM-Newton*, *BeppoSAX*, *CGRO*, and *SIGMA* data showed that the hard X-rays spectrum is well described by an absorbed power law with $\Gamma = 1.65 \pm 0.04$ and $N_H = 2.7 \times 10^{23} \text{ cm}^{-2}$, with no indication of a cut-off or reflection component. The data presented here now show evidence for a cut-off at 80 keV and $\Gamma = 1.3$. Recently, a turn over at $E_C = 30 \pm 13$ keV with $\Gamma = 0.9 \pm 0.3$ was also reported in *Suzaku* data of NGC 4388 (Shirai et al. 2008), detecting also significant spectral variability.

NGC 4507: this Seyfert 2 shows a reflection component of the order of $R = 0.5 - 1$ in *BeppoSAX* observations and a photon index of $\Gamma = 1.3 - 1.9$, while the cut-off energy was not constrained (Dadina 2007). The IBIS/ISGRI data do not require the presence of reflection, and a simple cut-off power law ($\Gamma = 1.1 \pm 0.2$, $E_C = 65^{+27}_{-12}$ keV) is sufficient ($\chi^2 = 3.5$ for 7 d.o.f.). Applying the PEXRAV model without cut-off, we obtained a chi-squared of $\chi^2 = 6.2$ for 7 d.o.f. The value of the photon index and the reflection obtained are $\Gamma = 1.7 \pm 0.1$ and $R = 0.6^{+1.5}_{-0.5}$, respectively, consistent with the *BeppoSAX* observations.

NGC 4593: *BeppoSAX* data of this Seyfert 1 showed a reflection component with $R = 1.1^{+2.6}_{-0.5}$ and $\Gamma = 1.9 \pm 0.1$ but no evidence for a cut-off (Dadina 2007). From IBIS/ISGRI and JEM-X data we found that a power law with a cut-off gives a

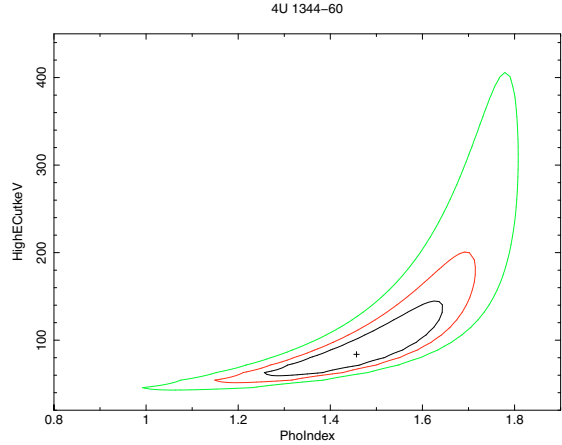


Fig. A.1. Contour plot of the 1–3 sigma confidence levels of cut-off energy [keV] versus photon index Γ . A steeper spectral fit requires a higher cut-off energy.

good fit to the data ($\Gamma = 1.5 \pm 0.1$, $E_C = 193^{+12}_{-93}$ keV, $\chi^2 = 15$ for 15 d.o.f.). The value of the absorption has been fixed to $N_H = 2 \times 10^{20} \text{ cm}^{-2}$. Applying a PEXRAV model with no cut-off also provides a good representation of the data with $\chi^2 = 10.7$ for 15 d.o.f. and gives a photon index of $\Gamma = 1.9 \pm 0.1$ and a reflection component of $R = 1.7^{+1.6}_{-0.8}$, both parameters consistent with the results by Dadina et al. (2007).

NGC 4945: the IBIS/ISGRI spectrum of the Seyfert 2 galaxy NGC 4945 (with an exposure of 276 ks) is amongst the six analyzed by Soldi et al. (2005). In their work the best model to the data is a simple power law ($\Gamma = 1.9^{+0.1}_{-0.1}$), and they give a lower limit to the possible high energy cut-off, $E_C \gg 130$ keV. Using the new IBIS/ISGRI and JEM-X data we found that a simple absorbed power law does not provide a good fit ($\chi^2 = 30$ for 12 d.o.f.) and a cutoff at high energy is necessary. This component improves significantly the goodness of the fit ($\chi^2 = 3.3$ for 11 d.o.f.) and gives a photon index of $\Gamma = 1.4^{+0.2}_{-0.2}$ and a cutoff at $E_C = 121^{+63}_{-34}$ keV. The absorption has been fixed to $N_H = 400 \times 10^{22} \text{ cm}^{-2}$. These values are also consistent with those obtained by Guainazzi et al. (2000), using *BeppoSAX* data.

Cen A is the only extragalactic object also seen by IBIS/PICsIT. Combined IBIS/ISGRI, SPI, and PICsIT data analysis gave a spectral slope of $\Gamma = 1.80 \pm 0.01$ (Lubiński 2009), close to the results presented here. It has been also detected by *Fermi*/LAT (Abdo et al. 2009) and at very high energy gamma-rays by HESS (Aharonian et al. 2009).

4U 1344-60: in Beckmann et al. (2006) the analysis of combined *XMM-Newton* and *INTEGRAL* data showed a good representation of the broad-band data with an absorbed power-law ($\Gamma = 1.65$) plus a Gaussian component. Applying the same simple model to the IBIS/ISGRI data used here, leads to a steep hard X-ray power law ($\Gamma = 1.9 \pm 0.1$) but gives a bad fit result ($\chi^2_\nu > 2$). Using the simultaneous JEM-X and ISGRI data and adding a cut-off, flattens the spectrum: the lower the cut-off energy, the flatter the resulting photon index ($\Gamma = 1.5^{+0.1}_{-0.2}$, $E_C = 86^{+31}_{-22}$), as can be seen in Fig. A.1. Panessa et al. (2008) analysed again non-simultaneous *XMM-Newton* and *INTEGRAL* data, finding a cut-off power law with photon index $\Gamma = 1.75^{+0.18}_{-0.14}$ and $E_C > 78$ keV. Fixing the spectral slope for the combined JEM-X and IBIS/ISGRI spectrum to $\Gamma = 1.75$, we also get a higher cut-off energy of $E_C = 214^{+73}_{-44}$ keV.

IC 4329A: the *BeppoSAX* spectrum of this Seyfert 1 analysed by Dadina (2007) by applying a PEXRAV model showed in several observations a cut-off at energies $E_C > 120$ keV, with a reflection component of $R = 0.5$ – 1.5 and a photon index of $\Gamma = 1.9$ – 2.0 . Using the same model for the combined JEM-X and ISGRI data, we get a flatter spectrum, with $\Gamma = 1.6 \pm 0.3$, $E_C = 124^{+243}_{-48}$ keV and $R = 0.3^{+0.8}_{-0.3}$, and thus a spectrum which is consistent with no reflection component. We therefore applied the simpler cut-off power law model which leads to $\Gamma = 1.4 \pm 0.1$ and $E_C = 86^{+18}_{-13}$ keV.

Circinus Galaxy: the combined IBIS/ISGRI and SPI spectrum of the Circinus galaxy has been studied by Soldi et al. (2005) based on 589 ks exposure time, finding as the best model to the data an absorbed power law ($\Gamma = 1.8^{+0.4}_{-0.5}$) with $N_H = 400 \times 10^{22}$ cm⁻² and a high-energy cutoff at $E_C = 50^{+51}_{-18}$ keV, values consistent with the ones obtained by previous *BeppoSAX* observations. Using the same model and fixing the hydrogen column density to the one used by Soldi et al. (2005), we found the best fit to the data ($\chi^2 = 16$ for 11 d.o.f.), with parameters consistent with the values listed above ($\Gamma = 1.2 \pm 0.2$, $E_C = 30 \pm 3$ keV). Dadina (2007) analysed two *BeppoSAX* observations applying reflection models with $\Gamma_1 = 1.7 \pm 0.1$, $R_1 = 0.29^{+0.05}_{-0.09}$ and $\Gamma_2 = 1.3 \pm 0.2$, $R_2 = 0.35^{+0.39}_{-0.09}$, both with cut-off at $E_C \lesssim 50$ keV. Adding a reflection component to the data presented here improves significantly the fit ($\chi^2 = 6.1$ for 9 d.o.f.) but the parameter are not well constrained: $\Gamma = 1.8^{+0.4}_{-0.6}$, $E_C = 76^{+180}_{-30}$ keV and $R = 1.6^{+8.0}_{-1.1}$.

PG 1416-129: the Seyfert 1 galaxy had been included in the first *INTEGRAL* AGN catalogue (Beckmann et al. 2006a). Subsequent analysis of the data with improved software showed that the detection of this source was indeed spurious, and we now do not consider this source to be an *INTEGRAL* detected object.

IGR J16351-5806: this Seyfert 2 galaxy has recently been claimed to be a Compton thick AGN with $N_H > 1.5 \times 10^{24}$ cm⁻² (Malizia et al. 2009). This is based on the observation that the hard X-ray spectrum is rather flat, as also shown here with $\Gamma = 1.5$, and that a strong iron $K\alpha$ line with $EW > 1$ keV is an indicator for a significant reflection component. Malizia et al. fit the spectrum therefore as a pure reflection spectrum. As the ISGRI data alone do not allow fitting the complex model, we assumed the simple model of an unabsorbed power law, as also observed in *Swift*/XRT data (Landi et al. 2007a).

IGR J16426+6536: this narrow-line Seyfert 1 ($z = 0.323 \pm 0.001$, Parisi et al. 2008; Butler et al. 2009) shows a rather high luminosity of $L_{(20-100 \text{ keV})} = 2 \times 10^{46}$ erg s⁻¹ but moderate mass of the central black hole ($M = 1.1 \times 10^7 M_\odot$). This leads to a large Eddington ratio of about $\lambda \simeq 90$ (defined in Sect. 4.2). It has to be pointed out though, that the soft X-ray counterpart as detected by *XMM-Newton* exhibits only a flux of 1.1×10^{-12} erg cm⁻² s⁻¹ (Ibarra et al. 2008), about 10 times below what would be expected from the *INTEGRAL* detection with $f_{(20-40 \text{ keV})} = 2.6 \times 10^{-11}$ erg cm⁻² s⁻¹. This might indicate that this source is strongly absorbed, highly variable, or that the optical counterpart is a misidentification, leading to the high super-Eddington accretion rate.

GRS 1734-292: the IBIS/ISGRI data of GRS 1734-292 (for a total exposure of 4040 ks) have been analyzed by Molina et al. (2006), along with *ASCA*/GIS data, who found that the best fit is obtained using an absorbed cut-off power law. Using the new IBIS/ISGRI and JEM-X data we found that the best model ($\chi^2 = 12.1$ for 11 d.o.f.) is an absorbed power-law with a cut-off and a reflection component with the following parameters: $N_H = 3.7 \times 10^{22}$ cm⁻², $E_C = 220^{+200}_{-150}$ keV, $\Gamma = 2.0^{+0.3}_{-0.4}$ and

$R = 2.7^{+3.1}_{-1.8}$. The black hole mass of GRS 1734-292 has been provided by I. Papadakis (private communication) based on the empirical relation found by Tremaine et al. (2002) between the black hole mass and the stellar velocity dispersion σ_* , estimating σ_* from the width of the [O III] line reported by Marti et al. (1998).

IGR J17488-3253: for this Seyfert 1 galaxy ($z = 0.02$) a fit of simultaneous JEM-X and IBIS/ISGRI data by a cut-off power law model results in $\chi^2_\nu = 5.8$ for 11 degrees of freedom. As the source is located in a dense area, it is possible that the JEM-X data are contaminated by sources within the field of view, especially as the JEM-X data are well represented by a black body model with a temperature of 0.7 keV. We therefore analysed *Swift*/XRT data of the source. A combined fit of XRT and ISGRI data results in $\chi^2_\nu = 1.1$ for 119 degrees of freedom, showing an absorbed power law model with $N_H = 0.72 \pm 0.04$ and $\Gamma = 1.63 \pm 0.03$, representing the data well over the 0.3 keV to 100 keV energy range.

QSO B1957+405 (Cyg A): the IBIS/ISGRI (together with *BeppoSAX*/MECS and PDS) spectrum of Cygnus A has been analyzed by Molina et al. (2006), using data for a total exposure of 426 ks. In their work they fitted the high-energy spectrum with a complex model in order to take into account also the gas emission of the galaxy cluster to which the AGN belongs. For doing so they used an absorbed power law plus a bremsstrahlung component. Following their work we fitted the IBIS/ISGRI and JEM-X spectrum using the same model (plus a cross-calibration constant) and we found that it provides the best fit ($\chi^2 = 6$ for 9 d.o.f.) and that the parameters obtained ($\Gamma = 1.9^{+0.1}_{-0.2}$ and $kT = 4.5^{+3.7}_{-2.7}$ keV) are in good agreement with those they obtained. The value of the absorption has been fixed to $N_H = 2 \times 10^{23}$ cm⁻².

IGR J21247+5058: the high-energy broad-band spectrum of this radio galaxy was obtained by Molina et al. (2007) by combining *XMM-Newton* and *Swift*/XRT observation with IBIS/ISGRI data. The 0.4–100 keV spectrum is well described by a power law, with slope $\Gamma = 1.5$, characterized by complex absorption due to two layers of material partially covering the source and a high-energy cut-off around 70–80 keV, consistent with our findings ($\Gamma = 1.4 \pm 0.1$, $E_C = 61^{+22}_{-11}$ keV) using JEM-X and ISGRI data. As Molina et al. point out, features such as a narrow iron line and a Compton reflection component, if present, are weak, suggesting that reprocessing of the power-law photons in the accretion disc plays a negligible role in the source.

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X-ray spectra of AGN

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With the advent of the latest generation of X-ray telescopes *XMM-Newton*, *Chandra* and *Suzaku* the X-ray spectra of AGN have been found to be more complex than it was originally believed. One of the most important features which have been observed in the last years are complex multi-phase warm absorbers (see Sect. 5.1.1), which, together with other outflows (Sect. 5.1.2), are believed to play an important role in the AGN-host galaxy feedback (Sect. 5.1). The physical mechanism driving these outflows is still unknown, and in Sect. 5.1.3 we will review the most important possibilities. The other striking features which have been observed in the last years are rapidly varying neutral absorbers (Sect. 5.2), a significant curvature around the iron $K\alpha$ line (Sect. 5.3), and extremely strong reflection components (Sect. 5.5). Moreover, even a well known feature as the soft excess has been shown to be very difficult to fully understand (Sect. 5.4). Although several different models have been proposed to explain all these characteristics (see Sect. 5.6), so far a clear consensus on which one represents the real physical situation has not been reached. Here we will first review the most important features of the X-ray spectra of AGN which have been found in the last ten years of study, and then we will introduce our work on the X-ray spectroscopical study of three hard X-ray selected objects which show peculiar characteristics (Sect. 5.7).

5.1 The AGN-host galaxy feedback

While it was well known that radio-loud AGN affect their galactic environment through the collimated emission of their jets (Sect. 1.2.6), it was ignored until the beginning of this century that a strong connection between the SMBH and the host galaxy existed also in radio-quiet objects. The discovery that SMBHs reside in almost every galaxy (Magorrian et al. 1998), together with that of a well defined correlation between the mass of the SMBH and the host galaxy bulge stellar velocity dispersion (the

$M_{\text{BH}} - \sigma_*$ relation, Ferrarese & Merritt 2000) led to think that every galaxy might have gone through an AGN-phase while building up its SMBH, and that the SMBH and its host galaxy might co-evolve, which implies that there might be some important feedback mechanism that connects them.

The feedback between the AGN and its host galaxy can be produced in two ways: through the injection in the galaxy of mechanical energy or by radiation pressure. One way to produce the mechanical feedback is through jets; however, these jets are relatively rare, and their highly collimated nature cannot produce an efficient transfer of energy over large solid angles (although they are very important in clusters of galaxies). Another possible way to produce mechanical feedback is through AGN winds and outflows, and it has been proposed (Di Matteo et al. 2005) that this kind of feedback might play an important role in creating the $M_{\text{BH}} - \sigma_*$ relation. Outflows in AGN are rather common, for instance absorption lines in the UV are found to be blue-shifted by about $10^{3-5} \text{ km s}^{-1}$ in $\sim 50\%$ of AGN (Crenshaw et al. 2003b, see Sect. 5.1.2) and similar percentage is found for X-ray ionized absorbers (Sect. 5.1.1).

In the following I will introduce some of the characteristics of AGN outflows, focusing in particular on their importance for a complete understanding of all the features observed in the X-ray spectra of AGN.

5.1.1 Warm absorbers

The first evidence for the presence of ionized absorbing gas in type-I AGN was obtained from *Einstein* observations of variations in the absorber of MR 2251-178 (Halpern 1984). Further evidence was gathered by *Ginga*, which found that about 50% of the Seyfert 1s observed showed absorption edges from ionized species of Fe (XXIV-XXVI), indicating that a significant amount ($N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$) of very highly ionized material exists in these nuclei (Nandra & Pounds 1994). An absorption feature at 0.8 keV, due to highly ionized oxygen was detected from *ROSAT* observations of MCG-6-30-15 (Nandra & Pounds 1992). This feature was also found to show variations that indicated changes in the absorbing gas and in its opacity (τ varying from 0.57 to 1.17) on timescales of few weeks (e.g., Fabian et al. 1994). Observations of other bright Seyfert 1s performed by *ROSAT* found strong individual features that allowed to isolate distinct zones of ionized gas (e.g., Nandra et al. 1993, Turner et al. 1993). Most of the detected features were interpreted to be a blend of O VII (739.3 eV) and O VIII (871.4 eV) bound-free edges. Deep *ASCA* observations of Seyfert 1s showed important spectral variability related to variations of the warm absorbers. Considering the fact that while the depth of the O VIII edge in MCG-6-30-15 was anti-correlated with the flux of the continuum, and that of the O VII edge was not, Otani et al. (1996) concluded that the gas might be composed of at least two different zones of gas, one of which having a significant recombination time. Studies of a large number of objects observed by *BeppoSAX* and *ASCA* showed that about 60% of Seyfert 1 galaxies show soft X-ray features which are consistent with ionized gas having column densities of $N_{\text{H}} \sim 10^{21} - 10^{23} \text{ cm}^{-2}$ and ionization parameters of $\xi \sim 10 - 50 \text{ erg cm s}^{-1}$ (e.g., George et al. 1998).

A great leap forward in the understanding of warm absorbers has been made in the last ten years thanks to the high spectral resolution observations of Seyfert 1s performed by *XMM-Newton* and *Chandra*. These observations have shown the existence of very complex outflowing structures, made of several phases of gas, with different column densities ($\log N_{\text{H}} \sim 20 - 23$) and ionization states ($\log \xi \sim 0 - 4$), with sometimes also cool and dusty zones (e.g., Lee et al. 2001). In NGC 3783 for example (Fig. 5.1), the ionized gas was found to have $\log \xi \simeq 3$ and $N_{\text{H}} \simeq 5 \times 10^{22} \text{ cm}^{-2}$, and possibly located at $\sim 0.1 \text{ pc}$ from the X-ray source (Kaspi et al. 2002). The velocities of these outflows have been found to span between hundreds to thousands of km s^{-1} in most cases (e.g., Kaspi et al. 2002, McKernan et al. 2007, Blustin et al. 2007). Several AGN were also found to have warm absorbers

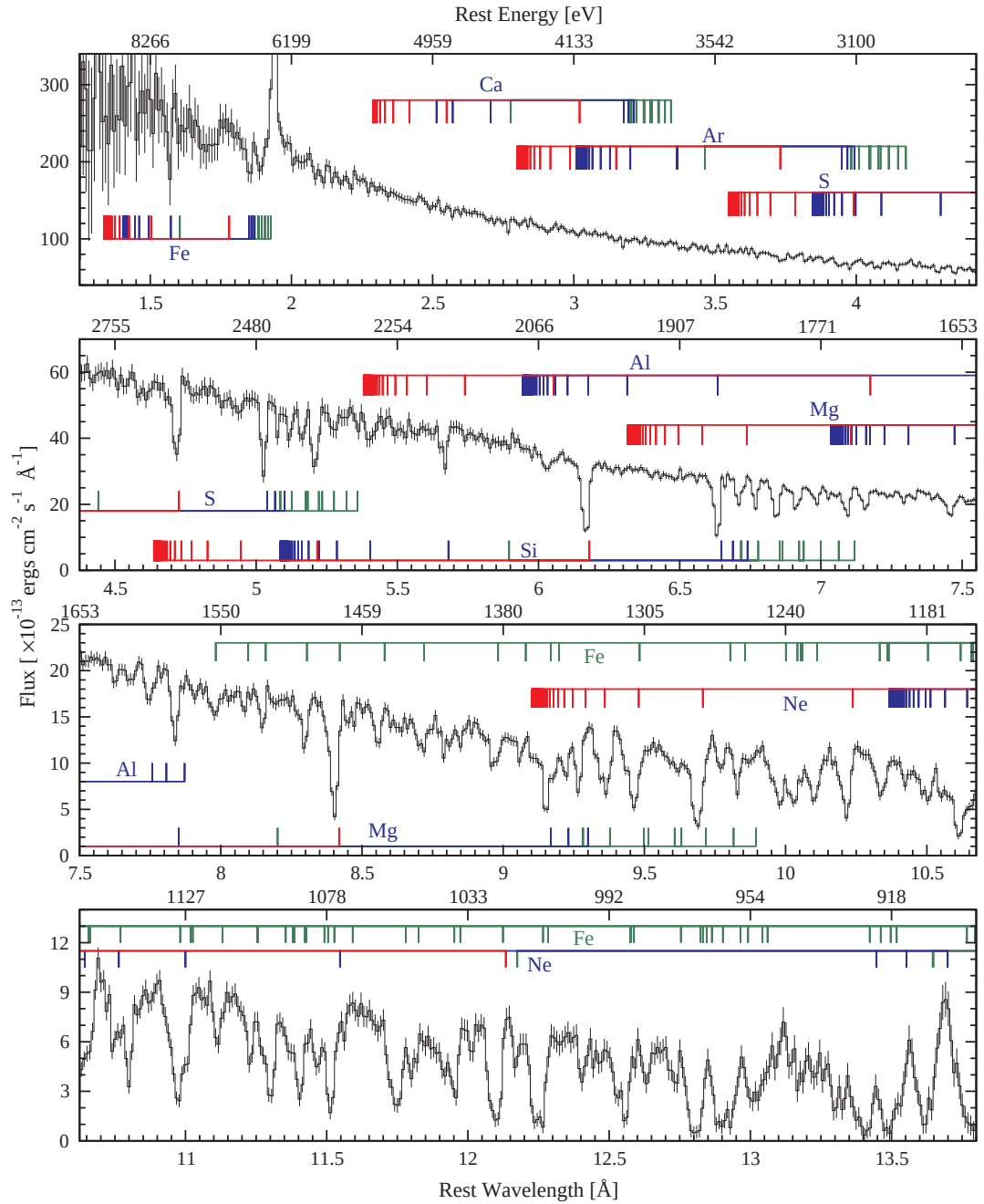


Figure 5.1: Very deep (900 ks) *Chandra* observation of NGC 3783. Figure reproduced by [Turner & Miller \(2009\)](#), originally from [Kaspi et al. \(2002\)](#). The H-like and He-like lines of the identified ions are marked in red and blue, respectively. Lines from other ions (such as lower ionization metals and Fe XVII, Fe XXIV) are marked in green.

covering only a part of the X-ray source. An example is given by NGC 3516 (Turner et al. 2005), for which the absorber has $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$, $\log \xi \sim 2$ and covers about 50% of the continuum source. In Fig. 5.2 the marks of a warm absorber with different values of the ionization parameter on the X-ray continuum of an AGN are shown.

Possibly, one of the main findings of *XMM-Newton* and *Chandra* was the detection of extremely highly ionized ($\log \xi \gtrsim 3 - 4$) spectral absorption lines in the iron K band, blue-shifted to velocities of $\sim 0.1 - 0.3 c$ (e.g., Pounds et al. 2003, Reeves et al. 2008). In a recent work, Tombesi et al. (2010) found possible evidence of these ultra-fast outflows in $\sim 40\%$ of AGN of their sample. However, the existence of these features has been questioned by several papers (e.g., Vaughan & Uttley 2008, Kaspi 2010, Gallo & Fabian 2011), and high resolution spectrometers, as the one that will be on board *ASTRO-H* (Takahashi et al. 2010) will be fundamental to assess their existence.

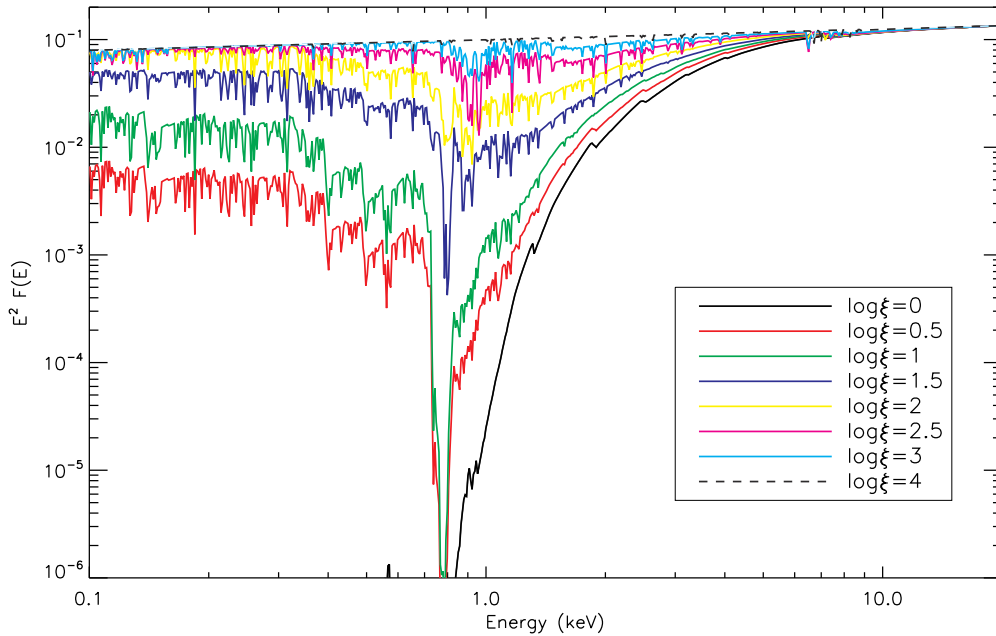


Figure 5.2: Effect of absorption from ionized material on the X-ray spectra of AGN (here assumed to be a power-law with $\Gamma = 1.9$) for different values of the ionization parameter ξ .

5.1.2 BAL QSOs

Broad Absorption Line Quasars (BAL QSOs, e.g., [Weymann et al. 1991](#)) represent $\sim 10\%$ of the optically selected quasars, and were the first objects to be found to have strong nuclear outflows ([Lynds 1967](#)). Their main characteristic is the presence of broad ($\text{FWHM} \gtrsim 2000 \text{ km s}^{-1}$) blueshifted ($\sim 10^3 \text{ km s}^{-1}$) UV absorption lines due to resonant transitions of ionized metals (e.g., Mg II, Al III, Si IV, C IV, NV and O VI). BAL QSOs are also characterized by a strong Fe II and a weak [O III] emission ([Weymann et al. 1991](#)), and by their high degree of polarization ([Moore & Stockman 1984](#)). BAL QSOs are divided in three main classes (see also Fig. 5.3).

- High Ionization BAL QSOs (HiBALs) are the most common BAL QSOs, and show deep absorption features due to resonant transitions of highly ionized elements.
- Low Ionization BAL QSOs (LoBALs) show features due to resonant transitions of both highly and lowly ionized elements.
- FeLoBALs are the rarest BAL QSOs and besides showing features due to highly and lowly ionized elements, also show broad absorption lines due to lowly ionized iron.

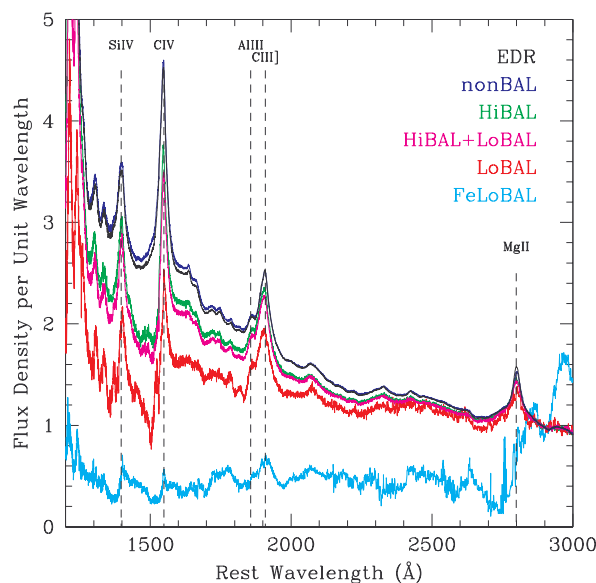


Figure 5.3: Composite SDSS spectra of the different classes of BAL quasars ([Reichard et al. 2003](#)). The image also shows the average QSO spectrum from the SDSS Early Data Release (EDR).

Other absorbers, narrower than the BALs, but characterized by the same resonant transitions, can be found. These are the mini-Broad Absorption Line Quasars (mini-BAL QSOs), with FWHM in the $500 - 2000 \text{ km s}^{-1}$ range, and the Narrow Absorption Line Quasars (NAL QSOs), for which $\text{FWHM} < 500 \text{ km s}^{-1}$.

The fact that only a fraction of QSOs show BALs can be due either to the small covering fraction of the outflowing gas ([Turnshek 1984](#)), or to an intrinsic property of AGN, possibly related to a different evolutionary phase (e.g., [Fabian 1999](#)).

BAL QSOs are known to be quite weak X-ray sources, and in the pre-*Chandra*/*XMM-Newton* era were studied little. Some of the first insights came from [Green et al. \(2001\)](#), who, stacking the

X-ray spectra of ten objects found evidence for a column density of $N_{\text{H}} \sim 7 \times 10^{22} \text{ cm}^{-2}$ of gas, and an underlying continuum well described by a power-law with a photon index of $\Gamma \sim 1.8$. Further studies showed that the X-ray spectra can be well represented by a partially covering absorber (e.g., [Gallagher et al. 2002](#)), in agreement with the hypothesis that the outflows cover only a part of the system. Studies of the absorption lines allowed to constrain outflowing velocities up to $\sim 0.3 c$ (e.g., [Chartas et al. 2003](#)).

5.1.3 Outflow mechanisms

The physical link between the UV and the X-ray absorbers is still not completely understood, as it is still not known what are the physical mechanism driving these outflows. So far, three possible mechanisms have been proposed to be able to produce disk winds (see also [Proga 2007](#) for a recent review).

- **Thermal pressure.** The atmosphere of the accretion disk can be heated up by Compton scattering of X-ray photons produced in the hot corona. The thermal pressure resulting from this process might be able to eject material from the disk if the thermal velocity v_T is larger than the local escape velocity v_e . This is more likely to happen at large distance ($\sim \text{pc}$ scales) from the SMBH, where v_e is smaller. The maximum velocity these winds can attain is $\sim 1000 \text{ km s}^{-1}$, and this mechanism could successfully explain the characteristics of low velocities warm absorbers and UV NALs (e.g., [Chelouche & Netzer 2005](#))
- **Radiation pressure.** When the accretion luminosity of an AGN overcomes the Eddington limit ($L > L_{\text{Edd}}$), the radiation pressure wins over gravity, and matter is expected to be ejected from the disk. However, one must take into account that for the right ionization state, the opacity of the UV resonance spectral lines is much larger than that of the continuum ($\sigma_{\text{line}} \gg \sigma_{\text{T}}$). Thus, also at $L < L_{\text{Edd}}$ the radiation pressure might create winds, these outflows are normally called *line-driven*. Hydrodynamical simulations (e.g., [Proga & Kallman 2004](#)) have shown that this mechanism can launch gas at velocities up to few times $0.1 c$.
- **Magnetic pressure.** Magnetic effects are thought to play an important role in AGN. They could provide turbulence, and transport the angular momentum in the accretion disks through the magneto-rotational instability ([Balbus & Hawley 1991](#)), and might thus control the accretion. Magnetically driven winds can be present in all AGN, regardless of their luminosity, and are normally divided into two classes: magneto-centrifugal winds and magnetic pressure-driven winds. Detailed predictions for magnetically driven accretion disks do not exist yet, and they are normally invoked only when the other two mechanisms are found to be unsuccessful in explaining the characteristics of the outflows.

5.2 Clumpy neutral absorbers

The first suggestion of clumpy absorbers came from the soft-band complexity found in certain AGN by *Einstein* observations ([Wilkes & Elvis 1987](#)). Since then, variations in the absorbing column density of AGN have been found in a large number of objects, implying that the absorbing medium presents a certain degrees of clumpiness. While, as we have seen in Sect. 5.1.1, outflowing material can easily provide the partially covering obscuration in type-1 objects, in Seyfert 2s (but also in some Sy1s and NLS1s) this material is found to be neutral, and it has probably a very different origin.

Clumpy neutral absorbers can be modeled using the following relation (assuming that the clumps are smaller than the X-ray source):

$$M(E) = f e^{-N_{\text{H}} \sigma(E)} + (1 - f)$$

where f is the covering fraction, i.e. the fraction of the X-ray source covered by the absorber. The soft X-ray spectra of about 55% of the 153 *Swift*/BAT hard X-ray selected AGN studied by [Winter et al. \(2009\)](#) can be well modeled using a power-law seen through a partially covering absorber.

Neutral absorption in AGN can have several different possible origins. The putative torus is certainly one of the most suitable candidates to account for the absorbing material in the line of sight. At even larger distances from the central X-ray source, *Hubble Space Telescope* observations have shown that dust lanes can be found in all types of Seyfert galaxies ([Malkan et al. 1998](#)). These dust lanes are thought to contribute significantly ($N_{\text{H}} < 10^{23} \text{ cm}^{-2}$) to the overall absorption ([Matt 2000](#)). Another possible source of obscuration are the BLR clouds, which are thought to live relatively close to the SMBH.

Looking for possible variations of the absorbing column density in 25 Seyfert 2s, on timescales ranging from months to years, [Risaliti et al. \(2002\)](#) found a significant variation of N_{H} (from 20% to 80%) in $\sim 90\%$ of the objects. The short time scales found being incompatible with the dusty torus, [Risaliti et al. \(2002\)](#) proposed the clumpy absorbers to be located on the pc-scale, and to be related to the BLR. Since then several more objects presenting significative variations of the column density have been found. The most famous of these is surely NGC 1365, a Seyfert 1.9 that shows extremely large variations of N_{H} , up to few times 10^{24} cm^{-2} , in a time-span of less than few days. Other "changing look" AGN, which have been observed passing from a Compton-thin to a reflection dominated state (or the other way round), are UGC 4203 ([Guainazzi et al. 2002](#)), NGC 6300 ([Guainazzi 2002](#)), NGC 2992 ([Gilli et al. 2000](#)), NGC 7674 ([Bianchi et al. 2005](#)), and NGC 7582 ([Piconcelli et al. 2007](#)).

Variations in the column density of the order of $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$ have been found in several other Seyfert 2s (NGC 4388 [Elvis et al. 2004](#), NGC 7582 [Bianchi et al. 2009](#), UGC 4203 [Risaliti et al. 2010](#)) in some Seyfert 1/1.5s (NGC 4151 [Puccetti et al. 2007](#), MCG-6-30-15, and NGC 3227 [Risaliti 2010](#)) and in the NLS1 Mrk 766 ([Risaliti et al. 2011](#)) (Fig. 5.4). The variations of N_{H} and their timescales are listed in Table 5.1. Observations of NGC 1365 showed that the absorbers present parameters that might be expected from the BLR clouds ([Risaliti et al. 2005, 2007, 2009b; Maiolino et al. 2010](#)). They have been shown to have a high velocity ($v > 10^3 \text{ km s}^{-1}$), to be located at $\sim 10^4 r_{\text{G}}$, to have a size of $\sim 10^{13} \text{ cm}$ and a density of $10^{10-11} \text{ cm}^{-3}$. Further studies have proposed that these clouds might have a cometary shape ([Maiolino et al. 2010](#)), with a CT high density core and a ionized tail ([Risaliti et al. 2011](#)).

Another possible source of clumpy neutral obscuration is the putative molecular torus. If the X-ray source is in fact observed nearly edge on, some continuum might still be able to leak out. Moreover, several theoretical studies predict the torus to be clumpy ([Krolik & Begelman 1988; Rowan-Robinson 1995; Nenkova et al. 2008a,b](#)), and this has been found to be in agreement with IR observations of AGN (e.g., [Elitzur & Shlosman 2006, Mor et al. 2009](#)). We will discuss in detail the possible structure of the torus in Chapter 8.

Another possible way to explain sources passing from a Compton-thin state to a reflection dominated one (or the contrary) is that the continuum source switches off (or on) ([Matt et al. 2003](#)). The "echo" of the continuum reflected from the distant torus would mimic the situation in which a CT clump is obscuring the X-ray source. In the case of NGC 2992 multiple observations suggest an intrinsic fading of the X-ray source rather than an eclipse of CT material ([Gilli et al. 2000](#)).

Table 5.1: Some of the recent identifications of varying neutral absorption in nearby AGN. Table adapted from Risaliti (2010).

Source	$\Delta N_{\text{H}} (\text{cm}^{-2})$	ΔT	Reference
NGC 1365	$> 10^{24}$	< 2 days	Maiolino et al. (2010)
NGC 1365	3×10^{23}	10 hours	Risaliti et al. (2009b)
NGC 4388	2×10^{23}	15 hours	Elvis et al. (2004)
NGC 4151	2×10^{23}	20 hours	Puccetti et al. (2007)
NGC 4151	10^{23}	< 2 days	Risaliti (2010)
NGC 7582	10^{23}	20 hours	Bianchi et al. (2009)
Mrk 766	3×10^{23}	10 to 20 hours	Risaliti et al. (2011)
MCG-6-30-15	10^{23}	10 hours	Risaliti (2010)
UGC 4203	3×10^{23}	< 15 days	Risaliti et al. (2010)
NGC 3227	7×10^{22}	1 day	Risaliti (2010)

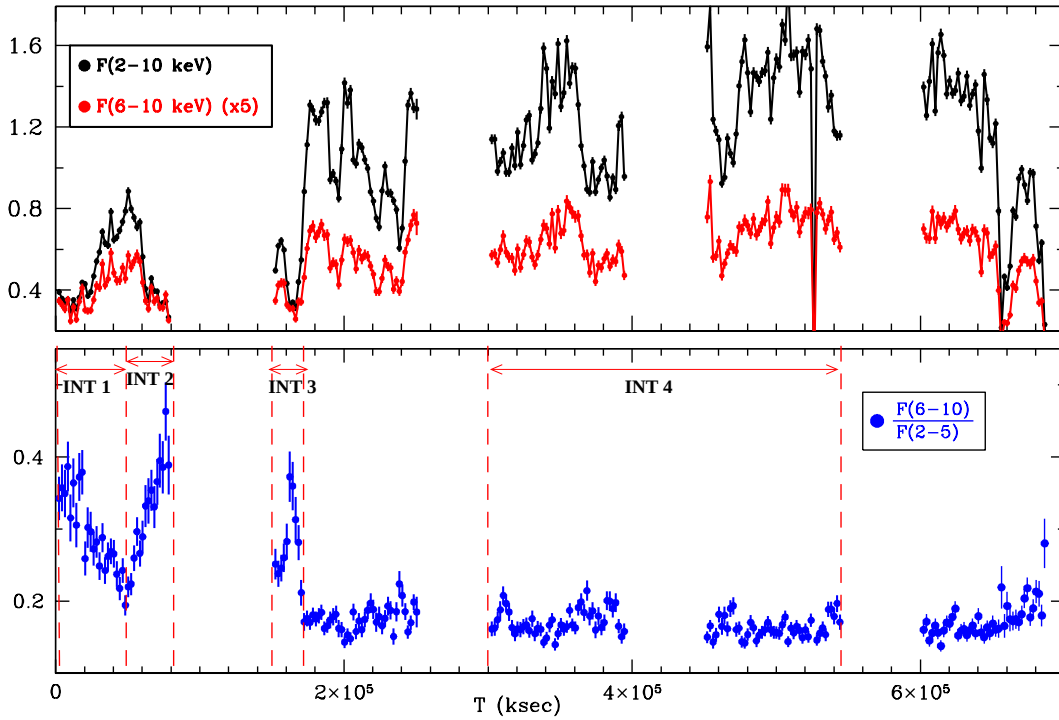


Figure 5.4: Flux (*top panel*) and hardness ratio $\text{HR} = F(6-10 \text{ keV})/F(2-5 \text{ keV})$ (*bottom panel*) of the 9-day long *XMM-Newton* observation of Mrk 766 (Risaliti et al. 2011).

5.3 The red wing of the iron $K\alpha$ line

The nature of the spectral curvature often seen in the 2–8 keV energy band (i.e., the red wing of the Fe $K\alpha$ line) has been the subject of a large number of studies (e.g., Wilms et al. 2001, see Fig. 5.5). So far two different possible explanations have been put forward: complex absorption or blurred reflection (e.g., Turner & Miller 2009; Miniutti et al. 2007).

As we saw in Sect. 2.3, the first studies on broad iron $K\alpha$ lines (e.g., Tanaka et al. 1995) concluded that this feature was probably produced by reflection from the inner parts of the accretion disk, namely very close to the event horizon. This conclusion has been questioned by several works, which have argued that complex absorption from ionized gas might also reproduce at least part of the observed broad lines (e.g., Inoue & Matsumoto 2003; Turner et al. 2008; Turner & Miller 2009), and be the responsible for the observed variability (e.g., Miller et al. 2010). For example, in NGC 3783 (Fig. 5.1) the high ionization ($\log \xi \sim 3$) gas, likely located close to the X-ray source (~ 0.1 pc), has been shown to be the responsible of a large part of the curvature, reducing the requirement for a relativistically-blurred disk-line.

Using principal component analysis (PCA), Vaughan & Fabian (2004) showed that MCG-6-30-15 can be described by a constant hard component (which includes the red wing) and a variable softer one. This behavior is not consistent with the idea that the structure at ~ 6 keV arises from reprocessing of the primary continuum. This has been explained by means of *light bending* occurring very close to the SMBH (Martocchia & Matt 1996, Reynolds & Begelman 1997, Miniutti & Fabian 2004), which disconnects the variations in the continuum from those of the reflected component. In this model, if the source continuum emission changes location at small distance from the SMBH, even if the continuum has a constant intrinsic luminosity, an observer would register a change in brightness. This is due to the gravitational bending, which deviates most of the radiation down onto the disc. This might lead to a decrease in the intensity of the primary continuum, with the reflection component not varying significantly. Recently, Zoghbi et al. (2010) found evidence of a lag of ~ 30 s between the flux in the 1–4 keV and that in the 0.3–1 keV in 1H 0707-495, with the hard component leading the soft one (i.e. the reflected one), as expected from reverberation. Re-analyzing the variability of the same source, Miller et al. (2010) found the lags being consistent with reverberation caused by scattering of X-rays passing through a partially covering absorbing medium with an opacity that decreases with the increasing energy.

5.4 The soft excess

More than 30 years after its discovery, the origin of the soft excess remains still unclear. While it has been shown (see Sect. 2.4) that it cannot be simply explained by the high-energy tail of the accretion disk emission, different alternative solutions have been found to present contradictory results.

The consistency of the soft excess feature over a large range of M_{BH} led to think that it might originate in some atomic process, which would be unaffected by the characteristics of the continuum. Studying the soft excess of a large sample of PG quasars, Gierliński & Done (2004) argued that strong spectral features in a partially ionized medium, such as O VII, O VIII and the Fe M-shell unresolved transition array in the 0.7 keV regime could play a role in the observed soft excess. In their model, the general smoothness of the soft excess would be due to the relativistic blurring of the absorption features in an outflowing wind (similar to those discussed in Sect. 5.1.1). The observed rms spectra have also been shown to be consistent with the expectations of an X-ray continuum absorbed by a rapidly outflowing plasma (Gierliński & Done 2006). However, theoretical works (Schurch & Done 2007, 2008) have demonstrated that extremely high velocities ($\sim 0.9c$) are needed for the absorption to be able to reproduce by itself the observed soft excesses. These velocities cannot be attained by line-driven winds (Schurch et al. 2009), and magnetic driving is the only acceleration mechanism that might produce them.

In the framework of atomic processes, another possible explanation to the origin of the soft excess is ionized reflection. In this scenario the emission lines would be smeared down by relativistic

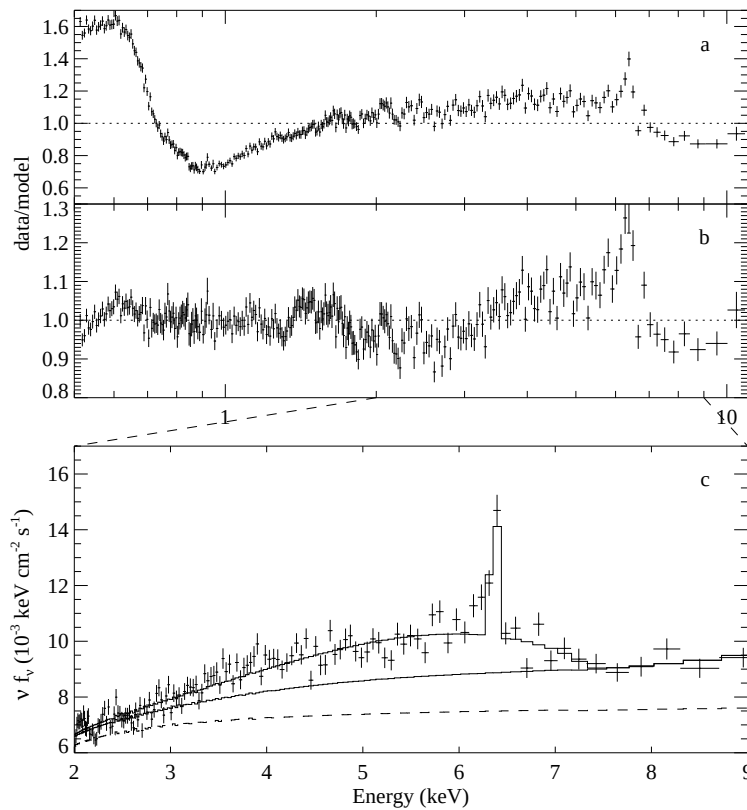


Figure 5.5: The *XMM-Newton*/EPIC spectrum of MCG-6-30-15 (Wilms et al. 2001). The panel *a* represents the ratio between the data and a power-law model, the panel *b* the ratio once the warm absorbers have been included in the model, and the panel *c* shows the deconvolved spectrum around the iron $K\alpha$ line, showing the model and the continuum including and not including (dashed line) reflection from an ionized disc.

blurring occurring very close to the SMBH. Using the same sample of PG quasars of Gierliński & Done (2004), Crummy et al. (2006) showed that blurred reflection can well model the observed soft excesses. Moreover the parameters required for the relativistic smearing can be the same of those used to reproduce the broad $K\alpha$ iron lines (always in the ionized reflection framework, e.g., Fabian et al. 2005). However, these parameters are in most cases quite extreme, needing maximally rotating SMBHs and extremely steep emissivities (see Fig. 5.6), which means that most of the emission is produced very close to the event horizon. An alternative explanation is that the disc is fragmented into inhomogeneous regions, which hide a direct view of the intrinsic source (e.g., Fabian et al. 2002).

Another possible explanation to the soft excess is that it is due to the Comptonization of the UV photons from the disk in a cooler (the rollover at 0.6 keV implies $kT_e \sim 0.2$ keV) and optically thicker ($\tau \sim 20$) corona. The problem with this scenario is that it cannot simply explain the lack of variation of the amplitude of the soft excess for different values of M_{BH} . However, several works have showed that, at least in some cases, a second Comptonizing plasma might be necessary to explain the soft excess (e.g. Dewangan et al. 2007, Middleton et al. 2009). In particular the recent work of Mehdipour et al. (2011), part of a multi-wavelength campaign on Mrk 509, showed a clear correlation between the flux in the optical/UV band and that in the soft X-rays ($E \lesssim 1$ keV), strongly suggesting a Comptonization origin for the soft excess.

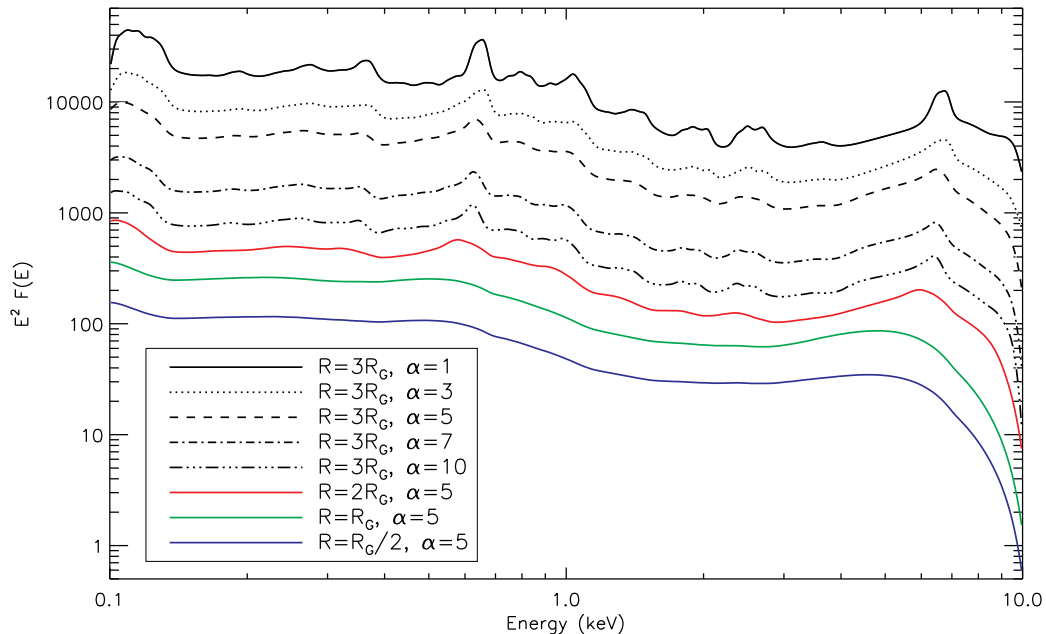


Figure 5.6: Blurred reflection for different values of the inner radius R and of the index of the emissivity profile α . In the model used the photon index and the ionization parameter were set to $\Gamma = 2$ and $\xi = 300 \text{ erg cm s}^{-1}$, respectively.

A possible new explanation to the origin of the soft excess in objects accreting at high Eddington luminosities (such as the NLS1s) has been recently proposed by [Done et al. \(2011\)](#). They argue that in high accreting objects the radiation might thermalize only at large distances from the SMBH, and thus the relationship $T_{\text{max}}^4 \propto (L/L_{\text{Edd}})/M$ does not hold close to the center of the accretion disk. This implies that higher temperatures can be reached, with the disk emission contributing to the X-ray emission below 1 keV. They also propose that this disk emission is then Comptonized in the disk itself, leading to the observed soft-excess.

5.5 The hard excess

The advent of *Suzaku* has allowed for the first time to study very high signal-to-noise broad band (0.5–80 keV) X-ray spectra. This kind of observations are fundamental to constrain the reflection hump, and to well characterize the continuum emission. One of the main findings of *Suzaku* has been the discovery of a *hard excess* above the power-law continuum (see Fig. 5.7), which requires values of the reflection parameter R exceeding the unity, i.e. the value expected from reflection from a disk subtending 2π steradians to the continuum source. Different explanations have been proposed to account for this effect.

The *Suzaku* broad band X-ray spectrum of MGC-6-30-15 has been found to yield $2 \lesssim R \lesssim 4.8$, and [Ballantyne et al. \(2003\)](#) proposed a model in which there are two reflectors, both associated with a (warped) accretion disk, one very close to the X-ray source, and the other one at $\sim 70 r_{\text{G}}$. A similar model consisting of two reflectors has been invoked also to explain the hard excess ($R \sim 2.8$) observed in Mrk 335 ([Larsson et al. 2008](#)). A different model, involving light bending, has instead

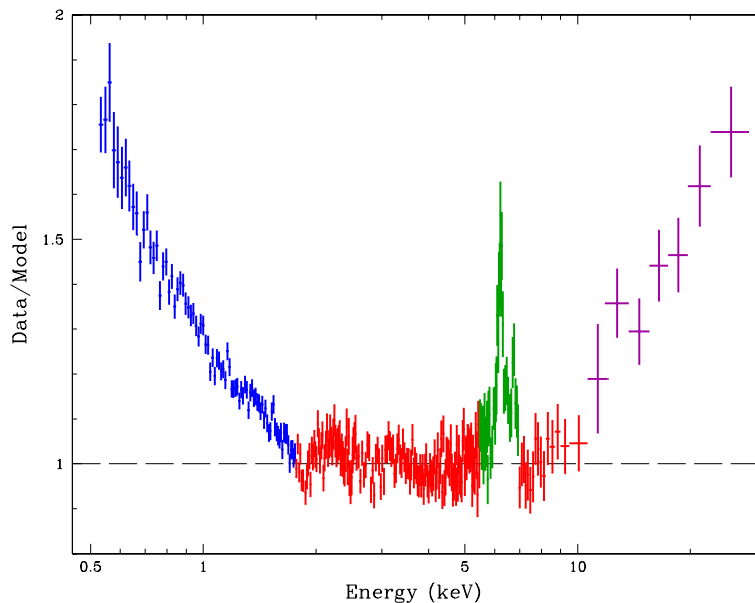


Figure 5.7: The hard (and soft) excess in the *Suzaku* broad-band X-ray spectrum of Ark 120 (Nardini et al. 2011).

been put forward by Miniutti et al. (2007) to explain the X-ray spectrum of MGC-6-30-15. One of the effects of light bending is in fact to remove the correlation between the reflection component and the continuum, thus allowing the reflection parameter to have very high values. In this framework the value of R loses its connection to the geometry. In MGC-6-30-15 the hard excess appears to be consistent with having a joint origin with the red wing, being less variable than the 2–10 keV flux. A reflection scenario has been invoked also to explain the hard X-ray spectrum of the Seyfert 1 Ark 120 (Nardini et al. 2011).

In NGC 4051, Terashima et al. (2009) found $R \sim 7$ and weak iron $K\alpha$ emission, which cannot be explained by light bending. This led the authors to propose the presence of a CT partial covering, which would suppress part of the continuum, leading to an (apparently) enhanced reflection component. A similar explanation, involving a CT absorber covering different fractions of the continuum source has been proposed to explain the hard excesses of 1H 0419 – 577 (Turner et al. 2009), of NGC 1365 (Risaliti et al. 2009a), and of the luminous quasar PDS 456 (Reeves et al. 2009).

In a recent paper, Walton et al. (2010) have discussed the results obtained in the framework of the partial-covering scenario in NGC 1365, PDS 456 and 1H 0419 – 577. They have concluded that, although the presence of partially covering CT material cannot be ruled out, all the spectra can be well represented by models based on blurred reflection.

5.6 Reflection and Absorption models

As discussed in the previous sections both reflection and absorption models are able to explain most of the features observed in the high resolution X-ray observations performed so far by *Chandra*, *XMM-Newton* and *Suzaku*.

Both absorption and reflection probably play an important role in shaping the X-ray spectra of AGN. High resolution UV spectroscopy has shown that multi-layered complex absorbers are fairly common in AGN, and X-ray observations have also found evidence of outflows in many AGN. However,

explaining the soft excess with absorption is problematic because extremely high velocity of the outflowing ionized gas required. The problem of explaining the red wing of the iron $K\alpha$ line with the absorption is the likelihood of partial covering. To cover only a fraction of the X-ray source the absorbers must have a similar size, and if they are located far away from the source there is some implied coincidence between the source and absorber sizes. A possible explanation (Turner & Miller 2009) is that the absorbers are a part of a clumpy disk wind (or of the BLR), and they cover a wide range of scale sizes.

Blurred ionized reflection from the accretion disk is also expected to be observed in the X-ray spectra of AGN. However, the parameters needed to explain the observed features, in particular both soft and hard excess, are quite extreme. A very steep emissivity profile and maximally rotating SMBH are often required to obtain models consistent with the data. Another problem of this model is the lack of lags between different energy band, contrarily to what one would expect in a reflection-dominated scenario. The possible detection of a broad iron L line (Fabian et al. 2009b) and of continuum-driven lags in the spectrum of 1H 0707–495 (Zoghbi et al. 2010) is clearly in favor of reflection models, although the veracity of these results have been put in discussion by the work of Miller et al. (2010).

The high spectral resolution and broad band coverage of the future X-ray mission *Astro-H* will probably shed light on the problem, and clearly discern between the two models.

5.7 A soft X-ray study of three peculiar sources from the Second *INTEGRAL* catalog

Many of the hard X-ray selected sources studied in the second *INTEGRAL* AGN catalog did not have published results on their value of the absorbing column density, which led us to analyze the X-ray spectra of about 30 objects using *Swift*/XRT and *XMM-Newton* data. Amongst the sources studied, three presented complex X-ray spectra which cannot be well explained by a simple model. These objects are a good example of the spectral complexity found in AGN in the last ten years thanks to the new generation of X-ray satellites, and are the Seyfert 1s UGC 3142 and ESO 140-43, and the Seyfert 2 ESO 383-18.

In the case of UGC 3142 and ESO 383-18 we found that the spectra are quite flat ($\Gamma \simeq 1$) and show a an apparent soft excess below ~ 2 keV when fitting with a simple power-law model. The 0.3–150 keV spectra can be well modeled using a two partially covering neutral absorbers, with covering fractions of $f_1 \simeq 0.92$ and $f_2 \simeq 0.57$ for UGC 3142, and of $f_1 \simeq 0.97$ and $f_2 \simeq 0.86$ for ESO 383-18. We looked for traces of variability on short or long time-scales and did not find any.

For ESO 140-43 we found that three partially covering ionized absorbers are necessary to well fit the X-ray emission. These three warm absorbers have values of the ionization parameter, of the column density and of the covering fraction very different from each other. ESO 140-43 was observed twice by *XMM-Newton* in a time span of six months. Between these two observations the source varied strongly both in flux (of a factor ~ 3 in the 2–10 keV, and of ~ 17 in the 0.1–2.4 keV band) and in spectral shape. From archival *ROSAT* and *EXOSAT* observations we confirmed the existence of large flux variations on the time-scale of years. We found that the spectral changes can be explained by the variation of the parameters of the absorbers, while the power-law continuum has a photon index of $\Gamma \sim 1.9$ in both observations. This allowed us to conclude that the warm absorber is part of a clumpy wind, similar to those introduced in Sect. 5.1.1.

The results of this work are presented in Ricci et al. (2010).

Multi-zone warm and cold clumpy absorbers in three Seyfert galaxies

C. Ricci^{1,2}, V. Beckmann³, M. Audard^{1,2}, and T. J.-L. Courvoisier^{1,2}

¹ ISDC Data Centre for Astrophysics, University of Geneva, ch. d'Ecogia 16, 1290 Versoix, Switzerland
 e-mail: Claudio.Ricci@unige.ch

² Geneva Observatory, University of Geneva, ch. des Maillettes 51, 1290 Versoix, Switzerland

³ APC, François Arago Centre, Université Paris Diderot, CNRS/IN2P3, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex, France

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ABSTRACT

Aims. We present the first detailed X-ray analysis of three active galactic nuclei, the Seyfert 1 galaxies UGC 3142 and ESO 140-43, and the Seyfert 2 galaxy ESO 383-18, to study the geometry and the physical characteristics of their absorbers.

Methods. High-quality *XMM-Newton* EPIC and RGS data were analyzed as well as Swift/XRT and BAT and INTEGRAL IBIS/ISGRI data to cover the 0.3–110 keV energy range. For ESO 140-43 also *XMM-Newton*/OM and Swift/UVOT data were used. We studied the variability of the three AGN on a time-scale of seconds using the EPIC/PN light curves, and the long-term time-scale variability of ESO 140-43 using two observations performed six months apart by *XMM-Newton*.

Results. The spectra of the three Seyfert galaxies present a “soft excess” at energies $E < 2$ keV above a power law continuum that can be modeled by complex absorption, without any additional emission component. The X-ray sources in UGC 3142 and ESO 383-18 are absorbed by two layers of neutral material, with covering fractions $f_1 \approx 0.92$ and $f_2 \approx 0.57$ for UGC 3142, and $f_1 \approx 0.97$ and $f_2 \approx 0.86$ for ESO 383-18. While the clumpy absorber could be part of a disk wind or of the broad line region for UGC 3142, for ESO 383-18 a clumpy torus plus Compton thin dust lanes are more likely. The spectra of ESO 140-43 can be well fitted with a power law absorbed by three clumpy ionized absorbers with different covering factors, column densities, and ionization parameters, likely part of a moving clumpy system, which could be a disk wind or the broad line region. The strong spectral and flux variability on a time-scale of six months seen in ESO 140-43 is likely due to changes in the moving absorbers. We were able to detect the variation of the covering factor of one of the three ionized absorbers on a kilo-seconds time-scale in the EPIC light-curve of ESO 140-43.

Key words. galaxies: general – X-rays: galaxies – X-rays: general – galaxies: active – galaxies: Seyfert

1. Introduction

Active galactic nuclei (AGN) are thought to be powered by accretion onto super massive black holes. In this picture the X-ray emission is produced by UV photons from the innermost edge of the accretion disk, which undergo multiple inverse Compton scatterings by a population of hot electrons located in a coronal region sandwiching the disk (Haardt & Maraschi 1991, 1993). The spectrum in the X-rays can be well approximated by a power law with an exponential cut-off at energy $E_C \approx kT_e$, where T_e is the temperature of the electrons. Besides the power law-like continuum, two prominent features generated by the reflection of the continuum are observed in the X-ray spectra of AGN: a neutral iron $K\alpha$ line (at 6.4 keV in the local reference frame) and a reflection hump which peaks at $E \approx 30$ keV (Magdziarz & Zdziarski 1995). Not all these components are clearly observed in all AGN (e.g., Soldi et al. 2005; Beckmann et al. 2004).

An alternative model for the accretion process onto black holes is that of clumpy accretion flows (e.g., Guilbert & Rees 1988). Courvoisier & Türler (2005) assume that the different elements (clumps) of the accretion flow have velocities that may differ substantially. As a consequence, collisions between these clumps will appear when the clumps are close to the central object, resulting in emission (Ishibashi & Courvoisier 2009).

At optical energies, AGN are classified according to their emission lines into type 1 (with broad and narrow emission lines), and type 2 (with only narrow lines). A similar distinction between the two types can be done in the X-rays. Here, type 2 objects show absorption which suppresses the soft X-ray spectrum. The dividing line between unabsorbed and absorbed AGN is often set at a hydrogen column density of $N_H = 10^{22} \text{ cm}^{-2}$. X-ray data show that most AGN unabsorbed in X-ray are optical Seyfert 1 type, and most, but not all, AGN that are absorbed belong to the Seyfert 2 group (e.g., Awaki et al. 1991). Antonucci (1993) proposed that the extinguishing region forms a torus around the central region. The presence of an absorbing torus guarantees anisotropic obscuration of the central region, so that the sources viewed face-on are type 1, and those observed edge-on are type 2 (for which, although it is highly extinguished, the broad line region exists). AGN spectra are mainly affected by absorption at energies $\lesssim 2$ keV, with the effect depending on whether the absorber is cold (neutral or weakly ionized), or warm (highly ionized). The geometry of the absorber also plays a major role. When it does not completely cover the source (partially covering absorber), some continuum leaks out and reaches the observer, resulting in an apparent excess over the continuum at higher energies. The *Einstein* satellite provided the first evidence that the absorbing gas can cover only a fraction of the line of sight towards the AGN (Reichert et al. 1985; Holt et al. 1980).

Table 1. Positions (J2000), redshift and Galactic hydrogen column densities (from Dickey & Lockman 1990) of the three sources analyzed in this work.

Object	Type	RA	Dec	z	Galactic N_{H} [10^{21} cm^{-2}]
UGC 3142	Seyfert 1	04 ^h 43 ^m 46.8 ^s	+28°58′19″	0.0217	1.9
ESO 383-18	Seyfert 2	13 ^h 33 ^m 26.3 ^s	−34°00′59″	0.0124	0.42
ESO 140-43	Seyfert 1	18 ^h 44 ^m 54.0 ^s	−62°21′53″	0.0141	0.73

The partial covering scenario can also explain some of the observed X-ray variability, which could be due to rearrangements of the cloud distribution (e.g., Abrassart & Czerny 2000).

The first evidence of absorption due to warm material came from studies of the *Einstein* X-ray spectrum of the QSO MR 2251-178 (Halpern 1984; Pan et al. 1990), and from AGN spectra taken with *ROSAT* (Turner et al. 1993). Since then, highly ionized absorbers have been observed in about half of the X-ray spectra of type 1 AGN, both Seyfert 1 (e.g., Reynolds 1997; George et al. 1998) and quasars (Piconcelli et al. 2005), with column densities up to $\geq 10^{23} \text{ cm}^{-2}$, and often consisting of several zones of ionized gas (e.g., Nandra et al. 1993; Pounds et al. 1994; Kaspi et al. 2002; Steenbrugge et al. 2005). For NGC 3783, Netzer et al. (2003) and Krongold et al. (2003) discussed the observed complexity in the context of several phases of absorbing gas with distinct temperatures and ionization states. Evidence of a multi-phase warm absorber was also recently reported by Longinotti et al. (2010). The observed absorption lines are often blue-shifted with respect to the optical emission lines, which implies that they are produced in an outflowing region, with mean velocities covering the range from hundreds to thousands of km s^{-1} (Kaspi et al. 2002; Krongold et al. 2003; Blustin et al. 2005; McKernan et al. 2007; Blustin et al. 2007). Analyzing NGC 3516, Turner et al. (2005) discovered a high column absorber with a hydrogen column density of $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$ and a ionization parameter of $\log \xi \sim 2$, covering about 50% of the continuum source. Changes in the covering fraction of the absorber could explain the spectral variability observed in this source (Turner et al. 2008). A complete review of the recent developments of absorption models can be found in Turner & Miller (2009).

A soft ($E \lesssim 2 \text{ keV}$) excess over the power law component dominant at higher energies has been found in the X-ray spectra of many Seyfert galaxies (Saxton et al. 1993). The origin of the soft excess is still an open issue. In the past the soft excess was often associated with the high-energy tail of the thermal emission of the disk, but it recently has been shown that the temperature of the disk should be constant (0.1–0.2 keV), regardless of the mass and luminosity of the AGN (Gierlinski & Done 2004). This result implies that some other mechanism is at work, as the temperature of the disk should depend on both the mass of the black hole and the accretion rate. Three competing models have been brought forward to explain the soft X-ray excess: i) an additional Comptonization component (e.g., Dewangan et al. 2007); ii) ionized reflection (e.g. from the disk, e.g. Crummy et al. 2006); iii) complex and/or ionized absorption (e.g., Gierlinski & Done 2004). Chevallier et al. (2006) examined these three main possibilities and showed that although the absorption model can successfully fit the data of several AGN, for many AGN the quality of the data does not allow a firm conclusion. Nevertheless, they favor a reflection model absorbed by a modest relativistic wind. Done & Nayakshin (2007) agree that the excess is most probably due to partially ionized material moving at relativistic speeds close to the black hole. The two potential scenarios for

this effect would be an accretion disk seen in reflection or a wind above the disk, seen in absorption. They show that the reflection model would require very specific ionization parameters, contrary to the disk wind model. Schurch & Done (2008) pointed out that although the absorption model with partially ionized material can be physically interpreted as a radiatively driven accretion disk wind, these winds would require velocities of $\sim 0.9c$ to reproduce the soft X-ray excess. They conclude that if the soft excess is produced by absorption, it seems more likely that the material is clumpy and/or only partially covers the source rather than forming a continuous outflow.

The three AGN discussed here are part of the *INTEGRAL* AGN catalog (Beckmann et al. 2009). Because at the time of the catalog’s compilation no absorption information was available for a number of sources, unpublished *XMM-Newton* and *Swift*/XRT data were used to constrain N_{H} . The three Seyfert galaxies UGC 3142, ESO 140-43, and ESO 383-18 are the sources which showed particularly strong evidence for excess in the soft X-ray spectra, which requires more complex modeling of the absorption.

The nearby Seyfert 1 UGC 3142 was first detected in X-ray by *ROSAT* (Boller et al. 1992), and in hard X-ray by *INTEGRAL* (Bassani et al. 2006). The Seyfert 2 ESO 383-18 was detected in hard X-ray by *INTEGRAL* (Krivonos et al. 2007). The Seyfert 1 ESO 140-43, also known as Fairall 51, was detected for the first time in the X-rays by *HEAO A-2* (Marshall et al. 1979), and subsequently by *ROSAT* (Boller et al. 1992). At hard X-rays ESO 140-43 was detected by *INTEGRAL* IBIS/ISGRI (Beckmann et al. 2007). Information on the three sources are reported in Table 1. We present here the first detailed X-ray spectral analysis of these three Seyfert AGN using *XMM-Newton*, *Swift* and *INTEGRAL* data. The data analysis is described in Sect. 2. In Sect. 3 we discuss the spectral modeling of the X-ray spectra, and we present the study of the X-ray and optical/UV variability in Sect. 4. In Sect. 5 we discuss the obtained results, and we present the conclusions in Sect. 6.

2. Data analysis

The journal of the observations is shown in Table 2.

2.1. *XMM-Newton* EPIC, RGS and OM

The Seyfert 1 UGC 3142 was observed by the European Photon Imaging Camera (EPIC) on board the *XMM-Newton* space observatory (Jansen et al. 2001) in March 2007. The EPIC observation was performed with the PN camera (Struder et al. 2001) and the MOS (1 and 2) cameras (Turner et al. 2001), all of them operating in prime full window mode, and all equipped with the “medium” blocking filter.

The Seyfert 2 ESO 383-18 was observed by *XMM-Newton* in October 2006 with the three EPIC cameras operating in Prime Full Window mode. The PN and MOS 1 cameras were used with

Table 2. X-ray observation log.

Object	Mission	Instrument	Start time [UT]	End time [UT]	Exposure [ks]	Observation ID
UGC 3142	<i>INTEGRAL</i>	IBIS/ISGRI	February 2003	October 2008	485	–
	<i>XMM-Newton</i>	EPIC/PN	2007-03-18 21:28:29	2007-03-19 00:15:51	8.5	0401790101
	<i>XMM-Newton</i>	EPIC/MOS	2007-03-18 21:06:10	2007-03-19 00:19:51	11.6	0401790101
	<i>XMM-Newton</i>	RGS	2007-03-18 21:05:31	2007-03-19 00:23:59	11.9	0401790101
ESO 383-18	<i>INTEGRAL</i>	IBIS/ISGRI	March 2003	August 2007	260	–
	<i>XMM-Newton</i>	EPIC/PN	2006-01-10 02:49:18	2006-01-10 06:50:06	14.5	0307000901
	<i>XMM-Newton</i>	EPIC/MOS	2006-01-10 02:26:59	2006-01-10 06:55:28	16.1	0307000901
	<i>XMM-Newton</i>	RGS	2006-01-10 02:26:21	2006-01-10 06:54:50	16.1	0307000901
ESO 140-43	<i>INTEGRAL</i>	IBIS/ISGRI	2007-10-29	2007-04-11	379	–
	<i>XMM-Newton</i>	EPIC/PN	2005-09-08 03:09:46	2005-09-08 10:07:29	22.5	0300240401
	<i>XMM-Newton</i>	EPIC/MOS	2005-09-08 02:47:28	2005-09-08 05:30:11	9.8	0300240401
	<i>XMM-Newton</i>	RGS	2005-09-08 02:46:44	2005-09-08 10:15:22	26.9	0300240401
	<i>XMM-Newton</i>	EPIC/PN	2006-03-07 12:36:40	2006-03-07 18:19:46	18	0300240901
	<i>XMM-Newton</i>	EPIC/MOS	2006-03-07 12:14:22	2006-03-07 18:23:52	17.6	0300240901
	<i>XMM-Newton</i>	RGS	2006-03-07 12:13:44	2006-03-07 18:27:15	22.4	0300240901
	<i>Swift</i>	XRT	2008-05-20 12:42:01	2008-05-20 14:25:13	6.2	00037809001
	<i>Swift</i>	XRT	2008-05-25 11:33:00	2008-05-25 12:26:20	3.2	00037809002

Table 3. Background and source radii used for the extraction of *XMM-Newton*/EPIC spectra.

Object	Instrument	Source	Background	Instrument	Source	Background
UGC 3142	EPIC/PN	34.5''	48.1''	EPIC/MOS	32.2''	62''
ESO 383-18	EPIC/PN	37''	43.6''	EPIC/MOS	24.2''	47.8''
ESO 140-43 ¹	EPIC/PN	36.7''	52.9''	EPIC/MOS	37.5''	66''
ESO 140-43 ²	EPIC/PN	34''	61.7''	EPIC/MOS	26.5''	50''

Notes. The index 1 refers to the 2005 observation of ESO 140-43, index 2 to the 2006 observation.

the “thin” blocking filter, while MOS 2 was using the “medium” filter.

The Seyfert 1 ESO 140-43 was observed twice by *XMM-Newton*. The first observation was performed in September 2005 (henceforth 2005-observation), while the second observation was carried out in March 2006 (henceforth 2006-observation). In both observations the three EPIC cameras were equipped with the “medium” blocking filter and operated in prime full mode.

We checked the background light curve in the 10–12 keV energy band for PN and above 10 keV for MOS in order to detect and filter the exposures for periods of high background activity. The recommended thresholds for the background count rate are 0.35 ct/s and 0.4 ct/s for the MOS and PN camera, respectively. For UGC 3142 only the PN is strongly affected, and the exposure is reduced from 10 ks to 8.5 ks. In the case of ESO 383-18 this does not change anything in the good time intervals (GTI), as the background count rates of the observations are well below the recommended thresholds. Particular care has to be taken in the case of ESO 140-43, because the EPIC detectors experienced a strong flux of high-energy particles during the observations. During the 2005-observation this flux was between 0.4 and 2.2 ct/s for the PN, while it was much below the recommended threshold for MOS. The contribution of the background to the spectrum of the 2005-observation is weak ($\ll 1\%$) over the range considered in the analysis (0.3–10 keV), thus we filtered only events with a background count rate higher than 1 ct/s, which reduces the GTI to 22.5 ks, excluding the last 2.5 ks of the observation. The 2006-observation presented a stronger flux of high-energy particles, with a maximum flux of 5 ct/s for PN and of 1.5 ct/s for MOS. In this observation the contribution of

the background is not strong either ($\approx 8\%$), and we set the background count rate threshold at 4 and 0.8 ct/s for the PN and MOS, respectively. This reduces the exposure time to 18 ks for the PN, and to 17.6 ks for the two MOS cameras.

We checked for pile-up with the *epatplot* task and found it to be negligible in all observations. For the analysis of EPIC data we used the *XMM-Newton* Standard Analysis Software (SAS) version 8.0.0, which also generates the ancillary response matrices (ARFs) and the detector response matrices (RMFs), through the tasks *arfgen* and *rmfgen*. We used the *epchain* and *emchain* tasks for processing the raw PN and MOS data files, respectively. We selected only patterns corresponding to single, double, triple, and quadruple events for EPIC/MOS ($\text{PATTERN} \leq 12$), while for EPIC/PN we considered only single and double events ($\text{PATTERN} \leq 4$). The source spectra were extracted from the final filtered event list using circular regions centered on the sources, while the background was estimated from regions close to the source (on the same CCD), where no source was present. The same regions were used to estimate the PN light curves of the sources, which were corrected for the influence of the background with the task *epicccorr*. The radii of these regions are listed in Table 3. The spectra obtained were grouped to have at least 20 counts per bin, in order to use χ^2 statistics.

The RGS spectra were extracted with the *rgsproc* task, and only the first-order spectra of the two RGS detectors were analyzed. The spectra were rebinned by a factor of 16.

In order to have information about the flux of the three sources in the optical and ultraviolet, we also analyzed the Optical/UV Monitor telescope (OM, Mason et al. 2001) data with the task *omichain*.

2.2. *Swift* XRT, BAT and UVOT

Two pointed *Swift* observations of ESO 140-43 were also analyzed. *Swift* (Gehrels et al. 2004) carries two narrow-field instruments, XRT (Burrows et al. 2005) with an energy range 0.3–10.0 keV and UVOT (Roming et al. 2005), which is equipped with six filters in the optical and UV range. The XRT and UVOT data were analyzed with HEADAS version 6.6.1, and applying the latest calibration files as available in January 2009. The analysis of XRT data was performed with the extraction of the source and the background spectra from the event lists using circular regions, in a similar way to what was done for the EPIC analysis. The ancillary response matrices were generated with the task *xrtmkarf*. The spectra were grouped to have at least 20 counts per bin.

The Seyfert galaxies ESO 140-43 and UGC 3142 were detected by *Swift*/BAT in the 22 month survey (Tueller et al. 2010) in the 14–195 keV band with a significance of 4.6σ and 4.9σ , respectively. The spectra used in this work are provided by the BAT team¹. The Seyfert 2 ESO 383-18 was detected with a significance of 8.6σ by BAT within the 39 month survey presented by Cusumano et al. (2010).

The UVOT analysis was performed creating a source and a background region file, and then using the task *uvotsource* to extract the flux values.

2.3. INTEGRAL IBIS/ISGRI

For the analysis of the IBIS/ISGRI spectra we used the observations for which the sources were at less than 10° from the instrument axis. Note that because of the nature of coded mask imaging the whole sky image taken by the instrument has to be considered in the analysis, because all sources in the field of view contribute to the background (Caroli et al. 1987). The exposures in Table 2 are the ISGRI effective on-source times. The analysis was performed using version 7.0 of the Offline Science Analysis (OSA) software distributed by the ISDC (Courvoisier et al. 2003). The analysis of the IBIS/ISGRI data is based on a cross-correlation procedure between the recorded image on the detector plane and a decoding array derived from the mask pattern. The ISGRI spectra were extracted with the standard method as described in Goldwurm et al. (2003): fluxes and count spectra are extracted at the source positions for each pointing in predefined energy bins. Spectra of the same source collected in different pointings are summed to obtain an averaged spectrum during the observation.

Because the full width at half maximum (FWHM) angular resolution of IBIS/ISGRI is 12 arcmin we investigated for possible contamination from sources close to the three AGN with *Simbad*² and *NED*³ and did not find any significant contamination.

3. X-ray spectral analysis

The spectra derived from *INTEGRAL*, *XMM-Newton* and *Swift* data were analyzed using XSPEC version 11.3.2 (Arnaud 1996). Throughout the paper we give symmetric and asymmetric errors which represent 1σ and 3σ confidence intervals, respectively.

¹ <http://swift.gsfc.nasa.gov/docs/swift/results/bs22mon/>

² <http://simbad.u-strasbg.fr/>

³ <http://nedwww.ipac.caltech.edu/>

The probabilities that additive parameters improve a fit are calculated with the F-test. The errors on the fluxes, luminosities and the equivalent widths were calculated at the 3σ level, with 1000 Monte Carlo simulations. We added a multiplicative factor to the models in all cases, to account for cross-calibration between the two EPIC detectors. We fixed the factor to 1 for EPIC/PN and left the factor for the two MOS detectors free to vary. The value of this factor turned out, as expected, to be close to 1 within a few percent (the differences in normalization of the two detectors should be below 5–10%)⁴.

The energy of the lines was calculated in the rest frame of the host galaxies, including in the model their redshifts.

3.1. UGC 3142

The 0.3–10 keV EPIC/PN and MOS spectrum of UGC 3142 cannot be well represented with a simple power law model absorbed by cold matter, resulting in $\chi^2 = 1488$ for 1028 degrees of freedom (d.o.f.). The absorbed power law gives a very flat photon index ($\Gamma \approx 0.9$) and results in a strong excess (Fig. 2) in soft X-ray ($E \lesssim 1$ keV). In order to account for the excess we tested several models, taking into account different emission processes. Considering a thermal origin of the excess, we added an accretion disk model consisting of multiple blackbody components (implemented as *diskbb* in XSPEC) to the power law. Such a model does not yield a good fit ($\chi^2 = 1225$ for 1026 d.o.f.), and the residuals still show a strong excess below 1 keV. We then modeled the excess with a second Comptonization region, using the *compTT* model of Titarchuk (1994). This second Comptonization region could be identified as a hot disk surface layer. Adding this model to the power law and considering absorption yields a good fit ($\chi^2 = 1035$ for 1024 d.o.f.), but with an unlikely very steep photon index of $\Gamma = 6.4^{+1.4}_{-1.9}$, and an overly strong Compton component. As an additional emission component cannot model the soft excess, we tested whether absorption could explain the observed excess. We used a multiplicative component for the absorption to account for a neutral absorber partially covering the X-ray source (implemented as *pcfabs* in XSPEC):

$$M(E) = f e^{-N_H \sigma(E)} + (1 - f), \quad (1)$$

where the parameter f is the covering fraction, which varies between 0 (absorber out of the line of sight) and 1 (absorber completely covering the source).

Using a power law model absorbed by Galactic cold matter plus a layer of partially absorbing neutral material significantly improved the results at the 99.9% confidence level ($\chi^2 = 1080$ for 1027 d.o.f.), and steepened the power law ($\Gamma = 1.13^{+0.04}_{-0.05}$). This power law is still quite flat, and the model does not connect with the hard X-ray spectrum obtained by *INTEGRAL* IBIS/ISGRI and *Swift*/BAT. Adding another layer of partially absorbing neutral material again the fit improved at the 99.9% confidence level ($\chi^2 = 1030$ for 1025 d.o.f.), and resulted in a photon index of $\Gamma = 1.4^{+0.1}_{-0.1}$. The two partially covering absorbers present different characteristics: one of them covers 92% of the X-ray emitting source and has a hydrogen column density of $N_H = 1.4^{+0.2}_{-0.2} \times 10^{22} \text{ cm}^{-2}$, while the other has a smaller covering factor ($\approx 57\%$) and a higher column density ($N_H = 5^{+1}_{-1} \times 10^{22} \text{ cm}^{-2}$).

Although the model fits the data well, an excess is still present around 6.4 keV. Adding a Gaussian line improves the

⁴ <http://xmm2.esac.esa.int/docs/documents/CAL-TN-0052-5-0.eps.gz>

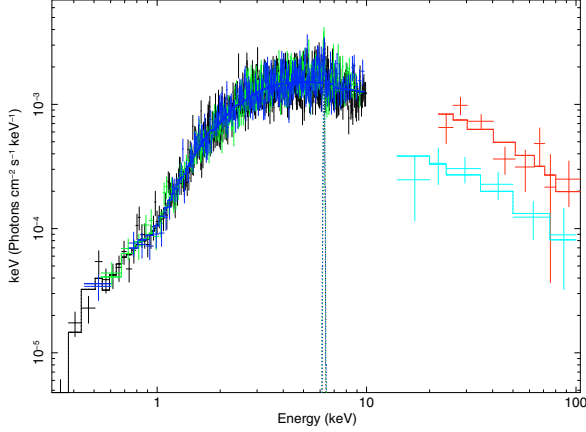


Fig. 1. 0.3–110 keV spectrum of UGC 3142 obtained using non simultaneous EPIC (in the 0.3–10 keV range), BAT (*lower flux*) and ISGRI (*higher flux*) data. The fit is a power law absorbed by cold Galactic matter and by two clumpy neutral absorbers, plus a Gaussian iron $K\alpha$ line (last row of Table 4).

fit at the 99.9% confidence level ($\chi^2 = 994$ for 1022 d.o.f.). The line is located at $6.38^{+0.03}_{-0.03}$ keV, and is therefore consistent with the iron $K\alpha$ line, and has a width of $\sigma = 41^{+32}_{-29}$ eV, and an equivalent width of $EW = 83^{+189}_{-60}$ eV. The X-ray spectra of AGN can show an additive broad line at 6.7 keV due to ionized iron (e.g., Matt et al. 2001). We investigated this feature adding another Gaussian line to our best model, and fixing the energy of the line at 6.7 keV, but this did not significantly improve the result ($\Delta\chi^2 \approx 0$).

The RGS spectrum of UGC 3142 has a very low signal to noise ratio, and was not analyzed.

In order to search for a cut-off or a reflection hump in hard X-ray, we combined the EPIC data with the *Swift*/BAT and *INTEGRAL* IBIS/ISGRI spectra. The 0.3–110 keV spectrum is well represented ($\chi^2 = 1011$ for 1034 d.o.f.) by the best model for the EPIC data alone, as presented above (power law absorbed by two layers of partially covering material). Adding a high-energy cut-off does not significantly improve the fit ($\chi^2 = 1008$ for 1033 d.o.f.). The high-energy cut-off is nevertheless constrained ($E_C = 63^{+118}_{-23}$ keV), but higher quality hard X-ray data will be necessary to verify it. As the observations were not simultaneous we added a cross-calibration constant to the model, which resulted to be $C_I = 1.4$ and $C_B = 0.5$, for ISGRI and BAT, respectively. We also tested the presence of a Compton reflection hump using the *pexrav* model in XSPEC, which implies the presence of reflection due to neutral material. We fixed the inclination angle at $i = 30^\circ$ (as a common assumption for type 1 AGN, see e.g. Matt et al. 2006; Decarli et al. 2008), and found that the data are consistent with such a feature, although the reflection normalization R and the cut-off energy E_C are not constrained, and have a strong degeneracy. The value of R in particular is consistent with no reflection ($R = 1^{+2}_{-1}$).

We can thus conclude that the best model for the 0.3–110 keV spectrum of UGC 3142 is a power law absorbed by two layers of partially covering material plus a Gaussian line. The results of the spectral analysis are reported in Table 4.

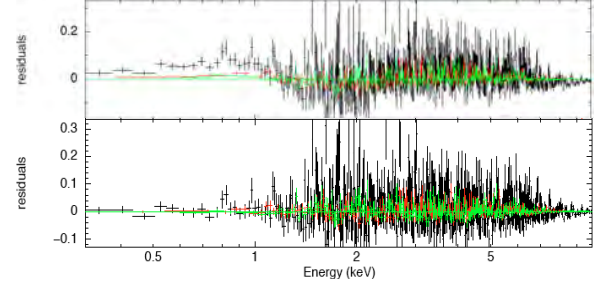


Fig. 2. UGC 3142 EPIC/PN (in black) and MOS residuals obtained with the simple power law model (*upper panel*) and the best (*lower panel*) model, respectively, as described in the first and third row of Table 4.

3.2. ESO 383-18

Applying a simple power law absorbed by cold matter into the EPIC spectrum (0.3–10 keV) of ESO 383-18 yields a poor fit ($\chi^2 = 1087$ for 432 d.o.f.), with a low photon index $\Gamma = 1.2 \pm 0.1$. As in the case of UGC 3142, the spectrum of ESO 383-18 presents an excess in the soft X-rays and one around 6.4 keV (Fig. 4), when a simple power law model is applied.

Adding to the power law continuum a thermal or a non-thermal component does not represent the emission at low energies ($\chi^2 = 930$ for 430 d.o.f. and $\chi^2 = 1051$ for 429 d.o.f., for the *diskbb* and *comptt* model, respectively). Applying a power law model absorbed by Galactic cold matter plus a layer of partially absorbing neutral material improves the results at the 99.9% confidence level ($\chi^2 = 533$ for 431 d.o.f.), and steepens the power law ($\Gamma = 1.47^{+0.03}_{-0.05}$). Adding another layer of partially absorbing neutral material again improves the result at the 99.9% confidence level ($\chi^2 = 504$ for 429 d.o.f.) and gives a photon index of $\Gamma = 1.8^{+0.1}_{-0.1}$. One of the absorbers almost completely covers the X-ray source ($f = 0.97^{+0.02}_{-0.04}$) and has a column density of $N_H = 10^{+1}_{-2} \times 10^{22} \text{ cm}^{-2}$, while the other one has $f = 0.86^{+0.05}_{-0.05}$ and a higher column density ($N_H = 20^{+2}_{-3} \times 10^{22} \text{ cm}^{-2}$). To this model we added a Gaussian line, which improves the fit again at the 99.9% confidence level ($\chi^2 = 485$ for 426 d.o.f.). This line is consistent with the iron $K\alpha$ line ($E = 6.3^{+0.1}_{-0.1}$ keV) and has a width of $\sigma = 23^{+100}_{-32}$ eV, and an equivalent width of $EW = 76^{+93}_{-66}$ eV. As for UGC 3142, adding another Gaussian component at 6.7 keV to the neutral iron line does not significantly improve the fit ($\Delta\chi^2 \approx 0$). Although the two absorbers have values of column density and covering fraction within the 3σ range of each other, the second absorber has been proven to be statistically required.

This model still displays an excess between 0.6–0.7 keV in both PN and MOS data. This excess could be due to the OVIII Ly α emission line (at 0.65 keV in the rest frame of the source). Implementing this feature in the model as a Gaussian line ($E = 0.62^{+0.02}_{-0.02}$ keV) improves the result at the 99% confidence level ($\chi^2 = 461$ for 423 d.o.f.), but the data are not sufficient to significantly constrain the equivalent width of the line: $EW = 144^{+200}_{-137}$ eV.

Due to its very low signal-to-noise ratio the RGS spectrum of ESO 383-18 was not analyzed.

The Seyfert galaxy ESO 383-18 was not detected within the 22-months BAT survey, and the *INTEGRAL* IBIS/ISGRI spectrum of ESO 383-18 in the 20–100 keV emission is well represented by a simple power law with a photon index of $\Gamma = 1.9^{+0.4}_{-0.3}$, consistent with the value obtained from the EPIC spectra. Combining the two spectra and using the best EPIC model

Table 4. Results obtained from the X-ray spectral analysis of UGC 3142.

Instruments	Energy [keV]	χ^2 (d.o.f.)	Γ	N_{H} [10 ²⁰ cm ⁻²]	N_{H}^1 [10 ²² cm ⁻²]	f^1	N_{H}^2 [10 ²² cm ⁻²]	f^2
EPIC ^a	0.3–10	1488 (1028)	$0.9^{+0.1}_{-0.1}$	$1.4^{+0.1}_{-0.1}$	—	—	—	—
EPIC ^b	0.3–10	1080 (1027)	$1.13^{+0.04}_{-0.05}$	0.19	$2.1^{+0.1}_{-0.1}$	$0.92^{+0.01}_{-0.01}$	—	—
EPIC ^c	0.3–10	994 (1022)	$1.4^{+0.1}_{-0.1}$	0.19	$1.4^{+0.2}_{-0.2}$	$0.92^{+0.01}_{-0.02}$	5^{+1}_{-1}	$0.57^{+0.08}_{-0.09}$
(EPIC + ISGRI + BAT) ^c	0.3–110	1011 (1034)	$1.5^{+0.1}_{-0.1}$	0.19	$1.4^{+0.3}_{-0.4}$	$0.92^{+0.02}_{-0.06}$	4^{+2}_{-1}	$0.6^{+0.2}_{-0.1}$

Notes. The data were modeled with an absorbed power law model (a), a power law absorbed by Galactic cold matter plus a layer of partially absorbing neutral material (b), and a power law absorbed by Galactic cold matter and two layers of partially absorbing neutral material, plus a Gaussian K α iron line (c). EPIC includes PN, MOS1 and MOS2 data.

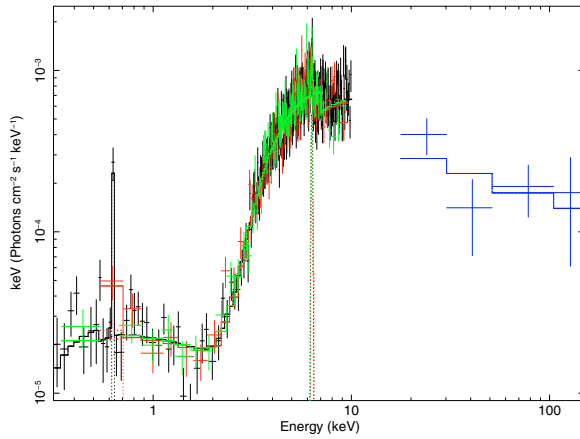


Fig. 3. 0.3–110 keV spectrum of ESO 383-18 obtained with non simultaneous EPIC (in the 0.3–10 keV range) and ISGRI data. The fit is a power law absorbed by cold Galactic matter and by two clumpy neutral absorbers plus two Gaussian emission lines (last row of Table 5).

we obtain parameters consistent with those obtained previously (Table 5), due to the much richer statistics of EPIC. Due to the low quality of the IBIS/ISGRI data, it is not possible to constrain the presence of a cut-off, or of a reflection component ($R \approx 0$) in the spectrum using *pexrav*. The fit included an inter-calibration constant ($C_1 = 0.7$) to account for variability, because ISGRI and EPIC observations were not simultaneous, and the inclination angle was set to $i = 60^\circ$ (Kinney et al. 2000) because this source is a type 2 AGN.

We can conclude that the best model for the spectrum of ESO 383-18 is a power law absorbed by cold Galactic matter and by a double layer of partially covering material, plus two Gaussian lines.

3.3. ESO 140-43

Two *XMM-Newton* observations of ESO 140-43 were performed, the first in September 2005 and the second in March 2006.

As in for ESO 383-18 and UGC 3142, in the 0.3–10 keV energy range a simple power law absorbed by cold neutral matter does not provide a good representation of the EPIC/PN and MOS data for both observations ($\chi^2 = 18189$ for 2153 d.o.f. and $\chi^2 = 3234$ for 947 d.o.f., for the 2005 and 2006 observation, respectively). It also results in a flat power law with a strong soft excess (Figs. 8 and 10). We used again a more complex cold absorber, but in this case the data are not consistent with neutral

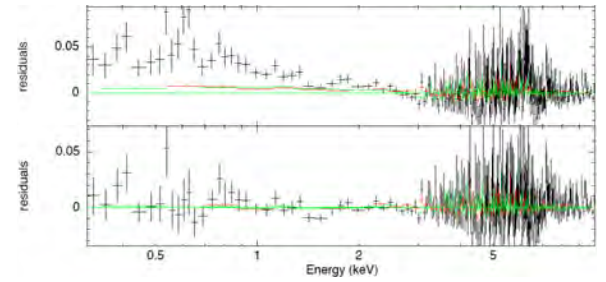


Fig. 4. ESO 383-18 EPIC/PN (in black) and MOS residuals obtained with the worst (upper panel) and best (lower panel) model, respectively the first and third row of Table 5.

absorption. Adopting a clumpy absorber model results in a chi-squared of $\chi^2 = 10861$ for 2151 d.o.f. for the EPIC spectrum of the 2005-observation. Jiménez-Bailón et al. (2008) found evidence of absorption features produced by highly ionized material in the RGS spectrum of ESO 140-43, due to three warm absorbers in the line of sight.

We analyzed the characteristics of the ionized matter with a model that uses the XSTAR code (e.g., Kallman et al. 1996; Kallman & Bautista 2001). This calculates the physical conditions and absorption-emission spectra of photo-ionized gases, and considers variable abundances. We used *zxipcf*, a model of partial covering absorption by partially ionized material, which uses a grid of XSTAR photo-ionized absorption models. In this model the state of the warm absorber is characterized by the column density of the absorber N_{H} , its covering fraction f , and the logarithm of the ionization parameter ξ , defined as

$$\xi = \frac{L_{\text{ion}}}{nr^2}, \quad (2)$$

where L_{ion} is the isotropic luminosity of the ionizing source in the 5 eV–300 keV energy range, r is the distance of the warm plasma to the source of radiation, and n is the proton density. This model is the ionized equivalent of the *pcfabs* model used for UGC 3142 and ESO 383-18.

In the case of the 2005 EPIC observation of ESO 140-43 adding a clumpy warm absorber improves the model ($\chi^2 = 3409$ for 2151 d.o.f.) with respect to a simple power law absorbed by cold matter. A second clumpy warm absorber again improves the result at a 99.9% confidence level ($\chi^2 = 2800$ for 2148 d.o.f.). The best model is obtained adding a third clumpy warm absorber, which improves the fit again at the 99.9% confidence level ($\chi^2 = 2575$ for 2145 d.o.f.). The best model has a photon index of $\Gamma = 1.89^{+0.01}_{-0.01}$ and three warm absorbers with quite different characteristics. The low ionized absorber (hereafter LIA)

Table 5. Results obtained from the X-ray spectral analysis of ESO 383-18.

Instruments	Energy [keV]	χ^2 (d.o.f.)	Γ	N_{H} [10 ²⁰ cm ⁻²]	N_{H}^1 [10 ²² cm ⁻²]	f^1	N_{H}^2 [10 ²² cm ⁻²]	f^2
EPIC ^a	0.3–10	1087 (432)	1.2 ± 0.1	15 ± 1	—	—	—	—
EPIC ^b	0.3–10	533 (431)	1.47 ^{+0.03} _{-0.05}	0.042	19.5 ^{+0.7} _{-0.7}	0.989 ^{+0.002} _{-0.003}	—	—
EPIC ^c	0.3–10	461 (423)	1.8 ^{+0.1} _{-0.1}	0.042	10 ⁺¹ ₋₂	0.97 ^{+0.02} _{-0.04}	20 ⁺² ₋₃	0.86 ^{+0.05} _{-0.05}
(EPIC + ISGRI) ^c	0.3–110	472 (426)	1.7 ^{+0.2} _{-0.2}	0.042	11 ⁺¹⁷ ₋₅	0.95 ^{+0.03} _{-0.15}	15 ⁺⁴ ₋₇	0.85 ^{+0.06} _{-0.07}

Notes. The data were modeled with an absorbed power law model (a), a power law absorbed by Galactic cold matter plus a layer of partially absorbing neutral material (b), and a power law plus two Gaussian lines (representing the iron K α and the OVIII Ly α emission lines) absorbed by Galactic cold matter and by two layers of partially absorbing neutral material (c). EPIC includes PN, MOS1 and MOS2 data.

($\log \xi = 0.28^{+0.05}_{-0.03}$ erg cm s⁻¹) with a hydrogen column density of $N_{\text{H}}^{\text{L}} = 3.7^{+0.3}_{-0.7} \times 10^{21}$ cm⁻² covers a fraction of $f = 0.70^{+0.04}_{-0.04}$ of the X-ray source. The intermediate ionized absorber (IIA) ($\log \xi = 1.94^{+0.02}_{-0.04}$ erg cm s⁻¹) has a higher hydrogen column density of $N_{\text{H}}^{\text{I}} = 2.99^{+0.07}_{-0.01} \times 10^{22}$ cm⁻² and a covering factor of $f = 0.98^{+0.01}_{-0.05}$. The third absorber has a value of the ionization parameter higher than the other two ($\log \xi = 2.73^{+0.06}_{-0.04}$ erg cm s⁻¹), and will therefore be called high ionization absorber (HIA). Its hydrogen column density and covering factor are $N_{\text{H}}^{\text{H}} = 1.1^{+0.2}_{-0.2} \times 10^{22}$ cm⁻² and $f = 0.99^{+0.01}_{-0.01}$, consistent with full coverage. The residuals of this fit (Fig. 8) show that there are still some components in the spectrum which are not yet accounted for, although the model provides an acceptable fit ($\chi^2_{\nu} = 1.17$). Higher quality data would be needed to investigate whether another absorption component could explain the remaining residuals.

The EPIC/PN and MOS X-ray spectra of the 2006 XMM-Newton observation of ESO 140-43 were analyzed with the models reported above. As for the 2005 observation the best fit ($\chi^2 = 1063$ for 940 d.o.f.) is obtained with a power law absorbed by three layers of partially covering ionized matter. The value of the photon index obtained ($\Gamma = 1.9^{+0.2}_{-0.2}$) is consistent with that of the 2005 observation, while the parameters of the absorbers show several important differences. The LIA has an even lower ionization parameter ($\log \xi^{\text{L}} = -1.3^{+1.0}_{-0.2}$ erg cm s⁻¹) than that of the 2005 observation, it has a higher hydrogen column density ($N_{\text{H}}^{\text{L}} = 1.6^{+0.5}_{-0.8} \times 10^{22}$ cm⁻²) and covers a bigger fraction of the X-ray source ($f = 0.88^{+0.03}_{-0.09}$). The IIA presents a value of the ionization parameter ($\log \xi^{\text{I}} = 1.89^{+0.03}_{-0.4}$ erg cm s⁻¹) and of the covering factor ($f = 0.86^{+0.09}_{-0.04}$) consistent with the 2005 observation, while its column density ($N_{\text{H}}^{\text{I}} = 11^{+3}_{-6} \times 10^{22}$ cm⁻²) is remarkably higher. The HIA has a higher value of the ionization parameter ($\log \xi^{\text{H}} = 3.6^{+0.8}_{-0.2}$ erg cm s⁻¹) and of the column density ($N_{\text{H}}^{\text{H}} = 8^{+12}_{-6} \times 10^{22}$ cm⁻²) with respect to the 2005 observation, while its covering factor ($f = 0.86^{+0.09}_{-0.04}$) is consistent.

The spectra of the two observations are reported together in Fig. 5.

A layer of neutral matter representing the Galactic absorption ($N_{\text{H}}^{\text{Gal}} = 7.34 \times 10^{20}$ cm⁻²) was added to all the models reported above. To discard neutral absorbers we added a layer of cold material to the models and found that its hydrogen column density is consistent with 0 for both observations, thus it can be ignored.

The first evidence of a K α iron line in the X-ray spectrum of ESO 140-43 was found through the analysis of EXOSAT data. Ghosh & Soundararajaperumal (1992) detected an excess around 6 keV, which they interpreted as an iron line of the equivalent width $EW = 354 \pm 144$ eV. We added a Gaussian line to

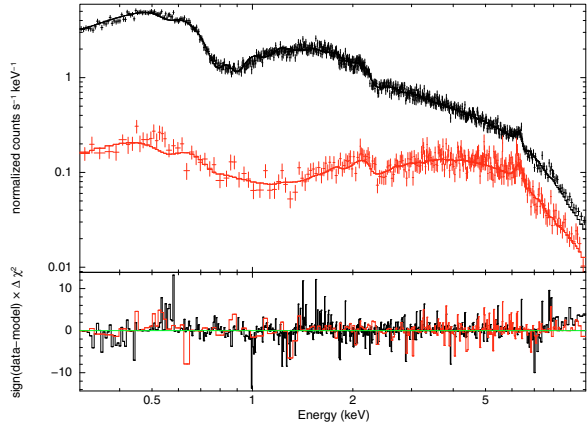


Fig. 5. EPIC/PN spectra of the 2005 (in black) and 2006 observation of ESO 140-43. The continuous lines represent the best models to the respective data-sets, as reported in Table 6.

the best-fit model and found that this component improves the fit at the 99.9% confidence level for both observations ($\chi^2 = 2511$ for 2142 d.o.f. and $\chi^2 = 2012$ for 937 d.o.f., for the 2005 and 2006 observation, respectively). From the spectrum of the 2005-observation we obtained a line located at $6.40^{+0.03}_{-0.03}$ keV, with a width of $\sigma = 83^{+34}_{-32}$ eV, an equivalent width of $EW = 118^{+51}_{-53}$ eV and a flux of $F_{\text{K}\alpha} = 4.4^{+0.9}_{-0.9} \times 10^{-15}$ erg cm⁻² s⁻¹. In the 2006-observation spectrum the K α iron line is at $6.39^{+0.05}_{-0.05}$ keV, has a width of $\sigma = 112^{+57}_{-37}$ eV, an equivalent width of $EW = 161^{+10}_{-71}$ eV and a flux of $F_{\text{K}\alpha} = 2.4^{+0.7}_{-0.6} \times 10^{-15}$ erg cm⁻² s⁻¹. This line is for both observations consistent with the K α iron line. For both observations adding another Gaussian line at 6.7 keV does not significantly improve the fit ($\Delta\chi^2 \approx 0$), which allows us to exclude an additive broad component to the neutral iron line. The results obtained with this model are reported in Table 6.

While the RGS spectrum of the 2005 observation (Fig. 6) shows a number of interesting features in the 0.3–2 keV energy range, the one obtained during the 2006 observation has a very low signal to noise ratio. The most evident absorption features detected by RGS during the 2005-observation are (the energy are given in the rest frame of the AGN): the N VII Ly α (0.5 keV; 24.8 Å), the O VIII Ly α (0.65 keV; 19 Å) and possibly the Ne X Ly α (1.02 keV; 12.1 Å) line. In Fig. 6 we plot the RGS spectrum using the best EPIC model, which fits the continuum well, but not the OVIII Ly α line and the continuum next to it, similarly to what happens in the best fit of Jiménez-Bailón et al. (2008). A more detailed analysis with

Table 6. Results obtained from the X-ray spectral analysis of the two *XMM-Newton* EPIC and the two *Swift*/XRT observations of ESO 140-43.

χ^2 (d.o.f.)	Γ	N_{H}^1 [10^{22} cm $^{-2}$]	$\log \xi^1$ [erg cm s $^{-1}$]	f^1	N_{H}^2 [10^{22} cm $^{-2}$]	$\log \xi^2$ [erg cm s $^{-1}$]	f^2	N_{H}^3 [10^{22} cm $^{-2}$]	$\log \xi^3$ [erg cm s $^{-1}$]	f^3
XMM-Newton EPIC/PN and MOS										
		LIA			IIA			HIA		
2005 Observation										
2511(2142)	$1.89^{+0.01}_{-0.01}$	$0.37^{+0.03}_{-0.07}$	$0.28^{+0.05}_{-0.03}$	$0.70^{+0.04}_{-0.04}$	$2.99^{+0.07}_{-0.01}$	$1.94^{+0.02}_{-0.04}$	$0.98^{+0.01}_{-0.05}$	$1.1^{+0.2}_{-0.2}$	$2.73^{+0.06}_{-0.04}$	$0.99^{+0.01}_{-0.01}$
2006 Observation										
1012(937)	$1.9^{+0.2}_{-0.2}$	$1.6^{+0.5}_{-0.8}$	$-1.3^{+1.0}_{-0.2}$	$0.88^{+0.03}_{-0.09}$	11^{+3}_{-6}	$1.89^{+0.03}_{-0.4}$	$0.86^{+0.09}_{-0.04}$	8^{+12}_{-6}	$3.6^{+0.8}_{-0.2}$	$0.99^{+0.01}_{-0.01}$
Swift/XRT										
First observation										
13.1(13)	$3.8^{+1.0}_{-2.2}$	7^{+13}_{-6}	$-0.5^{+2.3}_{-0.7}$	$0.99^{+0.01}_{-0.01}$						
Second observation										
12.9(12)	$2.9^{+1.4}_{-1.2}$	5^{+2}_{-1}	$-0.5^{+2.3}_{-0.1}$	$0.996^{+0.004}_{-0.03}$						

Notes. The model used is a power law plus a iron $K\alpha$ line absorbed by three layers of partially covering ionized matter for EPIC, and a power law absorbed by one layer of partially covering ionized material for XRT. An additional layer of cold matter representing neutral Galactic absorption was used, fixing the column density at $N_{\text{H}}^{\text{Gal}} = 7.3 \times 10^{20} \text{ cm}^{-2}$.

different parameters and possibly other model components is required, but is out of the scope of this paper.

We also analyzed the less significant data obtained during the two *Swift*/XRT observations. The two observations were performed a few days apart, but because the flux varied, we analyzed them individually. Fitting the spectra with a simple power law we obtained $\chi^2 = 18.3$ for 15 d.o.f. and $\chi^2 = 23$ for 14 d.o.f., for the first and second observation, respectively. Due to the low quality of the data it is impossible to resolve the three absorbers, thus we applied a simpler model than that used for EPIC data: a power law absorbed by only one layer of clumpy ionized material. This model fits well both observations and the results are reported in Table 6.

Analyzing IBIS/ISGRI and BAT spectra together with the most significant EPIC spectra, we checked for a cut-off and/or reflection from neutral material. No evidence of an exponential cut-off was found in the data, the energy of the cut-off reaches indeed the upper limit allowed by XSPEC and is not constrained ($E_{\text{C}} = 500 \pm 1000 \text{ keV}$). With the *pexrav* reflection model (fixing the inclination angle to $i = 30^\circ$ and the cut-off at $E_{\text{C}} = 10\,000 \text{ keV}$) we found that the fit improves at the 98% confidence level ($\chi^2 = 2540$ for 2150 d.o.f. and $\chi^2 = 2546$ for 2151 d.o.f., for the new and the old model, respectively). The value of the reflection obtained is $R = 0.6^{+0.1}_{-0.2}$.

We can conclude that the best model for the 0.3–110 keV spectrum of ESO 140-43 is that of a power law reflected by neutral material and absorbed by three layers of partially covering ionized material, plus a iron $K\alpha$ line.

4. Variability analysis

4.1. X-ray variability

We analyzed the 0.3–10 keV EPIC/PN light curves (with a binning of 200 s) of the three Seyfert galaxies (Fig. 11) and investigated whether variations in the absorbers can account for variability. We tested the light curves for a constant flux model, and rejected the null hypothesis (i.e. flux not variable) for values of the probability p lower than 5%.

The light curve of UGC 3142 is consistent with a constant flux ($\chi^2 = 54$ for 49 d.o.f., which leads to a probability of $p \sim 30\%$), with a mean count-rate of $f = 2.08 \pm 0.02 \text{ ct s}^{-1}$. The light curve of ESO 383-18 shows significant variability during

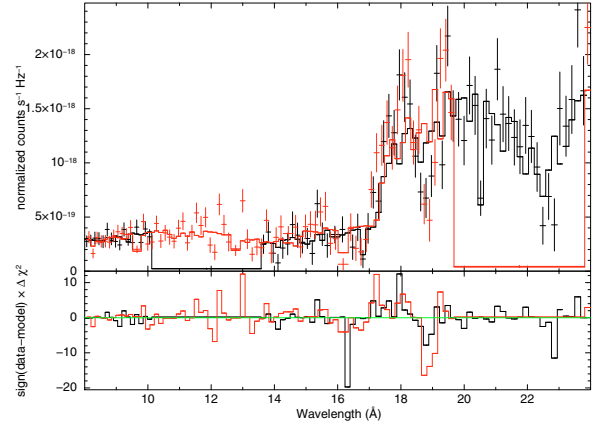


Fig. 6. Extract of the RGS spectrum of the 2005 observation of ESO 140-43, the solid line represents the best EPIC model (Table 6).

the observation, with $\chi^2 = 187.5$ for 70 d.o.f. ($p \sim 0\%$) for the assumption of constant flux. In order to better estimate the variability of these two light-curves we calculated their fractional rms variability amplitude F_{var} (as defined in Eq. (10) in Vaughan et al. 2003). For UGC 3142 we obtained $F_{\text{var}} = 1.5 \pm 2\%$, compatible with the lack of variability found above, while for ESO 383-18 we obtained $F_{\text{var}} = 14 \pm 2\%$. The errors on F_{var} were calculated with Eq. (B2) in Vaughan et al. (2003).

The light curves for the two observations of ESO 140-43 show evidence of variable flux, with $\chi^2 = 1575$ for 107 d.o.f. ($p \sim 0\%$) and $\chi^2 = 257$ for 99 d.o.f. ($p \sim 0\%$), for the 2005 and 2006 observations, respectively. The values of the fractional rms variability amplitude are consistent, $F_{\text{var}} = 8.9 \pm 0.3\%$ and $F_{\text{var}} = 9 \pm 1\%$, for the 2005 and 2006 observation, respectively.

The 2005-observation seems to be characterized by two different (at the 1σ level) flux states. The light curve indeed shows a constant flux of about 8 ct/s for the first 10 ks, then a dip and a flux oscillating around 6.7 ct/s for about 9 ks, then increasing again up to 10 ct/s. In order to test whether the different flux states can be accounted for by a change in the absorber or in the spectral shape, we divided the light curve into two parts: *part 1*, between 0 and 10 ks for the high flux state, and *part 2*, between 10 and 19 ks, for the low flux state. These two

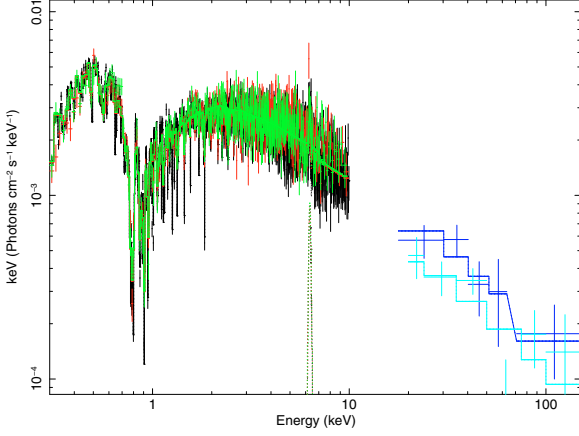


Fig. 7. 0.3–110 keV spectrum of ESO 140-43 obtained with the 2005 *XMM-Newton* EPIC (in the 0.3–10 keV range), and non simultaneous BAT (lower flux) and IBIS/ISGRI (higher flux) data. The model used is a power law absorbed by cold Galactic matter and by three clumpy ionized absorbers, plus a iron $K\alpha$ line and a reflection component.

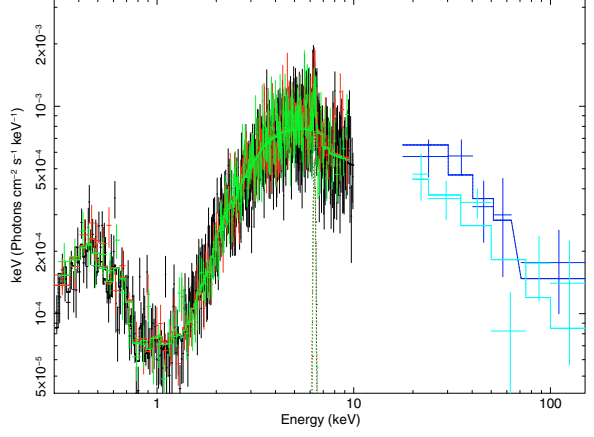


Fig. 9. 0.3–110 keV spectrum of ESO 140-43 obtained with the 2006 *XMM-Newton*/EPIC (in the 0.3–10 keV range), and non simultaneous BAT (lower flux) and IBIS/ISGRI (higher flux) data. The model is a power law absorbed by cold Galactic matter and by three clumpy ionized absorbers, plus a iron $K\alpha$ line and a reflection component.

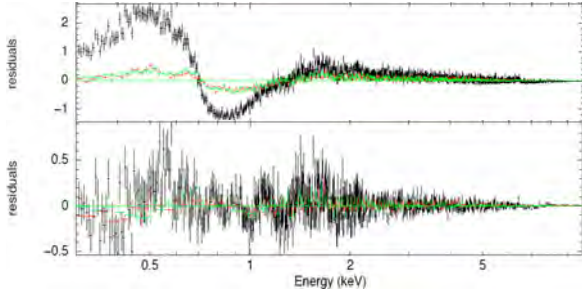


Fig. 8. EPIC/PN (in black) and MOS residuals of the 2005 *XMM-Newton* observation obtained with the worst (simple power law, top panel) and best fit (power law absorbed by cold Galactic matter and by three clumpy ionized absorbers, plus a iron $K\alpha$ line, bottom panel).

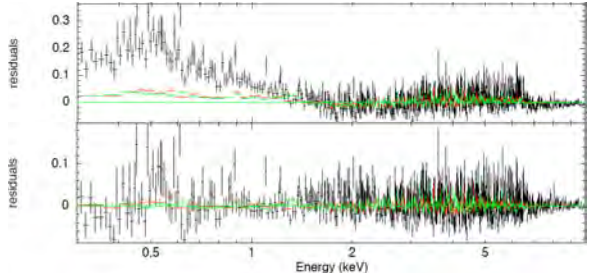


Fig. 10. EPIC/PN (in black) and MOS residuals of the 2006 *XMM-Newton* observation obtained with the worst (simple power law, top panel) and best fit (power law absorbed by cold Galactic matter and by three clumpy ionized absorbers, plus a Gaussian $K\alpha$ iron line, bottom panel).

light-curves have consistent intrinsic variabilities of a few percents ($F_{\text{var}}^1 = 5.1 \pm 0.4\%$ and $F_{\text{var}}^2 = 5.2 \pm 0.5\%$). In order to find a possible explanation for these two flux states, we analyzed the spectra obtained from the two time intervals (Fig. 12). We fitted the two spectra first freezing all the parameters except the normalization of the power law, and then also letting the other parameters free to vary. We explored several possibilities, as variations of the column densities, of the ionization parameters or of the covering fraction. We found that the only parameter, besides the normalization, whose variation could explain the different spectra is the covering factor of the LIA. In particular a variation of this parameter (from $f_1^{\text{LIA}} = 0.77^{+0.01}_{-0.02}$ to $f_2^{\text{LIA}} = 0.65^{+0.02}_{-0.03}$) is necessary at the 99.9% confidence level to account for these spectral differences.

In Table 8 we report the fluxes of the three sources based both on this work and previous literature. A strong variation in flux in the 14–150 keV band is evident between ISGRI and BAT observations of UGC 3142, while the values of ESO 383-18 and ESO 140-43 are consistent, and there is no evidence of hard X-ray variability. At lower energies flux (by a factor of 3) and spectral variability on a time-scale of months was detected between the two *XMM-Newton* observations of ESO 140-43. The fluxes of ESO 140-43 measured by *EXOSAT* are consistent with those obtained by the 2005 EPIC observation, while the flux was

much lower during the 2006 observation. Strong variability between the *ROSAT* observation and the second EPIC observation was also detected.

Thus of the three Seyferts only UGC 3142 shows strong hard X-ray variability, while in soft X-ray ESO 383-18 and ESO 140-43 show both variability on the 200s timescale, and ESO 140-43 shows remarkable flux and spectral variability on a monthly timescale, as is evident from *XMM-Newton* and historical observations.

4.2. Hardness ratios

In order to probe the possible role of absorption in the 0.3–10 keV flux variability of ESO 383-18 and ESO 140-43, we used two bands, a soft (S, 0.3–2 keV) band and a hard (H, 2–10 keV) band, and checked for variations of the hardness ratio with time. The hardness ratio is defined as

$$\text{HR} = \frac{H - S}{H + S}, \quad (3)$$

Table 7. Optical and ultraviolet apparent magnitudes measured by the two different *XMM-Newton*/OM and *Swift*/XRT observations.

Instrument		XMM/OM	XMM/OM	Swift/UVOT	Swift/UVOT
Time		08-09-2005	07-03-2006	20-05-2008	25-05-2008
Band	Wavelength	Magnitude	Magnitude	Magnitude	Magnitude
	Å	mag	mag	mag	mag
V	5430	14.56 ^{+0.01} _{-0.01}	14.57 ^{+0.01} _{-0.01}	—	—
B	4500	15.34 ^{+0.01} _{-0.01}	15.37 ^{+0.01} _{-0.01}	—	—
U	3440	14.90 ^{+0.01} _{-0.01}	14.94 ^{+0.01} _{-0.01}	—	—
UVW1	2910	15.14 ^{+0.01} _{-0.01}	15.18 ^{+0.01} _{-0.01}	—	16.0 ^{+0.1} _{-0.1}
UVM2	2310	16.14 ^{+0.04} _{-0.04}	16.67 ^{+0.04} _{-0.04}	16.8 ^{+0.1} _{-0.1}	—
UVW2	2120	16.57 ^{+0.08} _{-0.08}	—	—	—

Table 8. Comparison between fluxes in different energy bands obtained in this work and found in the literature.

Instrument	$F_{0.1-2\text{ keV}}$	$F_{0.1-2.4\text{ keV}}$	$F_{2-10\text{ keV}}$	$F_{14-150\text{ keV}}$
	[10 ⁻¹² erg cm ⁻² s ⁻¹]	[10 ⁻¹² erg cm ⁻² s ⁻¹]	[10 ⁻¹¹ erg cm ⁻² s ⁻¹]	[10 ⁻¹¹ erg cm ⁻² s ⁻¹]
UGC 3142				
EPIC/PN + MOS	0.69 ^{+0.04} _{-0.11}	1.24 ^{+0.1} _{-0.1}	1.7 ^{+0.1} _{-0.2}	—
Swift/BAT ^a	—	—	—	3.4 ^{+0.6} _{-0.6}
INTEGRAL IBIS/ISGRI	—	—	—	9.42 ^{+0.6} _{-0.8}
ESO 383-18				
EPIC/PN + MOS	0.06 ^{+0.18} _{-0.01}	0.08 ^{+0.18} _{-0.01}	0.6 ^{+0.1} _{-0.1}	—
Swift/BAT ^b	—	—	—	1.9 ^{+0.6} _{-0.8}
INTEGRAL IBIS/ISGRI	—	—	—	3.8 ^{+0.8} _{-1.5}
ESO 140-43				
ROSAT ^c	—	21 ⁺¹⁰ ₋₁₀	—	—
EPIC/PN + MOS ¹	6.5 ^{+0.1} _{-0.1}	8.5 ^{+1.1} _{-0.6}	2.46 ^{+0.05} _{-0.04}	—
EPIC/PN + MOS ²	0.4 ^{+0.1} _{-0.1}	0.5 ^{+0.2} _{-0.2}	0.8 ^{+0.2} _{-0.2}	—
EXOSAT ^d	8 ⁺³ ₋₃	—	2.5 ^{+0.2} _{-0.2}	—
Swift/BAT ^a	—	—	—	4.6 ^{+0.7} _{-0.7}
INTEGRAL IBIS/ISGRI	—	—	—	5.3 ^{+0.4} _{-0.5}

Notes. The indices 1 and 2 refer to the 2005 and 2006 *XMM-Newton* observation of ESO 140-43, respectively. The fluxes are model fluxes, not corrected for absorption.

(^a) Tueller et al. (2010); (^b) Cusumano et al. (2010); (^c) Boller et al. (1992); (^d) Ghosh & Soundararajaperumal (1992).

where S and H are in counts s⁻¹. We searched for correlations using Pearson's product moment correlation coefficient r , defined as

$$r = \frac{1}{n-1} \sum_{i=1}^n \left(\frac{x_i - \bar{x}}{\sigma_x} \right) \left(\frac{y_i - \bar{y}}{\sigma_y} \right), \quad (4)$$

where x_i and y_i are the values of the two data-sets we are comparing (namely the HR and the flux or the time), n the size of the samples, $\bar{x}$ and $\bar{y}$ are the averages of the data-sets, and σ_x and σ_y are their standard deviations. In order to calculate the probability the null hypothesis ($r = 0$, namely no correlations) is true, we used the Fisher transformation

$$F(r) = \frac{1}{2} \log \frac{1+r}{1-r}, \quad (5)$$

from which we calculated $z = \sqrt{n-3}F(r)$, a z -score of r , from which we derived the probability p . We rejected the null hypothesis for $p < 5\%$.

The hardness ratio of ESO 383-18 is not constant ($\chi^2 = 34$ for 70 d.o.f., $p = 0.03\%$), but does not show any significant correlation with time ($r = -0.3$, $p = 99\%$) or flux ($r = 0.05$, $p = 65\%$). This lack of correlations might imply that the observed spectral variability on this time-scale is not due to absorbing material.

During the 2005 observation of ESO 140-43 the hardness ratio varied ($\chi^2 = 188$ for 107 d.o.f., $p < 0.01\%$), while it is consistent with no variability during the 2006 observation ($\chi^2 = 24.3$ for 99 d.o.f., $p \approx 100\%$). The 2005 observation does not show any correlation of the hardness ratio with flux ($r = 0.26$, $p = 61\%$) or time ($r = -0.55$, $p = 99.9\%$), which indicates that changes in the absorbing material are not a likely explanation for the spectral variability on the 200 s time-scale. A strong variation of the average value of HR appears between the 2005 ($\overline{\text{HR}} = -0.186 \pm 0.003$) and the 2006 ($\overline{\text{HR}} = +0.53 \pm 0.02$) observations, consistent with the observed spectral variation.

4.3. Optical and UV variability

We analyzed the optical and UV emission of ESO 140-43 at the time of the X-ray observations with *XMM-Newton*/OM and *Swift*/UVOT data. In Table 7 the values of optical and ultraviolet magnitudes obtained are given. In the V, B, U, and UVW1 band the fluxes obtained by the two *XMM-Newton* observations are consistent, while in the UVM2 band the source varied by about $\Delta\text{UVM2} \approx 0.5$ mag. UVOT measured the flux only in the UVW1 and UVM2 bands, and registered strong flux variations in UVM1 with respect to the OM observations ($\Delta\text{UVW1} \approx 0.9$ mag), while the UVM2 flux remained constant.

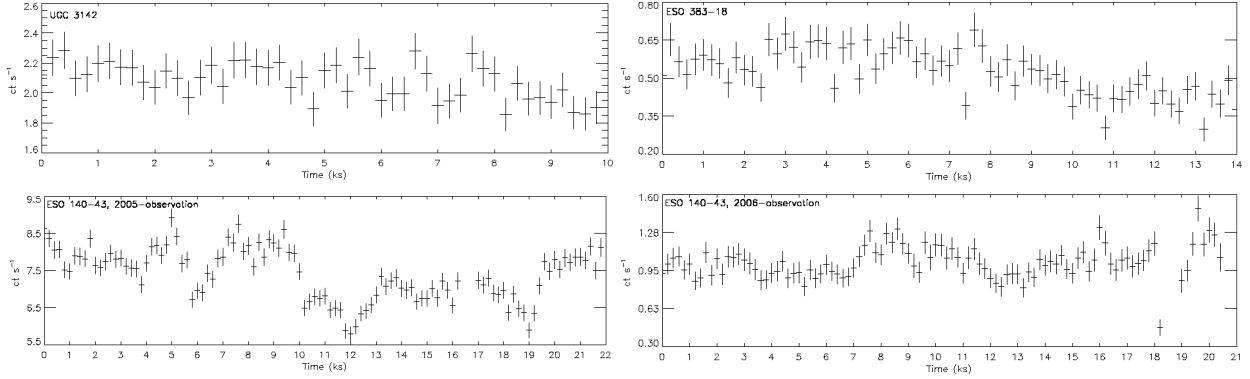


Fig. 11. EPIC PN light curves binned to 200 s for UGC 3142 (top left panel), ESO 383-18 (top right panel) and the 2005 (bottom left panel) and the 2006 observation of ESO 140-43 (bottom right panel).

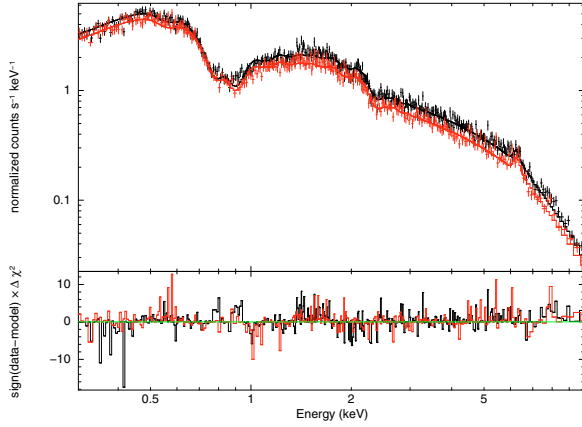


Fig. 12. EPIC/PN spectra of different time intervals according to the low flux state and the high flux state (in black) during the 2005-observation of ESO 140-43. The model is the best model obtained in Sect. 3.3, with all parameters fixed to the best model of this observation, except the covering factor of the LIA and the normalization.

5. Discussion

In this work we presented two AGN showing evidence for clumpy neutral absorbers and one showing evidence for clumpy ionized absorbers. We discuss these two cases separately, and then together in the light of the soft X-ray excess.

5.1. UGC 3142 and ESO 383-18

Recent results (e.g., Risaliti et al. 2009; Bianchi et al. 2009) show that clumpy absorbers can explain variability in AGN. Both Seyfert 1 (i.e. Guainazzi et al. 1998; Puccetti et al. 2007; Grupe et al. 2007) and Seyfert 2 (Risaliti et al. 2002) have been proven to show partial or total occultation events. In particular several Seyfert 2 have been observed changing state, switching from Compton-thin to reflection-dominated or vice versa (Matt et al. 2009). In their recent work Bianchi et al. (2009) propose a model consisting of three absorbers/emitters, not necessarily coexisting or observable in all the sources. These three components are a Compton-thick torus (at about parsec distance), a Compton-thin absorber ($N_H \sim 10^{22} \text{ cm}^{-2}$) at much larger scales, likely associated to dust lanes, which completely or partially

obscures the broad line region (BLR), and clouds at around the distance of the BLR. Recent evidence of clumpy structures in the torus has been found from *Spitzer*/IRS spectra (Mor et al. 2009). A clumpy moving absorber could also explain the optical change in the Seyfert type observed in some AGN (e.g., in Cohen et al. 1986; Aretxaga et al. 1999).

Both UGC 3142 and ESO 383-18 spectra show what at first sight appears to be a soft X-ray excess, though our analysis shows that the best fit to the data is obtained by a power law absorbed by two clumpy neutral absorbers. For the Seyfert 1 UGC 3142 we found that the two absorbers have column densities of the order of 10^{22} cm^{-2} , and covering fractions of about 92% and 60%. For the Seyfert 2 ESO 383-18 the column densities are higher ($\approx 10^{23} \text{ cm}^{-2}$), as expected from its optical classification, with covering fractions of about 97% and 86%. The intrinsic absorption of the Seyfert 1 galaxy UGC 3142 is above the dividing line of 10^{22} cm^{-2} , which usually points to a type 2 AGN. It has to be taken into account though that the transition between absorbed and unabsorbed sources is smooth, and that not all type 1 AGN necessarily exhibit low absorption (Awaki et al. 1991). In addition, Seyfert 2 galaxies like NGC 3147 and NGC 4698 show no intrinsic absorption (Pappa et al. 2001). The *INTEGRAL* AGN catalog (Beckmann et al. 2009) contains 9 type 1 AGN with $N_H > 10^{22} \text{ cm}^{-2}$ and 10 Seyfert 2 with $N_H < 10^{22}$ out of 154 Seyfert galaxies with known intrinsic absorption.

Following the model of Bianchi et al. (2009), the partially covering absorbers seen in ESO 383-18 and UGC 3142 imply a certain degree of clumpiness in the BLR or in the torus, or dust lanes. An additional component could be represented by a clumpy neutral (or weakly ionized) disk wind, crossing the line of sight. These outflows, originating in the accretion flow, are predicted by hydrodynamic simulations of accretions disks (e.g., Schurch et al. 2009). According to this, in the case of ESO 383-18 we could picture the absorption as due to a clumpy torus, plus a disk wind or Compton-thin dust lanes with a smaller column density, while for UGC 3142 we could make the conjecture that the observed absorbers are part of a disk wind or of the BLR.

Variations in the partial covering absorbers have been shown to cause strong spectral and flux variability in AGN (e.g., 1H 0707-495, Gallo et al. 2004). ESO 383-18 shows variability in both flux (of $\approx 14\%$) and hardness ratio, but, because the hardness ratio is not correlated with time or flux, we exclude that the changes on the 200 s time-scale could be caused by changes in the absorbers. The observed spectral variability is

probably due to changes of the continuum. In the EPIC spectrum of ESO 383-18 we detected a feature that could be associated with the OVIII Ly α emission line, but due to the low significance of the data this has to be considered as a tentative identification. The OVIII Ly α appears to be a common feature in absorbed AGN, and it was detected in 30 of the 69 nearby AGN studied by Guainazzi & Bianchi (2007).

For both objects we cannot confirm or rule out the hypothesis that the neutral matter responsible for clumpy absorption is part of a disk wind. Indeed no blue-shifted absorption lines, which would indicate out-flowing matter, are detected. We can nevertheless safely state that the iron K α line in both objects is not produced in out-flowing material, because the line's centroid is consistent with the redshift of the host galaxy. The non-detection of a reflection hump in the two AGN despite narrow neutral iron lines is probably due to the low significance of IBIS/ISGRI and BAT data for ESO 383-18, and might be hidden by the strong variability in hard X-rays for UGC 3142.

It should be taken into account that partial-covering models are indistinguishable from Thomson scattering models (Turner & Miller 2009), thus an alternative explanation could be that part of the continuum has been scattered energy-independently and that the absorbers are not partially covering the X-ray source.

5.2. ESO 140-43

Warm absorbers have been found to be a common characteristic of Seyfert 1 AGN. In a study of 15 Seyfert 1 McKernan et al. (2007) found that 10 sources of their sample present out-flowing photo-ionized absorbers, with velocities in the range $v \sim 0\text{--}2000\text{ km s}^{-1}$, column densities of about $N_{\text{H}} \sim 10^{20\text{--}23}\text{ cm}^{-2}$ and ionization parameters in a wide range of $\xi \sim 1\text{--}10^4\text{ erg cm s}^{-1}$. Several of these absorbers show multiple ionization and kinematics components.

The Seyfert 1 galaxy ESO 140-43 shows a very complex X-ray spectrum, which can be modeled with a power law absorbed by three layers of partially covering ionized material, plus a Gaussian iron K α line at the same redshift as the host galaxy, and a weak reflection hump. The *XMM-Newton*/RGS data of one of the two observations of ESO 140-43 were analyzed by Jiménez-Bailón et al. (2008), who also detected three warm absorbers, and, contrarily to what we obtained here, also found an additive cold absorber. The photon index they obtained ($\Gamma = 2.0 \pm 0.1$) is consistent with what was found here ($\Gamma \approx 1.9$). The results we obtained agree with the current picture of multi-structure warm absorbers of Seyfert 1 AGN, in which several zones of warm material with different ionization states are observed. Examples are the Seyfert 1 galaxies NGC 3783 (Netzer et al. 2003; Krongold et al. 2003) and MCG 6-30-15 (McKernan et al. 2007), the last of these showing evidence for a similar complex absorber consisting of three zones of ionized gas. The Seyfert 1 NGC 3516 (Turner et al. 2005) shows evidence for a warm absorber covering about 50% of the continuum source, with the variation of its covering factor being used to explain the observed spectral variability (Turner et al. 2008). A powerful tool for the diagnostic of the physical conditions of ionized material in AGN is the study of absorption lines below 2 keV (e.g., Porquet & Dubau 2000). The RGS spectrum of ESO 140-43 shows several absorption lines due to H- and He-like elements. These lines are a common characteristics of Seyfert 1 galaxies (e.g., Longinotti et al. 2008; Armentrout et al. 2007; Nucita et al. 2010) and are also found in several absorbed AGN (Bianchi & Guainazzi 2007). The best X-ray model, the

absorption lines due to ionized material and the strong variability of ESO 140-43 imply ionized clumpy absorbers, which cross the line of sight toward the central engine producing the X-ray continuum.

Due to the strong spectral and flux variability on a time-scale of months, the three clumpy warm absorbers detected in the spectrum of ESO 140-43 could be part of a disk wind, as seen in several other Seyfert 1 (e.g., Turner et al. 2008). But because we do not detect any evidence of outflows, we cannot confirm this hypothesis. Possible explanations of the mechanism by which the out-flowing gas is accelerated are thermal winds (Krolik & Begelman 1986), radiation pressure (Murray et al. 1995), or magnetically driven winds (Bottorff et al. 2000). In the disk-wind scenario the observed variability could be due to changes in the physical conditions of the disk, or caused by interaction of a wind with other material. The detection of UV variability, considering that the optical/UV emission is probably disk dominated, supports the assumption that the observed variability is due to changes in the physical conditions of the accretion disk. An alternative scenario could be that the three warm absorbers are part of the BLR, and we observe occultations as seen for NGC 1365 (Risaliti et al. 2007). Both EPIC observations of ESO 140-43 show a narrow neutral iron line and no evidence of a broad component. The line flux varied by about 45% between the two observations, comparable with the variation of the continuum. As all the absorbers we detected are ionized, we can conclude that the neutral iron line and the reflection hump (which is also due to reflection on neutral matter) are produced by material which is not located in the line of sight. Possible locations for the line emitting region might be the torus or the outer part of the accretion disk.

Flux (of $\approx 9\%$) and spectral variability on the time-scale of 200 s is observed in the light curves obtained from both EPIC observations, but the lack of significant correlations between the hardness ratio and the flux indicates that the absorbers do not strongly influence the variability on this time-scale, and that variations in the continuum probably play a more important role. On longer time-scales (kiloseconds) the influence of the absorbers starts to be more evident. A variation of the covering factor of the LIA is indeed necessary to model the change between the high and the low flux state of the 2005 observation. This result agrees with the strong influence of the absorbers on the observed spectral variability of ESO 140-43.

The location and geometry of the ionized gas are still debated, but a rough estimate of the upper limit on its distance to the ionizing source can be given (Turner et al. 2008) by

$$r \lesssim \frac{L}{\xi N_{\text{H}}} . \quad (6)$$

Using this relation, and considering the values obtained by the best fitting models, we estimated upper limits for the distance to the central engine of the three ionized absorbers. For the 2005 observation we obtained $r_{\text{HIA}} \lesssim 2.9\text{ pc}$, $r_{\text{LIA}} \lesssim 6.6\text{ pc}$ and $r_{\text{LIA}} \lesssim 2.5\text{ kpc}$, while for the 2006 observation $r_{\text{HIA}} \lesssim 0.05\text{ pc}$, $r_{\text{LIA}} \lesssim 2\text{ pc}$ and $r_{\text{LIA}} \lesssim 23\text{ kpc}$. The luminosity was calculated extrapolating the power law continuum into the 5 eV–300 keV band. These values are not constraining, except for the HIA, which appears to be significantly closer to the central engine than the torus. The value of the HIA obtained from the 2006 observation is similar to what has been found for the highest ionization absorber of NGC 3783 (Reeves et al. 2004). All the upper limits found here are well above the value of the inner radius of the BLR of ESO 140-43 found by Padovani & Rafanelli (1988),

$r_{\text{in}}^{\text{BLR}} \simeq 8.9 \times 10^{-3}$ pc. This result does not allow us to exclude the BLR to be, at least partially, responsible for the absorption.

5.3. Clumpy absorbers and the soft excess

The nature of the soft X-ray excess of AGN has remained a mystery for the past two decades. Several explanations have been proposed, here we focus in particular on the absorption models (e.g., Gierlinski & Done 2004; Guainazzi et al. 2005; Schurch & Done 2006). In the velocity-smeared, partially ionized absorption scenario (Gierlinski & Done 2004; Schurch & Done 2006) the observed soft excess is related to atomic transitions, in particular to the large increase in opacity in partially ionized material, due to lines and edges of ionized OVII, OVIII and iron at ~ 0.7 keV. In this model, the partially ionized material is thought to be a disk wind with a complex velocity structure, which makes it difficult to resolve the atomic features. Schurch & Done (2008) noted that magnetic driving is likely the only mechanism that could achieve the high velocities required. While we do not detect any evidence of high velocities components in the absorbing medium, we found that the absorbers are clumpy, consistent with the assumptions of Schurch & Done (2008).

Warm absorbers are likely to be the main cause for the soft X-ray excess observed in many AGN (Turner et al. 2009), in this context ESO 140-43, with its three partially covering ionized absorbers, gives further evidence on how absorption can explain the soft excess in some Seyfert galaxies. Neutral absorbers can also play a significant role in the observed soft excess of AGN (Matt et al. 2001; Guainazzi et al. 2005). In the clumpy neutral absorber scenario adopted here, the X-ray source is not completely covered by the absorbers, and this allows part of the flux below 2 keV to leak out. Considering an absorber totally obscuring the primary X-ray emission (i.e. the power law continuum), we over-estimate the absorption below 2 keV, which then results in an apparent excess over the model.

Although for the three AGN presented here the absorption model well fits the observed soft X-ray excess, from previous studies it is obvious that not one model alone can account for what is observed in the spectra of many sources. Guainazzi et al. (2005) showed in a sample of 26 X-ray spectra of Seyfert 2 galaxies that 18 were best represented by an additional component ($kT = 0.1\text{--}1.5$ keV), 4 objects required clumpy absorbers but no additional component, and 4 did not require any addition to the absorbed power law model.

It is remarkable that the type of model which fits the data best does not depend on the source type. There are type 1 and type 2 objects best modeled by an absorbing scenario (e.g. this work), and there are Seyfert 1 and Seyfert 2 galaxies for which a reflection model (e.g., Petrucci et al. 2007; Middleton et al. 2009; Wilkes et al. 2008), or an additional component like a cool corona (e.g., Dewangan et al. 2007; Guainazzi et al. 2005), represents the best model. This would indicate that the effects causing the soft excess do not depend on source type and inclination angle of the accretion disk. On the other hand, Pounds & Wilkes (2007) pointed out that the effect of the soft excess is more pronounced in type 1 than in type 2 objects, and that a Seyfert 1.5 like 2MASS 0918+2117 indeed shows an intermediate excess. This would point to an origin of the soft excess far within the absorbing material responsible for the type 1 / type 2 distinction, and would support the hypothesis of Bianchi et al. (2009) that the observed X-ray spectra are influenced by several different absorbers. Larger well-defined samples, as presented e.g. in Guainazzi et al. (2005), with a consistent modeling approach are necessary though to verify this hypothesis.

6. Summary and conclusions

We performed the first detailed X-ray analysis of the three Seyfert galaxies ESO 140-43, ESO 383-18, and UGC 3142 using *XMM-Newton* high resolution data in combination with *INTEGRAL*/IBIS and *Swift* BAT/XRT data. The spectra of the three AGN presented indeed show what looks like a soft excess at energies $E < 2$ keV, but which we have shown is due to complex absorption, without any additive emission to the power law continuum.

The 0.3–10 keV spectrum of the three Seyfert galaxies is well fit by a power law, absorbed by two partially covering neutral absorber for UGC 3142 and ESO 383-18, and by three clumpy ionized absorbers in the case of ESO 140-43. ESO 140-43 also shows evidence for a reflection hump.

The absorbing medium seen in ESO 383-18 could be a clumpy torus, plus a disk wind or Compton thin dust lanes. For UGC 3142 the observed absorbers might be part of a disk wind, or of the BLR. The variability of the flux and of the hardness ratio observed in the light curve of ESO 383-18 is not explainable by variations of the absorbers, and is likely related to changes of the continuum.

The absorbers of ESO 140-43 have different values of column densities and ionization states, according to the current picture of warm absorbers. Strong flux and spectral (accounted for by changes in the three warm absorbers) variability was detected between *ROSAT*, *EXOSAT*, and the two *XMM-Newton* observations of ESO 140-43. The spectral variability is likely due to the fact that the clumpy absorbers are moving, either as a part of a disk wind or of the BLR. During the 2005-observation of ESO 140-43 variability of the covering factor of the LIA is detected on a time-scale of kilo-seconds, while on shorter time-scales the observed spectral variability cannot be explained by changes in the absorbers. Thus the effects of absorption on the variability are observable only on time-scales longer than few kilo-seconds, and are probably hidden by changes of the continuum on shorter time-scales.

We reported the first detection of the iron $K\alpha$ line in the spectra of ESO 383-18 and UGC 3142, and confirmed its presence in the spectrum of ESO 140-43. We tentatively associate an excess around 0.6 keV in the spectrum of ESO 383-18 with OVIII $\text{Ly}\alpha$ emission. More sensitive data will be necessary to confirm or rule out the presence of this line. The detection of the iron $K\alpha$ line, but not of any additive sign of reflection (i.e. a reflection hump) for ESO 383-18 and UGC 3142 is probably due to the low significance of IBIS/ISGRI data and the hard X-rays variability, respectively.

In general there does not seem to be a common model explaining the soft X-ray excess in all the observed cases. Rather it is likely that several components play a role, like reflection processes, complex absorption, and additional thermal emission. Not all these components are observed in all objects, and it remains to be clarified whether the source type and inclination angle of the accretion disk has an influence on the type of soft excess observable in the X-ray spectra. It is anyway likely that some of the reported soft X-ray excesses in Seyfert galaxies are indeed caused by clumpy (neutral or ionized) absorbers, which allow a portion of the primary flux emitted by the central X-ray source to reach the observer directly. Thus the soft excess might simply be related at least in some cases to an incorrect absorption model, which over-estimates the absorbed flux below 2 keV.

New broad band X-ray observations of these three Seyfert galaxies, e.g. by *Suzaku*, would be fundamental to probe the hypothesis that the absorption is responsible for the month scale

variability, and to give better limits to the sizes and locations of the absorbers.

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A γ -ray view of AGN

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In the last couple of years, thanks to the launch of the *Fermi* satellite (Sect. 6.1), a large number of new γ -ray sources has been detected (Sect. 6.2), and a giant leap forward has been made in the understanding of the γ -ray sky. Besides the observational constraints *Fermi* observations have supplied to assess the validity of theoretical models (e.g., Sect. 6.3), the study of the extragalactic γ -ray sky has provided few surprises as the detection of misaligned AGN, of a new class of radio-loud NLS1s and of few radio-quiet Seyfert galaxies (Sect. 6.4). In this chapter we will first review the characteristics of the *Fermi* satellite, some of its main finding in the field of AGN, and then we will introduce our work on the subject, which includes the first detection at γ -rays of the well known Seyfert 2 NGC 1068, and a detailed study of the radio to γ -ray SEDs of NGC 1068 and NGC 4945 (Sect. 6.5).

6.1 The Fermi gamma-ray telescope

The *Fermi* gamma-ray Space Telescope was launched on June 11th 2008, and it is the latest γ -ray NASA mission. *Fermi* has two instruments on board: the Large Area Telescope (LAT, Atwood et al. 2009, Sect. 6.1.1) and the Gamma-ray Burst Monitor (GBM, Meegan et al. 2009, Sect. 6.1.2). *Fermi* is the successor of the Energetic Gamma-Ray Experiment Telescope (*EGRET*) on board the Compton Gamma-Ray Observatory (Thompson et al. 1993).

6.1.1 LAT

LAT is an imaging high-energy telescope, it uses the pair-conversion technique (Fig. 6.1) and it covers the range 20 MeV to > 300 GeV. The LAT consists of a 4×4 array of identical towers, and each 40×40 cm² tower includes a tracker, a calorimeter and the data acquisition module. The tracking detector consists of 18 layers of silicon strip detectors. The calorimeter in each tower consists of eight layers of 12 CsI bars which are read out by photodiodes. The incident radiation passes through an anti-coincidence shield, and then through thin layers of high atomic number matter, which causes the

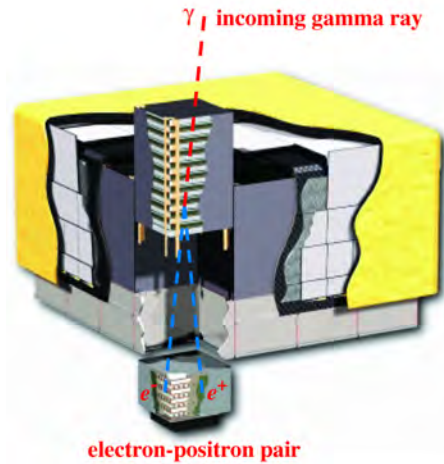


Figure 6.1: Schematic view of the *Fermi*/LAT (Atwood et al. 2009).

conversion of photons into $e^+ - e^-$ pairs. The trajectories of the resulting electrons and positrons are then measured by particle tracking detectors, and their energies are measured by a calorimeter.

LAT offers a major increase in sensitivity over EGRET and the Italian Space Agency Astro-rivelatore Gamma a Immagini Leggero (*AGILE* Tavani et al. 2008). The FoV of LAT covers $\sim 20\%$ of the sky, and in sky-survey mode (which is the main observing mode of *Fermi*), the LAT observes the entire sky every ~ 3 hours, providing effectively uniform exposure on the timescale of days.

6.1.2 GBM

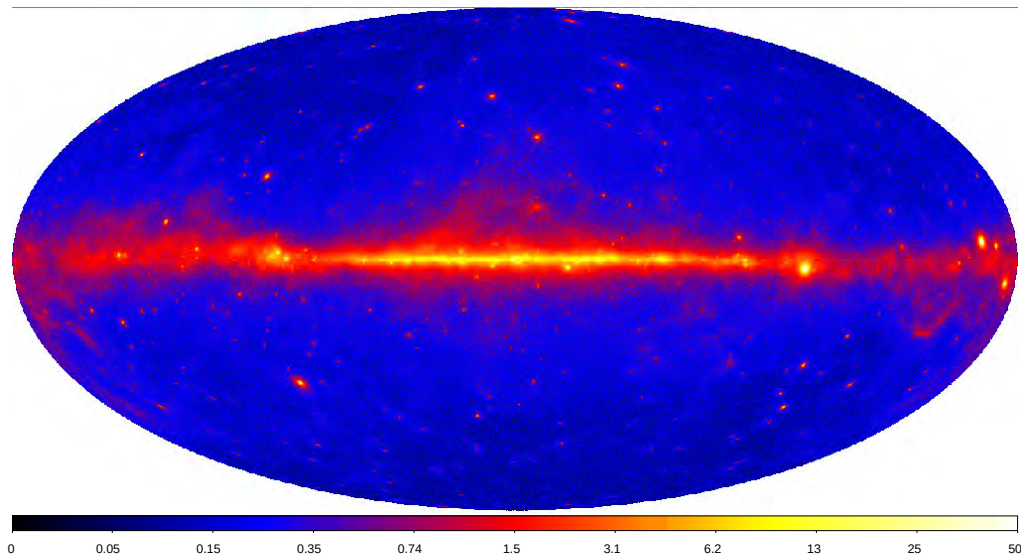


Figure 6.2: Sky map of the energy flux of LAT after two years of observations. The flux is in the 100 MeV–10 GeV energy range, in units of $10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Image taken from the second *Fermi*/LAT catalogue (The *Fermi*-LAT Collaboration 2011a).

The GBM is mostly used for Gamma-ray bursts, and it includes two sets of detectors: twelve sodium iodide (NaI) scintillators, and two cylindrical bismuth germanate (BGO) scintillators. The NaI detectors provide burst triggers, and are more sensitive at low energies (from a few keV to ~ 1 MeV). The BGO detectors cover the range 150 keV to 30 MeV.

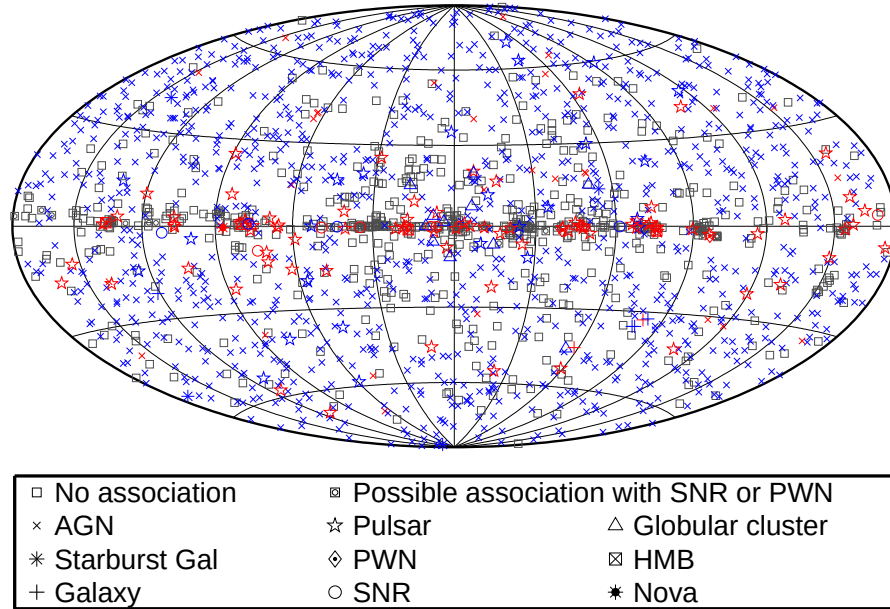


Figure 6.3: Distribution (in Galactic coordinates) of the sources reported in the second *Fermi*/LAT catalogue ([The Fermi-LAT Collaboration 2011a](#)). Identified sources are shown with a red symbol, associated sources in blue.

6.2 The Fermi catalogs

The first *Fermi*/LAT catalogue ([Abdo et al. 2010b](#)) contains all the 1451 sources detected within the first 11 months of operations. Of these, a large fraction ($\sim 50\%$) were not associated to any known source, while the rest were almost equally divided in Galactic ($\sim 26\%$) and extragalactic sources ($\sim 24\%$). Amongst the Galactic sources 16% were possibly associated to pulsars, 2% to supernovae remnants, 1% to magnetars, 2% to globular clusters and 4.7% to other types of binaries. Not surprisingly most of the extragalactic sources detected are beamed objects as blazars (15%), while the rest might be associated to misaligned sources (i.e. jetted sources not seen pole-on, 3.6%), starburst galaxies ($\sim 1\%$), clusters of galaxies ($\sim 3.3\%$) and dwarf spheroidals ($\sim 1\%$). The association of *Fermi*/LAT γ -ray sources to optical counterparts is not an easy task due to the large errors on the position at these energies.

Very recently (August 2011) the second *Fermi*/LAT catalogue ([The Fermi-LAT Collaboration 2011a](#)) has been released (Figs. 6.2 and 6.3). The catalogue contains 1873 sources, of these 127 are firmly identified, 1170 are reliably associated with known counterparts (and possible γ -ray sources), while the remaining 576 have not been identified or associated to any source. Amongst the firmly identified sources most (97) are Galactic objects (mostly pulsars, recognized by pulsation), while the rest are mainly blazars. Amidst the sources for which counterparts could only be associated, 87 are

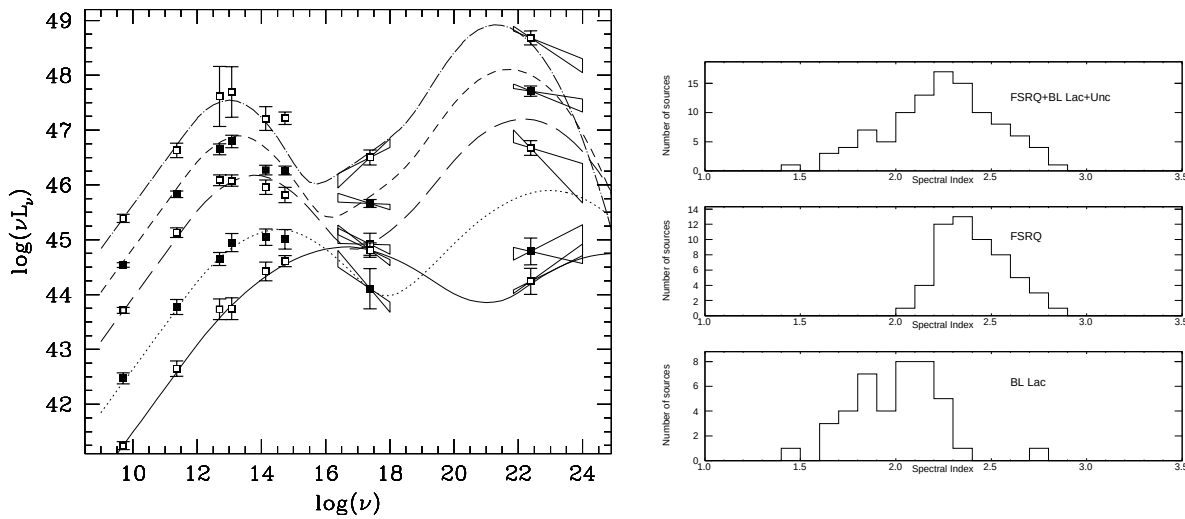


Figure 6.4: *Left panel:* the average SED of different classes of blazars (Fossati et al. 1998). From up to down the curves represent FSRQs, LBLs, IBLs and HBLs. *Right panel:* Photon index distribution of the different groups of blazars observed by *Fermi*/LAT during its first three months of operations (Abdo et al. 2009a).

pulsars or supernova remnants, 11 globular clusters, 428 BL Lacs, 353 FSRQ, 10 non blazar AGN, 10 radio galaxies, 5 Seyfert galaxies, 257 AGN of unknown type, and 9 normal or starburst galaxies.

6.3 Fermi observations of blazars

The spectral energy distributions (SED) of blazars are well known to be double peaked, with one peak in the IR to X-ray range, and another one at higher energies, in the MeV to GeV band. The low energy peak is believed to be due to synchrotron emission, while the high energy one to the Comptonization of some seed photons. In the synchrotron self-Compton (SSC) scenario these seed photons are produced in the jet itself, while in the external Compton models they are produced in the accretion disk, in the broad line region or in the dusty torus. BL Lacs are usually divided into high-frequency-peaked (HBL), intermediate-frequency-peaked (IBL) and low-frequency-peaked (LBL), depending on the energy of their peaks. Amongst the blazars, FSRQs are the most luminous, followed by LBLs and IBLs, while HBLs are the least luminous sources.

Fossati et al. (1998) remarked that in blazars the frequency of the SED peaks decreases with increasing luminosity, while the distance between the two peaks is almost constant (*left panel* of Fig. 6.4). They also found that the ratio between the inverse Compton and the synchrotron peak fluxes increases with increasing luminosity. An interpretation to this scaling of the SEDs with the luminosity, usually called the *blazar sequence*, was given by Ghisellini et al. (1998). They explained the sequence as being due to an increasing importance of the external radiation field going from HBLs to FSRQs. The electron cooling would be less efficient in HBLs, and dominated by synchrotron processes. The weakness of the external field in BL Lacs is also confirmed by the fact that optical emission lines are rarely observed in these objects. At the other end of the sequence, FSRQs would have a very intense external radiation field, which would cool down more efficiently the electron, shifting the SED peaks to lower energies. More recently, Ghisellini & Tavecchio (2008) proposed that both the jet power and the properties of the SEDs in blazars are ruled by two parameters, the black

hole mass and the accretion rate.

The *Fermi*/LAT catalogue of bright AGN, released after 3 months of observations (Abdo et al. 2009a) contained 58 FSRQs and 42 BLLacs. Fitting the γ -ray spectra with a single power law, a distinct separation between the two classes was found, with FSRQs being softer (*right panel* of Fig. 6.4). The divide between the two types of blazar was found at $\Gamma \sim 2.2$. This difference was confirmed by both the first (Abdo et al. 2010a), and the second (Ackermann et al. 2011) *Fermi*/LAT AGN catalogue. In particular the latest AGN catalogue showed that FSRQs have an average value of the photon index of $\langle \Gamma \rangle = 2.42$, LBL of $\langle \Gamma \rangle = 2.17$, IBL of $\langle \Gamma \rangle = 2.14$ and HBL of $\langle \Gamma \rangle = 1.90$. Ghisellini et al. (2009) suggested that this separation is due to different radiative cooling of the Comptonizing electrons due to distinct accretion regimes. In their scheme in BL Lacs ($\dot{M} < \dot{M}_{\text{divide}}$) accretion is radiatively inefficient, while in FSRQ ($\dot{M} > \dot{M}_{\text{divide}}$) the accretion disk is radiatively efficient. In BL Lacs the jet would propagate in a medium photon-starved medium, and this would make the emitting electrons accelerate in the jet cool less, enabling them to reach very high energies. Moreover the low luminosity of the disk would not be able to ionize enough matter to produce the BLR, which would also explain why BL Lacs normally show an almost featureless optical continuum.

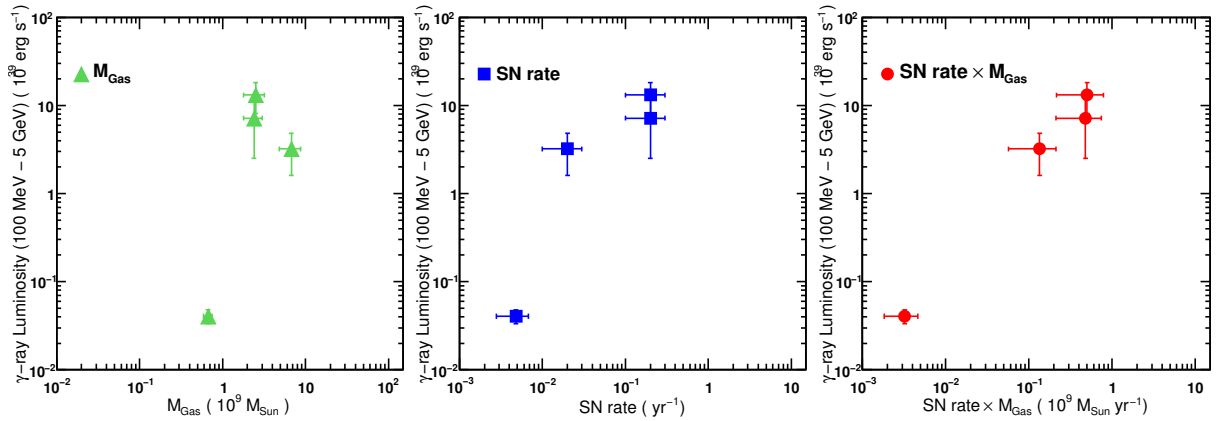


Figure 6.5: Scatter plot of the γ -ray luminosity L_γ and the total gas mass M_{gas} (*left panel*), of L_γ and the supernova rate R_{SN} (*central panel*), and of L_γ and $R_{\text{SN}} \times M_{\text{gas}}$ (*right panel*). Figure taken from Abdo et al. (2010c).

6.4 Fermi observations of non-blazar AGN

Besides blazars, *Fermi*/LAT detected also a small fraction of misaligned objects (as FRI and FR II radio galaxies), radio-loud NLS1s and a few radio-quiet starburst galaxies, some of them hosting AGN.

Amongst sources detected by *Fermi*/LAT and associated to misaligned radio-loud AGN after 15 months of operations (Abdo et al. 2010d), 7 are FRI radio galaxies, 2 FR II radio galaxies and 2 are steep spectrum radio quasars. In the γ -ray band misaligned AGN are distinguished from the aligned blazars by their soft spectra and very low γ -ray luminosities. Seven of these sources have $\Gamma > 2.3$, and the spectra of all of them could be well represented by a single power law, with the exception of NGC 1275, which requires a softening above $\sim 3 \text{ GeV}$. Of these 11 misaligned AGN, the only one that shows a significant variability in the γ -ray band is NGC 1275.

While most NLS1s are radio-quiet, a small percentage of them is well known to show a significant radio emission. One of the biggest surprises of *Fermi*/LAT was the detection of a new variable γ -ray source, which appeared to be associated to the radio-loud NLS1 PMN J0948+0022 (Abdo et al. 2009b). This source shows a strong, compact and variable radio emission, which suggests presence of a relativistic jet. The multi-wavelength campaign carried out in March-July 2009 showed a coordinated variability at different energies, which confirmed PMN J0948+0022 to be the real counterpart of the *Fermi*/LAT source (Abdo et al. 2009c). Following this, 3 other radio-loud NLS1s (PKS 1502+036, 1H 0323+342, PKS 2004-447) were detected by *Fermi*/LAT, which led to identify radio-loud NLS1s as a new class of γ -ray emitters (Abdo et al. 2009d). These objects have relatively low masses ($10^6 - 10^8 M_\odot$) and high accretion rates (up to $\lambda_{\text{Edd}} \simeq 0.9$), and are thought to be viewed pole-on with respect to the jet. Recently, it has been proposed that PKS 0558-504, the brightest radio-loud NLS1, belongs to the misaligned parent population of radio-loud NLS1s detected by *Fermi*/LAT (Gliozzi et al. 2010). If confirmed, this would strengthen the hypothesis that radio-loud NLS1s are the low mass cousins of blazars and radio galaxies.

The other class of non-blazar AGN detected by *Fermi*/LAT were starburst galaxies. Already before the launch of *Fermi* these objects were known to be γ -ray emitters, thanks to the detections of NGC 253 and M 82 by *Veritas* (e.g. VERITAS Collaboration et al. 2009) and *H.E.S.S.* (e.g. Acero et al. 2009). Both objects were found to have luminosities in the 100 MeV to 5 GeV energy band of $\sim 10^{40} \text{ erg s}^{-1}$. There is probably a clear link between cosmic rays and the γ -ray emission: cosmic rays are thought to be accelerated in supernova remnant shocks (Ginzburg & Syrovatskii 1964), and these processes are expected to produce significant quantities of γ -rays. *Fermi*/LAT observations of starburst galaxies (Abdo et al. 2010c) provided a very important insight on the parameters driving the production of γ -rays. While no correlation was found between the 100 MeV-5 GeV luminosity L_γ and the total gas mass M_{gas} , the data suggested a possible weak correlation between the supernova rate R_{SN} and L_γ . However, the most important finding was the discovery of a strong correlation between $R_{\text{SN}} \times M_{\text{gas}}$ and L_γ (Fig. 6.5). This can be explained by the models that link the γ -ray production to cosmic-ray processes, because they depend on both the supernova rate and on the mass of the gas present.

6.5 *Fermi*/LAT observations of Seyfert 2 galaxies

Aiming at expanding the sample of Seyfert 2 galaxies detected by *Fermi*/LAT, we looked for possible γ -ray emission from the brightest objects of this type. We found evidence of emission from the two nearby Seyfert 2s NGC 4945 and NGC 1068. Analyzing the SED of these two objects we found that while for NGC 4945 the γ -ray emission is consistent with that of other starburst galaxies, NGC 1068 is too bright to be explained by enhanced star formation, and we propose a leptonic scenario to explain its high luminosity in the *Fermi*/LAT band. These results are reported in Lenain et al. (2010). Teng et al. (2011) looking for γ -ray emission from 491 Seyfert galaxies detected by *Swift*/BAT in 2.1 years of *Fermi*/LAT data confirmed the detection of both NGC 4945 and NGC 1068, while no other sources of their BAT sample was detected. The nearby galaxies belonging to the local group also do not appear to show any γ -ray emission, as argued by Lenain & Walter (2011), who analyzed ~ 2.5 years of *Fermi*/LAT data around these objects. In a recent paper of the *Fermi* collaboration (The Fermi-LAT Collaboration 2011b) two new possible associations of radio-quiet Seyfert galaxies (the Sy2 ESO 323-077 and the Sy1 NGC 6814) to γ -ray sources have been found. Several more of these γ -loud radio-quiet AGN will probably be detected in the next decade, thanks the advent of the *Cherenkov Telescope Array*.

Seyfert 2 galaxies in the GeV band: jets and starburst

J.-P. Lenain, C. Ricci, M. Türlér, D. Dorner, and R. Walter

ISDC Data Centre for Astrophysics, Observatoire de Genève, Université de Genève, Chemin d'Ecogia 16, 1290 Versoix, Switzerland
 e-mail: jean-philippe.lenain@unige.ch

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ABSTRACT

Context. The *Fermi*/LAT collaboration recently reported the detection of starburst galaxies in the high energy γ -ray domain, as well as radio-loud narrow-line Seyfert 1 objects.

Aims. Motivated by the presence of sources close to the location of composite starburst/Seyfert 2 galaxies in the first year *Fermi*/LAT catalogue, we aim at studying high energy γ -ray emission from such objects, and at disentangling the emission of starburst and Seyfert activity.

Methods. We analysed 1.6 years of *Fermi*/LAT data from NGC 1068 and NGC 4945, which count among the brightest Seyfert 2 galaxies. We search for potential variability of the high energy signal, and derive a spectrum of these sources. We also analyse public *INTEGRAL* IBIS/ISGRI data over the last seven years to derive their hard X-ray spectrum.

Results. We find an excess of high energy γ -rays of 8.3σ and 9.2σ for 1FGL J0242.7+0007 and 1FGL J1305.4–4928, which are found to be consistent with the position of the Seyfert 2 galaxies NGC 1068 and NGC 4945, respectively. The energy spectrum of the sources can be described by a power law with a photon index of $\Gamma = 2.31 \pm 0.13$ and a flux of $F_{100 \text{ MeV} - 100 \text{ GeV}} = (8.60 \pm 2.27) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for NGC 1068, while for NGC 4945, we obtain a photon index of $\Gamma = 2.31 \pm 0.10$ and a flux of $F_{100 \text{ MeV} - 100 \text{ GeV}} = (1.58 \pm 0.32) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. For both sources, we detect no significant variability nor any indication of a curvature of the spectrum. While the high energy emission of NGC 4945 is consistent with starburst activity, that of NGC 1068 is an order of magnitude above expectations, suggesting dominant emission from the active nucleus. We show that a leptonic scenario can account for the multi-wavelength spectral energy distribution of NGC 1068.

Conclusions. High energy γ -ray emission is revealed for the first time in a Seyfert 2 galaxy. If this result is confirmed in other objects, new perspectives would be opened up into the GeV band, with the discovery of a new class of high energy γ -ray emitters.

Key words. gamma rays: galaxies – galaxies: Seyfert – galaxies: individual: NGC 1068 – galaxies: individual: NGC 4945 – radiation mechanisms: non-thermal

1. Introduction

Somewhat unexpectedly, the *Fermi*/LAT collaboration reported the discovery of four radio-loud narrow-line Seyfert 1 galaxies (Abdo et al. 2009a,b), suggesting that these objects, previously undetected at high energies, could constitute a new class of high energy emitters. Extending this idea to Seyfert 2 galaxies, we show here that two such active galactic nuclei (AGN) among the closest and brightest in the X-ray sky, NGC 1068 and NGC 4945, are detected at high energies using *Fermi*/LAT data. We investigate whether this emission is dominated by AGN or starburst activity.

NGC 1068 is an archetypal Seyfert 2 galaxy, located at $z = 0.003786$, i.e. 14.4 Mpc away, and harbours a hidden Seyfert 1 core. It was used by Antonucci & Miller (1985) to propose the AGN unification. Given the proximity of this spiral galaxy, its extension is well observable in visible light, and it is the closest, as well as one of the brightest, Seyfert 2 galaxy. This source exhibits both AGN and starburst activities in its central region (e.g. Lester et al. 1987; Jaffe et al. 2004). A dusty torus lies in its central part, dominating the soft X-ray emission by reflection from the central nucleus. A circumnuclear starburst region is located at ~ 1 kpc from the core, dominating the infrared emission of the broadband spectral energy distribution (SED) (Thronson et al. 1989).

Caproni et al. (2006) studied the morphology of the inner warped disc, likely due to the Bardeen-Petterson effect, using VLBA observations. Cotton et al. (2008) showed that the emission at 43 GHz from the so-called S1 central radio component is more likely dominated by thermal emission from the hot inner region of the obscuring torus, although Gallimore et al. (2004) pointed out that the North-East radio component could be dominated by synchrotron emission. This is corroborated by the results of Hönig et al. (2008), who argued that the radio emission from the core could be dominated by synchrotron or free-free emission, while near-IR data are dominated by the thermal emission from the dusty torus. Thanks to near-IR interferometric data using the MIDI instrument at the VLT, Raban et al. (2009) found the torus to be composed of two thermal components at 300 K and 800 K.

In the high energy domain, *Chandra* observations of the core of NGC 1068 (Ogle et al. 2003) showed that the X-ray emission is due to photoionisation in the extended, clumpy narrow line region. Matt et al. (2004) showed that the neutral reflector is Compton-thick, using *XMM-Newton* observations.

Motivated by the presence of a *Fermi*/LAT source, 1FGL J0242.7+0007, in the region of NGC 1068 in the 11-months *Fermi*/LAT catalogue (1FGL, Abdo et al. 2010a), with no proposed counterpart in radio nor in γ -rays, we analyse

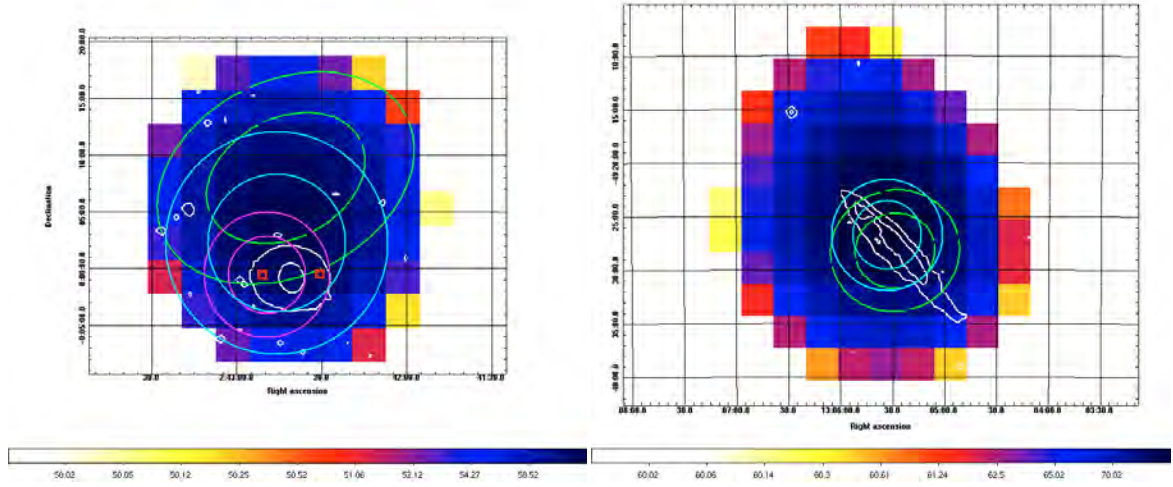


Fig. 1. Left: TS map of NGC 1068 between 100 MeV and 100 GeV. The green ellipses show the 68% and the 95% position errors from the 1FGL catalogue, the cyan and magenta circles show respectively the position error (at 68% and 95% CL) for the full data set with all the events accounted for, and for front events only. The white contours are taken from an optical image from the Digital Sky Survey, showing the extent of the Seyfert galaxy. The red boxed points denote the position of the two quasars nearby NGC 1068 (see text in Sect. 4 for more details). Right: same as left panel, for NGC 4945. For clarity, we only present here the position error circle for all events.

here 1.6 years of data from the *Fermi*/LAT instrument, in order to better constrain the origin and properties of the γ -ray emission in this region.

NGC 4945 is also a Seyfert 2 galaxy at $z = 0.001908$ exhibiting starburst activity in its central region (Iwasawa et al. 1993; Moorwood & Oliva 1994). Its emission extends up to soft γ -rays (Petty et al. 2009), as observed by *INTEGRAL*/SPI. It is one of the brightest hard X-ray AGN (see Itoh et al. 2008, and references therein, and Ricci et al., in prep.). NGC 4945 was found to be a Compton thick AGN, based on *GINGA* (Iwasawa et al. 1993) and *INTEGRAL* observations (Beckmann et al. 2009). This source was already reported as a high-energy γ -ray emitter by the *Fermi*/LAT collaboration in the 11-months catalogue (Abdo et al. 2010a), although the authors did not conclude whether this high energy emission is due to starburst or AGN activity.

We present here a detailed analysis of 1.6 years of *Fermi*/LAT data of NGC 4945 to compare the results to those of NGC 1068.

2. *Fermi*/LAT data analysis

We present in the following our analysis of *Fermi*/LAT data on the sources 1FGL J0242.7+0007 and 1FGL J1305.4–4928 reported in the 1FGL catalogue. We will show that these sources can be associated to the Seyfert 2 objects NGC 1068 and NGC 4945, respectively.

We analysed ~ 1.6 yr of *Fermi*/LAT data, spanning from August 4, 2008 to March 15, 2010, from a region of interest of 10° in radius around NGC 1068, using the publicly available *Science Tools*¹, and we followed the unbinned likelihood analysis scheme presented in Atwood et al. (2009). We always used the so-called “diffuse class” events, which are the events detected by the *Fermi*/LAT with the highest probability to be γ -ray photons, and the P6V3 instrument response.

¹ <http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/>

Using the *gtlike* tool and assuming a power-law shape for the source spectrum, the Test Statistic (TS, Mattox et al. 1996) of the likelihood analysis is 68.6, corresponding approximately to a 8.3σ source detection in the 100 MeV–100 GeV range. The corresponding TS map is shown in Fig. 1. The best-fit location of the source using the *gtfindsrc* tool is $\alpha_{J2000} = 2^h42^m46^s$, $\delta_{J2000} = 0^\circ2'14''$ with an error circle radius of $\sim 6'.1$ (68% confidence level, CL), and is fully compatible with the position reported in the 1FGL catalogue. The maximum photon energy detected from the source is 20.0 GeV, located at $0'.48$ from the position of NGC 1068.

Given the energy dependence of the point spread function (PSF) of *Fermi*/LAT, we performed a second analysis, using only front events for which the PSF is narrower². Front events are those converted in the top layers of the tracker of the LAT instrument (see Atwood et al. 2009, for more details). In this latter analysis, the TS of the source is 42, still sufficient to derive a position of the *Fermi*/LAT excess. The best-fit position of the source is then $\alpha_{J2000} = 2^h42^m49^s$, $\delta_{J2000} = -0^\circ0'30''$, with an error circle radius of $\sim 3'.4$ (68% CL), which is only $2'.1$ away from the nominal position of NGC 1068. This latter result on the position is only marginally compatible with the position reported in the 1FGL catalogue.

Given the angular distance between the *Fermi* source 1FGL J0242.7+0007 and NGC 1068, and its optical extension of $\sim 6'.5$, we propose that this *Fermi* source is actually associated with the Seyfert 2 galaxy NGC 1068.

All the sources reported in the *Fermi*/LAT 11-months catalogue (Abdo et al. 2010a) within a radius of 15° around NGC 1068 were included in the likelihood analysis, and modelled with power-law spectra. We first identify the sources not contributing significantly to the likelihood and remove them from the model. The spectral parameters of the remaining sources are left freely varying. For NGC 1068, we obtain $F_{100 \text{ MeV} - 100 \text{ GeV}} = (8.60 \pm 2.27) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ and

² See http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm

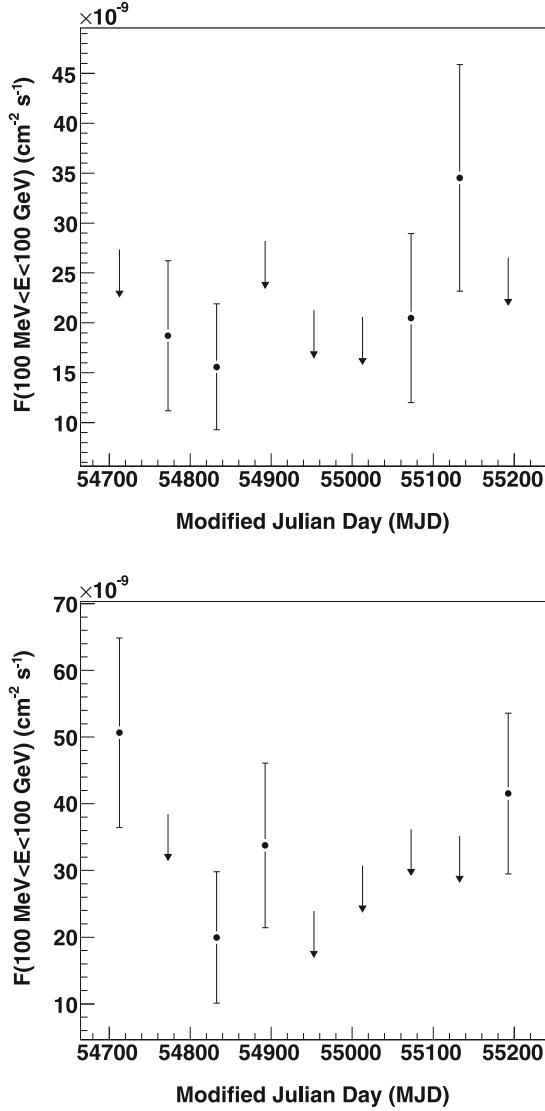


Fig. 2. *Top:* light curve of NGC 1068 in the 100 MeV–100 GeV energy band. The time bins are 60 days wide, and the arrows represent 95% CL upper limits. *Bottom:* same as top for NGC 4945. In both sources, no significant variability is visible.

$\Gamma = 2.31 \pm 0.13$. We also tried to fit the data with a broken power-law or a log parabola, but this did not improve the likelihood.

We performed two other analyses, focussing on the 1–100 GeV band, for all events and for front events only. This energy band benefits from a better PSF compared to lower energy events, despite a much smaller count rate due to the soft spectrum of the source. We obtain consistent results to those reported above, including comparable position error on the source.

We also investigated the potential variability, performing a likelihood analysis in different time intervals, for a time bin of 60 days, letting only the normalisation of the source free to vary. As shown in Fig. 2, no significant variability was detected.

We followed the same procedure for the analysis of *Fermi*/LAT data in the region of NGC 4945, for the source 1FGL J1305.4–4928. The likelihood analysis on NGC 4945 results in a TS of 85.3 in the 100 MeV–100 GeV band, equivalent

to a 9.2σ detection. Assuming a power-law shape on the source energy spectrum, a photon index of $\Gamma = 2.31 \pm 0.10$ and a flux of $F_{100 \text{ MeV}-100 \text{ GeV}} = (1.58 \pm 0.32) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ are found. The highest energy photon detected is 20.7 GeV, located at 0°22' from NGC 4945. As for NGC 1068, the use of a broken power-law or a log parabola did not improve the likelihood, and no significant variability was found in the data (see Fig. 2), which are statistically consistent with a constant for both sources.

The analysis of the whole data set gives a position of $\alpha_{J2000} = 13^{\text{h}}05^{\text{m}}33^{\text{s}}$, $\delta_{J2000} = -49^{\circ}26'44''$ with an error circle radius of 3'2 (68% CL), only 1'6 away from the nominal position of NGC 4945, while the analysis for the front events only results in a position of $\alpha_{J2000} = 13^{\text{h}}05^{\text{m}}34^{\text{s}}$, $\delta_{J2000} = -49^{\circ}26'49''$ with an error circle radius of 3'3 (68% CL). The source position is fully compatible with the results reported in the 1FGL catalogue.

It should also be noted that for both sources, the spectral parameters found are fully compatible with the ones reported in the 1FGL catalogue.

3. INTEGRAL data analysis

For the extraction of the IBIS/ISGRI spectra, we used all the public data obtained by *INTEGRAL* as of May 2010, for a total of 564 and 865 pointings (ScWs) on NGC 1068 and NGC 4945, respectively. The typical exposure of each pointing is $(1-3) \times 10^3$ s, and only ScWs with an effective exposure longer than 200 s were kept, spanning times between December 30, 2002 (revolution 26) and April 7, 2009 (revolution 791). The total exposure is of 622 ks for NGC 1068, and of 927 ks for NGC 4945. In the large 17–80 keV band, NGC 1068 and NGC 4945 were detected with a significance of 14.0σ and 138.8σ , respectively.

IBIS/ISGRI has a large field of view of $29^{\circ} \times 29^{\circ}$ with a spatial resolution of 12 arcmin. Note that because of the nature of coded mask imaging the whole sky image taken by the instrument has to be considered in the analysis, because all sources in the field of view contribute to the signal (Caroli et al. 1987).

The ISGRI data were reduced using the *INTEGRAL* Offline Scientific Analysis software³ version 9.0, publicly released by the *INTEGRAL* Science Data Centre (Courvoisier et al. 2003). The analysis of the IBIS/ISGRI data is based on a cross-correlation procedure between the recorded image on the detector plane and a decoding array derived from the mask pattern. We created mosaic images of all pointings in 10 energy bins, and extracted the spectra using *mosaic_spec*.

We used the latest detector redistribution matrix files (RMF) and calculated the ancillary response functions (ARFs) with a weighted average of the 9 available ARFs, based on the number of ScWs within the validity time of a particular ARF.

We have also checked the *Swift*/BAT (Barthelmy et al. 2005) spectra of the two sources. The 18 months *Swift*/BAT spectra have been extracted from the BAT archive (Segreto et al. 2010) served by the HEAVENS source results archive (Walter et al., in prep.). The ISGRI and BAT spectra are in good agreement for both sources.

A simple power-law fit to the combined *INTEGRAL*/ISGRI and *Swift*/BAT data of NGC 1068 using Xspec results in $\chi^2/\text{d.o.f.} = 10.21/11$. The resulting photon index is $\Gamma = 2.08^{+0.21}_{-0.19}$, and the flux density is $F_{17-80 \text{ keV}} = 1.86^{+0.15}_{-1.23} \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (both 90% CL).

The hard X-ray spectrum for the combined ISGRI and BAT data of NGC 4945 is not well reproduced by a simple

³ <http://www.isdc.unige.ch/integral/>

Table 1. Comparison of the starburst properties of NGC 1068 with NGC 4945, NGC 253, M 82, the LMC and the Milky Way.

Source	d (Mpc)	Γ^a	L_γ^a (10^{39} erg s $^{-1}$)	R_{SN}^b (yr $^{-1}$)	M_{gas}^c ($10^9 M_\odot$)	L_{IR} (10^{44} erg s $^{-1}$)	$L_{5 \text{ GHz}}$ (10^{38} erg s $^{-1}$)	$L_\gamma/L_{5 \text{ GHz}}$
NGC 1068	14.4	2.31 ± 0.13	170 ± 32	0.20 ± 0.08	4.4	2.7	16.6	102
NGC 4945	3.6	2.30 ± 0.10	19.5 ± 2.9	0.1–0.5	4.2	1.4	2.2	89
NGC 253	3.9	1.95 ± 0.4	7.2 ± 4.7	0.2 ± 0.1	2.5 ± 0.6	1.0	2.0	36
M 82	3.6	2.2 ± 0.2	13.0 ± 5.0	0.2 ± 0.1	2.5 ± 0.7	1.2	3.0	43
LMC	0.049	–	0.041 ± 0.007	0.005 ± 0.002	0.67 ± 0.08	0.016	0.017	24
Milky Way	–	–	3.2 ± 1.6	0.02 ± 0.01	6.5 ± 2.0	0.5	0.36	89

Notes. ^(a) Photon indices and luminosities in the γ -ray band from [Abdo et al. \(2010c\)](#) for M 82, NGC 253, the LMC and the Milky Way. The γ -ray luminosities are given in the 100 MeV–5 GeV band, and the photon indices Γ are given above 200 MeV for an easier comparison with the results from [Abdo et al. \(2010c\)](#).

^(b) SN rate estimates from [Wilson & Ulvestad \(1982\)](#); [Blietz et al. \(1994\)](#); [Mannucci et al. \(2003\)](#) for NGC 1068, from [Lenc & Tingay \(2009\)](#) for NGC 4945, and from [Abdo et al. \(2010c\)](#), and references therein for M 82, NGC 253, the LMC and the Milky Way.

^(c) Gas mass estimates from [Sage et al. \(1990\)](#) for NGC 1068, from [Weiß et al. \(2008\)](#) for NGC 4945, and from [Abdo et al. \(2010c\)](#), and references therein for M 82, NGC 253, the LMC and the Milky Way.

power-law, and a more complex model is required. A power-law with exponential cut-off yields $\chi^2/\text{d.o.f.} = 89.6/9$, which is not satisfactory, even though the data clearly show a curvature. Instead, an absorbed power-law yields $\chi^2/\text{d.o.f.} = 54.77/9$, with a photon index of $\Gamma = 2.03 \pm 0.04$, and an intrinsic absorption column $N_{\text{H}} = (6.66 \pm 0.45) \times 10^{24} \text{ cm}^{-2}$. Even though the χ^2 is not entirely satisfactory, we will use the latter spectral model to build the broadband SED of NGC 4945, because it provides a better description of the data. A detailed analysis of the hard X-ray spectral shape is beyond the scope of this paper.

4. Discussion

It shall be noted that two quasars are present in the field of view of NGC 1068. The quasar SDSS J024230.65-000029.6 ($z = 2.51$) lies ~ 2.4 from NGC 1068, and another quasar, SDSS J024250.98-000031.6 ($z = 2.18$, a.k.a. QSO 0240-0012), is ~ 2.6 away from NGC 1068. However, given their high redshift, it is unlikely that one of these objects could be at the origin of the high energy emission, although this can not be completely excluded. Indeed according to [Abdo et al. \(2010b\)](#), the highest redshift source detected by the *Fermi*/LAT is a flat spectrum radio quasar with a redshift of $z = 3.10$. Given the similarities of the high energy spectra of 1FGL J0242.7+0007 and NGC 4945, it appears however more likely that 1FGL J0242.7+0007 is associated with NGC 1068.

An obvious test to rule out the starburst origin of the high-energy emission would be to detect significant γ -ray variations from one of these objects, as the emission arising from starburst activity is expected to be steady. Due to the lack of statistics, no conclusions can be drawn about the variability of NGC 1068 or NGC 4945 from their light curves (see Fig. 2).

Another way to disentangle the starburst or AGN origin of the high-energy emission from these galaxies is to compare their γ -ray luminosity with those of the famous starburst galaxies NGC 253 and M 82, which are also detected in the very high energy domain by H.E.S.S. ([Acero et al. 2009](#)) and VERITAS ([Acciari et al. 2009](#)), respectively. Both have a luminosity in the 100 MeV–5 GeV band of the order of $\sim 10^{40} \text{ erg s}^{-1}$, as detected with *Fermi* ([Abdo et al. 2010c](#)). Computing the luminosities of NGC 1068 and NGC 4945 in the same energy band, for comparison, we obtain $1.7 \times 10^{41} \text{ erg s}^{-1}$ and $2.0 \times 10^{40} \text{ erg s}^{-1}$, respectively.

Following [Abdo et al. \(2010c\)](#), we compare the supernova rate R_{SN} , the total gas mass M_{gas} and the γ -ray luminosities of

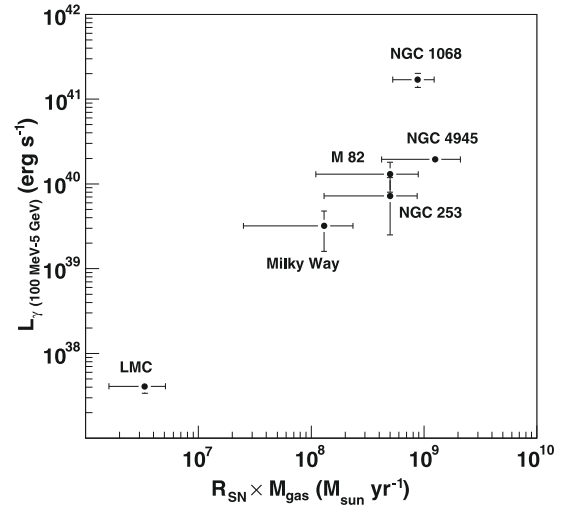


Fig. 3. Relationship between SN rate, total gas mass and γ -ray luminosity of NGC 1068, NGC 4945, NGC 253, M 82, the LMC and the Milky Way.

NGC 1068 and NGC 4945 to the ones of NGC 253, M 82, the Large Magellanic Cloud (LMC) and the Milky Way, as well as their infrared and radio luminosities (see Table 1). These objects are the only extragalactic sources which are not AGN known to emit high energy γ -rays. Models attributing the γ -rays to cosmic-ray processes, as expected in a starburst galaxy, depend on the product $M_{\text{gas}}R_{\text{SN}}$. Adding NGC 1068 and NGC 4945 to this picture (see Fig. 2 in [Abdo et al. 2010c](#)), and assuming that their γ -ray emission is entirely due to starburst activity, confirms the general trend, but we only find a correlation coefficient of 0.44 for a linear relationship between $M_{\text{gas}}R_{\text{SN}}$ and L_γ (see Fig. 3), corresponding to a null hypothesis probability as high as 38%, although the number of considered sources is obviously too small to definitely conclude.

The γ -ray luminosity and the SN rate of NGC 4945 are fully consistent with those of NGC 253 and M 82, hence even though this object is a composite starburst/AGN, its high energy emission detected using *Fermi* could be explained only in terms of its starburst activity. Concerning NGC 1068, the situation is more complex. Its SN rate is comparable to those of M 82 and NGC 253, but its radio and γ -ray luminosities are higher

Table 2. Model parameters for NGC 1068 and NGC 4945.

Source	Component ^a	δ_b	B (G)	r_b (cm)	T (K)	τL_{nuc} (erg s ⁻¹)	R (cm)	K (cm ⁻³)	n_1	n_2	γ_{break}	γ_{max}
NGC 1068	1	1.2	10^{-4}	2.0×10^{19}	130–520	1.5×10^{42}	2.2×10^{20}	12.5	2.2	3.3	10^4	10^6
NGC 1068	2	1.2	1	10^{15}	10^4	3.0×10^{41}	5×10^{14}	10^6	2.0	–	–	300
NGC 4945	2	1.2	1	2.6×10^{15}	10^4	5.0×10^{41}	5×10^{15}	10^6	1.5	–	–	160

Notes. ^(a) The component 1 refers to the model for the large outflow, while component 2 points to the model for the Seyfert emission in hard X-rays from the accretion disc.

by a factor ~ 10 . This would suggest that its high energy γ -ray emission is more likely dominated by the central AGN activity. Indeed, removing NGC 1068 from the sample of sources, the correlation coefficient for the relationship between $M_{\text{gas}} R_{\text{SN}}$ and the γ -ray luminosity becomes 0.95, with a null hypothesis probability of only $\sim 1\%$. This also tends to prove the peculiar role of NGC 1068 in this study. This is also strengthened by the fact that radio maps of NGC 1068 clearly show a structured jet, on parsec- and kiloparsec-scales, modelled by the outflow from the central AGN (see e.g. Gallimore et al. 2004, 2006). On the contrary, the radio morphology of NGC 4945 shows an extended emission consistent with the optical morphology tracing the edge-on galaxy (see e.g. Jones & McAdam 1992), indicating a starburst emission.

Assuming that the high energy emission of NGC 1068 is indeed due to the AGN activity, and taking a scenario similar to what was proposed in Lenain et al. (2008) where the jet is misaligned with respect to the line of sight, we consider here the possibility that the outflow in NGC 1068 could be a high energy emitter.

A large, mildly-relativistic zone of the wind-like outflow, at a few tenth of parsecs from the core, could emit high-energy γ -rays through external inverse Compton process (EIC) (see e.g. Begelman & Sikora 1987). At such distances, the infrared photon energy density is still high enough to ensure a significant emission while being not too important to prevent high optical opacity from pair production. At about 100 parsecs from the core, the magnetic field strength is also expected to be low, of the order of 10^{-4} G according to the estimate for the equipartition magnetic field of the radio component A, located at a projected distance of ~ 350 pc from the core of NGC 1068 (Pedlar et al. 1983). No significant short-term variability is expected from such a large emitting zone.

The stationary emission of a blob of plasma is modelled here through leptonic processes. The macrophysics of the blob is described by its bulk Doppler factor δ_b , radius r_b , and strength of the tangled magnetic field B filling it up. The energy distribution of the leptons is described by a broken power-law with the density normalisation K , the indices n_1 and n_2 , and the Lorentz factors of the individual particles γ_{min} , γ_{break} and γ_{max} , as follows:

$$N_e(\gamma) = \begin{cases} K\gamma^{-n_1} & \text{if } \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{break}} \\ K\gamma^{n_2-n_1}\gamma^{-n_2} & \text{if } \gamma_{\text{break}} \leq \gamma \leq \gamma_{\text{max}} \end{cases} \quad [\text{cm}^{-3}]. \quad (1)$$

These leptons emit through synchrotron self-Compton (SSC, see e.g. Ginzburg & Syrovatskii 1965) and EIC processes. The latter is described by the fraction of the core luminosity τL_{nuc} reprocessed by the emitting source (see Inoue & Takahara 1996), the temperature T of the seed radiation field described as a blackbody, and the distance R between the external radiation field and the re-emitting blob. Second order SSC emission (Rees 1967) is also accounted for in this model. More details on the model can

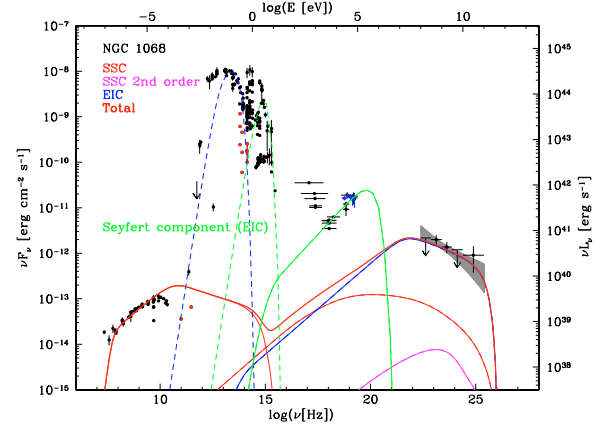


Fig. 4. Spectral energy distribution of NGC 1068, including the *Fermi*/LAT spectrum. The black and red points are archival data from the NED, the red ones denote data taken from the central region of NGC 1068. For clarity, we only show the *INTEGRAL* IBIS/ISGRI data in blue in the hard X-rays. The EIC model for the outflow is shown in blue, and the corresponding SSC emission is shown in thin red and magenta lines for first and second order components, respectively. The thick red line shows the sum of the different emission components from the large outflow. The EIC component from the accretion disc is shown in green.

be found in Katarzyński et al. (2001), Lenain et al. (2008), and Lenain (2009). We use $\gamma_{\text{min}} = 1$ in the following.

In Fig. 4, we present such a model with synchrotron emission responsible for the radio emission, while the *Fermi*/LAT data are interpreted as EIC emission with the infrared emission providing the seed photons, from a multi-temperature blackbody. We also show the contribution from the SSC process, which is negligible compared to the EIC emission at the highest energies. We note that the contribution of second order SSC is negligible in the case of our interpretation of the SED of NGC 1068. The model parameters are summarised in Table 2.

The hard X-ray spectrum observed with *INTEGRAL* does not seem to fit in this picture and we propose that this emission originates from EIC processes on another population of leptons, within hot plasma located in the vicinity of the accretion disc. The seed photons would then originate from the accretion disc itself as is usually invoked to explain the X-ray emission of Seyfert galaxies. Evidence for an accretion disc comes from the fact that the soft X-ray spectrum of NGC 1068, e.g. as observed with *XMM-Newton*, is dominated by thermal reflection emission (see e.g. Kinkhabwala et al. 2002; Pounds & Vaughan 2006). We checked that the synchrotron and the SSC emission from this component is negligible compared to the one from the large outflow described above.

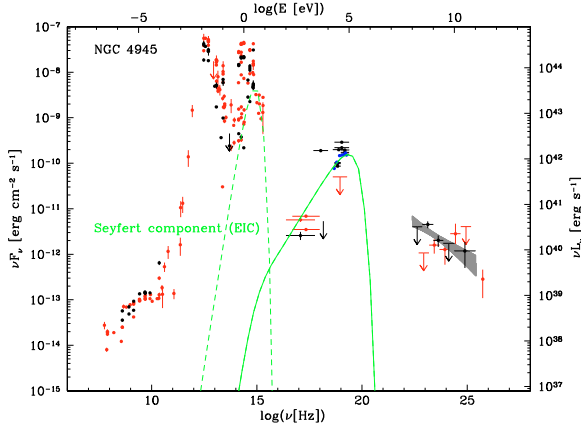


Fig. 5. Spectral energy distribution of NGC 4945, including the *Fermi*/LAT spectrum (black points). For clarity, we only show the *INTEGRAL* IBIS/ISGRI data in blue in the hard X-rays. The model for the EIC component from the accretion disc is shown in green. We show in red the data of NGC 253 as taken from the NED, with the *Fermi*/LAT spectrum published in Abdo et al. (2010c) as well as the H.E.S.S. flux measurement from Acero et al. (2009), for comparison. The two objects have clearly very similar SEDs. The luminosity axis on the right is given for NGC 4945.

It should be noted that imaging atmospheric Čerenkov telescopes have the ability to strongly constrain the highest energy part of the particle energy distribution. If the maximum energy of the leptons is $\gamma_{\max} \gtrsim 5 \times 10^6$, a significant signal could be detected from NGC 1068 with H.E.S.S., VERITAS, MAGIC, or the future Čerenkov Telescope Array (CTA) (CTA consortium 2010).

An alternative solution from our model would consist in interpreting the hard X-ray emission from *INTEGRAL* and the high energy γ -ray emission from *Fermi*/LAT as originating from the same spectral component. In this case, the overall high energy emission would be due to EIC process from the same lepton population. The spectral shapes of both *INTEGRAL* and *Fermi* data then strongly constrain the parameters on the lepton energy distribution, for which we obtain $n_1 = 2.0$, $n_2 = 3.6$, $\gamma_{\text{break}} = 700$ and $K = 450 \text{ cm}^{-3}$. However, such a particle energy distribution can not account correctly for the SED observed in the radio domain.

In Fig. 5, we show the SED of NGC 4945, including the *Fermi*/LAT and the *INTEGRAL* spectra we derived in Sects. 2 and 3, respectively. For comparison, we also show the data of the starburst galaxy NGC 253, as taken from the NED, along with the *Fermi*/LAT spectrum as published in Abdo et al. (2010c). Clearly, the two objects have very similar broadband SEDs, which match almost perfectly, strengthening the idea that the high energy γ -ray emission from NGC 4945 could be well explained only in terms of starburst activity. NGC 4945 should then be detectable in the very high energy domain, and especially with H.E.S.S. given its coordinates, at a flux level similar to NGC 253. However, one difference between NGC 4945 and NGC 253 resides in their hard X-ray emission. While NGC 253 is not thought to harbour a central AGN, NGC 4945 exhibits a characteristic Seyfert emission, which is modelled as above for NGC 1068. The corresponding parameters are also included in Table 2.

5. Conclusion

We reported the detection of the Seyfert 2 galaxy NGC 1068 in the high energy (100 MeV–100 GeV) domain with the *Fermi*/LAT, and compared the analysis of this source with the one of NGC 4945 obtained by extending the observing period to 1.6 years. The object 1FGL J0242.7+0007 was reported as a γ -ray source without association in the 1FGL catalogue. We can now associate it quite firmly to NGC 1068 with an overall detection significance of 8.4σ . The data do not show any significant variability over the whole period.

The high energy γ -ray spectrum of NGC 1068 is consistent with a power-law of index $\Gamma = 2.31 \pm 0.13$ and a flux density of $(8.60 \pm 2.27) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. Compared to the γ -ray luminosities of M82 and NGC 253, whose high-energy emission is dominated by starburst activity, we find a too high γ -ray luminosity of NGC 1068 to be explained only by starburst activity. We thus propose a leptonic scenario to interpret the high energy emission in terms of external inverse Compton process from an outflowing relativistic wind launched by the central AGN.

NGC 4945 is detected at a 9.2σ level in *Fermi*/LAT data, and its γ -ray spectrum is best described by a power-law of index $\Gamma = 2.31 \pm 0.10$ and a flux density of $(1.58 \pm 0.32) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. This object has a very similar multi-wavelength SED compared to NGC 253, and based on its radio, infrared and γ -ray luminosities, its high energy γ -ray emission is most likely due to starburst activity.

If high energy γ -ray emission due to AGN activity is confirmed in other Seyfert 2 galaxies, this would mark the discovery of yet a new class of high-energy γ -ray emitters. New data from *Fermi*/LAT in the coming years will be extremely valuable in this regard.

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Hard X-ray variability

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AGN are well known to show X-ray variability on all time-scales, and over the years it has been found that a large amount of information can be extrapolated from the study of their light curve (see the long-standing discussion on absorption and reflection model in Sect. 5.6). Here we will first review some general characteristics of the variability of AGN at X-rays (Sect. 7.1), we will then introduce some useful mathematical tools to estimate the amplitude of the variability (Sect. 7.2), for then discussing the results we recently obtained from a study of the hard X-ray variability of a sample of bright AGN (Sect. 7.3).

7.1 X-ray variability of AGN

Variability is one of the key features of AGN, and it was found to be significative in the X-ray band already in early observations of nearby Seyfert galaxies performed by *Ariel V* (Marshall et al. 1981).

One of the most common methods to study the variability is the fluctuation Power Spectral Density (PSD). The PSD represents the amount of variability power as a function of temporal frequency (timescale⁻¹). The high frequency PSDs of Seyfert galaxies are usually well represented by power laws over a broad range of frequencies ($P(f) \propto f^{-\alpha}$, where f is the frequency). *EXOSAT* observations showed that on short time-scales the variability of AGN could be described as red noise, with indices ranging between $\alpha \sim 1 - 2$ (e.g., McHardy & Czerny 1987). Studying *EXOSAT* data, Barr & Mushotzky (1986) were the first to show that the *two-folding time-scale* (i.e. the time-scale for which the flux changes of a factor 2) is shorter in lower-luminosity AGN. Few years later, exploiting the long observations of AGN performed by *EXOSAT*, Lawrence & Papadakis (1993) and Green et al. (1993) showed that the PSD amplitude at a given frequency decreases with increasing values of the luminosity. Using *ASCA* observations, Nandra et al. (1997) first, and then George et al. (2000), found evidence of an anti-correlation between the *excess variance* (the background corrected normalized variance, see Sect. 7.2) and the luminosity of the sources. Similar results were also obtained by Leighly (1999) and Turner et al. (1999), who also found that NLS1s show a systematically larger variability amplitude when compared to other types of AGN with the same luminosity (see Fig. 8.7 in Sect. 8.5). This anti-correlation was also extended to longer (months and years) timescales, thanks to the very long *RXTE* observations (Markowitz & Edelson 2001). *RXTE* observations also showed that AGN are more strongly variable on long time-scales (months and years) than on short ones (Markowitz & Edelson 2001). This corresponds to a break in the PSD (Fig. 7.1), with a flattening towards low frequencies (Uttley et al. 2002), as found in X-ray binaries. Markowitz et al. (2003) found

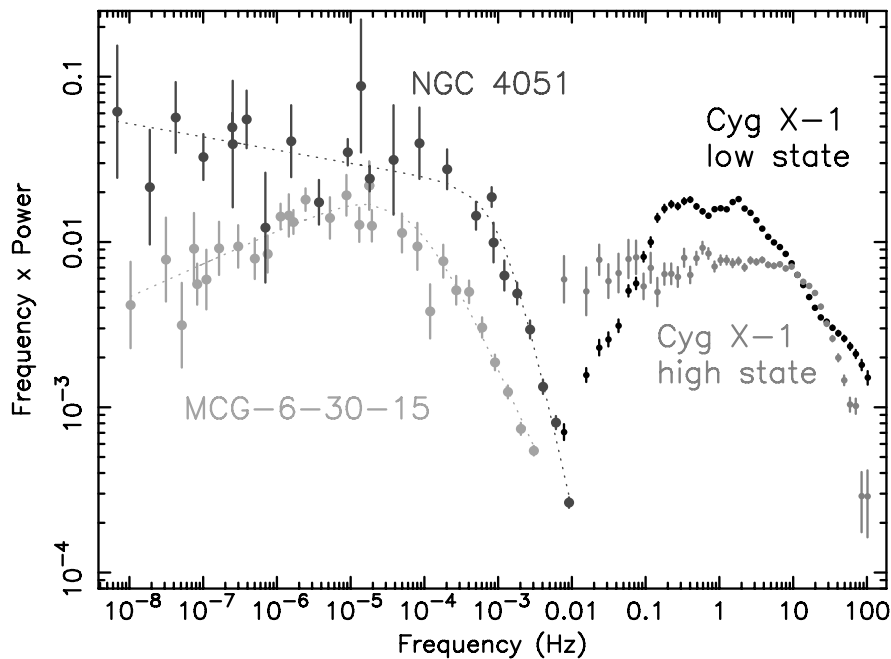


Figure 7.1: Power Spectral Density for two AGN with different black hole masses and for two spectral states of the X-ray binary Cygnus X-1 (McHardy et al. 2006a).

that this break time-scale scales linearly with the black hole mass. McHardy et al. (2006b) found that the break time-scale T_B also depends on a third parameter, the accretion rate. They found a relation that links these three quantities (T_B , $\dot{m}$ and M_{BH}), which works fine also for X-ray binaries (see Fig. 7.2):

$$T_B = 2.1 \log M_{BH} - 0.98 \log L_{bol} - 2.32,$$

where T_B is in units of days, M_{BH} in units of $10^6 M_\odot$ and L_{Bol} ($\propto \dot{m}$) in units of $10^{44} \text{ erg s}^{-1}$. In the hard X-rays, Beckmann et al. (2007) confirmed the existence of an anti-correlation of the variability amplitude with the luminosity, and found possible evidence of a correlation of the variability with the absorbing column density, with more absorbed sources tending to be more variable (Fig. 7.3). Soldi et al. (2009) also found possible evidence of an anti-correlation between the variability amplitude and the luminosity. More recently, Caballero-Garcia et al. (2011) studying the *Swift*/BAT a small sample of 5 AGN found variability on a time-scale of $\sim 1 - 2$ days, and a possible anti-correlation of the variability amplitude with the mass of the black hole.

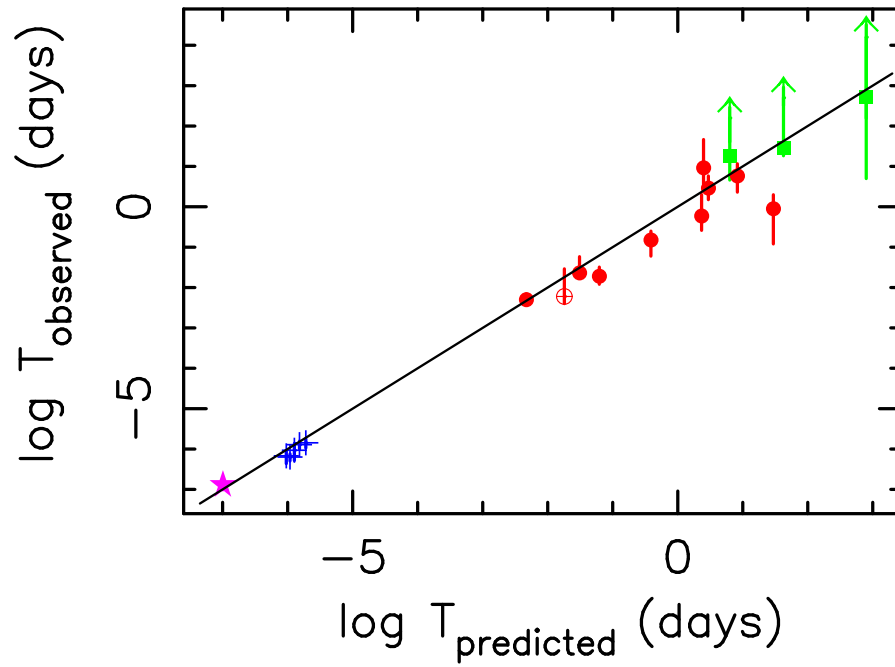


Figure 7.2: Measured T_B versus its expected value for AGN (square and circles) and Galactic black holes (star and crosses). Figure taken from McHardy et al. (2006b).

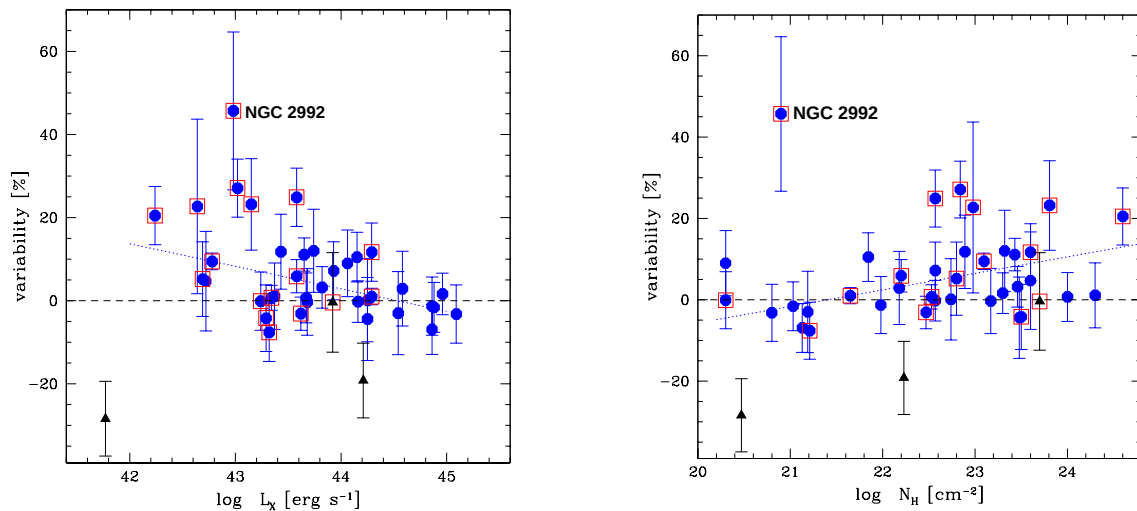


Figure 7.3: Scatter plot of the variability amplitude versus the luminosity (*left panel*) and the absorbing column density (*right panel*). Figure taken from Beckmann et al. (2007).

7.2 Variability estimators

A common way to estimate the variability is through the fractional root mean squared (rms) variability amplitude F_{var} (Edelson et al. 1990), defined as

$$F_{\text{var}} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{\bar{x}^2}}. \quad (7.1)$$

Where the sample variance S^2 is given by

$$S^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2, \quad (7.2)$$

while the mean square error $\overline{\sigma_{\text{err}}^2}$ by

$$\overline{\sigma_{\text{err}}^2} = \frac{1}{N} \sum_{i=1}^N \sigma_{\text{err},i}^2. \quad (7.3)$$

The error of F_{var} is given by

$$\text{err}(F_{\text{var}}) = \sqrt{\left(\sqrt{\frac{1}{2N}} \cdot \frac{\overline{\sigma_{\text{err}}^2}}{\bar{x}^2 F_{\text{var}}} \right)^2 + \left(\sqrt{\frac{\overline{\sigma_{\text{err}}^2}}{N}} \cdot \frac{1}{\bar{x}} \right)^2}. \quad (7.4)$$

Another way to estimate the amount of the variability is the *excess variance* (Nandra et al. 1997), which quantifies the intrinsic variance of a source:

$$\sigma_{\text{XS}}^2 = S^2 - \sigma_{\text{err}}^2.$$

Both F_{var} and σ_{XS}^2 provide the same information, but F_{var} gives the rms variability in percentage terms, so we will use it in the following to characterize the variability of AGN at hard X-ray.

7.3 Hard X-ray variability of AGN

BAT onboard *Swift* (Sect. 3.3.1) scans continuously the whole sky in the 14–195 keV energy range, and is thus an extremely well suited instrument for studying AGN variability at hard X-rays. In this chapter we report a study of the hard X-ray variability of a small sample of AGN. The sample consists of the 20 brightest AGN detected by *Swift*/BAT, of these 2 are blazars, 2 narrow-line radio galaxies (NLRG), 1 broad-line radio galaxy (BLRG), 6 Seyfert 1/1.5s, 8 Seyfert 2s and 1 Narrow Line Seyfert 1 (NLS1). The 1-month binned light curves have been taken from the NASA *Swift*/BAT 58 months catalog¹.

In Table 7.1 are listed the values of the fractional rms variability amplitude of the objects of our sample, and as a check, the value obtained from the light curve of the Crab ($F_{\text{var}} \sim 0.02$). The value of F_{var} for the Crab can be associated to the systematic error of the *Swift*/BAT data. In Figs. 7.4, 7.5 and 7.6 we show the light curves of the 20 sources of our sample. All the sources of our sample show hard X-ray variability on the time-scale of one month. As it can also be seen from Fig. 7.7, the value of

¹<http://swift.gsfc.nasa.gov/docs/swift/results/bs58mon/>

Table 7.1: Properties of the sources of our sample: (1) detection significances, (2) luminosities in the 14–195 keV energy range, (3) fractional rms variability amplitudes on a timescale of 30 days, (4) hydrogen column densities.

Source	(1) Det. Significance [σ]	(2) $\log L_{14-195 \text{ keV}}$ [erg s^{-1}]	(3) F_{var} (30-days)	(4) N_{H} [cm^{-2}]	Type
Cen A	428.7	44.01	0.399 ± 0.002	12^a	NLRG
NGC 4151	275.0	44.11	0.280 ± 0.004	6.9^b	Sy 1.5
3C 273	156.8	47.47	0.31 ± 0.01	0.5^b	Blazar
NGC 4388	110.7	44.64	0.31 ± 0.01	27^b	Sy 2
Mrk 421	109.5	45.46	0.96 ± 0.01	0.1^b	Blazar
Circinus Galaxy	101.7	43.09	0.13 ± 0.01	360^b	Sy 2
IC 4329A	101.1	45.22	0.19 ± 0.02	0.4^b	Sy 1
NGC 2110	98.1	44.60	0.32 ± 0.01	4.3^c	Sy2
NGC 5506	95.0	44.31	0.27 ± 0.02	3.4^c	NLS1
MCG+05-23-016	90.4	44.50	0.21 ± 0.01	1.6^c	Sy2
IGR J21247+5058	83.3	45.25	0.31 ± 0.01	0.6^b	BLRG
NGC 4945	76.1	43.37	0.35 ± 0.02	400^b	Sy2
Mrk 348	70.4	44.91	0.28 ± 0.02	30^c	Sy2
NGC 3783	68.7	44.60	0.26 ± 0.02	0.1^c	Sy1.5
NGC 4507	64.6	44.77	0.29 ± 0.02	29^c	Sy 2
NGC 3516	62.3	44.33	0.30 ± 0.02	4^c	Sy 1.5
NGC 7172	60.1	44.46	$0.35 \pm 0.04^*$	9^c	Sy 2
NGC 3227	56.2	43.57	0.16 ± 0.21	6.8^c	Sy 1.5
Cyg A	54.0	46.01	0.34 ± 0.02	11^b	NLRG
MCG +08-11-011	49.0	45.09	0.35 ± 0.03	0.2^c	Sy 1.5
<i>Crab</i>	7496	–	0.0215 ± 0.0004	–	–

Notes. ^a Beckmann et al. (2011), ^b Beckmann et al. (2009) and references therein, ^c Ricci et al. (2011) and ref. therein. * "Flare" of January 2008 removed.

the fractional rms variability amplitude is $F_{\text{var}} \sim 0.2 - 0.3$ for most of the objects of the sample, with the average value being $\overline{F_{\text{var}}} = 0.32$. Blazars are well known to show a very strong variability (e.g., Moraitis & Mastichiadis 2011), which is related to the jet emission and to beaming effects, so it comes as no surprise that Mrk 421 shows a much stronger variability ($F_{\text{var}} \sim 0.96$) than the average value of the sample. Amongst the radio-quiet NGC 7172 is the most variable, with a value of $F_{\text{var}} \sim 0.48$. This is due to what would appear to be a flare, registered in January 2008. Excluding this outlier point NGC 7172 shows a variability consistent with the average of our sample ($F_{\text{var}} = 0.35 \pm 0.04$). At the other end of the distribution, the Compton-thick Seyfert 2 Circinus Galaxy and the Seyfert 1 IC 4329A show the smallest amounts of variability ($F_{\text{var}} \sim 0.13$ and $F_{\text{var}} \sim 0.19$, respectively). The low value of F_{var} of Circinus Galaxy is very likely related to the reflection-dominated nature of its hard X-ray spectrum. Compton reflection is in fact expected to smooth down the variability amplitude, the reflection time-scales being much longer than the variability ones due to the size of the reflecting material.

Recently, Beckmann et al. (2007) studied the hard X-ray variability of the 44 brightest AGN

detected by BAT after 9 months of operations, and found that the anti-correlation between the variability amplitude and the X-ray luminosity found by Barr & Mushotzky (1986) might be extended to the hard X-ray band (see also Soldi et al. 2009). They also found a possible correlation between the hydrogen column density N_{H} and the variability amplitude. We investigated the existence of these two correlations in our sample (see Figs. 7.8 and 7.9). The variability amplitudes in our sample are confined in a small range of values, and no correlation with other parameters is evident. A Spearman rank test gives a correlation coefficient between F_{var} and the luminosity of $r_s = 0.27$, while it is $r_s = 0$ between F_{var} and N_{H} . These values correspond to a probability of correlation of 78% in the first case, and of 0% in the second case. Similar results are obtained also considering Mrk 421 as an outlier. No significant correlation is found also dividing the sample in three categories (Sy 1/1.5s, Sy2s, radio-loud). The lack of correlations might be due to the limited sample we used, and further studies are needed to better probe it.

It is important to remark that the fact that the variability amplitude of different type of radio-quiet AGN lie in a very narrow range of values is in good agreement with the unified model of AGN (see Sect. 8 for a detailed discussion).

Although so far it has not been well studied, hard X-ray variability can be an extremely useful tool, in particular it will prove to be very important once it will be possible to do reverberation studies of AGN around the peak of the Compton reflection hump. This will allow to map the material around the X-ray source, especially the accretion disk and the putative molecular torus.

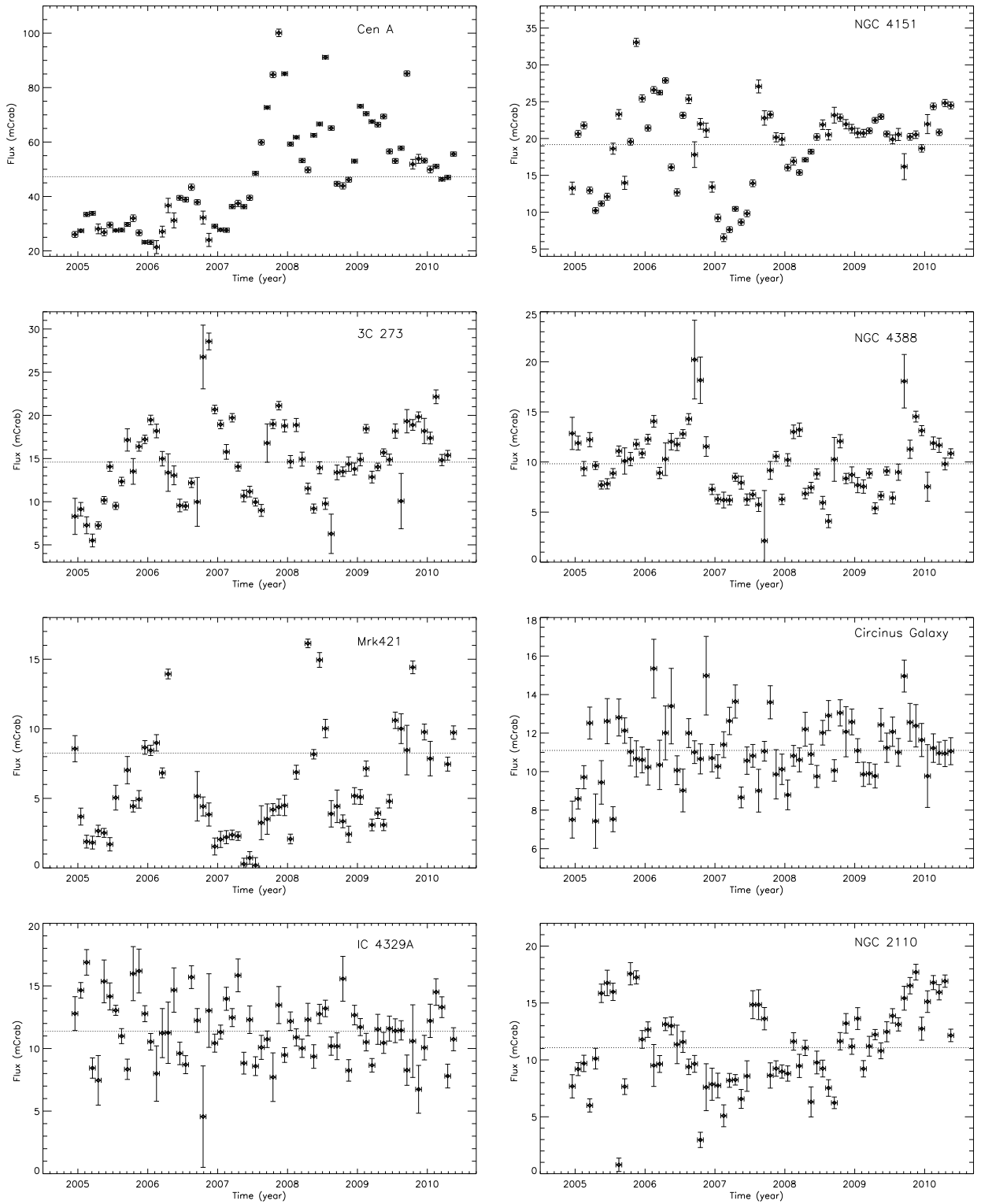


Figure 7.4: *Swift*/*BAT* 30-days binned light curves in the 14–195 keV band. The dotted horizontal lines represent the average value for each object.

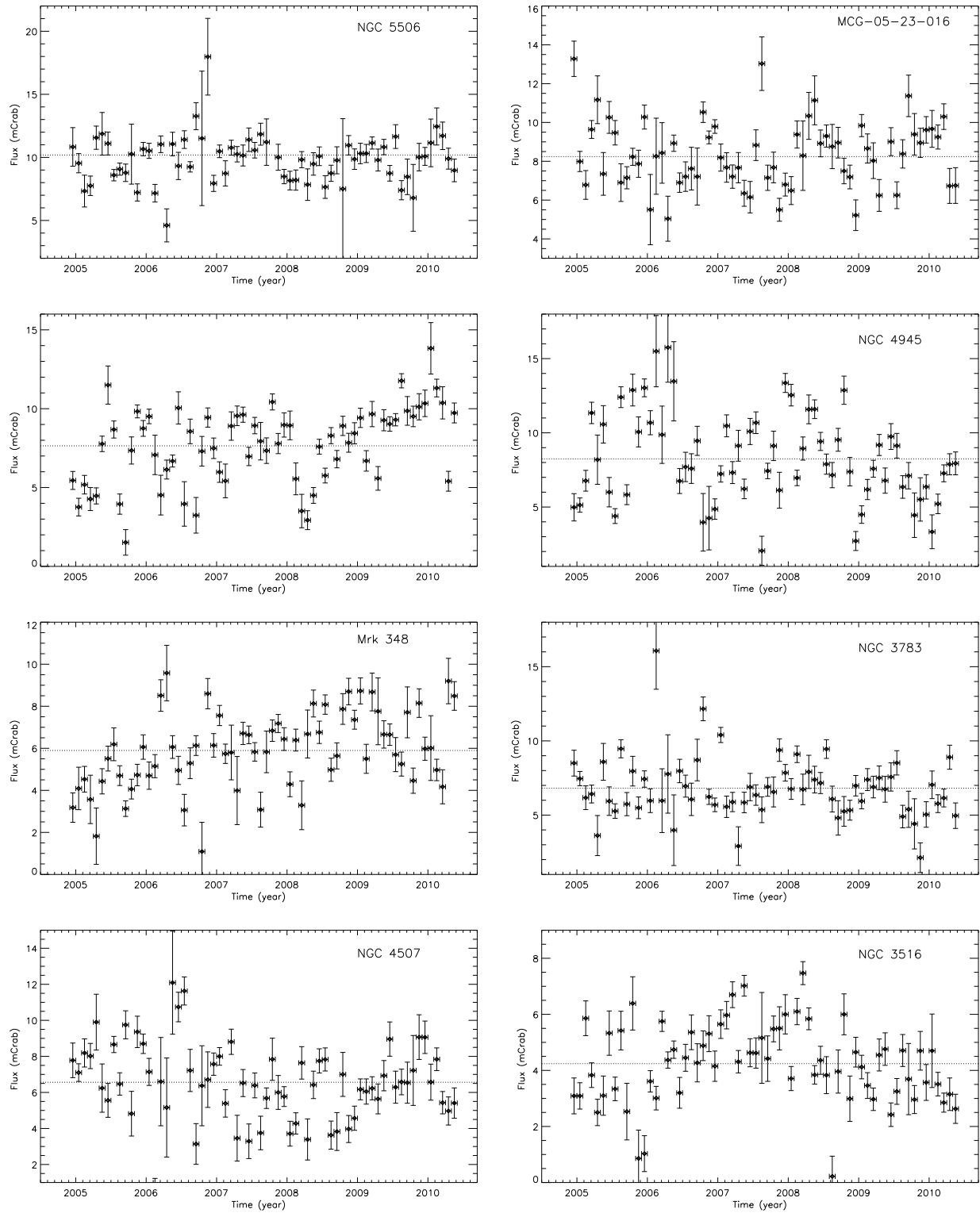


Figure 7.5: *Swift*/BAT 30-days binned light curves in the 14–195 keV band. The dotted horizontal lines represent the average value for each object.

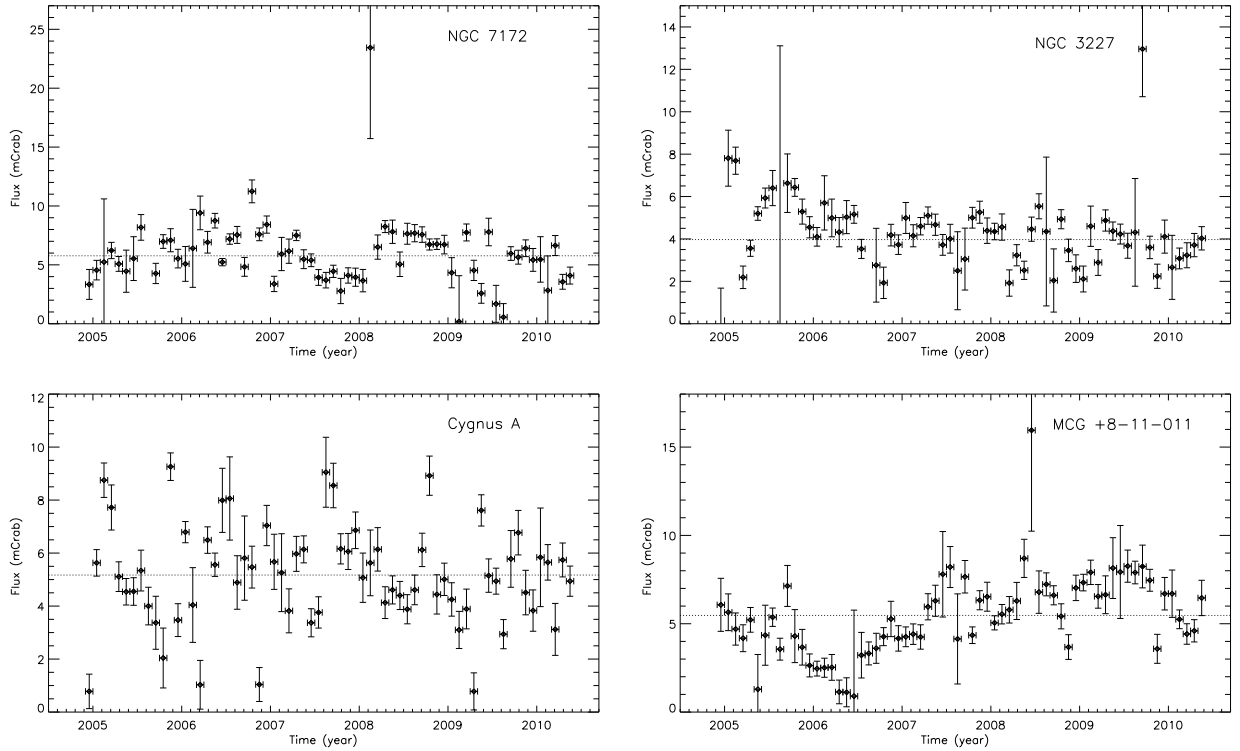


Figure 7.6: *Swift*/BAT 30-days binned light curves in the 14–195 keV band. The dotted horizontal lines represent the average value for each object.

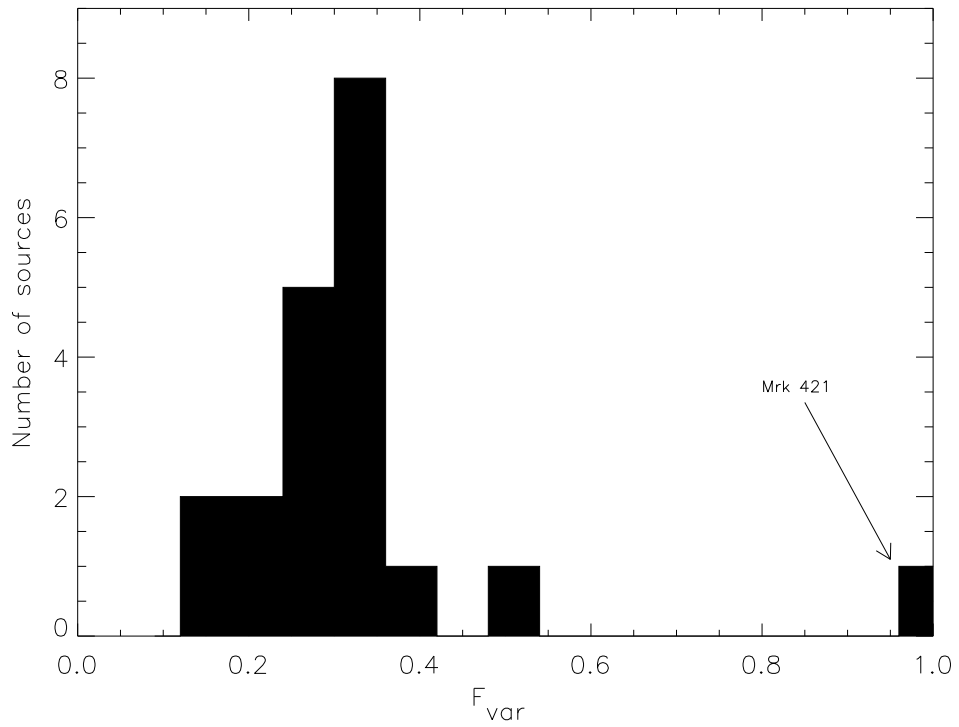


Figure 7.7: Distribution of the fractional rms variability amplitude for the 20 sources of our sample.

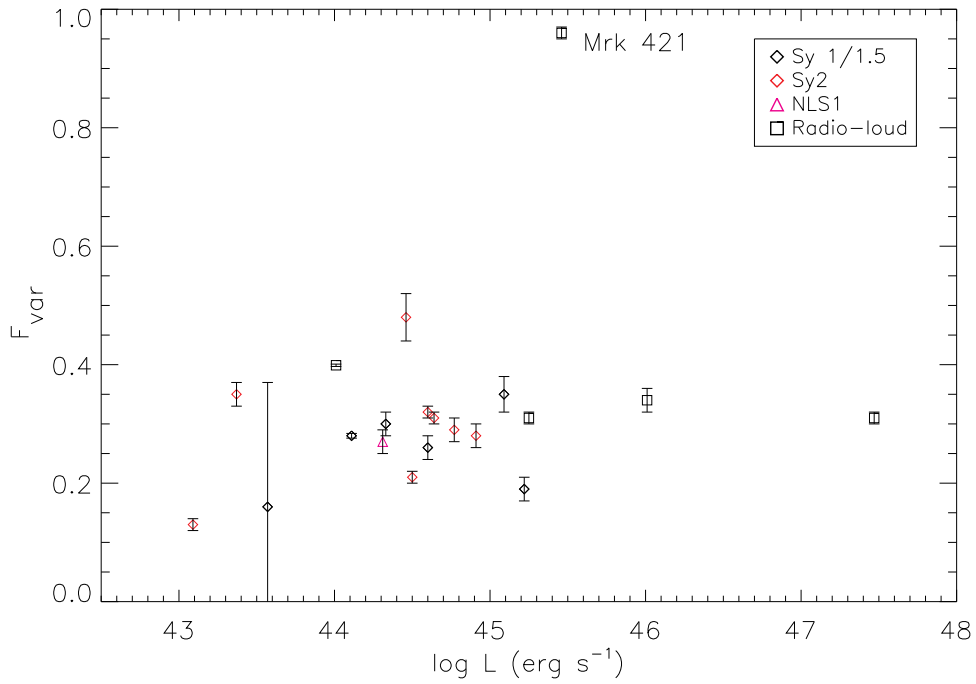


Figure 7.8: Scatter plot of the rms variability amplitude F_{var} and the hard X-ray (14–195 keV) luminosity of the sources of our sample.

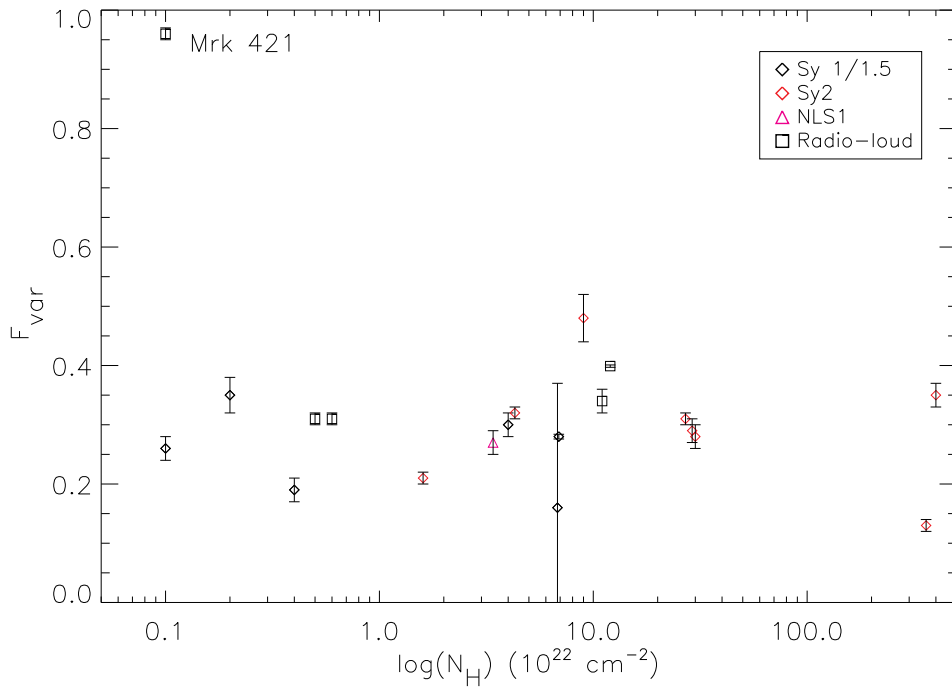


Figure 7.9: Scatter plot of F_{var} and the hydrogen column density of the sources of our sample.

Radio-quiet Unification models

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As we have seen in Sect. 1.4, unification models of AGN are able to explain many of the different multi-wavelength characteristics of different classes of objects. Here we will discuss in detail the radio-quiet unification, and the observations it still fails to explain (Sect. 8.1). In particular in Sect. 8.3 we will focus on the differences between different types of Seyfert galaxies observed at hard X-rays, an energy band which should allow to have a direct look at the X-ray source. We will then discuss the classes of objects that cannot fit in the simplest version of the unified model: in Sect. 8.4 we will discuss the case of bare Seyfert 2s, in Sect. 8.5 the NLS1s, in Sect. 8.6 the LINERs, and in Sect. 8.7 the buried AGN, an extremely interesting class of objects which has recently been discovered. In Sect. 8.8 we will present the results we obtained from the the deepest study of the average hard X-ray spectra of AGN ever performed, aimed at constraining and understanding possible intrinsic differences amongst different types of Seyfert galaxies using *INTEGRAL* IBIS/ISGRI data.

8.1 The unified model of radio-quiet AGN

The idea that different types of AGN are fueled by the same type of central engine (i.e. accretion onto a SMBH) has been confirmed by numerous pieces of evidence (see Sect. 1.2.1), and there is nowadays little doubt about its veracity. This point is at the basis of all unification models, for both radio-loud and radio-quiet AGN. An unification model for radio-quiet AGN should be able to explain all the differences observed along the whole spectrum between different types of Seyfert galaxies, although historically most unification models are based on the characteristics of the optical spectra.

8.1.1 Historical introduction

In Sect. 1.3 we have seen that most of the local AGN can be classified as Seyfert galaxies, of type-1, type-2 or intermediate, depending on the ratio between the narrow and broad lines in their optical spectra. Much work has been done since the first studies on radio-quiet AGN to understand whether all the observed characteristics could be explained by a single model. The first important work in the direction of an unification of Seyfert galaxies was done by Rowan-Robinson (1977), who found that Seyfert 2s have more dust emission relative to the optical continuum than Seyfert 1s. This allowed him to conclude that the dust surrounding the central engine might play a fundamental role in attenuating the broad wings of the optical lines, and to propose for the first time that Seyfert galaxies are a single class. Although, as discussed in Sect. 1.2, we now know that the broad and narrow lines are emitted by different regions, this was one of the first clear indications of the importance of absorption. In the following years several more pieces of the puzzle were put together. Keel (1980) discovered that Seyfert 1s are observed preferentially face on, and Osterbrock (1981b) inferred the importance of dust in intermediate Seyfert galaxies from their large Balmer decrements. The discovery of polarized broad lines with equivalent widths similar to those typically observed in Seyfert 1s in the optical spectrum of the nearby Seyfert 2 NGC 1068 (Miller & Antonucci 1983; Antonucci & Miller 1985), confirmed the idea that different types of Seyfert galaxies share the same central engine, with the only difference being the presence or absence of an absorbing medium in the line of sight. The absorbing gas would deplete the direct emission of the BLR, allowing the broad lines to be observed only through reflection from the surrounding gas. The photons undergoing Thomson scattering are in fact completely polarized, thus one would be able to observe the BLR only in polarized light. This absorbing medium was hypothesized to have some sort of toroidal shape (see the review of Antonucci 1993), which would make orientation with respect to it the only degree of freedom responsible for the differences in the optical spectra of AGN. The presence of an axisymmetric absorber in a rotating system would not be surprising, its doughnut-like shape possibly related to the sweeping of the gas by the radiation pressure generated by the accretion flow.

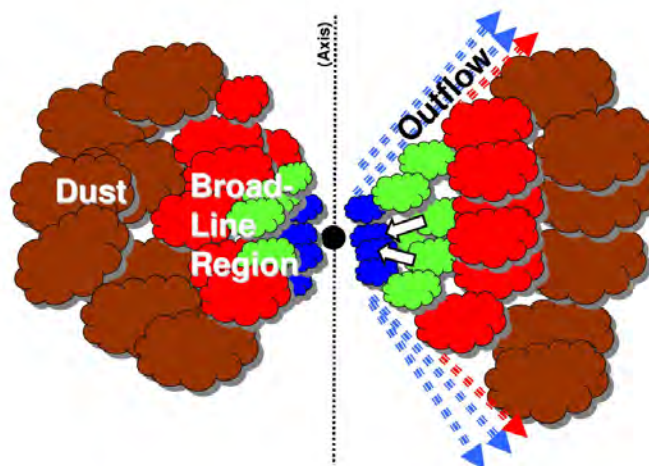


Figure 8.1: A possible geometry of the BLR in the framework of the unified model of radio quiet AGN (Gaskell 2011).

Another important step was the discovery of cone-shaped NLRs in some Seyfert 2s (e.g., [Tadhunter & Tsvetanov 1989](#)), which is in good agreement with the idea that these objects are seen edge-on. The existence of a larger amount of gas in the line of sight of Seyfert 2s with respect to Seyfert 1s was confirmed by early X-ray observations of nearby Seyfert galaxies performed by *Ginga* ([Awaki et al. 1991](#)), and later by many other X-ray studies (e.g., [Risaliti et al. 1999](#), [Brightman & Nandra 2011a](#), see also Sect. 4.3).

8.1.2 Problematics of the unified model

Although the unified model of AGN is able to account for several differences between different types of AGN, there is a considerable number of points it fails to explain.

- Seyfert 2s are preferentially hosted in galaxies of late Hubble type ([Malkan et al. 1998](#)), have a relatively young (~ 1 Gyr) stellar population ([Schmitt et al. 1999](#)) and an enhanced star formation with respect to Seyfert 1s ([Maiolino et al. 1997](#); [Buchanan et al. 2006](#)).
- Seyfert 2s have a larger overall dust content than Seyfert 1s ([Malkan et al. 1998](#)).
- Seyfert 2s have an excess of nearby companions with respect to Seyfert 1s ([Dultzin-Hacyan et al. 1999](#)).
- The nature of intermediate type Seyfert galaxies (i.e., Sy 1.2-1.9) is still not well understood. Is the line of sight to the central engine in these objects grazing the outer edge of the torus?
- Obscured Seyfert galaxies are sub-mm emitters, while unobscured are not (e.g., [Lutz et al. 2010](#), [Bielby et al. 2011](#)).
- Seyfert 2s have lower hard X-ray (14–195 keV) to [OIV] luminosity ratios ([Rigby et al. 2009](#)).
- The fraction of obscured sources decreases with increasing luminosities (see Sect. 8.2).
- There are possible differences at hard X-rays between different types of Seyfert galaxies (see Sect. 8.3).
- A large fraction of Seyfert 2s appear not to have the BLR (see Sect. 8.4).
- It cannot straightforwardly include NLS1s (see Sect. 8.5) or low luminosity objects (as LINERs, see Sect. 8.6).
- A new class of objects with peculiar characteristics (*buried* AGN) has been recently discovered from hard X-ray surveys (see Sect. 8.7).

8.1.3 The molecular torus and the BLR

Despite the fact that the molecular torus is a key ingredient for the unified model of AGN, so far only for very few objects a detection of this component has been claimed. Using interferometry at IR wavelengths, [Swain et al. \(2003\)](#) found a very compact emission from within 0.1 pc in the Sy 1.5 NGC 4151. [Jaffe et al. \(2004\)](#), studying NGC 1068 found evidence of warm (320 K) dust in a structure 2.1 pc thick and 3.4 pc in diameter, surrounding a smaller hot structure. A structure of ~ 2 pc was found in Circinus galaxy by [Tristram et al. \(2007\)](#), who argued that it would be extremely difficult to interpret their results without invoking clumpiness in the torus. Early studies of dusty tori performed

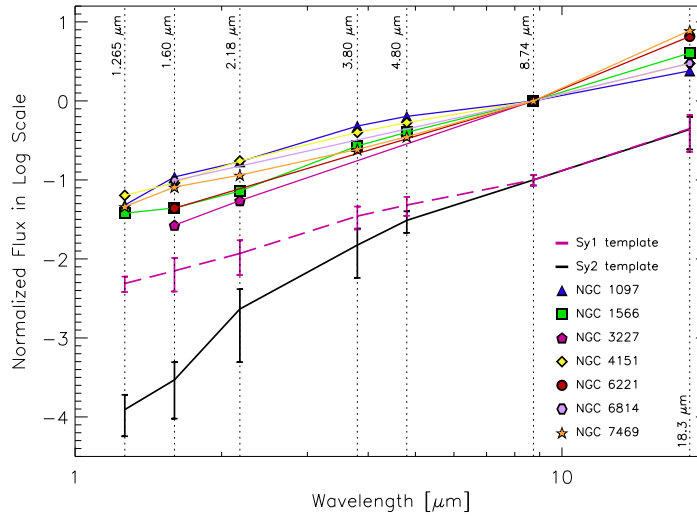


Figure 8.2: Observed IR SEDs of seven Sy1s, of their average emission (dashed pink), and of the average emission of Sy2s. The SEDs have been normalized at $8.74 \mu\text{m}$, and the average SEDs of Sy1s and Sy2 have been shifted (Ramos Almeida et al. 2011).

by Krolik & Begelman (1988) showed that absorbers with a smooth dust distribution cannot survive close to the AGN, which led to the idea that the material might be distributed in a clumpy structure. Analysis of IR observations of type-1 AGN performed by *Spitzer* have been shown to be consistent with this clumpy scenario (e.g. Elitzur & Shlosman 2006, Mor et al. 2009). Recently, Ramos Almeida et al. (2011) (see also Ramos Almeida et al. 2009), modeling the mid-IR spectra of a sample of ~ 20 Seyfert galaxies with the clumpy torus model developed by Nenkova et al. (2008a,b), have found that Seyfert 2s appear to have tori with larger covering factors ($C_T = 0.95 \pm 0.02$) than those of Seyfert 1s ($C_T = 0.5 \pm 0.1$). The average IR SEDs of the Sy1s and Sy2s of their sample are shown in Fig. 8.2. If confirmed, these results would have a strong impact on the formulation of unification models.

The structure of the BLR in AGN is also still debated. In the framework of the unified model, Gaskell et al. (2007) proposed that the BLR is simply the inner part of the dusty torus, and that it might be highly stratified in ionization and have a covering factor similar to that of the torus (see Fig. 8.1).

8.2 The receding torus model

The simplest form of the unified model cannot explain the decrease of the fraction of absorbed objects with the luminosity of AGN (see Sect. 4.3). Lawrence (1991) proposed a model, called the *receding torus model*, in which the inner radius of the torus is set by the dust sublimation radius ($R = R_d$), which increases with the source luminosity,

$$R_d \simeq 0.4 \left(\frac{L_{\text{bol}}}{10^{45} \text{ erg s}^{-1}} \right)^{0.5} \left(\frac{1500 \text{ K}}{T_{\text{sub}}} \right)^{2.6} \text{ pc},$$

where T_{sub} is the dust sublimation temperature. In this model, the radiation pressure exerted by the central engine plays a fundamental role, and strongly affects its surroundings. This is in agreement with what we have shown in Sect. 4.5, i.e. that for high Eddington ratios the dusty torus seems to

disappear.

Estimations of the angular size of the putative molecular torus based on the study of the relative frequency of Seyfert 2s have been carried out by several authors. [Maiolino & Rieke \(1995\)](#) found the ratio of Sy2s to Sy1s to be ~ 4 , from which they concluded that the ratio between the thickness of the external part of the torus H and the distance of its outer edge from the SMBH R was about $H/R \sim 1.33$. More recent studies have found this ratio to be closer to the unity (e.g., [Hao et al. 2005](#)), which would imply an half opening angle of the torus of $\theta \sim 30 - 50^\circ$. Studying a large sample of AGN detected by the Sloan Digital Sky Survey, it has been shown that also the ratio H/R depends on the bolometric luminosity ([Simpson 2005](#)), in good agreement with the receding torus model (Fig. 8.3). Assuming a constant ratio H/R , the fraction of obscured objects would be related to the luminosity as $f \propto L_{\text{bol}}^{-0.5}$, which is different from what has been observed in recent X-ray surveys (i.e., $f \propto L_X^{-0.28 \pm 0.02}$, [Hasinger 2008](#), see also Sect. 4.3). A possible solution has been given assuming a clumpy structure of the torus. [Hönig & Beckert \(2007\)](#) found, in the framework of what they defined the *radiation-limited clumpy dust torus*, $f \propto L^{-0.25}$, in good agreement with the observations.

Assuming that the obscuring clouds in the torus are created in a disk-wind outflow rather than being due to accretion of material from the galaxy, it has been proposed by [Elitzur & Shlosman \(2006\)](#) that at low luminosities (i.e. $< 10^{42} \text{ erg s}^{-1}$) the obscuring torus might disappear.

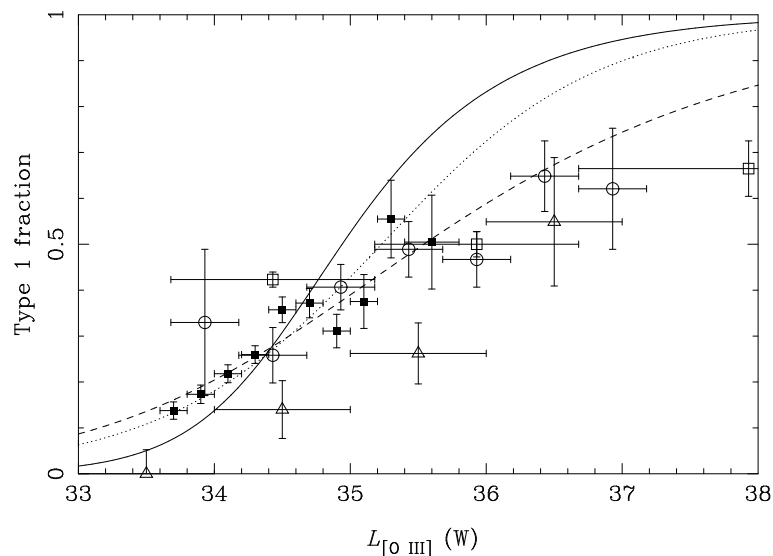


Figure 8.3: Fraction of Seyfert 1s versus their [O III] luminosity ([Simpson 2005](#)). The filled squares are the points from the SDSS sample of [Simpson \(2005\)](#), while the other points are taken from previous works.

8.3 Hard X-ray spectra of AGN

As we discussed in Sect. 2.2, at hard X-rays, namely at energies above $\sim 15 \text{ keV}$ (where the photoelectric absorption is negligible) and below $\sim 200 \text{ keV}$ (where relativistic effects are small), absorption is only ruled by Compton scattering, whose effect is independent of energy. This implies that at these energies, for Compton-thin AGN, the intrinsic emission is practically unaffected by absorption (see Fig. 8.4). Thus, excluding possible relatively small differences due to the different inclination of the

observer with respect to the accretion disk (see Fig. 2.7 in Sect. 2.3.1), one would expect on average consistent spectra for different types of Seyfert galaxies.

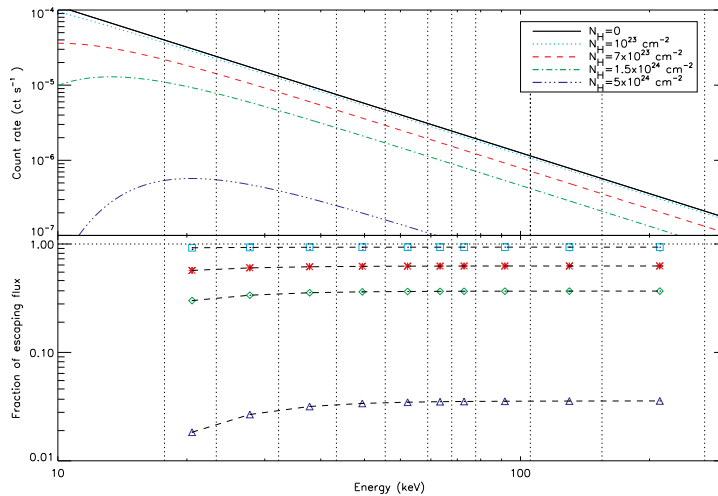


Figure 8.4: Effect of photoelectric absorption and Compton scattering (excluding relativistic effects) on a power law spectrum ($\Gamma = 1.95$) in the hard X-rays. The upper panel shows the observed spectrum for different values of the hydrogen column density N_H , and the lower panel shows the fraction of escaping flux in the 10 energy bins used in Ricci et al. (2011).

However, contrarily to what is expected by the unified model, significant differences have been found between the hard X-ray spectra of different types of Seyfert galaxies. Early studies using data obtained by *Ginga* and *Compton Gamma-Ray Observatory*/OSSE (Zdziarski et al. 1995) showed that the spectra of Seyfert 2s are harder than those of Seyfert 1s. This was later confirmed by Gondek et al. (1996) using combined *EXOSAT*, *Ginga*, *HEAO-1* and *Compton Gamma-Ray Observatory*/OSSE data, and by Done & Smith (1996), using only *Ginga* data. More recently, a substantially harder emission for Seyfert 2 than for Seyfert 1 was shown by a study of the average 3–200 keV *BeppoSAX* spectra of 23 Seyfert galaxies (Malizia et al. 2003). In their work, Malizia et al. (2003) found that Seyfert 1s had an average photon index of $\Gamma \sim 1.9$, a reflection component of $R \simeq 0.6 - 1$ and a high energy cutoff at $E \sim 200$ keV. The average X-ray spectrum of Seyfert 2s showed instead a possibly higher reflection component ($R \sim 3$), although this result depends on the choice of the model used. The authors concluded that the differences between the average spectra of Sy1s and Sy2s might be due either to a larger reflection component of Sy2s, or to a complex structure of the absorbers. Differences between the average spectra of type-1 and type-2 Seyfert galaxies were also found by Deluit & Courvoisier (2003), who studied the average *BeppoSAX*/PDS spectrum of 45 Seyfert galaxies. The advantage of their work, with respect to that of Malizia et al. (2003), was that they focused on a higher-energy band (i.e. 15–130 keV), much less affected by absorption. Deluit & Courvoisier (2003) found that, while the average spectrum of Seyfert 1s requires the presence of a high energy cutoff, that of Seyfert 2s does not. They also found that Seyfert 2s have on average a larger reflection component, while Seyfert 1.5s have an intermediate behavior, not requiring neither a high energy cutoff nor a reflection component (Fig. 8.5). Recently, Corral et al. (2011), studying the average 0.3–10 keV *XMM-Newton* spectra of ~ 300 Seyfert galaxies, also found a larger reflection component in absorbed ($R \sim 1$) than in unabsorbed objects ($R \sim 0.6$). Using *INTEGRAL* data Beckmann et al. (2006b), found significant differences between the slopes of different classes of objects, with

Sy2s being on average harder than Sy1s. However, in a successive work (Beckmann et al. 2009) the average photon indices obtained were consistent. Ajello et al. (2008c) using *Swift*/BAT data (in the 14–195 keV band) found an average value of the photon index of $\Gamma = 2.23 \pm 0.11$ for the Seyfert 1s, of $\Gamma = 1.95 \pm 0.11$ for the intermediate type Seyfert 1.2–1.5s, and of $\Gamma = 1.86 \pm 0.10$ for the Seyfert 2s. More recently, also Burlon et al. (2011) found analogous results studying a larger sample. A possible explanation to these differences has been proposed by Middleton et al. (2008), who argued that, analogously to black hole binaries, the different photon indices might be related to different accretion rates, with Seyfert 1s having larger values of λ_{Edd} than Seyfert 2s. The average values of Sy1s and Sy2s in the sample they used are indeed different ($\lambda_{\text{Edd}}^{\text{Sy1}} \sim 0.2$ and $\lambda_{\text{Edd}}^{\text{Sy2}} \sim 0.06$), although the distributions are not significantly different.

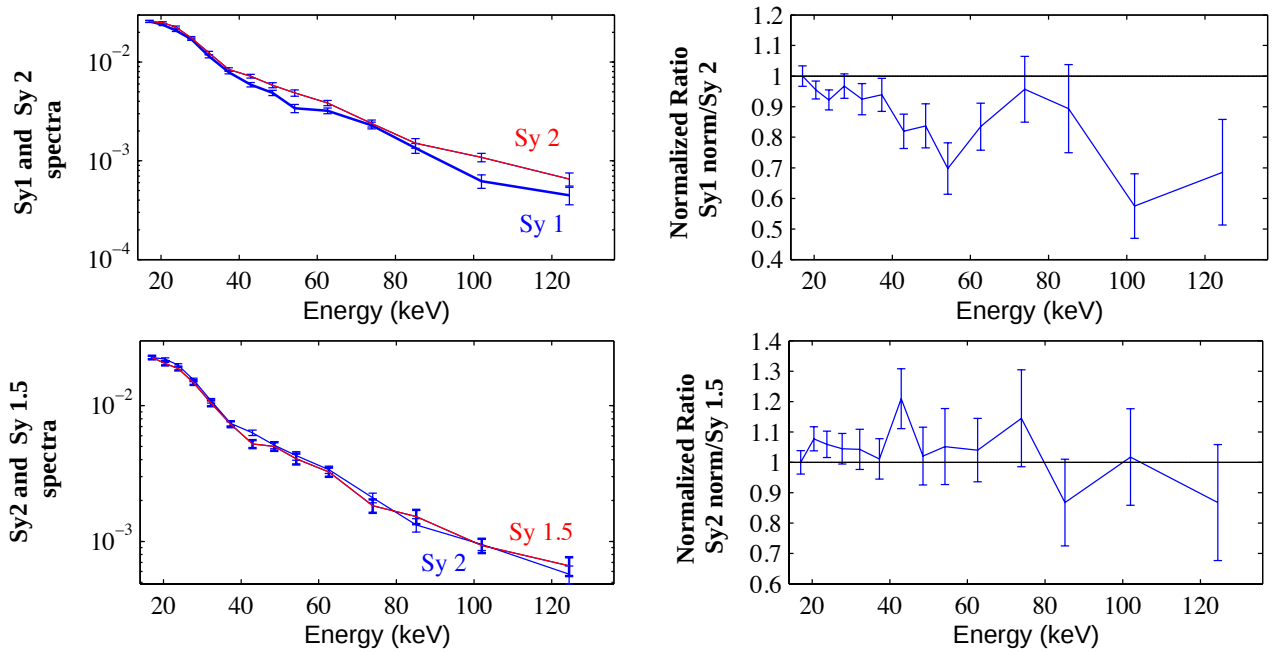


Figure 8.5: Normalized average *BeppoSAX* hard X-ray spectra of different classes of Seyfert galaxies (*left panels*) and their ratio (*right panels*). Figure taken from Deluit & Courvoisier (2003).

8.4 Seyfert 2s with and without BLR

One of the main problems of the unified model is to explain the existence of *naked Seyfert 2s*, namely Seyfert galaxies which show only narrow emission line in the optical, but are not absorbed in the X-rays (e.g., Pappa et al. 2001). While for some of these objects there might be a misinterpretation of the X-ray spectra (e.g., Brightman & Nandra 2008), many of them probably intrinsically lack the BLR (e.g., NGC 3147 and NGC 3660, Bianchi et al. 2008 and Brightman & Nandra 2008, respectively). The existence of naked Sy2s is confirmed by the results obtained by spectropolarimetric surveys, which have shown that only $\sim 30 - 50\%$ of the Seyfert 2s show polarized broad lines (e.g., Tran 2001). In the following we will refer to Sy2s showing polarized broad lines as PBL Sy2s, and to those which do not as NPBL Sy2s.

Heisler et al. (1997) carried out the first detailed study of the population of PBL and NPBL Seyfert 2s, finding that the presence of an hidden broad line region was correlated to the IRAS f_{60}/f_{25} flux ratio, with the objects showing *warm* IRAS colors ($f_{60}/f_{25} < 4.0$) being PBL Sy2s.

In their paper, they suggested that the IRAS colors reflected the inclination of the dusty torus, with *cooler* sources having more obscured nuclei. However, this result was found to be inconsistent with the X-ray observations of these objects (Alexander 2001, Gu et al. 2001), which found that statistically Sy2s with "warm" and "cool" IRAS colors have consistent distributions of the column density. Alexander (2001) argued that the IRAS f_{60}/f_{25} flux ratio might be related to the relative luminosities of galactic and AGN activity, and that the "cooler" color of NPBL Sy2s was due to either a low AGN luminosity or to a strong galactic emission.

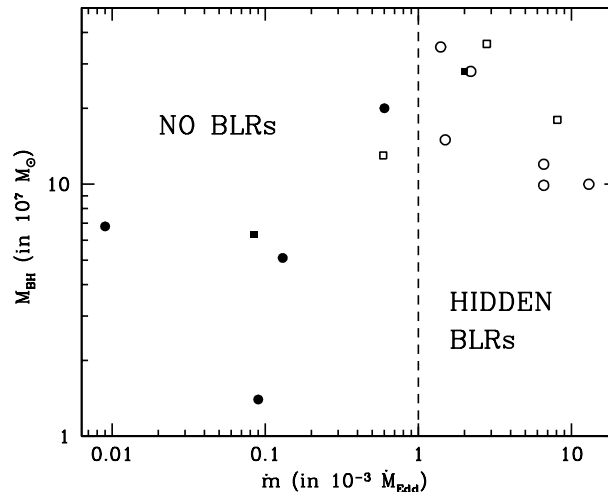


Figure 8.6: Black hole masses versus accretion rates (in Eddington units). Open symbols represent PBL Sy2s, and filled ones NPBL Sy2s. Figure taken from Nicastro et al. (2003).

Lumsden & Alexander (2001) found that PBL Sy2s are on average more luminous than NPBL Sy2s. This was confirmed by Tran (2003), who also found that PBL Sy2s tend to have hotter circumnuclear dust temperatures and show mid-IR spectra more similar to those of Seyfert 1s. Using a small sample of sources observed by *BeppoSAX*, Deluit (2004) found that at hard X-rays PBL Sy2s are quite similar to Sy1s, while they have characteristics different from those of NPBL Sy2s. In particular they found that PBL Sy2s are flatter than NPBL Sy2s, and have a cutoff at ~ 80 keV, while NPBL Sy2s do not show any evidence of a cutoff. A very important result was obtained by Nicastro et al. (2003), who found that almost all PBL Sy2s have accretion rates larger than the threshold value of $\dot{m}_T \simeq 10^{-3}$ (in Eddington units), while NPBL Sy2s are below this value (Fig. 8.6). They argued that at very low accretion rates (and therefore low luminosities) the clouds of the BLR might cease to exist. Their work agrees with the previous study of Nicastro (2000), who proposed that the BLR is formed by accretion disk instabilities occurring in proximity of the critical radius at which the disk changes from gas pressure dominated to radiation pressure dominated.

Although the accretion rate probably plays a very important role in the creation of the BLR, this might not be the end of the story. Shu et al. (2007) found that nuclear obscuration might also play a significant role in the visibility of the hidden BLR, with NPBL Sy2s being on average more obscured than PBL Sy2s. This might however be a simple side effect of different Eddington ratios. An alternative explanation has been given by Lumsden et al. (2004), who argued that long-term large-amplitude variations in the nuclear activity could affect the flux of the BLR in polarized light, and thus affect the detectability of PBL Sy2s.

8.5 Narrow line Seyfert 1s

While the simple orientation unified model (or as defined by Antonucci 1993, the *straw person model*) could explain most of the differences between Seyfert 1s and Seyfert 2s, it cannot provide an easy interpretation to the peculiar characteristics of NLS1s.

Some of the most remarkable properties of NLS1s are seen in the soft X-rays (0.1–10 keV). At these energies NLS1s show a very strong X-ray variability on short timescales (e.g., Boller et al. 1997, Gallo et al. 2004, see Fig. 8.7), a continuum usually steeper ($\Gamma > 2$) than that of their broad lines counterparts (e.g., Netzer 2000, Grupe 2000), a very strong soft excess (Pounds et al. 1995), and in some cases a hard excess (e.g., Terashima et al. 2009, see also Sect. 5.5). At hard X-rays little is known about the spectral features of these objects. The first systematic hard X-ray study of NLS1s was carried out by Malizia et al. (2008). From the spectral analysis of the average X-ray spectrum of their sample they found a cutoff at ~ 40 keV, significantly lower than the average value of Seyfert 1s (e.g., Dadina 2008), which they argued that this might be related to a lower temperature of the Comptonizing plasma in NLS1s.

In Sect. 1.3.1 we mentioned how the lower black hole masses and higher accretion rates of NLS1s might explain their characteristics. This has been confirmed by several pieces of evidence. It has been observed that large scale stellar bars are more frequent in NLS1s than in BLS1s (Crenshaw et al. 2003a), which might provide an efficient mechanism to transport gas from the outer to the inner nuclear region (Friedli & Benz 1993). Black hole mass estimates have confirmed that NLS1s have lower black hole masses (Wandel et al. 1999; Peterson et al. 2000). The fact that the $M - \sigma$ relation (see Sect. 5.1) is different for NLS1s with high L/L_{Edd} (Grupe & Mathur 2004), has been interpreted as being due to a higher accretion rate at earlier evolutionary epochs, emphasizing the hypothesis that NLS1s are young AGN (Grupe et al. 1999). It has been recently shown, using IR *Spitzer* observations, that NLS1s appear to have an enhanced star formation (Sani et al. 2010), which might imply that the star formation is tightly linked to the black hole growth.

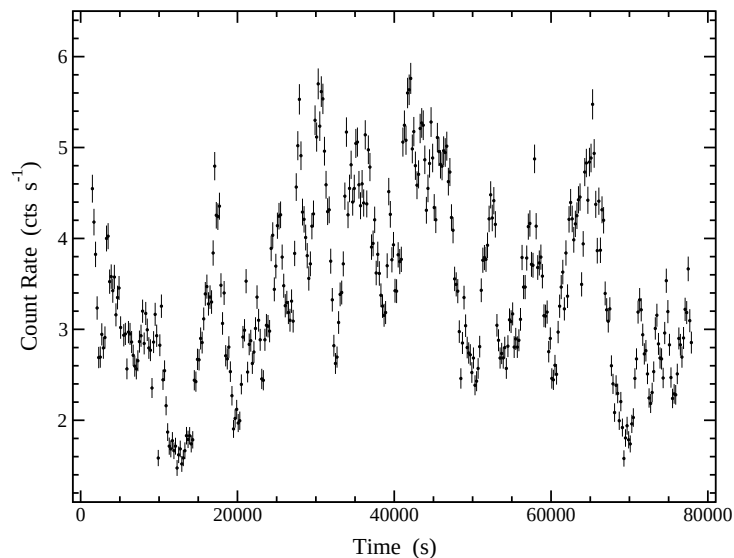


Figure 8.7: X-ray variability of 1H0707-495 in the 0.3–12 keV band measured by *XMM-Newton* EPIC/pn (Gallo et al. 2004). The bins used are of 200 s.

Although a large number of NLS1s has been detected so far, only few of their absorbed type-2 counterparts (the so-called NLS2s) are known. The first, and probably the most famous, NLS2 discovered is NGC 5506, which is also one of the brightest Seyfert galaxies in the local universe. NGC 5506 was thought to be a Seyfert 2 (De Robertis & Osterbrock 1986), until the discovery of the permitted OI λ 1.1287 μ m and 1 μ m Fe II emission lines in its near-IR spectrum, which can only originate in the optically-thick BLR (Nagar et al. 2002). Two more possible examples of NLS2s are given by Dewangan & Griffiths (2005), who found, analyzing the *XMM-Newton* spectra of NGC 7314 and NGC 7582, characteristics similar to those of NLS1s (i.e., steep spectra and rapid variability). Obscured NLS1s are quite difficult to recognize (i.e., they can be easily mistaken for Sy2s), and detailed near-IR, X-ray or spectropolarimetric observations are necessary to find them. However, the fact that only a handful of them have been seen so far might be related to an intrinsic rarity of this class. In fact, high accretion rates might be able to sweep the matter surrounding the SMBH (see Fig. 4.8 in Sect. 4.5), and NLS1s, having very high values of λ_{Edd} , might simply have absorbers with a very small covering factor. In agreement with this, it has been showed that hard X-ray selected NLS1s are on average less absorbed than "normal" Seyfert 1s (Sect. 8.8).

NLS1s show that a simple orientation unified model is not enough, and another very important degree of freedom has to be taken into account if one wants to link different types of radio-quiet AGN: the Eddington ratio ($\lambda_{\text{Edd}} = L/L_{\text{Edd}} \propto \dot{M}/\dot{M}_{\text{Edd}} \propto L/M$).

8.6 LINERs

Another class which cannot be easily fit into the unified model are the LINERs. These objects are defined by their optical spectra (see Section 1.3.1), and have usually lower X-ray luminosities ($L_{(2-10\text{ keV})} \sim 10^{39} - 10^{42} \text{ erg s}^{-1}$) than Seyfert galaxies ($L_{(2-10\text{ keV})} \sim 10^{42} - 10^{45} \text{ erg s}^{-1}$), e.g., Ho (2008). The mechanisms of ionization in LINERs are still not well understood, and over the years several hypothesis have been put forward, as shock heating (Dopita & Sutherland 1995), photoionization from Wolf-Rayet or OB stars in compact near-nuclear star clusters (Terlevich & Melnick 1985), or low luminosity AGN (Ho et al. 1997b).

Low-luminosity AGN in LINERs are usually recognized by the detection of unresolved nuclear sources. Using an optically selected sample Ho et al. (2001) found that $\sim 75\%$ of LINERs (both of type 1 and 2) contain X-ray cores, some as faint as $L_X(2-10\text{ keV}) \sim 10^{38} \text{ erg s}^{-1}$. A detection rate of 100% was obtained by Terashima & Wilson (2003) studying LINERs with a flat spectrum radio core, while González-Martín et al. (2009b) found that $\sim 60\%$ of the 82 LINERs appear to host AGN. In his very detailed review, Ho (2008) argues that the incidence of X-ray cores in LINERs is quite high, and ranges from 50% to 70%. However, it has been recently argued by Capetti (2011), that most of the object defined as LINERs are emission-line galaxies, and only $\sim 10\%$ of them contain AGN. Analyzing the multi-wavelength emission of luminous LINERs (Ho 1999), found that their SEDs show a significant deficiency in the optical/UV portion of the spectrum when compared to those of standard AGN, and suggested that this might be due to LINERs having a different kind (i.e., radiatively inefficient, see Sect. 1.2.2) of accretion flow. This has been also supported by the non-detection of broad iron $K\alpha$ lines (e.g., Ptak et al. 2004) and possibly by the absence of X-ray variability (e.g., Ptak et al. 1998). However, it is still not known whether the optical/UV deficiency in LINERs is intrinsic or rather due to a very large dust obscuration. From their *Chandra* study of LINERs, González-Martín et al. (2009b) concluded that LINERs have X-ray spectral shapes similar to those commonly observed in Seyfert 2s. González-Martín et al. (2009a) confirmed this result, arguing that $\sim 50\%$ of LINERs might be CT (a larger fraction than in Seyfert galaxies, see Sect. 4.3), and that

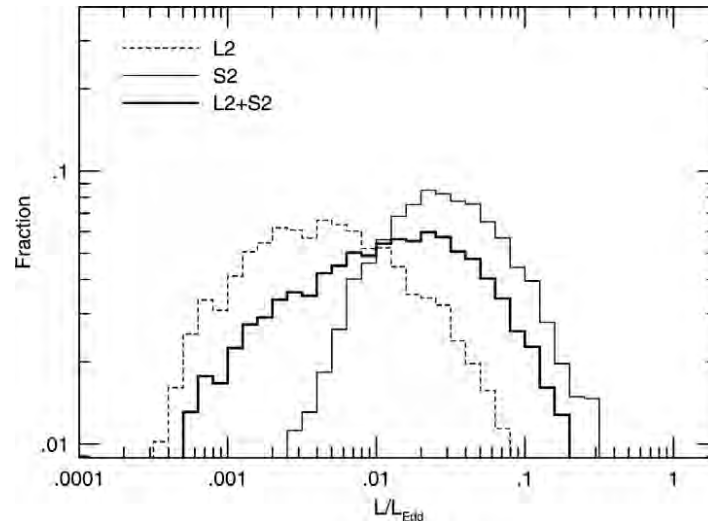


Figure 8.8: L/L_{Edd} distributions of Seyfert 2s (S2), type-2 LINERs (L2), and of the combined type-2 high S/N SDSS-DR4 sample (Netzer 2010).

most of the flux received might be electron-scattered nuclear emission, with the AGN being almost invisible. Moreover, the objects of their sample have larger black hole masses and lower Eddington ratios than Seyfert galaxies (as also found in previous works, e.g. Netzer 2010, see Fig. 8.8), which might allow the presence of a larger amount of absorbing material around the AGN.

No systematic study of the hard X-ray properties of LINERs has been performed yet. During its first 7 years of life, *INTEGRAL* IBIS/ISGRI detected ~ 10 LINERs in the 17–80 keV band, while slightly more (15) have been detected by *Swift*/BAT (Cusumano et al. 2010). Hard X-ray studies of these objects might be extremely important to understand whether a large fraction of them really harbors CT AGN.

8.7 Buried AGN

Studying the *Suzaku* broad-band X-ray spectra of AGN detected by *Swift*/BAT, Ueda et al. (2007) found two objects (SWIFT J0601.9-8636 and SWIFT J0138.6-4001, Fig. 8.9) with peculiar characteristics, which led them to put forward the hypothesis that they belong to a new class of absorbed AGN. These objects are set apart from "normal" Seyfert 2s by three main characteristics:

- Their optical spectra are almost featureless, with no evidence for $H\beta$ or $[\text{OIII}]\lambda 5007$ emission lines.
- Their X-ray spectra show a very high value of the reflection component ($R \simeq 2$)
- The fraction of scattered X-rays at low energies is very low ($f_{\text{scatt}} \lesssim 0.5\%$)

An important point to remark is that, based only on their optical spectra, these two sources would not have been identified as AGN. Both objects are Compton-thin ($\log N_{\text{H}} \simeq 23.5 \text{ cm}^{-2}$), and the high value of their reflection parameter has been explained by Ueda et al. (2007) with the hypothesis that part of the X-ray source is covered by CT material, which would increase the relative value of the reflected flux over the X-ray continuum. They argued that the transmission efficiency would

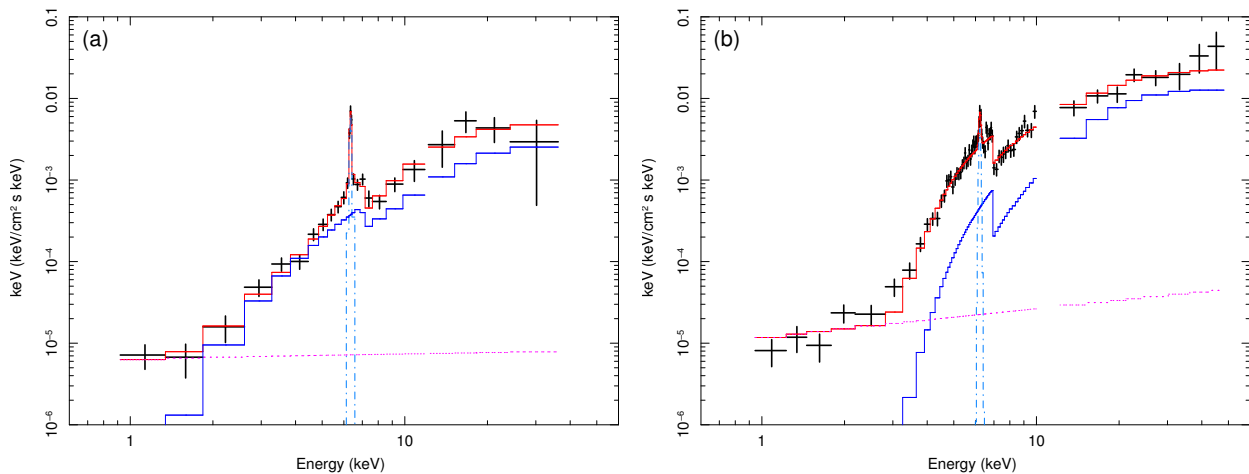


Figure 8.9: Broad-band *Suzaku* X-ray spectra of SWIFT J0601.9-8636 (*left panel*) and SWIFT J0138.6-4001 (*right panel*). Figures taken from Ueda et al. (2007).

be $T \lesssim 1/R$, and that these objects might be *buried AGN*, with absorbers covering a very large fraction of the AGN, which would deplete the emission lines in the optical band. In this scheme, the low fraction of radiation scattered at low energies is due to the small opening angle of the NLR (Fig. 8.10). They also discussed that the reflection-dominated nature of these objects, if found to be common, would have a very strong impact on the population synthesis models of the CXB (see Sect. 4.4).

From soft X-ray studies of hard X-ray selected AGN, Winter et al. (2008) found four sources with very low scattering fractions, which they tentatively identified as new cases of buried AGN. Studying a larger sample of *Swift*/BAT detected AGN, Winter et al. (2009) found that $\sim 24\%$ of the objects of their sample have low values of f_{scatt} ($< 3\%$), which led them to conclude that buried AGN might be rather common amongst hard X-ray selected AGN.

Following the work of Ueda et al. (2007), Eguchi et al. (2009) analyzing *Suzaku* observations of new *Swift*/BAT AGN (i.e., AGN which were not known from previous surveys in other energy bands) found another buried Sy2: SWIFT J0255.2-0011. They argued that a correlation between R and f_{scatt} might exist (see *left panel* of Fig. 8.10), and that the new hard X-ray selected AGN appear to lie in two different zones of the $R - f_{\text{scatt}}$ diagram, with the buried AGN having $R \gtrsim 0.8$ and $f_{\text{scatt}} \lesssim 0.5\%$. Eguchi et al. (2011), studying two more cases of new Seyfert 2s observed by *Suzaku* found another object (NGC 3081) with a large reflection component ($R \sim 0.9$) and low (although slightly above the threshold proposed by Eguchi et al. 2009) scattering fraction ($f_{\text{scatt}} \sim 0.7\%$). Using the physical model of Ikeda et al. (2009) they also found that the X-ray spectrum of NGC 3081 is consistent with an AGN with a torus having a very small opening angle of $\simeq 15^\circ$, in agreement with what has been proposed by Ueda et al. (2007). However, it must be remarked that, as argued by Ueda et al. (2007), it is possible that for some of these objects there might simply be less scattering material, which would imply that the value of f_{scatt} is not directly connected to the opening angle of the obscuring torus.

Noguchi et al. (2009), studying a sample of 22 AGN with low scattering fractions found that the objects with $f_{\text{scatt}} \lesssim 0.5\%$ have lower ratios of the [OIII] $\lambda 5007$ to the X-ray luminosities ($L_{[\text{OIII}]} / L_{2-10 \text{ keV}}$) than classical (i.e. selected by optical surveys) Seyfert 2s. This might be interpreted again as these objects having smaller NLRs than the other Sy2s. This has been confirmed using a larger sample by Noguchi et al. (2010), who also found a possible anti-correlation between the

Eddington ratio and the scattering fraction. This would imply that more rapidly growing SMBHs tend to have larger tori, i.e. objects having more matter to feed the SMBH would accrete more. Although the correlation is weak, it is worth mentioning that this result is quite surprising: one would in fact expect that a larger Eddington ratio would produce larger opening angles. Moreover, this anti-correlation would be quite difficult to explain if the NLR is a byproduct of disk winds or is related to radiatively-driven outflows.

The existence of AGN with a geometrically thick torus was predicted by [Fabian et al. \(1998\)](#), who proposed nuclear starburst to be the cause of this highly covering structure. However, [Noguchi et al. \(2010\)](#) argued that the lack of a correlation between the far-IR luminosity and f_{scat} might imply that the highly covering absorbers are not a by-product of starburst activity.

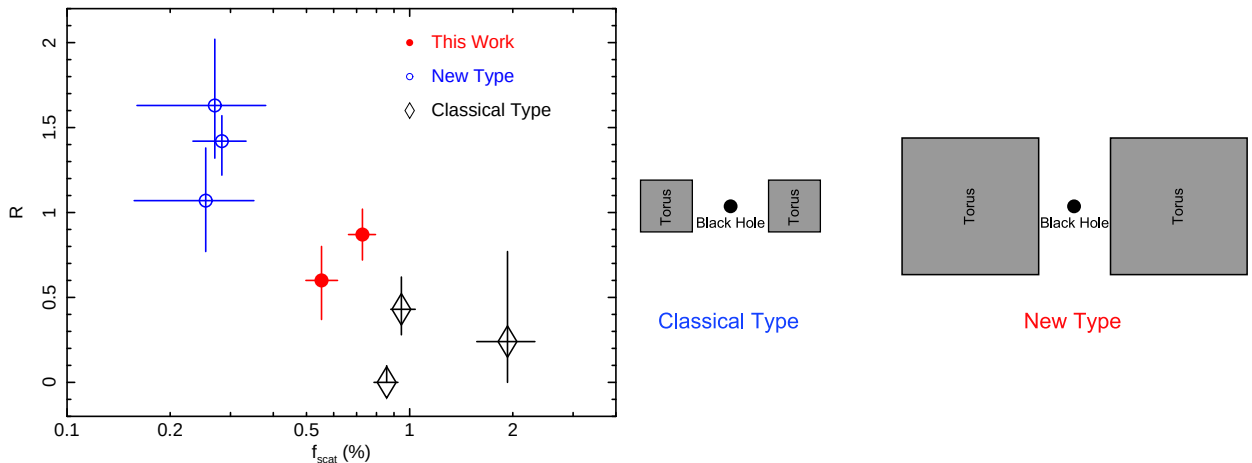


Figure 8.10: *Left panel:* scatter plot of the reflection parameter R vs the scattering fraction f_{scat} ([Eguchi et al. 2011](#)). *Right panel:* Schematic representation of buried AGN ([Eguchi et al. 2009](#)).

8.8 Reflection in Seyfert galaxies and the UM model of AGN

Aiming at testing the unified model of radio-quiet AGN at hard X-rays, we studied the average *INTEGRAL* IBIS/ISGRI spectra of 165 objects in the 17–250 keV energy range. The final sample consisted of 44 Seyfert 1s, 29 Seyfert 1.5s, 78 Seyfert 2s, and 14 NLS1s. To avoid the influence of absorption, we divided the Seyfert 2s in Compton-thin and Compton-thick (68 and 10 objects, respectively). Using all the available public data as of May 2010, for a total of ~ 100 Ms, we created the stacked spectra of each class of object. This is, as of October 2011, the deepest study of the average spectral characteristics of AGN ever performed in this energy range.

From both a model-dependent and a model-independent spectral analysis we found that, as foreseen by the unified model the average spectra of Sy1s and Sy1.5s are consistent. On the other hand, the average hard X-ray spectrum of Seyfert 2s shows a stronger reflection component than that of Seyfert 1s and Seyfert 1.5s. We found that most of this difference is due to what we defined mildly obscured (MOB, $10^{23} \leq N_H < 10^{24} \text{ cm}^{-2}$) Sy2s (see Fig. 8.11), while lightly obscured (LOB, $N_H < 10^{23} \text{ cm}^{-2}$) Sy2s have characteristics more similar to those of Sy1s and Sy1.5s.

The larger reflection component we found in MOB Sy2s cannot be easily explained by the unified model. As we discussed in Sect. 8.7 an enhanced reflection in Seyfert 2s might imply the existence of partially covering Compton-thick material in the line of sight. Our results could be explained assuming that the matter surrounding more obscured objects has on average a larger covering factor

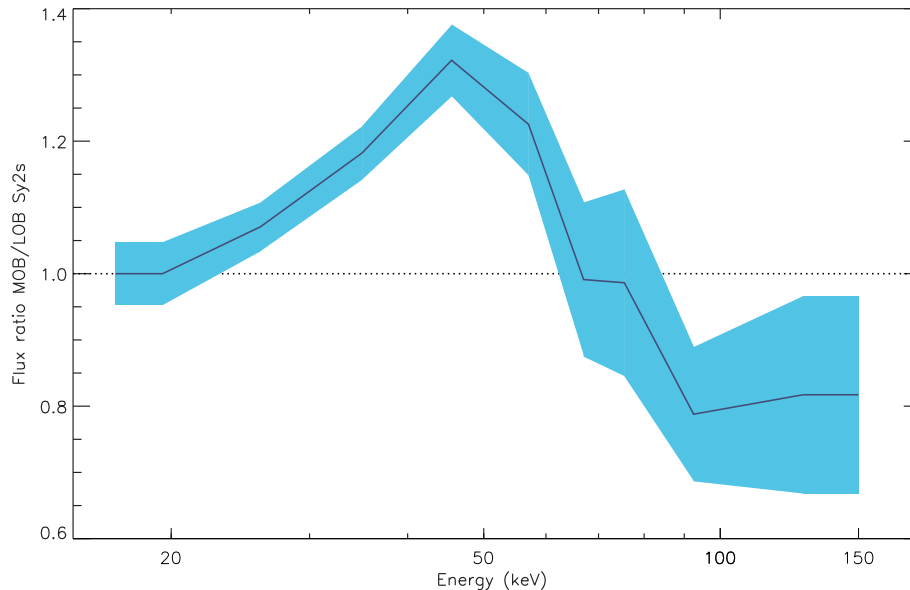


Figure 8.11: Ratio between the normalized average hard X-ray spectra of lightly (LOB, $N_{\text{H}} < 10^{23} \text{ cm}^{-2}$) and mildly obscured (MOB, $10^{23} \leq N_{\text{H}} < 10^{24} \text{ cm}^{-2}$) Sy2s. The blue area represents the 3σ uncertainty on the ratios.

(as proposed by [Ramos Almeida et al. 2011](#)), which would lead to the presence of a significant number of reflection-dominated Seyfert 2s in our hard X-ray selected sample (Fig. 8.12). The fact that the three buried AGN with a high reflection parameter reported in the paper of [Eguchi et al. \(2011\)](#) are amongst the Seyfert 2s of our sample, together with the finding of [Winter et al. \(2009\)](#) that a large fraction of hard X-ray selected AGN have a low scattering fraction, might hint to the existence of a significant population of highly reflecting buried AGN, which emerges from hard X-ray surveys because they are practically unbiased by absorption. The fact that once one has taken into account a larger reflection component for MOB Sy2s the parameters of the primary emission (power law photon index and energy of the cutoff) are consistent, agrees with the weakest form of AGN unification, i.e. that the central engine is on average the same for all type of objects. The existence of a large fraction of reflection dominated Sy2s might be extremely important for the development of realistic population synthesis models of the CXB (see Sect. 4.4 and 8.7), in particular buried AGN might decrease the number of CT objects needed to explain the peak of the CXB at $\sim 30 \text{ keV}$.

At hard X-ray only few NLS1s are detected, and little is known about the characteristics of their spectra. Our sample of 14 objects represents the largest study ever performed at these energies. We found that, similarly to what observed at softer energies, the average spectrum of NLS1s is steeper than that of Sy1s. However, this appears to be due to a lower energy of the cutoff for this particular group, as the average hard X-ray spectrum of NLS1s starts to diverge from that of Sy1s only above 40 keV. Moreover from an inspection of the soft X-ray spectra of the 14 NLS1s of our sample we found that they are not steeper than Sy1s. A selection bias might be at the origin of this, being flatter objects easier to detect at hard X-rays. A lower energy of the cutoff might imply differences in the physical condition of the hot plasma surrounding the SMBH in NLS1s, as suggested by [Malizia et al. \(2008\)](#).

To understand whether PBL and NPBL Sy2s are intrinsically the same objects or not, we pro-

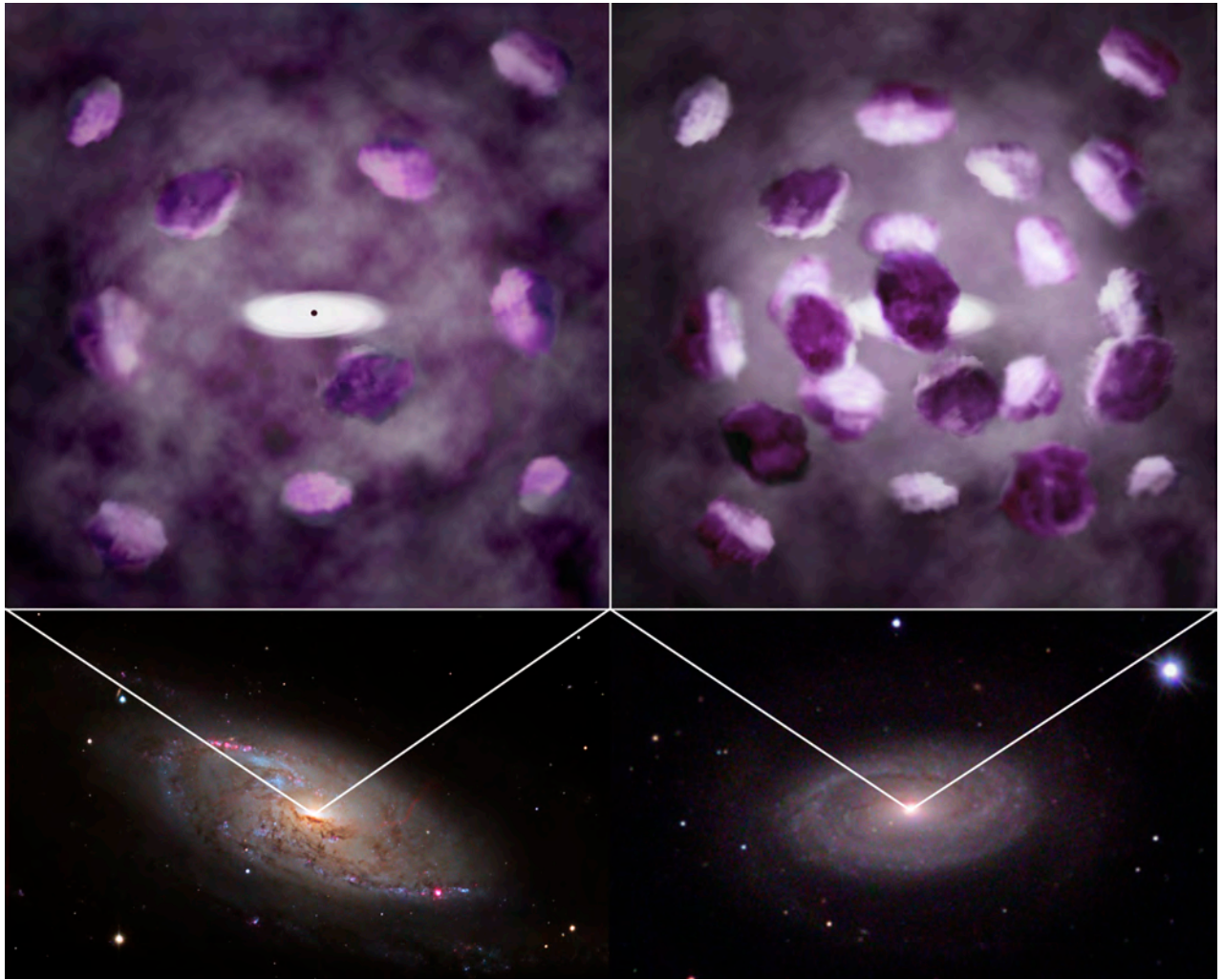


Figure 8.12: Artist view of lightly (*left panel*) and mildly (*right panel*) obscured AGN. Credits: *ESA/AOES Medialab and NOAO/AURA/NSF*.

duced and compared their average hard X-ray spectra. Only for 19 Seyfert 2s spectropolarimetric information was available, of these 11 are PBL and 8 are NPBL Sy2s. We found that, differently from what has been found by [Deluit \(2004\)](#), the two classes appear to have consistent average hard X-ray spectra, which implies that their X-ray sources have on average the same characteristics.

These results are reported in [Ricci et al. \(2011\)](#), and were the subject of an ESA press release¹, and of the *INTEGRAL* picture of the month² in August 2011.

¹<http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=49019>

²http://www.rssd.esa.int/index.php?project=INTEGRAL&page=POM_generation&yr=2011&mon=08&extn=jpg

Reflection in Seyfert galaxies and the unified model of AGN[★]

C. Ricci^{1,2}, R. Walter^{1,2}, T. J.-L. Courvoisier^{1,2}, and S. Paltani^{1,2}

¹ ISDC Data Centre for Astrophysics, University of Geneva, ch. d'Ecogia 16, 1290 Versoix, Switzerland
e-mail: claudio.ricci@unige.ch

² Geneva Observatory, University of Geneva, ch. des Maillettes 51, 1290 Versoix, Switzerland

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ABSTRACT

We present a deep study of the average hard X-ray spectra of Seyfert galaxies. We aim to test the unified model of active galactic nuclei, and constrain differences and similarities between different classes of objects. We analyzed all public INTEGRAL IBIS/ISGRI data available on all the 165 Seyfert galaxies detected at $z < 0.2$. Our final sample consists of 44 Seyfert 1s, 29 Seyfert 1.5s, 78 Seyfert 2s, and 14 narrow-line Seyfert 1s. For each subsample, we stacked all the images, and derived their average hard X-ray spectra in the 17–250 keV energy range. We performed a detailed spectral analysis using both a model-independent and a model-dependent approach. All classes of Seyfert galaxies show on average the same nuclear continuum, as foreseen by the zeroth order unified model, with a cutoff energy of $E_C \gtrsim 200$ keV, and a photon index of $\Gamma \simeq 1.8$. The average optical depth of the Comptonizing medium is consistent for the different classes ($\tau \simeq 0.8$). Compton-thin Seyfert 2s show a reflection component stronger than Seyfert 1s and Seyfert 1.5s. Most of this reflection is due to mildly obscured ($10^{23} \text{ cm}^{-2} \leq N_H < 10^{24} \text{ cm}^{-2}$) Seyfert 2s, which have a significantly stronger reflection component ($R = 2.2^{+4.5}_{-1.1}$) than Seyfert 1s ($R \leq 0.4$), Seyfert 1.5s ($R \leq 0.4$), and lightly obscured ($N_H < 10^{23} \text{ cm}^{-2}$) Seyfert 2s ($R \leq 0.5$). This cannot be explained easily by the unified model. The absorber/reflector in mildly obscured Seyfert 2s might cover a large fraction of the X-ray source, and contain clumps of Compton-thick material. The large reflection found in the spectrum of mildly obscured Seyfert 2s reduces the amount of Compton-thick objects needed to explain the peak of the cosmic X-ray background. Our results are consistent with the fraction of Compton-thick sources being $\sim 10\%$. The spectra of Seyfert 2s with and without polarized broad lines do not show significant differences, the only difference between the two samples being the higher hard X-ray and bolometric luminosity of Seyfert 2s with polarized broad lines. The average hard X-ray spectrum of narrow-line Seyfert 1s is steeper than those of Seyfert 1s and Seyfert 1.5s, probably due to a lower energy of the cutoff.

Key words. galaxies: active – galaxies: Seyfert – X-rays: galaxies – galaxies: nuclei – X-rays: diffuse background

1. Introduction

Active galactic nuclei (AGN) emit over the entire electromagnetic spectrum, and are commonly assumed to be powered by accretion onto a super massive black hole (Rees 1984). Seyfert galaxies host AGN, and are classified according to their emission lines as Seyfert 1s (Sy1s, showing broad and narrow emission lines), and Seyfert 2s (Sy2s, showing only narrow lines). Many Seyfert galaxies exhibit optical spectra with properties in-between those of Sy1 and Sy2 galaxies (e.g., Osterbrock & Koski 1976). These objects have been classified as type 1.2, 1.5, 1.8, or 1.9 Seyfert galaxies, depending on the details of their optical spectra. Studies of the optical spectra of Seyfert 2 galaxies using polarized light (Miller & Antonucci 1983; Antonucci & Miller 1985) showed that broad emission lines can also be detected in some of these objects, and led to the development of the so-called unified model (UM, Antonucci 1993). According to this model, the same engine is at work in all kind of Seyfert galaxies, and the differences between Seyfert 1s and Seyfert 2s can be ascribed solely to orientation effects and anisotropic obscuration. In this model, the line of sight to the nucleus is (Seyfert 2s) or is not (Seyfert 1s) obstructed by optically thick material, possibly distributed in a toroidal geometry. X-ray observations have confirmed this idea, showing that most AGN unabsorbed in X-rays are of the optical Seyfert 1 type, and that

most AGN that are absorbed belong to the Seyfert 2 group (e.g., Awaki et al. 1991).

However, in the past few years observational evidence of significant differences between Seyfert 1s and Seyfert 2s has been discovered. Seyfert 1s with significant absorption have been found (e.g., Fiore et al. 2001; Cappi et al. 2006), along with Seyfert 2s without X-ray absorption (e.g., Pappa et al. 2001; Panessa & Bassani 2002). Furthermore, spectropolarimetric surveys indicate that only ~ 30 – 50% of Seyfert 2s have polarized broad lines (PBLs), which might imply that not all of them harbor hidden BLRs (e.g., Tran 2001, 2003; Gu & Huang 2002). In the soft X-rays the photon index distribution is found to be skewed towards low values of Γ for obscured objects (Brightman & Nandra 2010), while in the hard X-rays, Seyfert 2s have been found to have harder spectra than Seyfert 1s (e.g., Zdziarski et al. 1995; Malizia et al. 2003; Deluit & Courvoisier 2003; Ajello et al. 2008a; Burlon et al. 2011).

Two subclasses of objects cannot be easily explained by the unified model: narrow-line Seyfert 1s (NLS1s) and low ionization nuclear emission line regions (LINERs). It has been suggested that NLS1s are AGN in their early phase (Grupe et al. 1999), characterized by relatively low black hole masses (e.g., Grupe & Mathur 2004) and very high accretion rates in terms of Eddington units (e.g., Grupe et al. 2010). LINERs (Heckman 1980) are low luminosity AGN, and display multiwavelength peculiar characteristics. They could be the link between AGN and normal galaxies (Zhang et al. 2009; Rovilos et al. 2009), or their

[★] Appendices are available in electronic form at
<http://www.aanda.org>

SMBH might accrete differently from normal Seyfert galaxies (Ho 2008).

The X-ray emission of Seyfert galaxies is thought to be produced by the Comptonization of ultraviolet (UV) photons generated in the innermost edge of the accretion disk by a population of hot electrons located in a coronal region sandwiching the disk (Haardt & Maraschi 1991, 1993). The X-ray spectrum of AGN can be normally well described by a power law model with a photon index between $\Gamma \approx 1.8$ (e.g., Dadina et al. 2008) and $\Gamma \approx 2$ (e.g., Beckmann et al. 2009). Other common characteristics are an exponential cutoff at an energy depending on the temperature of the plasma T_e and its Thomson opacity, and photoelectric absorption at low energies, caused by material along the line of sight. Two prominent features generated by the reflection of the continuum are also observed in the X-ray spectra of AGN: a neutral iron $K\alpha$ line (at 6.4 keV in the local reference frame) and a reflection hump peaking at $E \approx 30$ keV (Magdziarz & Zdziarski 1995). At energies $\gtrsim 20$ keV, the photoelectric cross-section sharply declines, and the presence of matter along the line of sight does not play a significant role, unless the source is Compton-thick (CT; $N_H > 1.5 \times 10^{24} \text{ cm}^{-2}$). Therefore hard X-rays are ideal for probing the intrinsic emission of AGN and testing the UM, according to which different types of Seyfert galaxies should show on average the same characteristics.

The INTERNATIONAL Gamma-Ray Astrophysics Laboratory (INTEGRAL; Winkler et al. 2003) is a hard X-ray/soft γ -ray mission, designed for imaging and spectroscopy with high angular and spectral resolution in the energy range from ~ 3 keV to 10 MeV. Since its launch on October 17, 2002, the soft γ -ray imager IBIS/ISGRI (15–1000 keV; Lebrun et al. 2003, Ubertini et al. 2003) on board INTEGRAL has detected more than 200 AGN, among which about 90 were detected for the first time in the hard X-rays. IBIS/ISGRI uses the coded-aperture technique (Caroli et al. 1987) and has a large field of view of 29° square with a spatial resolution of 12 arcmin.

We present a very deep study of the average hard X-ray spectra of Seyfert galaxies. Our main aim is to test the unified model by studying the average hard X-ray emission of different types of radio-quiet AGN detected by INTEGRAL IBIS/ISGRI, and to constrain the average spectral characteristics of each class. We also investigate whether Seyfert 2s showing (hereafter PBL Sy2s) and not showing (hereafter NPBL Sy2s) PBLs are intrinsically similar objects or not. In Sect. 2, we present the sample of AGN; in Sect. 3, we describe how the data analysis was performed and how the hard X-ray spectra were obtained; in Sect. 4, we present the results obtained from a model-independent analysis of the spectra, and in Sect. 5, we discuss the model-dependent spectral analysis. We study the origin of a strong reflection component found in the spectrum of Seyfert 2s in Sect. 6; and in Sect. 7, we discuss our results and their implications for the UM and the cosmic X-ray background (CXB). In Sect. 8, we present our conclusions and summarize our findings.

2. The sample

The sample consists of all the 205 Seyfert galaxies detected (significance $> 5\sigma$) in the hard X-rays by INTEGRAL IBIS/ISGRI during its first eight years of operations. We considered as their optical classifications the ones reported in the latest version of the Veron Catalog of Quasars and AGN (Veron-Cetty & Veron 2010).

The sample consists of 38 Seyfert 1s, 17 Seyfert 1.2s, 34 Seyfert 1.5s, 3 Seyfert 1.8s, 15 Seyfert 1.9s, 75 Seyfert 2s,

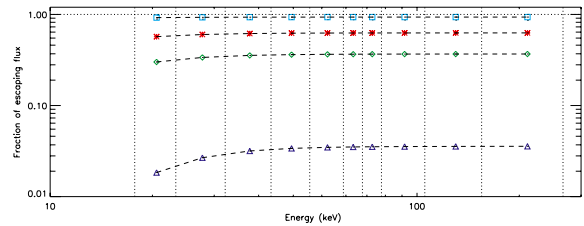


Fig. 1. Fraction of escaping flux in the 10 energy bins used. Squares represent $N_H = 10^{23} \text{ cm}^{-2}$, stars $N_H = 7 \times 10^{23} \text{ cm}^{-2}$, diamonds $N_H = 1.5 \times 10^{24} \text{ cm}^{-2}$, and triangles $N_H = 5 \times 10^{24} \text{ cm}^{-2}$.

8 LINERs, and 15 NLS1s. We excluded from these subsamples the LINERs, because the physical characteristics of their accretion flow might differ from those of the others. We grouped Seyfert 1.2s with Seyfert 1s, and both Seyfert 1.8s and Seyfert 1.9s with Seyfert 2s because of their similarity.

2.1. The role of absorption

To model the effect of absorption on the X-ray spectra of AGN, one has to take into account both photoelectric absorption and Compton scattering. The photoelectric cross-section σ_{ph} has a strong dependence on the energy, while Compton scattering in the hard X-rays depends on the Thomson cross-section σ_T , and is constant with energy up to the Klein-Nishina decline. The cumulative effect of the two cross-sections is given by

$$M(E) = e^{-\sigma_{ph}(E)N_H} \times e^{-\sigma_T N_H}. \quad (1)$$

For column densities of the order of $\sigma_T^{-1} = 1.5 \times 10^{24} \text{ cm}^{-2}$, only about 30% of the flux is able to escape at ~ 20 keV (see Fig. 1). About 60% of the original emission is unabsorbed for $N_H = 7 \times 10^{23} \text{ cm}^{-2}$, and we used this value as a threshold between Compton-thin and Compton-thick sources. Thus, we included in our final sample of Seyfert 2s only the objects with a value of column density of $N_H \leq 7 \times 10^{23} \text{ cm}^{-2}$, and placed the 10 Seyfert 2s with $N_H > 7 \times 10^{23} \text{ cm}^{-2}$ in the CT Seyfert 2s sample. We note, however, that none of the sources in our sample has a N_H in the $(7-10) \times 10^{23} \text{ cm}^{-2}$ range, so in the following we refer to 10^{24} cm^{-2} as the threshold between Compton-thin and Compton-thick objects. In the following, we use solar abundances and the photoelectric cross section of Morrison & McCammon (1983).

2.2. Excluded sources

To avoid contamination and problems related to the way we obtain the average spectra (see Sect. 3), we excluded from the sample 10 sources which are too close ($\leq 0.4^\circ$) to each other or to other bright sources. We excluded 11 sources with redshift $z > 0.2$ to avoid spurious effects due to redshifted spectral features (i.e. the high-energy cutoff and the reflection hump). We removed the 5 sources detected with a significance $> 50\sigma$, to prevent them from dominating the final spectra.

Four sources with either an uncertain classification or peculiar absorbers were also excluded from the analysis. Was 49 is an interacting system of galaxies containing two Seyfert nuclei (Moran et al. 1992). The AGN IGR J16426+6536 shows characteristics typical of both NLS1 (Masetti et al. 2009) and Seyfert 1.5 (Butler et al. 2009) galaxies. The Seyfert 1.8 NGC 1365 has been found to undergo transitions from a “transmission dominated” to a “reprocessing dominated” state and

Table 1. Sources detected by INTEGRAL IBIS/ISGRI but excluded from the analysis, and reason for their exclusion.

Source	Type	Reason for the exclusion
4U 1344–60	Sy 1.5	C
Circinus Galaxy	CT Sy 2	B
ESO 138–1	Sy 2	C
ESO 383–18	Sy 2	C
GRS 1734–292	Sy 1	B
IC 4329A	Sy 1	B
IGR J00465–4005	Sy 2	R
IGR J05270–6631	Sy 1	R
IGR J06117–6625	Sy 1.5	R
IGR J09523–6231	Sy 2	R
IGR J10147–6354	Sy 1	R
IGR J12131+0700	Sy 1.5	C
IGR J13038+5348	Sy 1	R
IGR J14515–5542	Sy 2	C
IGR J16024–6107	Sy 2	C
IGR J16056–6110	Sy 1.5	C
IGR J16426+6536	NLS1	U
IGR J17476–2253	Sy 1	C
IGR J17488–3253	Sy 1	C
IGR J18249–3243	Sy 1	R
IGR J21272+4241	Sy 2	R
NGC 1365	Sy 2	U
NGC 4151	Sy 1.5	B
NGC 4388	Sy 2	B
NGC 4939	Sy 2	U
NGC 6221	Sy 2	C
PKS 0637–752	Sy 1.5	R
QSO B1821+643	Sy 1	R
SWIFT J0216.3+5128	Sy 2	R
Was 49a + Was 49b	Sy 1 + Sy 2	U

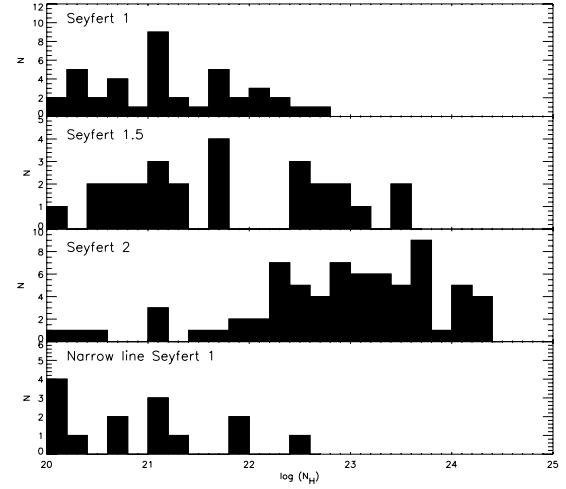
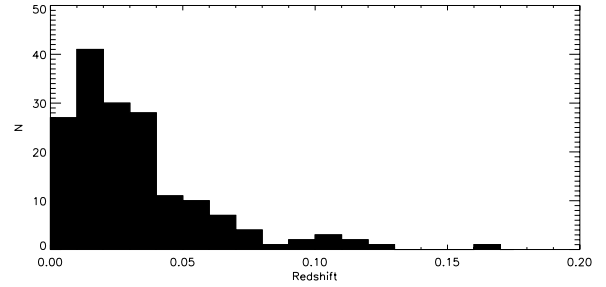
Notes. More details can be found in Sect. 2.2. C: close to other detected sources ($\leq 0.4^\circ$); U: classification; unclear or with particular characteristics; R: $z > 0.2$; B: bright (detection significance $> 50\sigma$ in the 17–80 keV band).

back in a few weeks time, which have been interpreted as due to eclipses of CT material along the line of sight (Risaliti et al. 2005). A similar state transition has been observed in NGC 4939 (Guainazzi et al. 2005), a Seyfert 2 that was previously classified as Compton-thick by *BeppoSAX* observations (Maiolino et al. 1998). The excluded sources are reported in Table 1.

2.3. The final sample

The final sample used for the analysis consists of 165 AGN, of which 44 are Seyfert 1s, 29 Seyfert 1.5s, 68 Compton-thin Seyfert 2s, 10 CT Seyfert 2s, and 14 NLS1s. Spectropolarimetric data are available for only 19 of the 68 Compton-thin Seyfert 2s of our sample. Among these, 11 show and 8 do not show PBLs. The sources and their characteristics are reported in Appendix A.

Figure 2 shows the distribution of the column density for the different classes of AGN. The average values of the column densities of the different classes are $N_{\text{H}}^{\text{Sy1}} = 5.4 \times 10^{21} \text{ cm}^{-2}$, $N_{\text{H}}^{\text{Sy1.5}} = 3.7 \times 10^{22} \text{ cm}^{-2}$, $N_{\text{H}}^{\text{Sy2}} = 1.5 \times 10^{23} \text{ cm}^{-2}$, $N_{\text{H}}^{\text{NLS1}} = 1.9 \times 10^{21} \text{ cm}^{-2}$, and $N_{\text{H}}^{\text{CT}} = 1.5 \times 10^{24} \text{ cm}^{-2}$, for Seyfert 1s, Seyfert 1.5s, Seyfert 2s, NLS1s, and CT Seyfert 2s, respectively. These values agree with the paradigm that Seyfert 2s are more obscured than Seyfert 1s and Seyfert 1.5s. Considering the average column densities of the different samples, the percentage of

**Fig. 2.** Hydrogen column density distributions of Seyfert 1s, Seyfert 1.5s, Seyfert 2s and narrow-line Seyfert 1s.**Fig. 3.** Redshift distribution of our final sample of INTEGRAL IBIS/ISGRI detected Seyfert galaxies.

flux absorbed in the first band (17–22 keV) by photoelectric processes is about 0.01%, 0.5%, and 2% for Seyfert 1s, Seyfert 1.5s, and Seyfert 2s, respectively. Compton processes have a stronger influence at these energies, and the fraction of scattered flux is of 0.3%, 2.4% and 9.5%, for Seyfert 1s, Seyfert 1.5s and Seyfert 2s, respectively. In the case of CT Seyfert 2s, the influence of the obscuring material is stronger and $\approx 18\%$ of the flux is photoelectrically absorbed, whereas when we also consider Compton scattering, only $\approx 30\%$ of the flux escapes. A Kolmogorov-Smirnov (KS) gives a probability of $\approx 67\%$ that the column density distributions of Seyfert 1s and Seyfert 1.5s are drawn from the same parent population. The probability is much lower when comparing NLS1s to Seyfert 1s and Seyfert 1.5s ($\approx 10\%$).

In Fig. 3, we show the redshift distribution of our final sample. The average value of the redshift is $z = 0.03$, and the average detection significance is 12.7σ .

In Fig. 4, we show the luminosity distributions in the 17–80 keV band of our samples of Seyfert galaxies. The luminosities were calculated assuming a standard Λ CDM cosmological model, Crab-like spectra (e.g., Jourdain & Roques 2009), and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The average values of the luminosity are $L_{\text{Sy1}} = 5.0 \times 10^{43} \text{ erg s}^{-1}$, $L_{\text{Sy1.5}} = 3.7 \times 10^{43} \text{ erg s}^{-1}$, $L_{\text{Sy2}} = 2.1 \times 10^{43} \text{ erg s}^{-1}$, $L_{\text{CTSy2}} = 8.3 \times 10^{42} \text{ erg s}^{-1}$, and $L_{\text{NLS1}} = 1.7 \times 10^{43} \text{ erg s}^{-1}$, for Sy1s, Sy1.5s, Sy2s, CT Sy2s, and NLS1s, respectively. The luminosity of CT Sy2 was corrected for Compton scattering. A KS test gives a probability of $\approx 53\%$ that the luminosity distributions of Seyfert 1s and Seyfert 1.5s

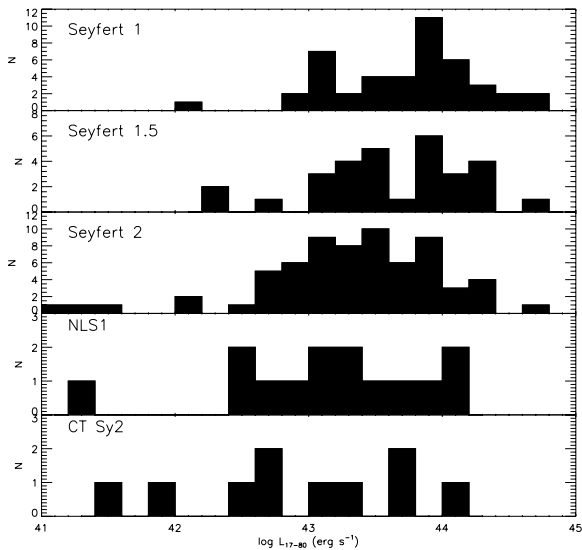


Fig. 4. Luminosity distribution of Seyfert 1s, Seyfert 1.5s, Compton-thin Seyfert 2s, NLS1s, and CT Sy2s in the 17–80 keV energy band.

are statistically compatible. The probability is much lower when comparing Seyfert 1s to Seyfert 2s ($\approx 2\%$), and Seyfert 1s to NLS1s ($\approx 10\%$).

3. INTEGRAL IBIS/ISGRI data analysis

We used all the public data obtained by INTEGRAL IBIS/ISGRI as of May 2010, for a total of more than 50 thousands pointings or “science windows” (SCWs). The typical exposure time of these pointings is of $(1-3) \times 10^3$ s. Several thousand pointings, including at least one source of the sample in its field of view and with an effective exposure longer than 120 s were selected, spanning times between December 30, 2002 (revolution 26) and April 7, 2009 (revolution 791).

The ISGRI data were reduced using the INTEGRAL Offline Scientific Analysis software¹ version 9.0, publicly released by the ISDC Data Centre for Astrophysics (Courvoisier et al. 2003).

Individual sky images for each pointing were produced in a broad energy band (17–250 keV), and divided into ten bins as follows: 17–22, 22–30, 30–40, 40–51, 51–63, 63–71, 71–80, 80–105, 105–150, and 150–250 keV.

To extract the average spectra of the different AGN samples, we followed the procedure adopted by Walter & Cabral (2009). We created 500×500 -pixels mosaic images modifying the coordinate system of each individual image, setting the coordinates of each source of the sample to an arbitrary fixed position ($\alpha = 0$, $\delta = 0$). The geometry of the image was also modified to have a consistent PSF independently of the position of the source in the field of view (FOV). These mosaic images provide a stack of all the selected IBIS/ISGRI data for each considered sample.

To minimize the systematics in the mosaic images, we excluded 1455 individual sky images (many obtained before revolution 38, when the IBIS bottom anti-coincidence was reconfigured) that had a background fluctuation rms larger than 1.1σ in the significance image, and 779 images with a minimum significance smaller than -5.5σ . In addition to these, we excluded 627 images taken when the ISGRI was in staring mode. A total of

Table 2. Number of sources.

Sample	(1) Srcs	(2) Exp. [Ms]	(3) Det. Significance [σ]	(4) Ct rate [ct/s]
Seyfert 1	44	37.6	91.1	0.396 ± 0.004
Seyfert 1.5	29	13.2	59.1	0.429 ± 0.007
Seyfert 2	68	44.0	102.8	0.390 ± 0.004
CT Sy2	10	4.7	32.9	0.405 ± 0.012
NLS1	14	10.1	44.3	0.377 ± 0.008
MOB Sy2	27	13.8	59.6	0.430 ± 0.007
LOB Sy2	34	23.4	78.1	0.424 ± 0.006
PBL Sy2	11	4.2	99.0	1.301 ± 0.013
NPBL Sy2	8	2.9	31.2	0.479 ± 0.015

Notes. Number of sources (1); effective exposures (2); detection significances (3); and count rates (4) of the different samples. All the values refer to the 17–80 keV band.

56611 images were finally included in the processing (some of them many times, when including several sources). All known ISGRI sources with significance above 5σ were used for image cleaning. When known accurately, the position of these sources was fixed to catalogue values taken from the INTEGRAL general reference catalog (Ebisawa et al. 2003)².

The mosaic images were built with a tangential projection using a factor of two oversampling when compared to the individual input sky images, this results in a pixel size of 2.4 arcmin at the center of the mosaic. The photometric integrity and accurate astrometry were obtained by calculating the intersection between input and output pixels, and weighting the count rates according to the overlapping area.

The average signal extracted in the large 17–80 keV band from each ISGRI mosaic, and both the exposures and the number of sources used are reported in Table 2. The detection significances in the 17–80 keV band range between 102.8σ and 32.9σ , for the largest and smallest sample (i.e. Seyfert 2s and CT Sy2s), respectively. The effective exposure obtained at the center of the mosaics are between 4.7 Ms (for CT Sy2s) and 44.0 Ms (for Seyfert 2s).

The ten-bin spectra of the final samples were extracted from the images in the 10 narrow bands using `mosaic_spec`. In all spectra, the highest energy bin (i.e. 150–250 keV) has a low significance ($\sim 2.5-3\sigma$), but we use it for the sake of completeness. We used the latest detector response matrix (RMF), and calculated the ancillary response matrices (ARFs) of each sample with a weighted average of the nine available ARFs, based on the number of SCWs within the validity time of a particular ARF.

4. Model-independent spectral analysis

A model-dependent spectral analysis has the drawback of possible parameter degeneracy, which might not allow us to constrain several parameters at the same time. An alternative method to characterize differences and similarities between different classes of Seyfert galaxies, independently of their average flux, is by means of a model-independent approach. This was achieved by normalizing the flux of the two different spectra in the first bin (17–22 keV), and then calculating their ratio.

¹ <http://www.isdc.unige.ch/>

² <http://www.isdc.unige.ch/integral/science/catalogue>

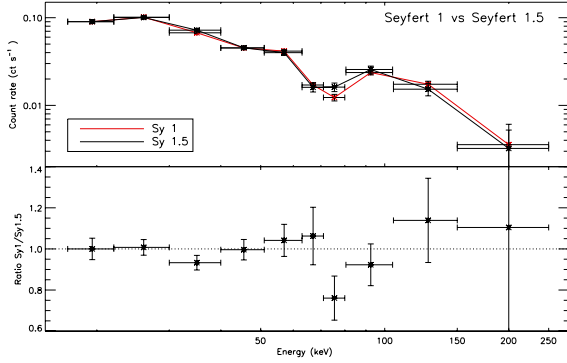


Fig. 5. Normalized spectra (*upper panel*) and ratio (*lower panel*) of Seyfert 1s to Seyfert 1.5s.

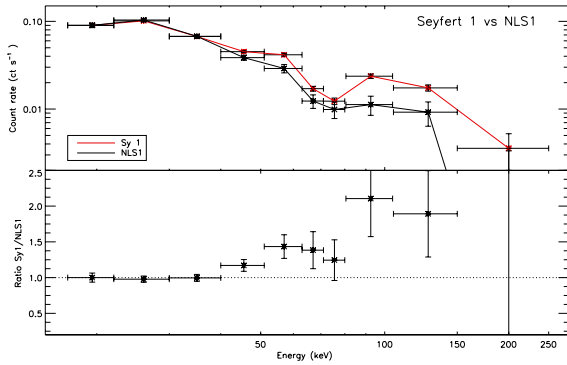


Fig. 6. Normalized spectra (*upper panel*) and ratio (*lower panel*) of Seyfert 1s to NLS1s.

4.1. Seyfert galaxies

We have no information about the value of the hydrogen column density of seven Seyfert 2s. To discard the possibility that these objects are CT, which might influence significantly the result, we calculated the ratio between the spectra of the Seyfert 2 sample including and excluding these seven objects. This ratio is fully consistent with 1.

In Fig. 5, we show the normalized spectra of Sy1s and Sy1.5s (in the upper panels) and their ratios (in the lower panel). The average spectrum of Seyfert 1s is consistent with that of Seyfert 1.5s along the whole spectrum. The ratio of the average spectrum of Seyfert 1 galaxies to the normalized one of NLS1s diverges from the unity from ~ 40 keV (Fig. 6), with the spectrum of NLS1s being steeper than that of Sy1s. Since the spectra of Seyfert 1s and Seyfert 1.5s are very similar, we merged them and compared the resulting spectrum to that of Seyfert 2s. We show in Fig. 7 the ratio obtained after normalization. The spectrum of Seyfert 2s displays a clear excess over those of the Seyfert 1s and Seyfert 1.5s of $48 \pm 8\%$ in the 22–63 keV band. This bump peaks around 40 keV, reaching 20%, and might indicate that Seyfert 2s have a stronger reflection component than Seyfert 1s and Seyfert 1.5s. At energies higher than 60 keV, the ratio is consistent with 1, indicating similar cutoff energies. The ratio of the spectra of Compton-thin to Compton-thick Seyfert 2s is consistent with one up to 150 keV (Fig. 8). Including in our sample of Sy2s the two objects excluded because of their complex absorption does not affect the results, and the ratio between the spectra with and without these sources is consistent with one.

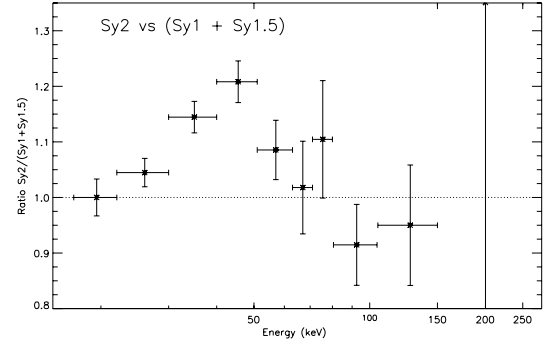


Fig. 7. Ratio between the normalized spectra of Compton-thin Seyfert 2s and that of both Seyfert 1s and Seyfert 1.5s.

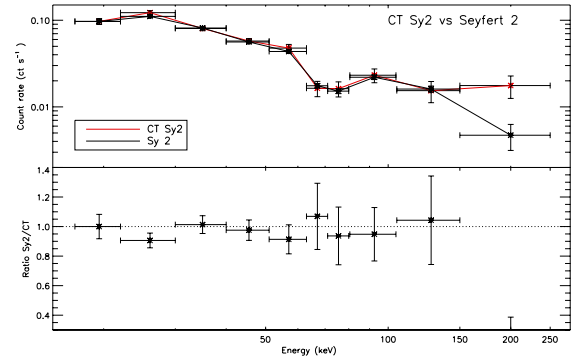


Fig. 8. Normalized spectra (*upper panel*) and ratio (*lower panel*) of Compton-thin Seyfert 2s to CT Sy2s.

4.2. Lightly obscured and mildly obscured Seyfert 2s

The Seyfert 2s contained in our sample appear to have characteristics that differ significantly from those of Seyfert 1 and Seyfert 1.5 galaxies. To test whether absorption might still play a role in the hard X-ray spectra of Compton-thin Seyfert 2 galaxies, we divided the sample into two subsamples, one including the objects with $10^{23} \text{ cm}^{-2} \leq N_{\text{H}} < 10^{24} \text{ cm}^{-2}$ (henceforth mildly obscured Seyfert 2s, MOB Sy2s), and the other those with $N_{\text{H}} < 10^{23} \text{ cm}^{-2}$ (henceforth lightly obscured Seyfert 2s, LOB Sy2s). The MOB and LOB Sy2 samples contain 27 and 35 objects, respectively. In Table 2, we report the detection significances, exposures, and fluxes obtained for these samples. We did not consider the sources with an unknown value of N_{H} .

In Fig. 9, we show the ratio obtained by comparing the spectrum of MOB Sy2s to that of LOB Sy2s. The figure highlights significant differences between the two spectra, with the emission of MOB Sy2s being harder up to ~ 60 keV and then softer (up to ~ 150 keV) than that of LOB Sy2s. This clearly shows that the bump seen by comparing the spectrum of Seyfert 2s to those of Seyfert 1s and Seyfert 1.5s (Fig. 7) comes prevalently from the contribution of MOB Sy2s (see Fig. 10).

The spectrum of LOB Sy2s appears to be very similar to that of Seyfert 1s (Fig. 10), although an excess of $\sim 20\%$ is evident in the 30–50 keV band. This excess might be related to a stronger reflection component in LOB Seyfert 2s than in Seyfert 1s. MOB Sy2s present instead a spectrum similar to that of CT Sy2s, and their ratio is consistent with 1 (Fig. 10).

To test the influence of bright MOB Sy2s on their average spectrum, we compared the spectra obtained with and without

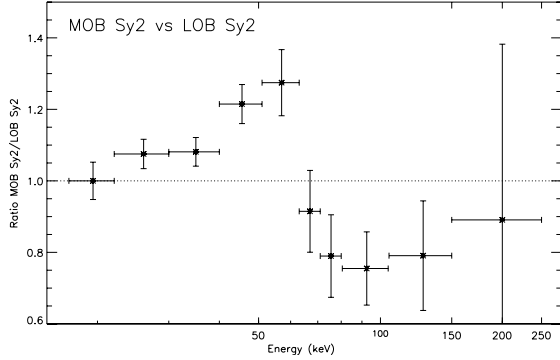


Fig. 9. Ratio of the normalized spectra of MOB to LOB Seyfert 2 galaxies.

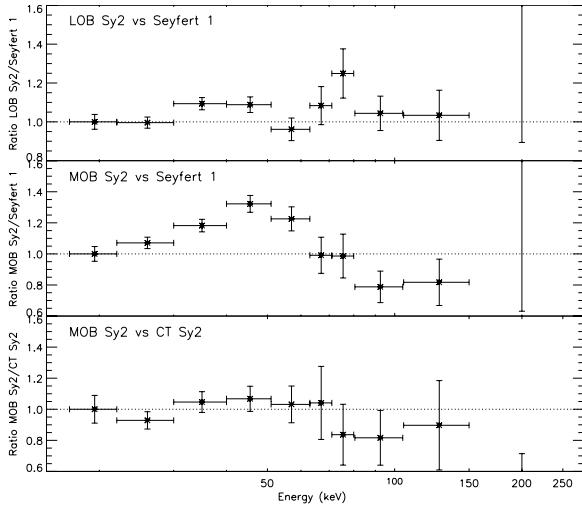


Fig. 10. Ratio between the normalized spectra of LOB Seyfert 2s and Seyfert 1s (top panel), between the spectra of MOB Seyfert 2s and Seyfert 1s (center panel), and between the spectra of MOB Seyfert 2s and CT Seyfert 2s (bottom panel).

the five brightest sources ($>20\sigma$). The ratio obtained after normalizing the two spectra is fully consistent with one, from which we can conclude that the average spectrum of MOB Sy2s is not influenced by peculiar bright sources.

4.3. Seyfert 2s with and without PBLs

To test whether PBL and NPBL Sy2s have different characteristics, we extracted and analyzed their average hard X-ray spectra. In Table 2, we report the detection significances, exposures, and fluxes obtained for the two samples.

Comparing the spectrum of PBL Sy2s to the one of NPBL Sy2s (Fig. 11), it is evident that the ratio is consistent with 1.

When compared to the spectrum of Seyfert 1s, the spectra of PBL and NPBL Sy2s have similar characteristics. As for the whole Seyfert 2 sample, both PBL and NPBL Sy2s display evidence of a greater reflection component. This is probably due to the contribution of the MOB Sy2s present in the samples.

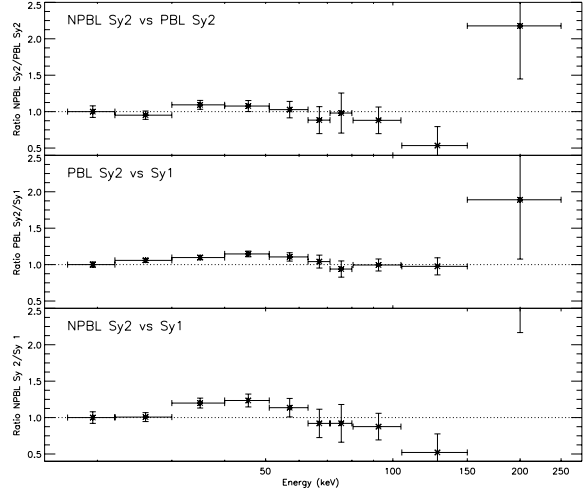


Fig. 11. Ratio between the normalized spectra of PBL and NPBL Sy2s (top panel), between Seyfert 1s and PBL (center panel), and NPBL Sy2s (bottom panel).

4.4. Comparison with a simulated power law spectrum

In Fig. 12, we show the ratios between the normalized spectra of Seyfert galaxies and a simulated power law spectrum with a photon index of $\Gamma = 1.9$. Using XSPEC (version 12.5.0, Arnaud 1996), we simulated 20 power-law spectra, using the *fakeit* command. We used the latest RMF and calculated the ARF from a weighted average of the nine available ARFs, with the weights proportional to the validity period duration of each ARF. The power law spectrum used is the average of the 20 simulated spectra, and the errors are their standard deviations.

Seyfert 1s and Seyfert 1.5s show a ratio close to unity below 100 keV, and a small excess around 30 keV, which is possibly a signature of reflection. The excess in the 22–40 keV band is $8 \pm 3\%$ and $9 \pm 3\%$ for Seyfert 1s and Seyfert 1.5s, respectively.

The spectrum of Seyfert 2s displays a stronger excess ($27 \pm 3\%$) in the same band, and is harder than the power law up to 80 keV. Above 150 keV, the spectra of Seyfert 1s, Seyfert 1.5s and Seyfert 2s become softer than the power law; this effect might be related to the presence of a high-energy cutoff.

LOB Sy2s show an excess of $17 \pm 3\%$ over the simulated power law in the 22–40 keV band, and do not present any significant softening above 100 keV. MOB Sy2s show the most significant differences, being harder below ≈ 60 keV and softer above 80 keV. The excess is of $87 \pm 9\%$ in the 22–63 keV band, and of $34 \pm 5\%$ in the 20–40 keV band. A similar excess ($78 \pm 17\%$ and $36 \pm 9\%$) is found by comparing the average spectrum of CT Seyfert 2s to the simulated power law in the same bands.

To estimate the amount of curvature in the spectrum, we introduce the parameter ρ_R given by

$$\rho_R = \frac{R_{30}}{R_{80}}, \quad (2)$$

where R_{30} and R_{80} are the ratios of the normalized spectra to the power law in the 30–40 keV and 80–105 keV band, respectively. Seyfert 1s ($\rho_R = 1.09 \pm 0.07$) have a value of ρ_R consistent with those of Seyfert 1.5s ($\rho_R = 1.06 \pm 0.11$) and LOB Sy2s ($\rho_R = 1.14 \pm 0.03$). The value of this parameter is significantly larger for MOB Sy2s ($\rho_R = 1.63 \pm 0.14$), while it is $\rho_R = 1.27 \pm 0.24$ for CT Sy2s.

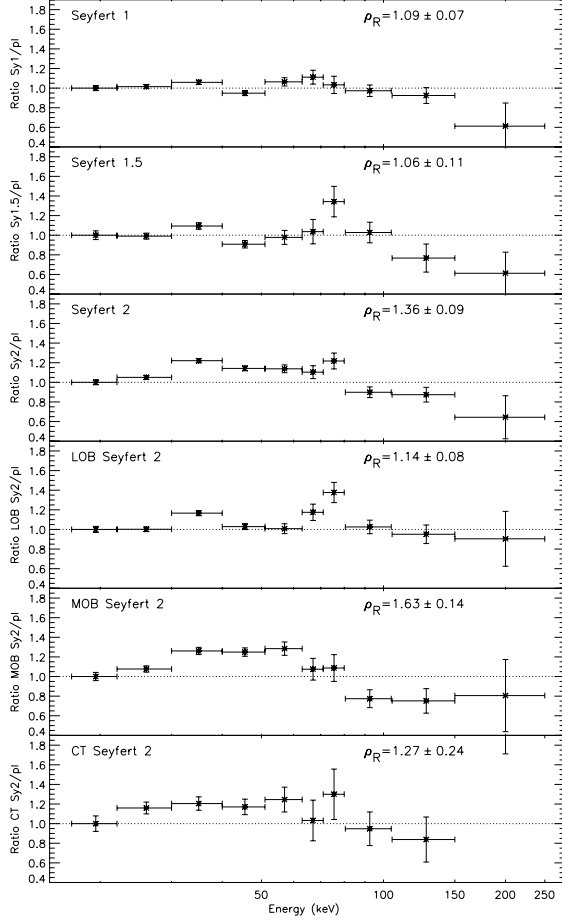


Fig. 12. Ratio between the normalized spectra of Seyfert 1s, Seyfert 1.5s, Compton-thin Seyfert 2, LOB Seyfert 2s, MOB Seyfert 2s, and Compton-thick Seyfert 2s, and a simulated power law spectrum ($\Gamma = 1.9$). The parameter ρ_R is defined in Eq. (2).

5. Model-dependent spectral analysis

We analyzed the average IBIS/ISGRI spectra using XSPEC. Throughout the paper, we used 3σ errors. The probabilities that additive parameters improve a fit are calculated with the F-test.

We tested simple models such as a power law, and a power law with an exponential cutoff at high energies. To account for the presence of reflection, we used the *pexrav* model (Magdziarz & Zdziarski 1995). *Pexrav* calculates the spectrum produced by an X-ray source reflected by an optically thick neutral slab. In this model, the parameter R measures the reflection component. If the source is isotropic, R can be linked to the solid angle Ω as $R \approx \frac{\Omega}{2\pi}$. The value of R depends on the inclination angle i between the perpendicular to the accretion disk and the line of sight. The smaller the inclination angle, the larger the resulting reflection component. The quality of the data does not allow us to constrain both R and i at the same time, so we fixed the inclination angles to $i = 45^\circ$ for all the classes. We used the same value of i for all the classes to characterize the reflection with a single parameter. We note that by doing this R no longer represents $\Omega/2\pi$, and becomes only an indicator of the reflection amplitude.

5.1. Seyfert galaxies

Fitting the spectra of Seyfert 1s, Seyfert 1.5s, and Seyfert 2s with a simple power law yields a reduced chi-squared of $\chi^2_\nu = 1.4$, $\chi^2_\nu \approx 1.4$, and $\chi^2_\nu \approx 3.9$, respectively. The null-hypothesis probability is 20%, 18%, and $<0.1\%$ for Sy1s, Sy1.5s, and Sy2s, respectively.

Applying a cutoff power law improves the fit of both Seyfert 1s and Seyfert 2s at a confidence level of 84% and 99.6%, respectively. Adding a reflection component to the power law model also significantly improves the fit for both Seyfert 1s and Seyfert 2s. The fit to the spectrum of Seyfert 1.5s does not improve significantly by adding any of these features to the baseline power law model. Fitting with different models the spectrum of Seyfert 1.5s, one notes that most of the chi-squared comes from a single bin (71–80 keV, see Appendix B). On the basis of this, and that in Sect. 4 we have shown that the spectra of Seyfert 1s and Seyfert 1.5s are very similar, we use the same models to characterize their spectra. The results of the spectral analysis are reported in Table 3.

Both a high-energy cutoff and a reflection component from neutral matter are thought to play an important role in the hard X-ray emission of Seyfert galaxies, thus in the following we discuss only the results obtained using *pexrav*. Applying this model, we obtained a lower limit to the high-energy cutoff of $E_C \gtrsim 190$ keV, and a reflection normalization of $R \leq 0.4$ for both Seyfert 1s and Seyfert 1.5s. The consistency of these parameters agrees with that found in Sect. 4. Using the same model for the average spectrum of Seyfert 2s, we obtained $E_C = 154^{+185}_{-84}$ keV and $R \leq 2.6$, which confirms the greater curvature observed.

Owing to its low statistics, a simple power law model provides a good fit ($\chi^2_\nu = 1$) to the stacked spectrum of the ten CT Seyfert 2 galaxies of our sample. Although statistically not required, a cutoff and a reflection component reduce the chi-squared of $\Delta\chi^2 = 3.8$ and $\Delta\chi^2 = 5.1$, respectively. Using *pexrav*, we could not constrain E_C , while we obtained an upper limit to the reflection normalization of $R \leq 11.2$.

A power-law model cannot represent well the hard X-ray spectrum of NLS1s. Adding a cutoff and a reflection component significantly improves the fit, although it is not possible to constrain the two parameters at the same time. We obtained a photon index of $\Gamma = 2.3^{+0.1}_{-0.6}$, a lower limit to the energy of the cutoff of $E_C \leq 53$ keV, and to the reflection parameter of $R \geq 0.1$.

The average photon indices obtained are consistent for the different subsamples of Seyfert galaxies, and have values of $\Gamma \approx 1.8$, in agreement with previous studies (e.g., Dadina et al. 2008). The spectra of Seyfert 1s, Seyfert 1.5s, Seyfert 2s, CT Seyfert 2s, and NLS1s are shown in Appendix B.

5.2. MOB and LOB Seyfert 2s

Using *pexrav* to fit the spectra of MOB and LOB Sy2s, we confirmed the different curvatures of the spectra of the two subsamples, obtaining values of the reflection parameter of $R \leq 0.5$ and $R = 2.2^{+4.5}_{-1.1}$, for LOB and MOB Sy2s, respectively. The photon indices ($\Gamma \sim 1.8$) and the energies of the cutoff ($E_C^{\text{LOB}} = 425^{+267}_{-120}$ keV and $E_C^{\text{MOB}} = 287^{+105}_{-64}$ keV) obtained by the fit are consistent to within 3σ . The results are reported in Table 4, while the spectra of MOB and LOB Sy2s are shown in Appendix B.

The spectral analysis performed using different models confirms that the average hard X-ray spectrum of LOB Sy2s is more similar to those of Seyfert 1s and Seyfert 1.5s than to that of MOB Sy2s.

Table 3. Results obtained from the spectral analysis of the average hard X-ray spectra of Seyfert 1s, Seyfert 1.5s, Seyfert 2s, CT Sy2s, and NLS1s.

Model	Γ	E_C [keV]	R	χ^2/DOF	FTEST
Seyfert 1s					
Power law	$1.97^{+0.05}_{-0.05}$	—	—	11/8	—
Cut-off power law	$1.8^{+0.1}_{-0.2}$	293^{+NC}_{-150}	—	8.2/7	0.17
*Pexrav	$1.96^{+0.04}_{-0.04}$	—	$0.2^{+0.2}_{-0.2}$	9.8/7	0.38
Pexrav	$1.8^{+0.2}_{-0.1}$	340^{+NC}_{-155}	$0.1^{+0.3}_{-0.1}$	8.3/6	0.43
Seyfert 1.5s					
Power law	$1.97^{+0.09}_{-0.08}$	—	—	11.4/8	—
Cut-off power law	$1.9^{+0.1}_{-0.3}$	500^{+310}_{-250}	—	11.3/7	0.81
*Pexrav	$1.97^{+0.05}_{-0.05}$	—	$0.2^{+0.3}_{-0.2}$	11.3/7	0.81
Pexrav	$1.8^{+0.2}_{-0.1}$	332^{+NC}_{-145}	$0.1^{+0.3}_{-0.1}$	11.3/6	0.97
Seyfert 2s					
Power law	$1.93^{+0.03}_{-0.03}$	—	—	31/8	—
Cut-off power law	$1.4^{+0.2}_{-0.2}$	86^{+41}_{-22}	—	8.9/7	<0.01
*Pexrav	$1.97^{+0.05}_{-0.05}$	—	$2.0^{+3.9}_{-1.2}$	9.3/7	<0.01
Pexrav	$1.6^{+0.4}_{-0.4}$	154^{+185}_{-84}	$0.4^{+2.2}_{-0.4}$	7.4/6	0.01
CT Seyfert 2s					
Power law	$1.9^{+0.1}_{-0.1}$	—	—	8/8	—
Cut-off power law	$1.5^{+0.2}_{-0.2}$	100^{+NC}_{-51}	—	4.2/7	0.04
*Pexrav	$1.9^{+0.1}_{-0.1}$	—	$1.4^{+9.6}_{-1.2}$	2.7/7	<0.01
Pexrav	$2.0^{+0.1}_{-0.1}$	NC	$1.5^{+9.7}_{-1.5}$	2.7/6	0.04
Narrow Line Seyfert 1s					
Power law	$2.23^{+0.08}_{-0.08}$	—	—	24.6/8	—
Cut-off power law	$1.7^{+0.2}_{-0.6}$	70^{+43}_{-36}	—	11.6/7	0.03
*Pexrav	$2.28^{+0.08}_{-0.08}$	—	$4.3^{+NC}_{-3.0}$	9.5/7	0.01
Pexrav	$2.3^{+0.1}_{-0.6}$	310^{+NC}_{-257}	$4.2^{+NC}_{-4.1}$	9.5/6	0.06

Notes. The inclination angle i was fixed to 45° . NC: the parameter or the 3σ error were not constrained. * Pexrav: the high-energy cut off was not included, being fixed to its upper limit $E_C = 10^6$ keV.

5.3. Seyfert 2s with and without PBL

Consistently with what was obtained for the whole sample of Seyfert 2s, the spectra of PBL and NPBL Sy2s cannot be reproduced using solely a power law, but need to be fitted using a more complex model. Adding a high-energy cutoff or a reflection component to the power law significantly improves the fit for both spectra. All the models used give values of the parameters of the two spectra that are consistent to within 3σ , confirming the similarities found by the model-independent analysis. The results of the spectral analysis are reported in Table 5.

6. Reflection in MOB Sy2s

We have shown that the spectrum of MOB Sy2s shows a stronger reflection component than those of LOB Sy2s, Seyfert 1s, and Seyfert 1.5s, and we now investigate the possible causes of this effect.

The spectrum of lightly obscured objects (LOB Sy2s, Sy1s, and Sy1.5s) can be expressed by

$$F(E) = AE^{-\Gamma} e^{-E/E_C} + R(E), \quad (3)$$

where A is the normalization and $R(E)$ the reflection component, which was accounted for using *pexrav*. The observed 20–60 keV bump might be due to a distant (i.e. unabsorbed) reflection component, which becomes more important for MOB Sy2s due to

Table 4. Results obtained from the spectral analysis of the average hard X-ray spectra of MOB and LOB Seyfert 2s.

Model	Γ	E_C [keV]	R	χ^2/DOF	FTEST
MOB Seyfert 2s					
Power law	$1.94^{+0.05}_{-0.05}$	—	—	45.2/8	—
Cut-off power law	$1.0^{+0.3}_{-0.3}$	47^{+20}_{-11}	—	7.6/7	<0.01
*Pexrav	$1.95^{+0.05}_{-0.05}$	—	7^{+7}_{-2}	9.8/7	<0.01
Pexrav	$1.82^{+0.06}_{-0.06}$	287^{+105}_{-64}	$2.2^{+4.5}_{-1.1}$	8.8/6	<0.01
LOB Seyfert 2s					
Power law	$1.91^{+0.04}_{-0.04}$	—	—	15.9/8	—
Cut-off power law	$1.7^{+0.2}_{-0.2}$	224^{+NC}_{-98}	—	12.8/7	0.23
*Pexrav	$1.91^{+0.04}_{-0.04}$	—	$0.4^{+0.5}_{-0.3}$	13.7/7	0.32
Pexrav	$1.8^{+0.2}_{-0.3}$	425^{+267}_{-120}	$0.2^{+0.3}_{-0.2}$	12.9/6	0.53

Notes. The inclination angle i was fixed to 45° . NC: the parameter or the 3σ error were not constrained. * Pexrav: the high-energy cut off was not included, being fixed to its upper limit $E_C = 10^6$ keV.

Table 5. Results obtained from the spectral analysis of the average hard X-ray spectra of PBL and NPBL Seyfert 2s.

Model	Γ	E_C [keV]	R	χ^2/DOF	FTEST
PBL Seyfert 2s					
Power law	$1.94^{+0.03}_{-0.03}$	—	—	23.7/8	—
Cut-off power law	$1.6^{+0.2}_{-0.2}$	136^{+135}_{-48}	—	11.7/7	0.03
*Pexrav	$1.95^{+0.03}_{-0.03}$	—	$1.0^{+0.6}_{-0.4}$	8.5/7	<0.01
Pexrav	$1.9^{+0.2}_{-0.3}$	803^{+NC}_{-660}	$0.7^{+0.8}_{-0.6}$	8.5/6	0.05
NPBL Seyfert 2s					
Power law	$1.95^{+0.09}_{-0.09}$	—	—	22.9/8	—
Cut-off power law	$1.1^{+0.5}_{-0.5}$	49^{+70}_{-20}	—	13.9/7	0.07
*Pexrav	$1.97^{+0.09}_{-0.09}$	—	$3^{+NC}_{-2.3}$	14.4/7	0.08
Pexrav	$1.9^{+0.1}_{-0.1}$	874^{+NC}_{-548}	$2.9^{+NC}_{-2.3}$	13.7/6	0.21

Notes. The inclination angle i was fixed to 45° . NC: the parameter or the 3σ error were not constrained. * Pexrav: the high-energy cut off was not included, being fixed to its upper limit $E_C = 10^6$ keV.

the larger fraction of Compton scattered continuum. This reflector has been associated with the inner wall of the torus, or the outer part of the disk. The spectrum of MOB objects can be represented by

$$F(E) = M(E, N_H) AE^{-\Gamma} e^{-E/E_C} + R(E). \quad (4)$$

In the following, we assume that $\Gamma = 1.8$, $E_C = 300$ keV. We first simulated and compared several spectra with the same continuum and reflection component, but with different values of N_H , to see whether absorption might explain the differences observed. The value of R associated with the torus remains unknown (e.g., Gilli et al. 2007, consider a value of $R_T = 0.37$). To obtain an upper limit to the effect, we assumed $R = 1$ (for both LOB and MOB objects), and column densities of $N_H = 7 \times 10^{23} \text{ cm}^{-2}$ and $N_H = 0$ for MOB and LOB objects, respectively. We tested two different values of the inclination angle for MOB Sy2s ($i = 30^\circ$ and $i = 60^\circ$), while we set $i = 60^\circ$ for LOB objects. The parameter $M(E, N_H)$ includes both Compton scattering (through the *cabs* model) and photoelectric absorption (implemented as *wabs*), as given in Eq. (1). In Fig. 13 (left panel), we show the ratios obtained comparing the simulated

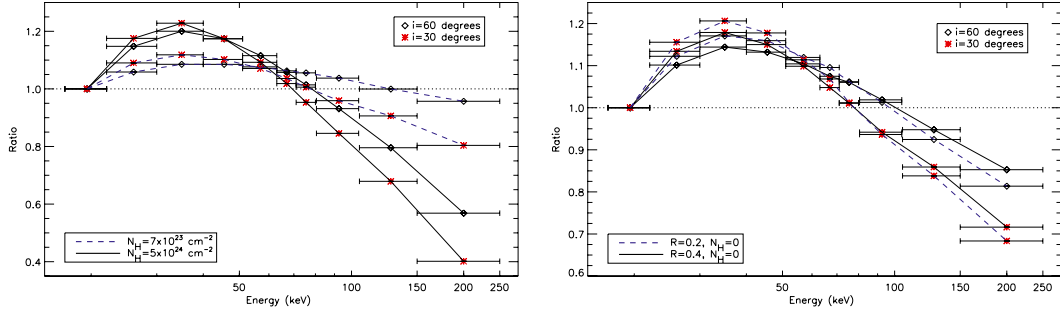


Fig. 13. Ratios of simulated spectra of MOB (Eq. (4)) to LOB (Eq. (3)) objects. We assumed $\Gamma = 1.8$, $E_C = 300$ keV for the continuum of all spectra. We tested different values of i and N_H ($N_H = 7 \times 10^{23} \text{ cm}^{-2}$ and $N_H = 5 \times 10^{24} \text{ cm}^{-2}$) for the spectrum of MOB Sy2s, assuming $R = 1$ for all the spectra, and $N_H = 0$ for LOB Sy2s (left panel). We tested different values of the reflection parameter ($R = 0.4$ and $R = 0.2$ for LOB objects, fixing $R = 1$ for MOB Sy2s), and of i (only for MOB Sy2s), setting $N_H = 3 \times 10^{23} \text{ cm}^{-2}$ for MOB Sy2s and $N_H = 0$ for LOB Sy2s (right panel).

Table 6. Results obtained by fitting the spectrum of MOB Seyfert 2s with Eq. (4), fixing N_H to the average value of the sample.

E_C [keV]	Γ	R	i	χ^2	DOF
300*	$1.78^{+0.07}_{-0.07}$	3^{+10}_{-1}	60°	9.6	7
	$1.74^{+0.06}_{-0.06}$	2^{+3}_{-1}	45°	9.7	7
	$1.76^{+0.09}_{-0.09}$	$1.3^{+1.8}_{-0.5}$	30°	9.9	7
	$1.83^{+0.07}_{-0.07}$	$3.5^{+NC}_{-2.0}$	60°	10.3	7
500*	$1.82^{+0.06}_{-0.06}$	$2.5^{+7.8}_{-1.5}$	45°	10.3	7
	$1.81^{+0.07}_{-0.07}$	$2.0^{+3.5}_{-1.1}$	30°	10.4	7
	$1.99^{+0.06}_{-0.06}$	13^{+NC}_{-10}	60°	11.9	7
	$1.95^{+0.06}_{-0.06}$	$5.3^{+NC}_{-2.7}$	45°	11.8	7
∞^*	$1.96^{+0.05}_{-0.05}$	3^{+NC}_{-2}	30°	11.9	7

Notes. We tested different values of the cutoff energy and the inclination angle. NC: 3 σ error not constrained; *: parameter fixed.

spectra. From the figure, it is evident that a column density of $N_H = 7 \times 10^{23} \text{ cm}^{-2}$ is largely insufficient to explain the observed differences. To provide an excess closer to what is observed, one would need a value of the column density as large as $N_H = 5 \times 10^{24} \text{ cm}^{-2}$.

We then tested different values of the reflection parameter. From the spectral analysis, we found upper limits of the reflection parameter of $R \leq 0.4$ for Seyfert 1s and Seyfert 1.5s, and of $R \leq 0.5$ for LOB Sy2s. These values are significantly lower than that obtained for MOB Sy2s ($R = 2.2^{+4.5}_{-1.1}$). We simulated and compared spectra obtained using Eqs. (3) and (4), considering different amounts of reflection and absorption for LOB ($R = 0.5$ and $R = 0.2$, $N_H = 0$, $i = 60^\circ$) and MOB ($R = 1$, $N_H = 7 \times 10^{23} \text{ cm}^{-2}$, $i = 60^\circ$ and $i = 30^\circ$) objects. From Fig. 13 (right panel), one can see that a greater unabsorbed reflection component in MOB Seyfert 2s would explain their larger amount of flux in the 20–60 keV energy band with respect to LOB objects.

We fitted the spectrum of MOB Sy2s with Eq. (4) in XSPEC, setting the column density of the absorbing medium to the average value (weighted by the detection significance) of the sample ($N_H = 3 \times 10^{23} \text{ cm}^{-2}$). We first assumed an edge-on reflector ($i = 60^\circ$), and fixed E_C to different values. The best fit yields $R \geq 2$ and is obtained for $E_C = 300$ keV. The value of the reflection parameter is $R > 1$ even when considering higher values of E_C . Considering a face-on reflector ($i = 30^\circ$), we obtained a lower value of the reflection parameter for $E_C = 300$ keV ($R = 1.1^{+3.5}_{-0.5}$), while we obtained $R \geq 1$ for higher values of E_C . The results of the fits are listed in Table 6.

7. Discussion

We now discuss the average hard X-ray spectra of the different classes of Seyfert galaxies, the differences and similarities between PBL and NPBL Sy2s, the average hard X-ray emission of NLS1s, and all this in the framework of the unified model and the cosmic X-ray background.

7.1. Seyfert galaxies: the continuum

From our analysis of the average hard X-ray spectra of Seyfert galaxies, we found that the primary power law emission is similar for both Seyfert 1s and Seyfert 2s, and can be described by a photon index of $\Gamma \approx 1.8$. Comparing the average spectra to a simulated power law, we found for Sy1s, Sy1.5s and Sy2s only a weak softening in the last energy bin, which might imply that on average the cutoff is at energies $E_C \geq 150$ keV. This was confirmed by the model-dependent spectral analysis, from which we found $E_C \geq 200$ keV, which is consistent with the results of *BeppoSAX* observations (Dadina 2008).

In the thermal Comptonization scenario, the power law emission of AGN is commonly assumed to arise from inverse Comptonization of soft photons in a hot plasma. Within this scenario, the cutoff energy and the photon index are linked to the temperature and the optical depth of the hot plasma responsible for the Comptonization. According to Petrucci et al. (2001), the temperature can be estimated as $kT_e = E_C/2$ for $\tau \lesssim 1$, or $kT_e = E_C/3$ for $\tau \gg 1$, and the three parameters are related by

$$\Gamma - 1 \approx \left\{ \frac{9}{4} + \frac{m_e c^2}{kT_e \tau (1 + \tau/3)} \right\}^{1/2} - \frac{3}{2}. \quad (5)$$

Using Eq. (5) and the values of the parameters obtained using the *pexrav* model, we calculated the average optical depths of the different classes of Seyferts. For Seyfert 1s and Seyfert 1.5s, we obtained $\tau = 0.8^{+0.6}_{-0.5}$, which is consistent with the values obtained for LOB ($\tau = 0.7^{+0.6}_{-0.4}$) and MOB Seyfert 2s ($\tau_2 = 0.9^{+0.3}_{-0.3}$). The consistency of τ indicates that the average physical characteristics of the Comptonizing medium are similar for different classes of Seyferts, as expected from the UM.

7.2. Seyfert galaxies: the reflection component

The hard X-ray spectrum of Seyfert 2s shows a harder emission in the 20–60 keV band than those of Seyfert 1s and Seyfert 1.5s (Fig. 7). Most of this difference can be ascribed to the contribution of MOB Sy2s (Fig. 9), while LOB Sy2s show characteristics more similar to Seyfert 1s and Seyfert 1.5s (Fig. 10), although still having a $\sim 20\%$ excess in the 30–50 keV band.

The greater reflection of MOB Sy2s cannot be explained solely by the dampening of the continuum caused by absorption, but we have demonstrated that different values of R must also be taken into account (Fig. 13). We have in fact shown that the average value of Seyfert 1/1.5s and LOB Sy2s is $R \leq 0.4$ and $R \leq 0.5$ (Sect. 5), respectively, while for MOB Sy2s this value is greater ($R > 1$, see Sect. 6).

From a purely geometrical point of view, and considering the disk as the main reflector, one would expect a greater influence of the reflection component in the spectrum of Seyfert 1s rather than in that of Seyfert 2s, the angle i between the normal to the disk and the observer being smaller. Different luminosity distributions could introduce a bias in our hard X-ray selected sample of MOB Sy2s, with sources having a stronger reflection component being brighter and thus more easily detected. However, the difference between the average luminosities of MOB ($L^{\text{MOB}} \approx 1.7 \times 10^{43} \text{ erg s}^{-1}$) and LOB Sy2s ($L^{\text{LOB}} \approx 2.1 \times 10^{43} \text{ erg s}^{-1}$) is insignificant. Moreover, a KS test results in a probability of $\approx 86\%$ that the two samples of Seyfert 2s are statistically compatible. Different inclination angles might also play a role in explaining the large reflection of MOB Sy2s, although the average values of i would have to be extreme to account for the observed differences.

A possible explanation is that in MOB Sy2s the putative torus, which is also the dominant reflector, covers a larger fraction of the X-ray source than in lightly obscured objects. A similar geometry was hypothesized by Ueda et al. (2007) to explain the *Suzaku* spectra of SWIFT J0601.9–8636 and SWIFT J0138.6–4001. Further evidence for the existence of these deeply buried AGN was found by Eguchi et al. (2009). Being more absorbed, MOB Sy2s might on average have more matter surrounding the active nucleus, which would be responsible for the larger reflection. Ramos Almeida et al. (2009, 2011) analyzing the mid-infrared emission of Seyfert galaxies found that the clumpy absorbers in Sy2s have larger covering factors ($C_T = 0.95 \pm 0.02$) than those in Sy1s ($C_T = 0.5 \pm 0.1$). Among the 12 Sy2s in their sample, ten have $N_H \gtrsim 10^{23} \text{ cm}^{-2}$, which supports our argument of a larger average covering fraction of the absorber for more obscured sources. The small value of the average reflection parameter of Sy1s and Sy1.5s might imply that on average the reflection from the disk does not play as important a role as that of the absorber.

A value of $R > 1$ is unphysical if related only to the geometry, and might imply that part of the direct emission is blocked by partially covering material, with the transmission efficiency being $\lesssim 1/R$ (Ueda et al. 2007). If the X-ray source is partially covered by Compton-thick material, the reflected component would in fact have a stronger relative influence over the continuum. Krolik & Begelman (1988) showed that a torus with a smooth dust distribution cannot survive close to the AGN, and proposed that the material is distributed in a clumpy structure. Mid-infrared spectra of Seyfert galaxies have been proven to be consistent with the clumpy torus scenario (e.g., Mor et al. 2009). Evidence has been found in the past few years of significant variations in N_H , with changes from Compton-thick to Compton-thin states on timescales from weeks (Risaliti et al. 2005) to ~ 10 h (Risaliti et al. 2009). These variations have been interpreted as eclipses of the X-ray source caused by the BLR. If the BLR lies between the X-ray source and the putative torus, then it could provide the CT clumps needed to deplete the continuum emission. The variations observed in NGC 1365 (Risaliti et al. 2005, 2009) might be common in MOB Sy2s, and the extremely long INTEGRAL IBIS/ISGRI observations we used to derive the average spectra might have registered some of them. The

presence of CT clumps might be a common characteristic in the absorbers of Seyfert galaxies, and be responsible, at least in part, for the large reflection observed in MOB Sy2.

Both effects might be at work in MOB Sy2s, with more absorbed objects having on average more matter around the X-ray source, and the distribution of this matter being clumpy.

7.3. Seyfert 2s with and without PBLs

Spectropolarimetric surveys indicate that only 30–50% Seyfert 2s show PBLs (Tran 2001, 2003). The reason for the non-detection of PBLs in all Seyfert 2s is still debated, and it has been hypothesized (Tran 2001, 2003) that NPBL Sy2s might be a different class of Seyfert 2, that possibly lack the BLR and have large-scale characteristics more similar to Seyfert 1s. Deluit (2004) discussed the possible existence of differences in the 15–136 keV spectra of Seyfert 2s with and without PBLs using *BeppoSAX* data, and concluded that the characteristics of PBL Sy2s appear to be more similar to those of Seyfert 1s than NPBL Sy2s. Using a slightly larger sample, but broader energy range and much longer exposures, we analyzed the stacked spectra of PBL and NPBL Sy2s, finding that the two samples do not show any significant spectral differences. The greatest difference between the two samples is their luminosities. The average 17–80 keV luminosity of PBL Sy2s ($L^{\text{PBL}} \approx 1.9 \times 10^{43} \text{ erg s}^{-1}$) is greater by a factor of ≈ 3 than that of NPBL Sy2s ($L^{\text{NPBL}} \approx 6 \times 10^{42} \text{ erg s}^{-1}$). The luminosity of the [OIII] line is often used as an indicator of the bolometric luminosity of AGN. Collecting data from the literature, we found that the average luminosity of PBL Sy2s ($L_{[\text{OIII}]} = 4.2 \times 10^{40} \text{ erg s}^{-1}$) is still higher than that of NPBL Sy2s ($L_{[\text{OIII}]} = 10^{40} \text{ erg s}^{-1}$). Although this does not give any indication of the intrinsic luminosity of the BLR, it implies that the bolometric luminosity of PBL Sy2s is on average greater than that of NPBL Sy2s, confirming what was found by Tran (2001) and Lumsden & Alexander (2001). We also found that in our sample NPBL Sy2s are on average slightly more absorbed ($N_H^{\text{NPBL}} = 3 \times 10^{23} \text{ cm}^{-2}$) than PBL Sy2s ($N_H^{\text{PBL}} = 1.5 \times 10^{23} \text{ cm}^{-2}$).

The lack of remarkable differences in the hard X-ray spectra of PBL and NPBL Seyfert 2s fits the UM, according to which they are supposed to belong to the same family.

7.4. Narrow-line Seyfert 1s

The 0.1–10 keV spectra of NLS1s are steeper than those of their broad-line counterparts (e.g., Netzer 2001). Owing to this, few of them are detected above 20 keV, and only a handful of NLS1s have been studied so far in the hard X-rays. A sample of five objects was examined using IBIS/ISGRI data (up to 100 keV) by Malizia et al. (2008), who found that their spectra present a continuum significantly steeper than Seyfert 1s and have an average photon index of $\Gamma = 2.6 \pm 0.3$. They interpreted this as being due to a low energy ($E_C \leq 60 \text{ keV}$) of the cutoff. Our sample of 205 Seyfert galaxies contains 14 NLS1s, which makes it the largest ever studied at these energies. In our sample, NLS1s represent $\approx 15\%$ of the total number of Sy1s and Sy1.5s. This is a much smaller fraction than the $\sim 50\%$ of *ROSAT* soft X-ray selected NLS1s (Grupe 2004), but is consistent with the $\sim 15\%$ obtained from an optically selected sample (Williams et al. 2002). From our analysis, we confirmed that in the hard X-rays the average spectrum of NLS1s is also steeper than those of Sy1s and Sy1.5s, with the spectra clearly diverging above $\sim 40 \text{ keV}$. This might be due to different values of Γ or to different energies

of the cutoff. The fact that up to ~ 40 keV the average spectrum of NLS1s is consistent with that of Sy1s favors the hypothesis that the photon indices are consistent, while the energy of the cutoff is lower for NLS1s. This is supported also by the fact that for the objects for which good quality data are available in the soft X-ray band, the values of the photon indices are not significantly different from those of Sy1s (Malizia et al. 2008; Jiménez-Bailón et al. 2008; Winter et al. 2009). Consistent photon indices might be due to a bias towards low values of Γ for our hard X-ray selected sample.

7.5. The unified model of AGN

The fact that the average primary (i.e. excluding the reflected component) hard X-ray emission of Seyfert galaxies is independent of their optical classification, and that PBL and NPBL Sy2s have consistent hard X-ray spectra fits well the zeroth order UM. However, the idea that the anisotropic absorber is the same for all classes does not allow us to easily explain the large reflection seen in Seyfert 2s, and in particular in MOB Seyfert 2s.

A possible geometry might be that in MOB Sy2s the absorbing material covers a large fraction of the X-ray source, which is seen through clumps of Compton-thick material, possibly located in the Compton-thin absorber ($N_H \approx 10^{23} \text{ cm}^{-2}$). This geometry would also explain the low hard X-ray to [OIV] ratio found in Compton-thin Seyfert 2s by Rigby et al. (2009), and why the luminosity of the Compton-thin Sy2s of our sample is significantly lower than that of Sy1s and Sy1.5s.

7.6. The cosmic X-ray background

The CXB is known to be produced by the integrated emission of unresolved AGN. Thus, to fully understand the spectrum of the CXB, it is extremely important to study the average hard X-ray spectra of Seyfert galaxies. In their CXB synthesis model, Gilli et al. (2007) assumed the disk to be the main reflector, considering a weaker reflection for Seyfert 2s than for Seyfert 1s, and a value of $R = 0.37$ for the unabsorbed reflector. Using these parameters, they hypothesized that, to explain the great amount of flux around ~ 30 keV, CT Sy2s contribute up to $\sim 30\%$ of the CXB. Risaliti et al. (1999) and Guainazzi et al. (2005) estimated that $\sim 50\%$ of all obscured AGN are CT. However, so far this large amount of CT AGN has not been observed (e.g., Ajello et al. 2008a, Paltani et al. 2008), and only few of them are known. Treister et al. (2009, hereafter T09) discussed the strong degeneracy between the fraction of CT AGN and the value of the reflection parameter used, finding that for a value of $R \approx 1$, a lower fraction of CT objects ($\sim 10\%$) is needed. Gandhi et al. (2007) also showed how an enhanced reflection component, due to light bending in their case, might decrease the large fraction of heavily absorbed AGN.

We have shown here that the average spectrum of MOB Sy2s has a strong reflection component, and an average value of $R \gtrsim 1$, although for LOB objects we found a value of R smaller than that used by Gilli et al. (2007). This might imply that obscured objects start to contribute significantly to the peak of the CXB already for $N_H \sim 10^{23} \text{ cm}^{-2}$. To test this, we calculated the average value of R for AGN, and extrapolated the CT AGN density as shown in Fig. 4 of T09. To obtain the average value of R , we used the N_H distribution of T09, which considers about the same amount of absorbed (AB, $N_H \geq 10^{23} \text{ cm}^{-2}$, which includes MOB and CT AGN) and LOB ($N_H < 10^{23} \text{ cm}^{-2}$) objects. We showed that the average spectra of CT and MOB Sy2s are consistent, thus we divided the AGN into two classes, AB and

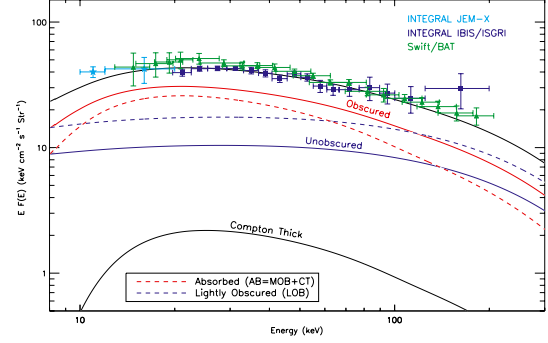


Fig. 14. Fit to the spectrum of the CXB measured by INTEGRAL IBIS/ISGRI (squares, Türlér et al. 2010). The model used is a combination of our best-fit models for the average spectra of the different classes of objects (AB and LOB), normalizing their ratio using the N_H distribution of Treister et al. (2009). We also show the data obtained by INTEGRAL JEM-X (stars, Türlér et al. 2010) and Swift BAT (triangles, Ajello et al. 2008b) above 10 keV.

LOB, and used their average reflection parameters (Sect. 5.1) to calculate the average value of R . The value obtained $R \sim 1.1$ agrees with that found by T09, and implies that CT AGN have a local density of $\sim 2 \times 10^{-6} \text{ Mpc}^{-3}$, and represent a fraction of $\sim 10\%$ of the total population of AGN.

We fitted the INTEGRAL IBIS/ISGRI CXB spectrum of Türlér et al. (2010) with the sum of the best-fit models obtained for AB and LOB objects³, fixing all the parameters to the best-fit values found in Sect. 5.1, leaving only the normalization free to vary. Following the N_H distribution of T09, and assuming that all the objects contribute equally to the CXB, we forced the two values of the normalization to have the same value ($A_{\text{LOB}} = A_{\text{AB}}$). We set the redshift to $z = 1$. We thus obtained a fit with only one free parameter, the global normalization. This simplified model yields a good fit of the CXB spectrum ($\chi^2 = 13.5$ for 15 DOF) in the 20–200 keV band.

In Fig. 14, we show our fit to the CXB, and the contribution of the different components to the spectrum. Using the N_H distribution of T09, we transformed the models of the average spectra of LOB and AB objects into those of the three classes used by Gilli et al. (2007): obscured ($10^{24} \geq N_H \geq 10^{22} \text{ cm}^{-2}$), unobscured ($N_H < 10^{22} \text{ cm}^{-2}$), and CT objects. We added Compton scattering and photoelectric absorption to the model of CT AGN (setting $N_H = 10^{24} \text{ cm}^{-2}$).

8. Summary and conclusion

We have presented a study of the average hard X-ray spectra of Seyfert galaxies performed using INTEGRAL IBIS/ISGRI data. In the following, we summarize our findings:

- Different classes of Seyfert galaxies have the same average nuclear continuum ($\Gamma \approx 1.8$, $E_C \gtrsim 200 \text{ keV}$), and their Comptonizing medium has on average a consistent value of the optical depth ($\tau \approx 0.8$).
- NLS1s have a steeper hard X-ray spectrum than Seyfert 1s and Seyfert 1.5s above ~ 40 keV. This is likely due to a lower cutoff energy, as proposed by Malizia et al. (2008).
- PBL and NPBL Sy2s have similar hard X-ray spectra, the only difference between the two classes in our incomplete sample being their luminosity.

³ In XSPEC, this is translated as `pexrav+pexrav`.

- Seyfert 2s have on average a stronger reflection component than Seyfert 1s and Seyfert 1.5s.
- Most of the reflection of Seyfert 2s comes from MOB ($10^{23} \text{ cm}^{-2} \leq N_{\text{H}} < 10^{24} \text{ cm}^{-2}$) Sy2s.
- The large amount of reflection observed in MOB Seyfert 2s might be explained by an X-ray source highly covered by the absorbing material. The Compton-thin absorber might contain CT clumps, partially covering the X-ray source.
- The large amount of reflection of MOB Sy2s reduces by a factor of ~ 3 the amount of CT Seyfert 2 needed to explain the CXB peak. Our results are consistent with the fraction of CT AGN being $\sim 10\%$.

Our results, while confirming that the X-ray engine is the same for all classes of Seyfert galaxies, point towards the existence of significant differences in the structure of the medium surrounding the X-ray source between LOB Seyfert galaxies and MOB Seyfert 2s. These differences cannot be solely due to viewing angle dependence, but might imply that there are morphological differences between LOB and MOB AGN.

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⁴ <http://irfu.cea.fr/Sap/IGR-Sources/>

Appendix A: List of sources

In the following, we list the coordinates, redshifts, detection significances, count rates, column densities, and luminosities of the samples of Seyfert 1s (Table [A.1](#)), Seyfert 1.5s ([A.2](#)), Compton-thin Seyfert 2s ([A.3](#)), CT Seyfert 2s ([A.4](#)), and NLS1s ([A.5](#)) used for the stacking analysis.

Appendix B: Spectra

In Fig. [B.1](#), we show the average 17–250 keV spectra of Seyfert 1s, Seyfert 1.5s, Seyfert 2s, CT Seyfert 2s, and NLS1s. The parameters of the models used for the fit are reported in Table [3](#). In Fig. [B.2](#), we show the average spectra of MOB and LOB Seyfert 2s. The parameters of the models are reported in Table [4](#).

Table A.1. Coordinates, redshifts, detection significances, count rates, column densities, and luminosities of the Seyfert 1s used for the stacking analysis.

Name	RA [h m s]	Dec [° ' '']	<i>z</i>	Det. significance [σ]	Count rate [ct s ⁻¹]	<i>N_H</i> [10 ²² cm ⁻²]	log <i>L</i> _{17–80 keV} [erg s ⁻¹]
IGR J02086–1742	02 08 31.4	–17 43 04.8	0.129	7.3	0.31 ± 0.04	<0.017 ^a	44.78
IGR J02097+5222	02 09 37.7	+52 26 43.6	0.049	13.5	0.56 ± 0.04	0.03 ^b	44.20
Mrk 590	02 14 33.6	–00 46 00.3	0.027	5.0	0.13 ± 0.03	0.03 ^c	43.05
Mrk 1040	02 28 14.6	+31 18 39.4	0.016	8.4	0.72 ± 0.09	0.067 ^d	43.33
RBS 345	02 42 16.0	+05 31 48.0	0.069	5.1	0.23 ± 0.04	–	44.11
ESO 548–01	03 41 54.7	–21 15 28.8	0.014	6.1	0.64 ± 0.11	–	43.17
UGC 3142	04 43 46.9	+28 58 19.0	0.022	13.8	0.58 ± 0.04	1.4 ^e	43.52
LEDA 168563	04 52 04.7	+49 32 45.0	0.029	11.6	0.51 ± 0.04	<0.22 ^b	43.70
Ark 120	05 16 11.5	–00 09 00.6	0.033	29.3	0.77 ± 0.03	<0.1 ^c	43.99
EXO 055620–3820.2	05 58 02.0	–38 20 01.0	0.034	5.6	0.31 ± 0.06	2.57 ^f	43.62
IRAS 05589+2828	06 02 09.7	+28 28 17.0	0.033	17.5	0.61 ± 0.03	< 0.04 ^b	43.89
SWIFT J0640.4–2554	06 40 10.8	–25 49 48.0	0.026	5.0	0.39 ± 0.08	0.33 ^f	43.49
IGR J07597–3842	07 59 41.7	–38 43 57.4	0.040	21.8	0.60 ± 0.03	0.05 ^d	44.05
PG 0804+761	08 10 58.7	+76 02 42.5	0.100	5.0	0.20 ± 0.04	0.023 ^d	44.37
Fairall 1146	08 38 30.7	–35 59 35.0	0.032	14.0	0.34 ± 0.02	0.1 ^d	43.61
IGR J09026–4812	09 02 37.3	–48 13 34.1	0.039	21.6	0.37 ± 0.02	0.9 ^g	43.82
SWIFT J0917.2–6221	09 16 09.4	–62 19 29.5	0.057	12.1	0.34 ± 0.03	0.5 ^h	44.11
4U 0937–12	09 45 42.1	–14 19 35.0	0.008	17.1	0.99 ± 0.06	1.19 ^f	42.87
SWIFT J1038.8–4942	10 38 45.0	–49 46 55.0	0.060	9.3	0.25 ± 0.03	1.55 ^f	44.02
IGR J11457–1827	11 45 41.0	–18 27 29.0	0.033	6.8	0.87 ± 0.13	≈0 ^f	44.05
IGR J12107+3822	12 10 43.4	+38 22 51.6	0.023	5.3	0.17 ± 0.03	–	43.02
IGR J12136–0527	12 13 37.0	–05 26 53.0	0.066	5.3	0.16 ± 0.03	2.0 ⁱ	43.91
IGR J12172+0710	12 17 09.0	+07 09 33.0	0.007	8.3	0.22 ± 0.03	0.15 ⁱ	42.10
Mrk 50	12 23 24.1	+02 40 44.8	0.023	8.9	0.22 ± 0.02	0.018 ^d	43.14
NGC 4593	12 39 39.4	–05 20 39.3	0.009	39.7	1.03 ± 0.03	0.02 ^j	42.99
ESO 323–77	13 06 26.6	–40 24 50.0	0.015	16.6	0.50 ± 0.03	6.0 ^k	43.12
IGR J13109–5552	13 10 43.1	–55 52 11.7	0.104	15.2	0.31 ± 0.02	<0.1 ^c	44.60
Mrk 279	13 53 03.5	+69 18 29.2	0.031	5.0	0.64 ± 0.13	0.02 ^f	43.86
RHS 39	14 19 22.2	–26 38 41.0	0.022	10.4	0.46 ± 0.04	<0.05 ^c	43.42
IGR J14471–6414	14 46 28.3	–64 16 24.1	0.053	9.7	0.19 ± 0.02	<0.1 ^c	43.80
IGR J16119–6036	16 11 51.4	–60 37 53.1	0.016	14.8	0.33 ± 0.02	0.1 ^d	43.00
IGR J16482–3036	16 48 14.9	–30 35 06.1	0.031	29.9	0.62 ± 0.02	0.13 ^c	43.85
IGR J16558–5203	16 56 05.7	–52 03 41.2	0.054	23.9	0.47 ± 0.02	0.011 ^c	44.21
IGR J17418–1212	17 41 55.3	–12 11 57.5	0.037	19.4	0.43 ± 0.02	0.1 ^d	43.84
IGR J18027–1455	18 02 48.0	–14 54 54.8	0.035	23.6	0.42 ± 0.02	0.41 ^l	43.78
IGR J18259–0706	18 25 57.6	–07 10 22.8	0.037	13.2	0.24 ± 0.02	0.6 ^c	43.58
ESO 140–43	18 44 54.0	–62 21 52.9	0.014	11.8	0.52 ± 0.04	1.8 ^e	43.08
IGR J18559+1535	18 56 00.6	+15 37 58.0	0.084	18.3	0.35 ± 0.02	0.7 ^a	44.46
ESO 141–55	19 21 14.2	–58 40 15.0	0.037	12.7	0.64 ± 0.05	0.004 ^c	44.01
SWIFT J1933.9+3258	19 33 47.3	+32 54 25.0	0.056	7.0	0.22 ± 0.03	<0.04 ^m	43.91
IGR J19405–3016	19 40 15.2	–30 15 48.5	0.052	9.0	0.29 ± 0.03	< 0.1 ^c	43.97
RX J2135.9+4728	21 35 54.4	+47 28 28.3	0.025	14.1	0.28 ± 0.02	0.4 ^c	43.31
IGR J22292+6647	22 29 13.5	+66 46 51.8	0.113	9.7	0.22 ± 0.02	0.2 ^c	44.52
IGR J23206+6431	23 20 36.8	+64 30 42.8	0.072	9.0	0.15 ± 0.02	0.6 ^c	43.96

Notes. Detection significances, count rates, and luminosities are in the 17–80 keV band. The flux of the Crab in the 17–80 keV band is of 278 ct s⁻¹.

(^a) Rodríguez et al. (2010); (^b) Winter et al. (2008) and references therein; (^c) Beckmann et al. (2009) and ref. therein; (^d) Bodagheer et al. (2007) and ref. therein; (^e) Ricci et al. (2010); (^f) Winter et al. (2009); (^g) Tomsick et al. (2008); (^h) Malizia et al. (2007); (ⁱ) Paltani et al. (2008) and ref. therein; (^j) Beckmann et al. (2006) and ref. therein; (^k) Jiménez-Bailón et al. (2008); (^l) Panessa et al. (2008); (^m) Landi et al. (2007a).

Table A.2. Coordinates, redshifts, detection significances, count rates, column densities, and luminosities of the Seyfert 1.5s used for the stacking analysis.

Name	RA [h m s]	Dec [° ′ ″]	<i>z</i>	Det. significance [σ]	Count rate [ct s ⁻¹]	N_{H} [10 ²² cm ⁻²]	log $L_{17-80 \text{ keV}}$ [erg s ⁻¹]
IGR J00335+6126	00 33 18.4	+61 27 42.4	0.105	9.2	0.14 ± 0.02	0.5 ^a	44.26
Mrk 1152	01 13 50.1	-14 50 44.1	0.052	5.0	0.47 ± 0.09	2.7 ^b	44.17
NGC 985	02 34 37.8	-08 47 15.4	0.043	14.9	0.42 ± 0.03	0.6 ^c	43.96
IGR J03334+3718	03 33 18.8	+37 18 11.4	0.055	5.0	0.18 ± 0.03	—	43.81
4U 0517+17	05 10 45.5	+16 29 55.0	0.017	25.3	0.90 ± 0.04	0.1 ^c	43.40
SWIFT J0519.5-3140	05 19 35.7	-32 39 25.0	0.013	14.9	0.67 ± 0.05	26.6 ^e	43.12
MCG+08-11-011	05 54 53.6	+46 26 21.8	0.020	24.9	1.81 ± 0.07	0.18 ^c	43.93
Mrk 6	06 52 12.3	+74 25 36.8	0.019	16.7	0.74 ± 0.04	10 ^d	43.50
ESO 209-12	08 01 57.6	-49 46 42.0	0.040	15.8	0.34 ± 0.02	0.1 ^c	43.81
IGR J09253+6929	09 25 47.6	+69 27 51.5	0.039	5.1	0.29 ± 0.06	8 ^f	43.72
NGC 3227	10 23 30.6	+19 51 53.7	0.003	17.4	1.88 ± 0.11	6.8 ^c	42.30
NGC 3516	11 06 47.6	+72 34 08.3	0.009	6.5	1.26 ± 0.19	4 ^g	43.08
NGC 3783	11 39 01.8	-37 44 18.7	0.009	10.9	2.05 ± 0.19	0.08 ^b	43.29
IGR J12415-5750	12 41 25.4	-57 50 04.0	0.024	16.2	0.33 ± 0.02	<0.11 ^c	43.35
IGR J13133-1109	13 13 17.0	-11 08 34.0	0.034	5.0	0.20 ± 0.04	—	43.43
MCG-06-30-015	13 35 53.8	-34 17 44.0	0.008	23.2	0.74 ± 0.03	0.03 ^c	42.75
IGR J14080-3023	14 08 06.6	-30 23 52.6	0.023	5.0	0.18 ± 0.04	0.03 ^h	43.05
NGC 5548	14 17 59.7	+25 08 13.4	0.017	7.1	0.49 ± 0.07	0.51 ^d	43.22
QSO B1419+480	14 21 29.6	+47 47 26.0	0.072	5.2	0.25 ± 0.05	0.5 ⁱ	44.18
PG 1501+106	15 04 01.2	+10 26 16.2	0.036	7.2	0.49 ± 0.07	3.9 ^j	43.87
SWIFT J1930.5+3414	19 30 13.7	+34 10 52.0	0.062	8.8	0.28 ± 0.03	27.5 ^e	44.10
NGC 6814	19 42 40.4	-10 19 24.0	0.005	25.9	0.79 ± 0.03	<0.05 ^d	42.37
SWIFT J2009.0-6103	20 08 47.0	-61 05 48.0	0.015	7.6	0.61 ± 0.08	4.53 ^e	43.21
Mrk 509	20 44 09.8	-10 43 24.7	0.035	16.0	1.12 ± 0.07	<0.01 ^d	44.21
1RXS J211928.4+333259	21 19 35.5	+33 33 03.6	0.051	9.8	0.29 ± 0.03	—	43.95
1RXS J213944.3+595016	21 39 42.7	+59 49 37.2	0.114	5.5	0.13 ± 0.02	—	44.30
1H 2251-179	22 54 05.9	-17 34 55.3	0.064	9.5	1.12 ± 0.12	<0.19 ^d	44.73
NGC 7469	23 03 15.8	+08 52 25.9	0.017	10.3	0.78 ± 0.08	0.061 ^c	43.42
MCG-02-58-022	23 04 43.5	-08 41 08.6	0.047	8.2	0.71 ± 0.09	<0.08 ^d	44.27

Notes. Detection significances, count rates, and luminosities are in the 17–80 keV band. The flux of the Crab in the 17–80 keV band is of 278 ct s⁻¹.

References. ^(a) Beckmann et al. (2009) and ref. therein; ^(b) Fiore et al. (1997); ^(c) Bodaghee et al. (2007) and ref. therein; ^(d) Beckmann et al. (2006) and ref. therein; ^(e) Winter et al. (2009) and ref. therein; ^(f) Rodriguez et al. (2008); ^(g) Guainazzi et al. (2002); ^(h) Landi et al. (2010); ⁽ⁱ⁾ Barcons et al. (2003); ^(j) Longinotti et al. (2010).

Table A.3. Coordinates, redshifts, detection significances, count rates, column densities, and luminosities of the Seyfert 2s used for the stacking analysis.

Name	RA [h m s]	Dec [° ' "]	<i>z</i>	Det. significance [σ]	Count rate [cts s ⁻¹]	<i>N_H</i> [10 ²² cm ⁻²]	PBL	log <i>L</i> _{17–80 keV} [erg s ⁻¹]
IGR J00040+7020	00 04 01.5	+70 19 16.5	0.096	9.4	0.18 ± 0.02	3 ^a	–	44.29
IGR J00254+6822	00 25 31.4	+68 21 41.3	0.012	12.2	0.21 ± 0.02	40 ^b	–	42.55
Mrk 348	00 48 47.1	+31 57 25.1	0.014	23.2	1.59 ± 0.07	30 ^b	Yes ¹	43.56
NGC 526	01 23 54.2	–35 03 55.0	0.019	6.5	0.69 ± 0.11	1.6 ^c	–	43.47
ESO 297–18	01 38 37.2	–40 00 40.7	0.025	9.6	0.76 ± 0.08	42 ^b	–	43.75
IGR J01528–0326	01 52 48.9	–03 26 51.0	0.017	9.1	0.26 ± 0.03	14 ^b	–	42.95
NGC 788	02 01 06.5	–06 48 55.9	0.013	37.4	0.94 ± 0.03	<0.02 ^b	Yes ²	43.27
Mrk 1018	02 06 08.2	–00 17 02.4	0.043	8.2	0.22 ± 0.03	0.03 ^d	–	43.68
IGR J02343+3229	02 34 19.9	+32 30 20.0	0.016	10.5	0.75 ± 0.07	2.2 ^b	–	43.35
IGR J02501+5440	02 50 41.8	+54 42 15.1	0.015	7.1	0.29 ± 0.04	<70 ^e	–	42.89
IGR J02524–0829	02 52 23.3	–08 30 38.0	0.017	5.1	0.18 ± 0.04	12 ^f	–	42.79
NGC 1142	02 55 12.3	–00 11 01.7	0.029	25.0	1.03 ± 0.04	45 ^b	No ³	44.01
NGC 1194	03 03 46.1	–01 08 49.2	0.013	6.7	0.34 ± 0.05	1 ^g	–	42.83
SWIFT J0318.7+6828	03 19 02.4	+68 25 48.0	0.090	5.1	0.24 ± 0.05	4.1 ^h	–	44.36
LEDA 15023	04 23 48.2	+04 08 42.0	0.046	8.4	0.36 ± 0.04	–	No ¹	43.95
SWIFT J0444.1+2813	04 44 09.0	+28 13 00.0	0.011	7.4	0.33 ± 0.04	3.39 ^h	–	42.67
SWIFT J0453.4+0404	04 53 31.0	+04 02 02.4	0.029	9.6	0.27 ± 0.03	–	–	43.43
ESO 33–2	04 55 59.6	–75 32 26.0	0.019	8.7	0.35 ± 0.04	0.1 ^c	–	43.17
SWIFT J0505.7–2348	05 05 45.7	–23 51 14.0	0.035	14.8	0.86 ± 0.06	6.57 ^h	–	44.09
NGC 2110	05 52 11.4	–07 27 22.4	0.007	48.5	2.4 ± 0.05	4.3 ^b	Yes ²	43.14
IGR J06239–6052	06 23 45.6	–60 58 45.0	0.041	6.0	0.31 ± 0.05	20 ^b	–	43.78
LEDA 96373	07 26 26.3	–35 54 21.0	0.029	5.9	0.39 ± 0.07	7 ⁱ	–	43.59
IGR J07565–4139	07 56 19.6	–41 37 42.1	0.021	9.3	0.23 ± 0.02	1.1 ^c	–	43.08
SWIFT J0920.8–0805	09 20 46.3	–08 03 21.9	0.020	6.8	0.56 ± 0.08	11.4 ^h	–	43.42
MCG–05–23–016	09 47 40.2	–30 56 54.0	0.008	39.4	2.16 ± 0.06	1.6 ^c	Yes ²	43.21
NGC 3081	09 59 29.5	–22 49 34.6	0.007	15.7	0.95 ± 0.06	66 ^b	Yes ²	42.74
SWIFT J1009.3–4250	10 09 48.3	–42 48 40.4	0.032	15.6	0.55 ± 0.03	30 ^b	–	43.82
IGR J10404–4625	10 40 22.3	–46 25 24.7	0.024	12.4	0.45 ± 0.04	3 ^b	–	43.48
SWIFT J1049.4+2258	10 49 30.9	+22 57 51.9	0.033	5.1	0.42 ± 0.08	42 ^j	–	43.73
SWIFT J1200.8+0650	12 00 57.9	+06 48 23.1	0.036	9.8	0.32 ± 0.03	9.3 ^j	–	43.69
IGR J12026–5349	12 02 47.6	–53 50 07.7	0.028	25.1	0.57 ± 0.02	2.2 ^c	–	43.72
NGC 4074	12 04 32.6	+20 14 56.4	0.022	5.9	0.29 ± 0.05	30 ^h	No ⁴	43.22
NGC 4138	12 09 29.9	+43 41 06.0	0.003	8.6	0.30 ± 0.04	8 ^b	–	41.50
NGC 4258	12 18 57.5	+47 18 14.3	0.002	5.5	0.23 ± 0.04	8.7 ^b	No ⁵	41.03
NGC 4395	12 25 48.8	+33 32 49	0.001	9.5	0.29 ± 0.03	0.15 ^b	–	40.53
NGC 4507	12 35 36.5	–39 54 33.3	0.012	49.6	2.29 ± 0.05	29 ^b	Yes ¹	43.59
SWIFT J1238.9–2720	12 38 54.5	–27 18 28.0	0.024	11.5	1.06 ± 0.09	60 ^b	–	43.86
IGR J12391–1612	12 39 06.3	–16 10 47.1	0.036	11.2	0.55 ± 0.05	3 ^b	–	43.92
IGR J12482–5828	12 47 57.8	–58 29 59.1	0.028	6.7	0.13 ± 0.02	0.3 ⁱ	–	43.08
ESO 323–32	12 53 20.4	–41 38 13.8	0.016	6.8	0.23 ± 0.03	7 ^b	–	42.84
NGC 4941	13 04 13.1	–05 33 05.7	0.003	6.5	0.19 ± 0.03	45 ^k	No ¹	41.30
MCG–03–34–064	13 22 24.5	–16 43 42.9	0.017	6.0	0.40 ± 0.07	41 ^h	Yes ²	43.13
NGC 5252	13 38 16.0	+04 32 32.5	0.022	42.1	1.40 ± 0.03	0.68 ^b	Yes ¹	43.90
Mrk 268	13 41 11.1	+30 22 41.2	0.041	8.4	0.34 ± 0.04	30 ^e	No ⁴	43.83
1AXG J135417–3746	13 54 15.4	–37 46 33.0	0.052	8.3	0.22 ± 0.03	1.6 ^l	–	43.85
IGR J14175–4641	14 17 03.9	–46 41 39.1	0.076	10.4	0.24 ± 0.02	–	–	44.21
IGR J14471–6319	14 47 14.7	–63 17 19.6	0.038	8.5	0.16 ± 0.02	2 ^b	–	43.43
IGR J14561–3738	14 56 08.2	–37 38 53.8	0.024	7.9	0.18 ± 0.02	–	–	43.09
IGR J14579–4308	14 57 41.3	–43 07 57.0	0.016	17.1	0.36 ± 0.02	20 ^b	–	43.04
ESO 328–36	15 14 47.2	–40 21 35	0.024	7.9	0.17 ± 0.02	–	–	43.06
IGR J15161–3827	15 15 59.3	–38 25 48.3	0.036	5.0	0.11 ± 0.02	22 ^m	–	43.22

Table A.3. continued.

Name	RA [h m s]	Dec [° ' '']	z	Det. significance [σ]	Count rate [ct s ⁻¹]	N_{H} [10 ²² cm ⁻²]	PBL	log $L_{17-80 \text{ keV}}$ [erg s ⁻¹]
NGC 5995	15 48 25.0	-13 45 28.0	0.025	8.3	0.39 ± 0.05	0.7 ^b	Yes ¹	43.46
IGR J15539-6142	15 53 35.2	-61 40 55.4	0.015	9.8	0.21 ± 0.02	18 ^b	—	42.74
SWIFT J1650.5+0434	16 50 35.3	+04 35 42.0	0.032	5.4	0.27 ± 0.05	—	—	43.51
NGC 6300	17 16 59.2	-62 49 11.0	0.003	32.4	1.11 ± 0.03	22 ^b	No ¹	42.07
IGR J17513-2011	17 51 13.0	-20 12 14.5	0.047	22.3	0.31 ± 0.01	0.6 ^b	—	43.91
IGR J18244-5622	18 24 19.5	-56 22 08.7	0.017	14.4	0.56 ± 0.04	14 ^b	—	43.28
Fairall 49	18 36 58.1	-59 24 08.0	0.019	5.2	0.22 ± 0.04	0.01 ⁿ	Yes ²	42.97
ESO 103-35	18 38 20.3	-65 25 41.0	0.013	26.2	1.19 ± 0.05	21.6 ^h	—	43.37
IGR J19077-3925	19 07 38.6	-39 25 37.2	0.073	9.8	0.27 ± 0.03	—	—	44.23
IGR J19473+4452	19 47 19.4	+44 49 42.4	0.053	11.2	0.33 ± 0.03	11 ^b	—	44.04
IGR J20216+4359	20 21 48.1	+44 00 32.0	0.017	8.3	0.17 ± 0.02	13 ^o	—	42.76
IGR J20286+2544	20 28 34.9	+25 43 59.7	0.013	19.1	0.66 ± 0.03	42 ^b	—	43.12
Mrk 520	22 00 30.2	+10 36 10.8	0.028	7.6	0.75 ± 0.10	2.4 ^h	—	43.84
NGC 7172	22 02 01.7	-31 52 18.0	0.008	19.1	1.31 ± 0.07	9 ^b	No ¹	42.99
NGC 7314	22 35 46.1	-26 03 01.7	0.005	5.1	0.43 ± 0.09	0.12 ^b	Yes ¹	42.10
IGR J23308+7120	23 30 37.3	+71 22 44.8	0.037	5.0	0.11 ± 0.02	6 ^b	—	43.25
IGR J23524+5842	23 52 22.0	+58 45 31.5	0.162	11.5	0.18 ± 0.02	6 ^b	—	44.75

Notes. Detection significances, count rates, and luminosities are in the 17–80 keV band. The flux of the Crab in the 17–80 keV band is of 278 ct s⁻¹. References for the column density.

References. ^(a) Landi et al. (2007b); ^(b) Beckmann et al. (2009) and ref. therein; ^(c) Bodaghee et al. (2007) and ref. therein; ^(d) Pfeerkorn et al. (2001); ^(e) Masetti et al. (2008); ^(f) Rodriguez et al. (2010); ^(g) Greenhill et al. (2008); ^(h) Winter et al. (2009) and ref. therein; ⁽ⁱ⁾ Landi et al. (2010); ^(j) Winter et al. (2008) and ref. therein; ^(k) Paltani et al. (2008); ^(l) Risaliti et al. (2000); ^(m) Rodriguez et al. (2008); ⁽ⁿ⁾ Dadina et al. (2007); ^(o) Bikmaev et al. (2008).

References for the PBL ¹ Shu et al. (2007) and ref. therein; ² Veron-Cetty & Veron (2010) and ref. therein; ³ Cai et al. (2010); ⁴ Nagao et al. (2000); ⁵ Barth et al. (1999).

Table A.4. Coordinates, redshifts, detection significances, count rates, column densities, and luminosities of the Compton-thick Seyfert 2s used for the stacking analysis.

Name	RA [h m s]	Dec [° ' '']	z	Det. significance [σ]	Count rate [ct s ⁻¹]	N_{H} [10 ²² cm ⁻²]	log $L_{17-80 \text{ keV}}$ [erg s ⁻¹]
NGC 1068	02 42 40.8	-00 00 48.4	0.003	14.0	0.45 ± 0.03	150 ^a	41.91
SWIFT J0601.9-8636	06 05 39.1	-86 37 52.0	0.006	7.3	0.40 ± 0.06	101 ^b	42.40
Mrk 3	06 15 36.3	+71 02 14.9	0.014	31.3	1.43 ± 0.05	110 ^c	43.70
NGC 3281	10 31 52.1	-34 51 13.3	0.011	12.0	0.78 ± 0.07	151 ^d	43.26
IGR J13091+1137	13 09 05.6	+11 38 02.9	0.025	14.8	0.51 ± 0.03	90 ^c	43.73
NGC 5643	14 32 41.3	-44 10 24.0	0.003	9.2	0.20 ± 0.02	60–100 ^e	41.50
Mrk 477	14 40 38.1	+53 30 15.9	0.037	5.8	0.44 ± 0.07	>100 ^f	44.09
NGC 5728	14 42 23.3	-17 16 51.6	0.009	13.6	0.80 ± 0.06	210 ^a	43.12
IGR J16351-5806	16 35 13.2	-58 04 49.7	0.009	12.9	0.28 ± 0.02	>150 ^g	42.69
NGC 7582	23 18 23.5	-42 22 14.1	0.005	5.5	1.20 ± 0.20	160 ^a	42.77

Notes. Detection significances, count rates, and luminosities are in the 17–80 keV band. The flux of the Crab in the 17–80 keV band is of 278 ct s⁻¹.

References. ^(a) Della Ceca et al. (2008) and ref. therein; ^(b) Ueda et al. (2007); ^(c) Beckmann et al. (2006) and ref. therein; ^(d) Bodaghee et al. (2007) and ref. therein; ^(e) Guainazzi et al. (2004); ^(f) Bassani et al. (1999); ^(g) Malizia et al. (2009).

Table A.5. Coordinates, redshifts, detection significances, count rates, column densities, and luminosities of the Narrow Lines Seyfert 1s used for the stacking analysis.

Name	RA [h m s]	Dec [° ′ ″]	<i>z</i>	Det. significance [σ]	Count rate [ct s ⁻¹]	<i>N_H</i> [10 ²² cm ⁻²]	log <i>L</i> _{17–80 keV} [erg s ⁻¹]
1H 0323+342	03 24 41.2	+34 10 45.9	0.063	5.9	0.20 ± 0.03	0.1 ^a	43.97
Mrk 110	09 25 12.9	+52 17 10.5	0.035	5.0	0.86 ± 0.17	0.019 ^a	44.09
NGC 4051	12 03 09.6	+44 31 53.2	0.002	13.6	0.47 ± 0.03	<0.02 ^b	41.34
Mrk 766	12 18 26.6	+29 48 45.6	0.013	7.7	0.26 ± 0.03	0.8 ^c	42.71
NGC 4748	12 52 12.0	-13 25 48.0	0.014	5.2	0.16 ± 0.03	≈0 ^d	42.57
Mrk 783	13 02 58.8	+16 24 27.5	0.067	7.3	0.25 ± 0.03	0.046 ^a	44.12
NGC 5506	14 13 14.9	-03 12 27.0	0.007	47.2	2.7 ± 0.06	3.4 ^b	43.19
IGR J14552–5133	14 55 17.9	-51 34 13.3	0.016	12.5	0.25 ± 0.02	0.1 ^a	42.88
IRAS 15091–2107	15 11 54.0	-21 21 21.6	0.044	5.3	0.22 ± 0.04	0.7 ^e	43.70
IGR J16185–5928	16 18 26.4	-59 28 45.3	0.035	10.7	0.23 ± 0.02	<0.1 ^f	43.52
IGR J16385–2057	16 38 31.1	-20 55 25.0	0.027	7.7	0.26 ± 0.03	0.21 ^g	43.35
IGR J19378–0617	19 37 33.1	-06 13 04.0	0.010	11.2	0.32 ± 0.03	≈ 0 ^h	42.58
ESO 399–20	20 06 57.2	-34 32 54.0	0.025	6.5	0.23 ± 0.04	0.048 ^a	43.23
IGR J21277+5656	21 27 45.9	+56 56 34.4	0.014	24.2	0.52 ± 0.02	0.1 ^a	43.08

Notes. Detection significances, count rates, and luminosities are in the 17–80 keV band. The flux of the Crab in the 17–80 keV band is of 278 ct s⁻¹.

References. ^(a) Bodaghee et al. (2007) and ref. therein; ^(b) Beckmann et al. (2009) and ref. therein; ^(c) Beckmann et al. (2006) and ref. therein; ^(d) Grupe et al. (1998); ^(e) Jiménez-Bailón et al. (2008); ^(f) Malizia et al. (2008); ^(g) Rodríguez et al. (2008); ^(h) Malizia et al. (2008).

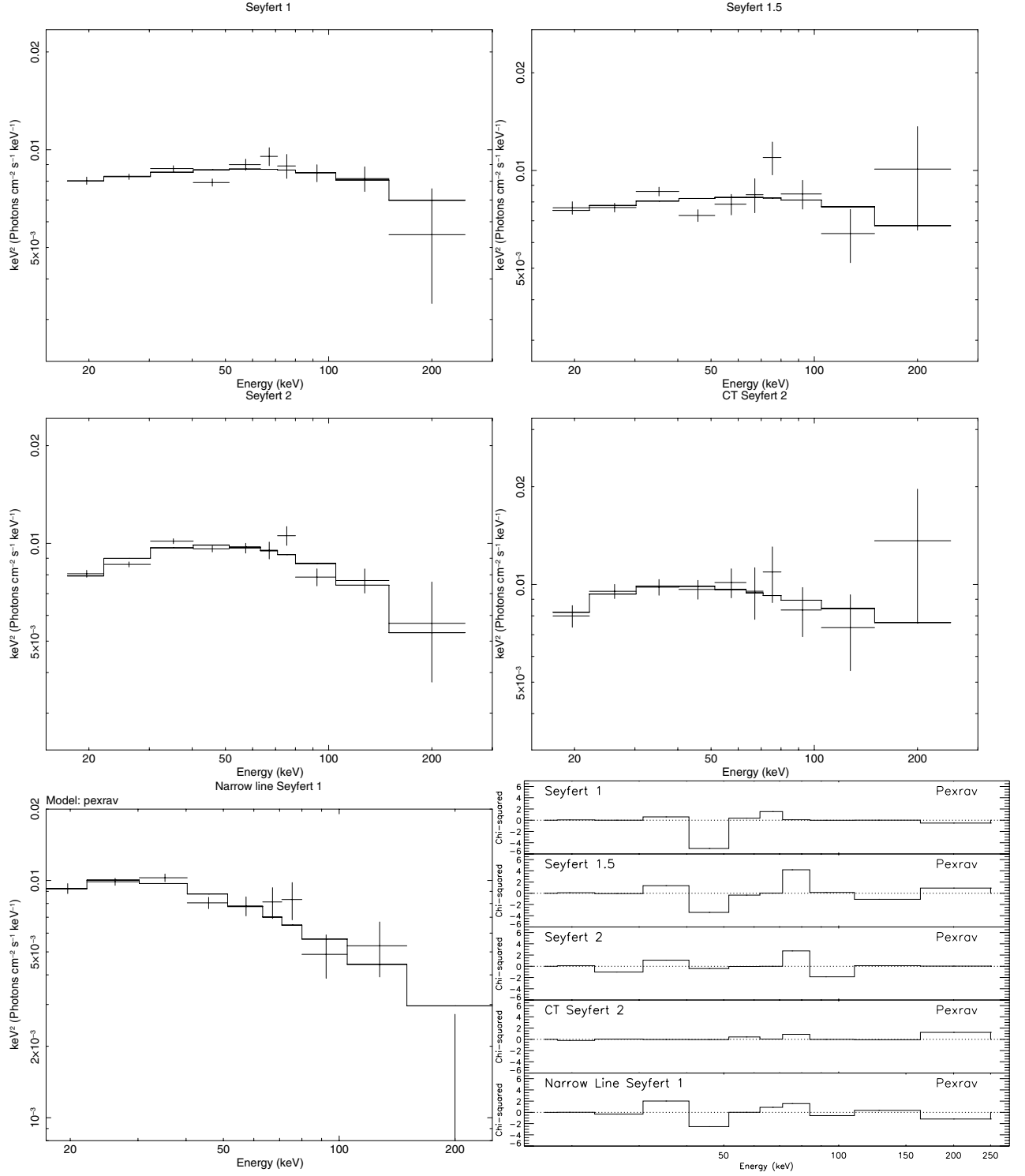


Fig. B.1. Spectra of different classes of AGN obtained using the *pexrav* model. We also show the contributions to the χ^2 relative to the best fits. The results of the spectral analysis are reported in Table 3.

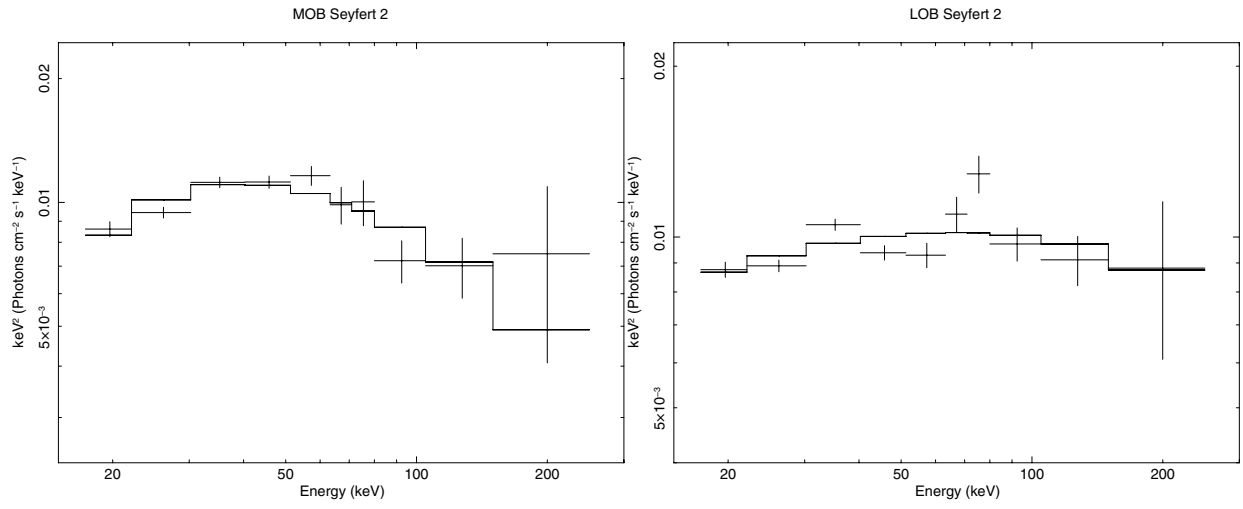


Fig. B.2. Spectra of MOB (*left panel*) and LOB (*right panel*) Seyfert 2s, the model used is a cutoff power law plus a reflection component from neutral matter (*pexrav*). The results of the analysis are reported in Table 4.

Other Scientific Contributions

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In this Chapter, I will summarize the scientific activities I was involved in during my PhD time, and which are not directly related to AGN astrophysics. During the four years I spent at the ISDC I participated, as scientist on duty (*Scody*), to the scientific operations of the *INTEGRAL* mission. In Sect. 9.1 I will illustrate the duties of the Scody, and the most significant results I obtained during my shifts. In Sect. 9.2 I will discuss the results we obtained studying the nature of the unidentified source AX J1910.7+0917. This work also led to the discovery of three new hard X-ray sources: IGR J19173+0747, IGR J19294+1327 and IGR J19149+1036.

9.1 Scientist on Duty

Each Scody is on duty for one week every 2–3 months, and his/her main task is to monitor the hard X-ray sky through the near-real time data analysis of the incoming data, promptly alerting the scientific community of any significant event.

9.1.1 Near-real time data analysis

The ISDC is in charge of collecting and archiving all the data products of the *INTEGRAL* mission, and is also the place where the nearly real-time analysis is performed. The *INTEGRAL* data are in fact received by the ISDC shortly after having been produced (see Sect. 3.1.6). The technical monitoring of the data, which consists in verifying that the reception and processing of the raw data is flawless, is performed by the operator. The duty of the Scody is to check the scientific content of the data. This is done thanks to the Interactive Quick Look Analysis (IQLA), a reduced version of the *INTEGRAL* analysis software OSA, that allows to analyze IBIS/ISGRI and JEM-X data. The IQLA produces automatically images, one per science window, in the 20–40 and 40–80 keV energy band for IBIS/ISGRI, and in the 3–10 and 10–30 keV band for JEM-X. Automatic alerts are also displayed whenever a new source is detected in the single science window, or in the case of a strong increase in flux (exceeding a pre-set specific threshold for each object) of a known source. Alerts are produced also for the detection of Gamma-ray bursts in the field of view of the instruments. At the end of each observation, the IQLA produces automatically a mosaic for IBIS/ISGRI and JEM-X, and

is the task of the Scody to analyze them, looking for possible new sources. Light-curves for all the sources detected are also produced by the IQLA, allowing the Scody to monitor for possible variability. Most of the new transient sources are accreting Galactic objects located around the Galactic plane (Fig. 9.1). These objects are normally binary systems, with a compact source (as a black hole, a neutron star or a white dwarf) which accretes matter from a companion star. The accretion can be either by a stellar wind (for a high mass companion star) or by Roche-lobe overflow (in the case of a low-mass companion star). In the case a new transient source or a strong flux variability is detected, an Astronomer Telegram (ATel) is issued to quickly notify the scientific community. In the following I will briefly discuss the ATels I produced while on shift.

9.1.2 H 1743-322 in stable outburst phase

The Galactic black-hole candidate and X-ray transient H 1743–322 was observed to be in outburst in the hard X-rays by *INTEGRAL* (Kuulkers et al. 2008; Prat et al. 2008) and in the radio domain by ATCA (Corbel et al. 2008). During my shift in October 2008, *INTEGRAL* observed the source during the on-going outburst, as part of a ToO. The source showed only 5% variability in the 20–40 keV band, at a flux level of 170 mCrab. We extracted the broad band X-ray spectrum of H 1743–322 using 86.4 ks of JEMX-1 data (3–20 keV), 80.4 ks of IBIS/ISGRI (20–200 keV) data, and 84.1 ks of SPI (25–200 keV) data. The spectrum could be well fit ($\chi^2_\nu = 1.1$) by an absorbed Comptonization model (compTT, Titarchuk 1994). The temperature of the seed photons could not be well constrained due to the fact that no data below 3 keV were available, and it was fixed to $kT_0 = 100$ eV. The absorbing column density was found to be $N_H = 1.8 \pm 1.5 \times 10^{22} \text{ cm}^{-2}$, the temperature of the hot plasma $kT_e = 39 \pm 1$ keV, and the optical depth of the plasma $\tau = 1.2 \pm 0.1$. The model flux of the outburst was $1.0 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $2.1 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$, in the 3–20 keV and 20–200 keV energy band, respectively. These results were reported in Ricci et al. (2008b).

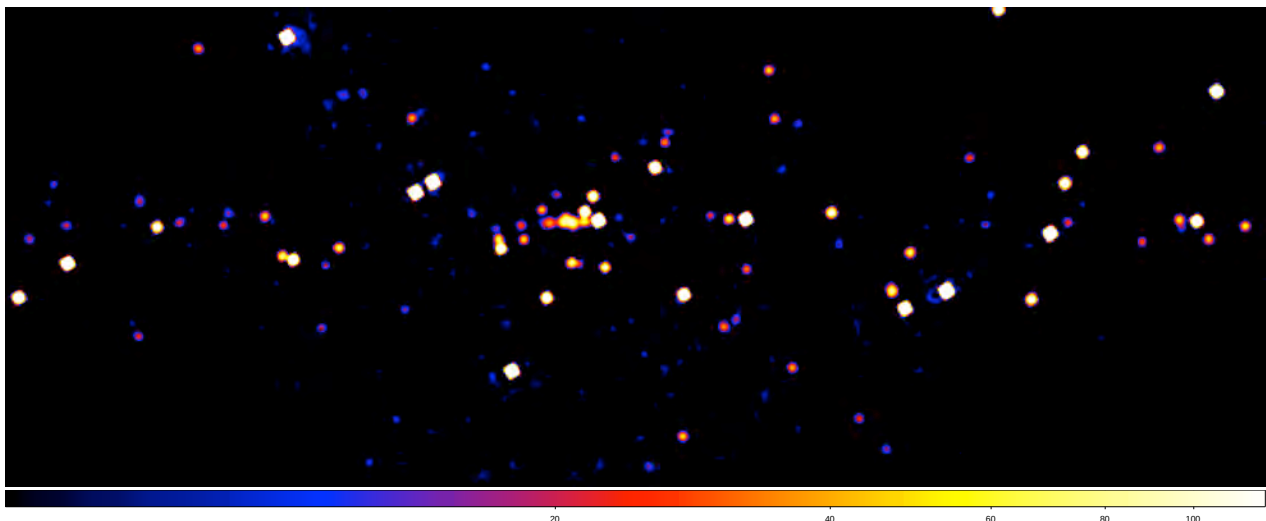


Figure 9.1: *INTEGRAL* IBIS/ISGRI 17–80 keV significance map around the Galactic center.

9.1.3 IGR J17375–3022: a new hard X-ray transient detected by INTEGRAL

During the second part of the ToO observation on H 1743-322, *INTEGRAL* IBIS/ISGRI detected a new transient source, IGR J17375–3022, located in the Galactic bulge at (RA=264.3946, Dec=−30.3817),

with an uncertainty on the position of 2.2 arcmin. IGR J17375–3022 was not revealed in the single science windows, but it was clearly detected within the 82 ks IBIS/ISGRI observation with a detection significance of 12σ and a flux of 10 ± 1 mCrab. In the 40–80 keV band the source was detected at 6.7σ , with a flux of 7 ± 1 mCrab. JEM X-1 did not detect the source during its 11 ks observation, and for SPI only a 3σ upper limit in the 20–40 keV band of ~ 18 mCrab was obtained. IGR J17375–3022 was not detected in the 20–40 keV energy band neither in the previous *INTEGRAL* revolution (with a 3σ upper limit of 4 mCrab), nor in the following one (with a 3σ upper limit of 6 mCrab).

The 20–150 keV IBIS/ISGRI spectrum of IGR J17375–3022 could be well fit by a single power-law model ($\Gamma = 2.0 \pm 0.2$). The model flux was 7×10^{-11} erg cm $^{-2}$ s $^{-1}$ and 2×10^{-10} erg cm $^{-2}$ s $^{-1}$, in the 20–40 keV and 20–150 keV band, respectively.

After our ATel (Ricci et al. 2008c), Remillard & Levine (2008) analyzing *RXTE*/ASM data found that IGR J17375–3022 is a long-term, faint transient, and that the outburst began in late 2005 or early 2006. In April 2009 *XMM-Newton* detected IGR J17375–3022 while performing a slew between targets, suggesting a possible new outburst (Saxton et al. 2009).

9.1.4 Localization of the hard X-ray transient IGR J17062-6143

During my shift as a Scody in November 2008 *INTEGRAL* observed for 95 ks the field containing the hard X-ray transient IGR J17062–6143, whose detection was reported by Churazov et al. (2007). The source was detected by IBIS/ISGRI with a flux of 4.5 ± 0.8 mCrab in the 20–40 keV band, and we were able to define the position within 4 arcmin. The hard X-ray spectrum of IGR J17062–6143 could be well fit with a single power-law with a photon index $\Gamma = 2.8 \pm 0.7$, or by a black body with $kT = 7 \pm 2$ keV. The model flux obtained in the 18–50 keV band was 4×10^{-11} erg cm $^{-2}$ s $^{-1}$. The source had also been detected by *Swift* as SWIFT J1706.6–6146. Analyzing the 13 ks XRT observation we could better constrain the position of the source within 3.5 arcsec. The soft X-ray (0.3–7 keV) spectrum could be well represented by an absorbed power-law model, with a column density of $N_{\text{H}} = 1.7 \times 10^{21}$ cm $^{-2}$, and a photon index of $\Gamma = 1.86 \pm 0.02$. The source was also detected by *Swift*/UVOT, with magnitudes in the *U* and *UVW2* of 18.4 mag and 18.1 mag, respectively. All these results have been presented in Ricci et al. (2008a).

9.2 AX J1910.7+0917 and three newly discovered INTEGRAL sources

The latest version of the *INTEGRAL* data reduction software (OSA9) has brought a great improvement to the quality of the processed data (see as an example Fig. 9.2). The improvements obtained thanks to the new image cleaning tools implemented in OSA9 can allow to detect faint new sources even in crowded fields, or around very bright objects. An example of this is shown in Pavan et al. (2011), in which we report the detection of three new sources around the very bright X-ray binary GRS 1915+105 ($S/N \simeq 400\sigma$). These objects are IGR J19173+0747, IGR J19294+1327 and IGR J19149+1036. The main purpose of the study of Pavan et al. (2011) was to understand the nature of the AX J1910.7+0917, an X-ray source firstly observed by *ASCA* (Sugizaki et al. 2001). Using all the available *INTEGRAL*, *Chandra*, *XMM-Newton* and *ASCA* X-ray data, we found the source to be strongly variable (of a factor $\gtrsim 60$). The X-ray spectrum could be well represented by an absorbed ($N_H \sim 5 \times 10^{22} \text{ cm}^{-2}$) power-law ($\Gamma \sim 1.4$) plus a neutral iron emission line. No obvious counterparts in the optical and radio band could be identified, while in the infrared band the source appears to be consistent with 2MASS J19104360+0916291. Although the fact that the source is located on the Galactic plane might hint to a Galactic origin, the data do not allow to fully discern its nature.

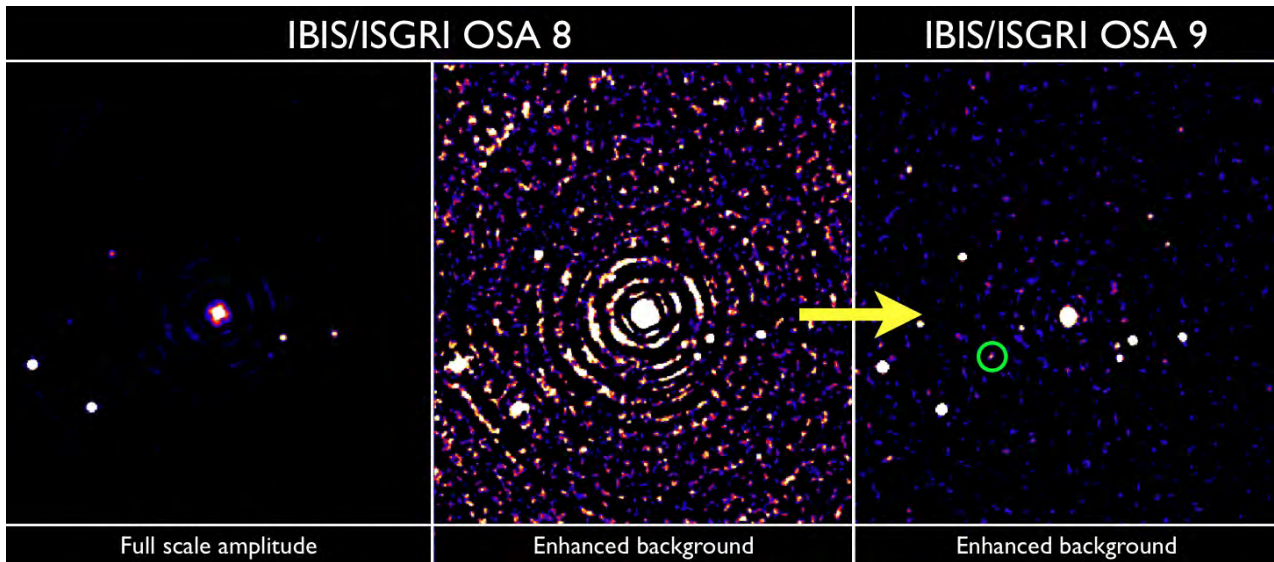


Figure 9.2: The image shows the improvement obtained with the latest release of *INTEGRAL* data analysis software OSA. The source in the center of the three panels is Cygnus X-1. *INTEGRAL* picture of the month, May 2010.

AX J1910.7+0917 and three newly discovered *INTEGRAL* sources

L. Pavan^{1,2}, E. Bozzo^{1,2}, C. Ferrigno^{1,2}, C. Ricci^{1,2}, A. Manousakis^{1,2}, R. Walter^{1,2}, and L. Stella³

¹ ISDC, INTEGRAL Science Data Centre, Université de Genève, Chemin d'Ecogia 16, 1290 Versoix, Switzerland
 e-mail: lucia.pavan@unige.ch

² Observatoire de Genève, Université de Genève, Chemin des Maillettes 51, 1290 Sauverny, Switzerland

³ INAF – Osservatorio Astronomico di Roma, via Frascati 33, 00044 Rome, Italy

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ABSTRACT

Aims. We take advantage of the high sensitivity of the IBIS/ISGRI telescope and the improvements in the data analysis software to investigate the nature of the still poorly known X-ray source AX J1910.7+0917, and search for closely previously undetected objects.

Methods. We analyze all publicly available *INTEGRAL* data of AX J1910.7+0917, together with a number of archival observations that were carried out in the direction of the source with *Chandra*, *XMM-Newton*, and *ASCA*. In the IBIS/ISGRI field-of-view around AX J1910.7+0917, we discovered three new sources: IGR J19173+0747, IGR J19294+1327 and IGR J19149+1036; the latter is positionally coincident with the *Einstein* source 2E 1912.5+1031. For the first two sources, we also report the results of follow-up observations carried out with *Swift*/XRT.

Results. AX J1910.7+0917 features a clear variability in the X-rays. Its spectrum can be well described with an absorbed ($N_H \sim 6 \times 10^{22} \text{ cm}^{-2}$) power-law ($\Gamma \simeq 1.5$) model plus an iron line at 6.4 keV. We also obtained a refined position and report on possible infrared counterparts.

Conclusions. The present data do not allow for a unique classification of the sources. Based on the property of its X-ray emission and the analysis of a likely infrared counterpart, we investigate different possibilities for the nature of AX J1910.7+0917.

Key words. X-rays: individuals: AX J1910.7+0917 – X-rays: individuals: IGR J19173+0747 – X-rays: individuals: IGR J19294+1327 – X-rays: individuals: IGR J19149+1036 – X-rays: individuals: 2E 1912.5+1031

1. Introduction

The wide field-of-view of the IBIS/ISGRI telescope (FOV, $19^\circ \times 19^\circ$; Ubertini et al. 2003) onboard *INTEGRAL* (Winkler et al. 2003) and its unprecedented sensitivity in the hard X-ray domain (17–100 keV) have made this instrument particularly successful in the past few years in revealing new high-energy sources. The latest available IBIS/ISGRI catalog contains more than 700 objects (Bird et al. 2010) and an increasing number of sources are being discovered thanks to ongoing *INTEGRAL* surveys of the high-energy sky. Since 2003, the relatively large exposure time available (~ 1 –6 Ms) permitted to achieve in the galactic plane a limiting sensitivity of $\lesssim 1$ mCrab in the 17–100 keV energy range and a point-source location accuracy of ≈ 2 –3 arcmin. Besides the increasing amount of observing time, the identification of a number of new hard X-ray sources has benefited from improvements in the data analysis software.

In this paper, we take advantage of the new version of the *INTEGRAL* OSA software released by the ISDC (Courvoisier et al. 2003) to investigate the nature of the still poorly known source AX J1910.7+0917, and search for nearby previously undetected faint X-ray sources in the field-of-view (FOV) around this source. In Sect. 2 we summarize all previous observations of AX J1910.7+0917 and the analysis of all the publicly available *INTEGRAL* data. We also carried out an analysis of all archival *Chandra*, *XMM-Newton*, and *ASCA* observations that included AX J1910.7+0917 in the instruments' FOVs. The analysis of the *INTEGRAL* data also led to the discovery of three new hard X-ray sources in the IBIS/ISGRI FOV around AX J1910.7+0917, independently detected through data

analysis also with the — software (A. Segreto, priv. comm.). For two of these sources, we obtained follow-up observations with *Swift*/XRT and present these results in Sect. 3. Our discussion and conclusion are summarized in Sect. 4.

2. AX J1910.7+0917

AX J1910.7+0917 is a relatively faint and poorly known X-ray source discovered with *ASCA* during the survey of the Galactic plane. The best-determined position so far is $\alpha_{J2000} = 19^h 10^m 47^s.00$ and $\delta_{J2000} = 09^\circ 17' 06''.0$, with an associated error of $57.6''$ (90% c.l., Sugizaki et al. 2001). The *ASCA* spectrum could be fitted with an absorbed power-law model ($\chi^2_{\text{red}}/\text{d.o.f.} = 0.72/10$). The measured photon index was $\Gamma = 1.1^{+0.5}_{-0.4}$, for an absorption column density of $N_H = (2.6^{+1.4}_{-1.0}) \times 10^{22} \text{ cm}^{-2}$. The estimated 0.7–10 keV X-ray flux was $2.4 \times 10^{-12} \text{ erg/cm}^2/\text{s}$. Sugizaki et al. (2001) associated AX J1910.7+0917 to the *Einstein* source 2E 1908.3+0911, which is characterized by an averaged X-ray flux of $(6.9 \pm 1.4) \times 10^{-13} \text{ erg/cm}^2/\text{s}$ (0.2–3.5 keV, Hertz & Grindlay 1988). The source was also detected with *INTEGRAL*, and classified by Bird et al. (2010) as a likely variable source. The source maximum detection significance in the IBIS/ISGRI data is 8.3σ (18–60 keV), and the corresponding time-average flux is 0.4 ± 0.1 mCrab (0.6 ± 0.1 mCrab) in the 20–40 keV (40–100 keV) energy band (corresponding to $3.0 \times 10^{-12} \text{ erg/cm}^2/\text{s}$ and $5.7 \times 10^{-12} \text{ erg/cm}^2/\text{s}$, respectively). No other detections and counterparts in different energy band have been reported so far.

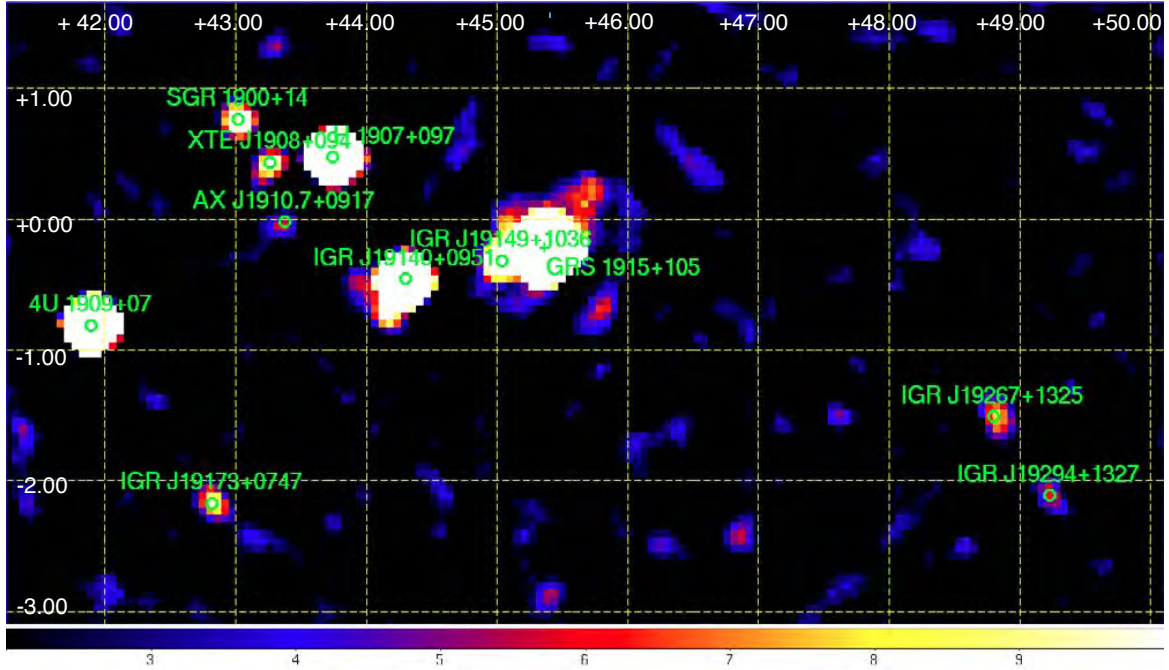


Fig. 1. IBIS/ISGRI mosaic around AX J1910.7+0917 (17–80 keV, significance map). We also show the newly discovered nearby sources (see Sect. 3 and the electronic version of the paper for the colored picture). The dashed grids denote galactic coordinates.

2.1. Data analysis and results

We analyzed all archival *INTEGRAL*, *ASCA*, *XMM-Newton*, and *Chandra* observations that included the position of AX J1910.7+0917 in their FOV. This is the first in-depth study of the emission from this source up to hard X-ray energies. In Sect. 2.1.1 we report the details of the *INTEGRAL* observations. A log of all other observations is given in Table 1. Throughout the paper, all uncertainties are given at 90% c.l. (unless otherwise stated).

2.1.1. *INTEGRAL*

INTEGRAL observations are commonly divided into ~ 2 – 3 ks short pointings called “science windows” (SCWs). We considered all publicly available SCWs for the IBIS/ISGRI (17–80 keV, Lebrun et al. 2003) and for the two JEM-X telescopes (3–23 keV, Lund et al. 2003) that were performed in the direction of AX J1910.7+0917 from 2003 March 6 to 2009 April 15 (see Sect. 2). This permitted us to achieve an effective exposure time on the source of 4.8×10^2 ks and 2.7×10^3 ks for JEM-X and ISGRI respectively. All data, here and below, were analyzed with version 9.0 of the OSA software (Courvoisier et al. 2003).

The source was not detected in the JEM-X1 and JEM-X2 mosaics, and we derived an upper limit on the source X-ray flux by using the tool `upperlimit`. From the JEM-X1 mosaic we derived a 3σ upper limit of 1.0×10^{-11} erg/cm²/s, 5.8×10^{-12} erg/cm²/s, and 9×10^{-12} erg/cm²/s respectively in the energy bands 3–7 keV, 7–11 keV, and 11–19 keV. The corresponding 3σ upper limits derived from the JEM-X2 mosaic were 1.7×10^{-11} erg/cm²/s, 1.2×10^{-11} erg/cm²/s, and 1.8×10^{-11} erg/cm²/s. These are compatible with the measured averaged *ASCA* flux reported in Sect. 1.

We produced an IBIS/ISGRI mosaic of the region around AX J1910.7+0917, using the energy band 17–80 keV to maximize the S/N . In this energy band AX J1910.7+0917 is detected with a significance of 5.8σ . A close view of the ISGRI mosaic is shown in Fig. 1. We checked that the best-fit position of the source obtained from the mosaic is compatible with both its *ASCA* and *XMM-Newton* refined position (see Sect. 2.1.2).

We derived a count rate of 0.09 ± 0.02 cts/s, corresponding to a flux of 0.31 ± 0.05 mCrab. This flux is higher than any contamination expected in the same energy band from the nearby supernova remnant (SNR, see Miceli et al. 2006, and Sect. 2.1.2).

We also performed a spectral analysis and extracted its lightcurve in the two energy bands 20–40 keV and 40–80 keV. The averaged IBIS/ISGRI spectrum of the source is shown in Fig. 5 and discussed in Sect. 2.1.2. We barycenter-correct the photon arrival times in the source lightcurves with the OSA9 tool.

No evidence for a coherent periodicity could be found. This is also confirmed by the analysis of the data from *Swift*/BAT (Cusumano, priv. comm.), which operates in a similar energy band to that of IBIS/ISGRI.

2.1.2. *XMM-Newton*

AX J1910.7+0917 was serendipitously¹ observed in two *XMM-Newton* (Jansen et al. 2001) observations performed in 2004 April in the direction of the nearby SNR W49B (Miceli et al. 2006). We processed *XMM-Newton* observation data files (ODFs) to produce calibrated event lists using the `epic` and `mos` tasks (Science Analysis System, SAS, v.10.0) for the *Epic* and the *MOS* cameras. The event files of the two observations were filtered to exclude high background time intervals follow-

¹ AX J1910.7+0917 is named as 2XMMJ191043.4+091629 in the *XMM-Newton* serendipitous source catalogue (Watson et al. 2009).

Table 1. Observation log of AX J1910.7+0917.

OBS ID	Instr	Date ^a	Exp ^b (ks)	N_{H} (10^{22} cm^{-2})	Γ	F_{obs}^c ($\text{erg/cm}^2/\text{s}$)	$\chi^2_{\text{red}}/\text{d.o.f.}$ (C-stat/d.o.f.)
ASCA							
50005000	GIS2+GIS3	1993-04-24	95	$4.8^{+1.5}_{-1.9}$	1.4 ± 0.5	$8.2^{+0.7}_{-2.7}$	0.4/53
13000000 ^d	GIS2	1993-05-03	2.3	4.8 (fixed)	1.4 (fixed)	<4.2	–
	GIS3	1993-05-03	2.3	4.8 (fixed)	1.4 (fixed)	<4.9	–
13000010 ^d	GIS2	1993-05-03	2.3	4.8 (fixed)	1.4 (fixed)	<1.1	–
	GIS3	1993-05-03	2.3	4.8 (fixed)	1.4 (fixed)	<1.6	–
13000030 ^d	GIS3	1993-05-03	1.4	4.8 (fixed)	1.4 (fixed)	<2.1	–
	GIS3	1993-05-03	1.4	4.8 (fixed)	1.4 (fixed)	<3.1	–
50005010 ^d	GIS2	1993-10-16	12	4.8 (fixed)	1.4 (fixed)	<0.6	–
	GIS3	1993-10-16	12	4.8 (fixed)	1.4 (fixed)	<0.6	–
50005020 ^d	GIS2	1993-10-17	20	4.8 (fixed)	1.4 (fixed)	<1.1	–
	GIS3	1993-10-17	20	4.8 (fixed)	1.4 (fixed)	<1.4	–
10020000	GIS2+GIS3	1993-11-03	26	$6.3^{+1.6}_{-1.4}$	2.3 ± 0.5	$4.9^{+4.3}_{-0.4}$	(146.1/157)
10020010 ^d	GIS2	1993-11-03	19	4.8 (fixed)	1.4 (fixed)	<2.1	–
	GIS3	1993-11-03	19	4.8 (fixed)	1.4 (fixed)	<2.3	–
57005050	GIS2+GIS3	1999-04-27	23	$5.0^{+3.4}_{-2.4}$	1.6 ± 0.8	$2.5^{+0.2}_{-1.4}$	(70.7/59)
XMM-Newton							
0084100401	Epic-pn	2004-04-03	14.0	$6.3^{+0.5}_{-0.4}$	1.4 ± 0.1	$17.1^{+1.0}_{-2.1}$	1.1/147
0084100501 ^e	Epic-pn	2004-04-05	14.7	5.0 ± 0.3	1.28 ± 0.08	$24.3^{+1.2}_{-1.7}$	0.9/168
Chandra							
9615 ^f	ACIS-S	2008-05-31	1.7	–	–	<0.4	–

Notes. ^(a) Format is YYYY-MM-DD; ^(b) Exp indicates the total exposure time of each observation; ^(c) observed flux in the 1–10 keV energy band in units of 10^{-12} ; ^(d) 90% c.l. upper limit; ^(e) this fit includes also a Gaussian line at ~ 6.4 keV, see text for details; ^(f) 68% c.l. upper limit.

ing the recommendations of the SAS online analysis threads². We excluded from further analysis time intervals in observation 0084100401 (0084100501) during which the count-rate of the entire detector FOV in the 10–12 keV energy band was higher than 0.2 (0.15) cts/s for the Epic-MOS and 0.35 (0.4) for the Epic-pn. We also carefully checked that none of these rises in the total field count-rate was due to a flare from AX J1910.7+0917.

In both observations 0084100401 and 0084100501, the three Epic cameras were operated in full frame and the source AX J1910.7+0917 was located at the rim of their FOV. In the Epic-MOS1 AX J1910.7+0917 lied on the border between two CCDs, and thus we excluded these data from the analysis. The total effective exposure time is of 14.0 ks (18.1 ks) for the Epic-pn (Epic-MOS2) in the observation 0084100401 and 14.7 ks (18.0 ks) in the observation 0084100501. In order to maximize S/N , source lightcurves and spectra were extracted by using an elliptical region (see Fig. 2). As we discuss also below in more detail, the elongated shape of the source is due to the off-axis point spread function of the *XMM-Newton* telescope for sources close to the border of the FOV³. Background lightcurves and spectra were extracted in the closest source-free region to AX J1910.7+0917. We checked that none of the results reported in this paper changed significantly by using different (reasonable) source and background extraction regions. We corrected all lightcurves for vignetting, bad pixels, point-spread-function (PSF) losses, and dead time with the SAS tool. All EPIC images and spectra were corrected for out of time events,

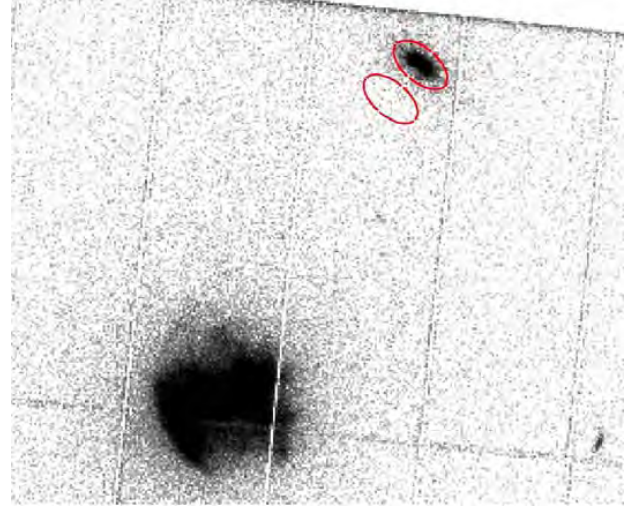


Fig. 2. Image of AX J1910.7+0917 as observed by the Epic-pn detector (0.5–12.0 keV). The extraction region for source and background are also shown. The bright object in the center is the SNR W49B.

according to the instructions provided by the SAS online analysis threads. Epic-pn and Epic-MOS spectra were rebinned before fitting so as to have at least 25 counts per bin and, at the same time, prevent oversampling the energy resolution by more than a factor of three. Given the relatively short exposure time and low X-ray flux of the source, we report below only results from the

² <http://xmm.esac.esa.int/sas/documentation/threads/>.

³ See also http://xmm.esa.int/external/xmm_user_support/documentation/uhb/node18.html

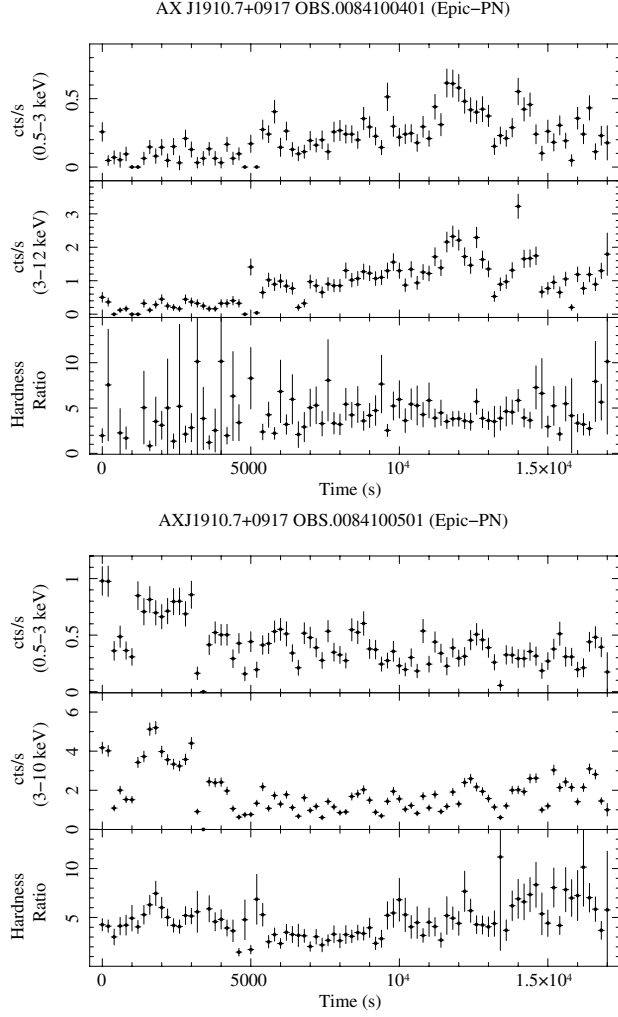


Fig. 3. *XMM-Newton* Epic-pn background-subtracted lightcurves of AX J1910.7+0917 extracted in the two energy bands 0.5–3 keV and 3–12 keV for the two observations 0084100401 (top) and 0084100501 (bottom). The hardness ratio is reported in the bottom panel of each figure. The time bin is 200 s.

Epic-pn analysis and checked that the Epic-MOS2 data would give compatible results in all cases.

In Fig. 3 we report the Epic-pn lightcurves of the source in the 0.5–3 keV and 3–12.0 keV energy bands, extracted from the two *XMM-Newton* observations. The hardness ratio, defined as the ratio of the count rate in the hard (3–12 keV) to soft (0.5–3 keV) energy band versus time, is also shown. A pronounced variability on timescales of hundreds of seconds is clearly visible from these lightcurves, but only marginal variations in the hardness ratio were measured (the most prominent feature is the increase of a factor ~ 2 at the beginning of observation 0084100501, see Fig. 3). From the 0.5–12 keV Epic-pn lightcurves in observation 0084100401 (0084100501) we estimated a minimum source count rate of 0.25 ± 0.03 (0.6 ± 0.2) cts/s and a maximum source count rate of 5.6 ± 0.5 (6.2 ± 0.5) cts/s.

In order to search for spectral variations with the source intensity, we extracted from observation 0084100401 two

XMM-Newton spectra by selecting time intervals in which the source count-rate in the 0.3–12 keV energy band was <2 and >2 cts/s. The first spectrum (effective exposure time 12 ks) could be reasonably well described ($\chi^2_{\text{red}}/\text{d.o.f.} = 1.2/125$) by using an absorbed power-law (PL) model with $N_{\text{H}} = (6.3^{+0.6}_{-0.5}) \times 10^{22} \text{ cm}^{-2}$ and $\Gamma = 1.4^{+0.2}_{-0.1}$. The estimated 1–10 keV X-ray flux was $1.3 \times 10^{-11} \text{ erg/cm}^2/\text{s}$. Alternatively, this spectrum could be well described ($\chi^2_{\text{red}}/\text{d.o.f.} = 1.0/125$) by using a blackbody (BB) model with a temperature of $kT_{\text{BB}} = (1.78 \pm 0.08) \text{ keV}$ and a radius of $R_{\text{BB}} = 0.42 \pm 0.03 \text{ km}$ (for an assumed distance of 10 kpc). The spectrum extracted at higher count-rates (effective exposure time 2 ks) could be reasonably well fitted by using the same models discussed above. This gave $N_{\text{H}} = (6.2^{+0.9}_{-0.8}) \times 10^{22} \text{ cm}^{-2}$, and $\Gamma = 1.3 \pm 0.2$ for the PL model and $N_{\text{H}} = (3.2 \pm 0.5) \times 10^{22} \text{ cm}^{-2}$, $kT_{\text{BB}} = (2.0 \pm 0.2) \text{ keV}$, and $R_{\text{BB}} = 0.60 \pm 0.07 \text{ km}$ for the BB model. In this case the estimated flux is $3.8 \times 10^{-11} \text{ erg/cm}^2/\text{s}$ (1–10 keV). This analysis did not reveal any significant change in the spectral parameters between the higher and lower count-rate spectra. We thus also extracted the average spectrum of this observation (see Fig. 4). This could be well fitted with an absorbed PL model, the parameters of the fit are reported in Table 1. A similar good fit ($\chi^2_{\text{red}}/\text{d.o.f.} = 0.9/147$) could also be obtained by using a BB model ($kT_{\text{BB}} = (1.85 \pm 0.07) \text{ keV}$, $R_{\text{BB}} = 0.45 \pm 0.03 \text{ km}$, $N_{\text{H}} = (3.3 \pm 0.3) \times 10^{22} \text{ cm}^{-2}$).

We carried out a similar analysis for the observation 0084100501. The rate-resolved spectra were extracted during the time intervals in which the source count-rates were >2 and <2 cts/s (0.5–12 keV). We fitted both spectra with an absorbed power-law model and noticed that the residuals from these fits indicated the presence of an iron line at $\sim 6.4 \text{ keV}$ (see Fig. 4). We therefore added a Gaussian line to the spectral model used for the fit. The spectrum extracted at higher count rates (effective exposure time 4.4 ks) gave ($\chi^2_{\text{red}}/\text{d.o.f.} = 1.1/134$) a power-law photon index of $\Gamma = 1.3 \pm 0.1$, an absorption column density of $N_{\text{H}} = (5.3 \pm 0.4) \times 10^{22} \text{ cm}^{-2}$, an energy for the iron line centroid of $E_{\text{line}} = 6.45 \pm 0.06 \text{ keV}$ and an equivalent width of $EW = 0.06^{+0.04}_{-0.05} \text{ keV}$ (errors on the EWs are given at 68% c.l. throughout the paper). The normalization of the line was $(3.8 \pm 2.4) \times 10^{-5}$, only yielding an indication of the presence of the line. For this spectrum the estimated 1–10 keV X-ray flux was $(4.3^{+0.1}_{-0.3}) \times 10^{-11} \text{ erg/cm}^2/\text{s}$. By using a BB model instead of a PL, we obtained $N_{\text{H}} = (2.7 \pm 0.3) \times 10^{22} \text{ cm}^{-2}$, $kT_{\text{BB}} = (1.95 \pm 0.08) \text{ keV}$, and $R_{\text{BB}} = 0.63 \pm 0.04 \text{ km}$.

The spectrum extracted at a lower count rate (effective exposure time 10.3 ks) gave $\Gamma = 1.4 \pm 0.1$, $N_{\text{H}} = (4.6 \pm 0.4) \times 10^{22} \text{ cm}^{-2}$, $E_{\text{line}} = 6.42 \pm 0.03 \text{ keV}$, $EW = 0.14 \pm 0.06 \text{ keV}$ ($\chi^2_{\text{red}}/\text{d.o.f.} = 1.0/132$), and a flux of $(1.7^{+0.1}_{-0.3}) \times 10^{-11} \text{ erg/cm}^2/\text{s}$ (1–10 keV). The normalization of the line in this case was $(3.3 \pm 1.1) \times 10^{-5}$, thus indicating a detection significance $>3\sigma$. By using an absorbed BB instead of the PL component to fit the lower count-rate spectrum in the observation 0084100501 would give $N_{\text{H}} = (2.2 \pm 0.2) \times 10^{22} \text{ cm}^{-2}$, $kT_{\text{BB}} = 1.77 \pm 0.08 \text{ keV}$, and $R_{\text{BB}} = 0.44 \pm 0.03 \text{ km}$. We also extracted the source spectrum by using the total exposure time of the observation 0084100501. This spectrum is shown in Fig. 4 and the best-fit parameters obtained with an absorbed PL model plus a Gaussian line are reported in Table 1. In this case we found $E_{\text{line}} = 6.44 \pm 0.03 \text{ keV}$ and an $EW = 0.09 \pm 0.03 \text{ keV}$. The normalization of the line was $(3.4 \pm 1.0) \times 10^{-5}$. By using a BB component instead of the PL for this spectrum would give $N_{\text{H}} = (2.4 \pm 0.2) \times 10^{22} \text{ cm}^{-2}$, $kT_{\text{BB}} = 1.85 \pm 0.06 \text{ keV}$, $R_{\text{BB}} = 0.51 \pm 0.03 \text{ km}$, $\chi^2_{\text{red}} = 1.0/168$ and parameters for the iron line fully in agreement (within the errors) with those reported above.

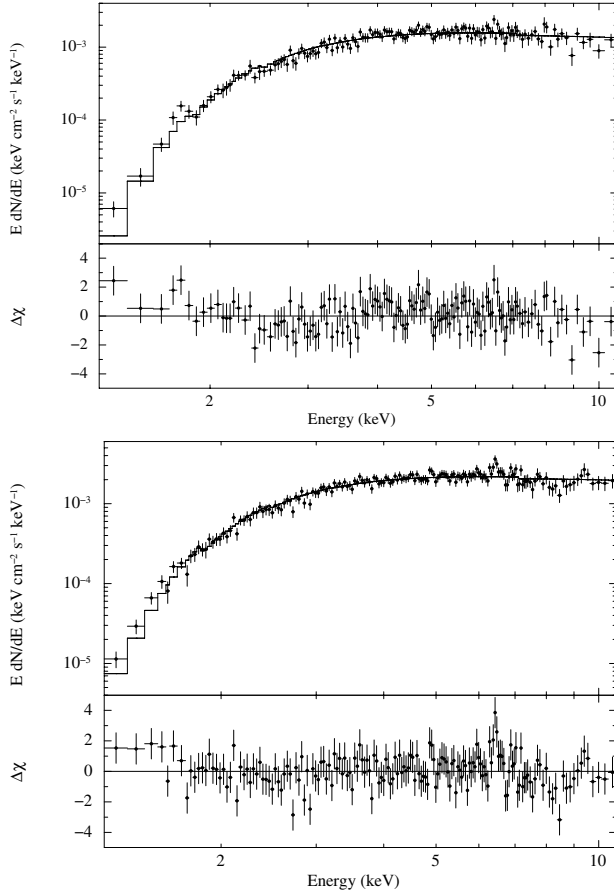


Fig. 4. Averaged *XMM-Newton* Epic-pn spectra of AX J1910.7+0917 extracted from the observations 0084100401 (top) and 0084100501 (bottom). In both cases we also show the best-fit model (an absorbed power-law) and the residuals from these fits. In the observation 0084100501 the residuals clearly showed an iron line at ~ 6.4 keV.

In order to compare the results found for the two *XMM-Newton* observations of AX J1910.7+0917, we added an iron line with a centroid energy fixed at 6.44 keV to the spectrum extracted by using the total exposure time of observation 0084100401 and determined the 90% c.l. upper limit on its normalization at 1.5×10^{-5} . This value is lower than the one measured in observation 0084100501, but still compatible with that expected due to the lower flux ($\sim 40\%$) of the source in the observation 0084100401. We thus conclude that it is not possible to infer unambiguously from the present data a variation of the iron line parameters between the two observations. Even though no simultaneous *XMM-Newton* and *INTEGRAL* observation were available, we tried a fit to the combined averaged ISGRI spectrum and the Epic-pn averaged spectrum of the observation 0084100501. This spectrum could be well described with an absorbed power law model, and we introduced a normalization constant to take into account both the intercalibration between the Epic-pn and ISGRI instruments and the variability of the source. The values of the absorption column density and power-law photon index were found to be fully consistent with those of the averaged Epic-pn spectrum, but the normalization constant turned out to be 0.04 ± 0.02 (this value would be 0.06 ± 0.03

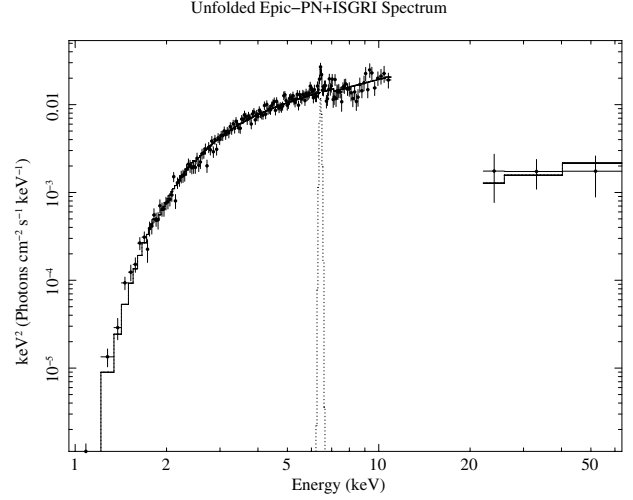


Fig. 5. Unfolded Epic-pn+ISGRI spectrum of AX J1910.7+0917. The best-fit model is obtained with an absorbed power-law model plus a Gaussian line at ~ 6.4 keV (see text for details).

if the same fit were performed by using the *XMM-Newton* spectrum of the observation 0084100401). The relatively low value of the normalization constant between the two instruments indicates that on average the X-ray flux of the source is much lower than that measured during the *XMM-Newton* observations. This is consistent with the results reported in Table 1. The unfolded Epic-pn+ISGRI spectrum is shown in Fig. 5.

Finally, we also extracted for both *XMM-Newton* observations a spatially resolved X-ray spectrum by selecting different regions centered on the source in order to search for spectral shape variations and investigate a possible extended nature of the source. We did not find any evidence for a significant change in the spectral parameters, and concluded that the elongated shape of the source is most likely caused by distortion of the instrument PSF for sources close to the border of the FOV (see also above). Because of this problem, the determination of an improved source position requires some caution. We used the automatic *XMM-Newton* source-detection task

(with manually fine-tuned parameters), to have an estimate of the source position and error in the two *XMM-Newton* observations for both the Epic-pn and Epic-MOS2 cameras. In the observation 0084100401, the two best-determined positions are (i) $\alpha_{J2000} = 19^{\text{h}}10^{\text{m}}43^{\text{s}}.42$, $\delta_{J2000} = 09^{\circ}16'29''.3$ and (ii) $\alpha_{J2000} = 19^{\text{h}}10^{\text{m}}43^{\text{s}}.37$, $\delta_{J2000} = 09^{\circ}16'29''.3$, for the Epic-pn and the Epic-MOS2, respectively. The corresponding positions obtained in the observation 0084100501 were (i) $\alpha_{J2000} = 19^{\text{h}}10^{\text{m}}43^{\text{s}}.44$, $\delta_{J2000} = 09^{\circ}16'30''.7$ and (ii) $\alpha_{J2000} = 19^{\text{h}}10^{\text{m}}43^{\text{s}}.39$, $\delta_{J2000} = 09^{\circ}16'30''.0$. According to the latest calibration document available, the relative astrometry among all EPIC cameras is estimated to be better than $1.5''$, and the absolute astrometric accuracy of any source in the *XMM-Newton* FOV is of $\sim 2''$. Only for faint MOS sources near the detection limit this error can be as large as $4''$ (90% c.l.). In the present case all results on the positions we obtained are consistent within $1.5''$ as expected. Given the position of AX J1910.7+0917 at the very rim of the *XMM-Newton* detector, we assume in the following as the best determined position of the source: $\alpha_{J2000} = 19^{\text{h}}10^{\text{m}}43^{\text{s}}.39$, $\delta_{J2000} = 09^{\circ}16'30''.0$ (J2000), with a conservative associated error of $2''$ (90% c.l.). In Sect. 2.1.5 we use this result to search for possible counterparts to AX J1910.7+0917.

A Fourier analysis of the *XMM-Newton* data of AX J1910.7+0917 did not reveal any indication for a possible coherent periodicity.

2.1.3. ASCA

AX J1910.7+0917 was serendipitously observed in several ASCA (Tanaka et al. 1994) observations performed in 1993 and 1999. A log of these observations is provided in Table 1. We used data from the two gas-imaging spectrometers (GIS2 and GIS3, Ohashi et al. 1996; Makishima et al. 1996) and applied standard screening criteria⁴. We extracted the source light curves and spectra from a circular region of 2' radius. A larger extraction region could not be used because of the emission from the nearby SNR (see also Sect. 2.1.2). For the background, we used a similar extraction region, located in the same part of the FOV as the source events, as described in the ASCA ABC guide. Note that AX J1910.7+0917 is located well within the Galactic disk and thus we could not use the ASCA blank-sky observations (see p. 80 of the ASCA ABC guide). We used the latest available GIS2 and GIS3 instrument response files (gis2v4_0.rmf and gis3v4_0.rmf) and generated for each observation the corresponding ancillary file with the tool

Only in observation 50 005 000 was the statistics sufficiently high to rebin the spectrum to have at least 20 photons per bin and perform a minimum χ^2 fitting. In all observations where the source was detected but the statistics was relatively poor, the C-statistics was used for the fits. We also determined a 90% c.l. upper limit on the source X-ray flux in all the observations in which AX J1910.7+0917 was not detected. In these cases, we obtained a source and background spectrum by using the same extraction regions adopted in the other observations, and fitted them with an absorbed PL model. The absorption column density and PL photon index were fixed to those of observation 50 005 000, and the 90% c.l. error on the model normalization was used to obtain an upper limit on the flux (1–10 keV energy band). All these results are reported in Table 1. Given the low *S/N* of the ASCA observations of AX J1910.7+0917, we did not investigate possible timing features in these data.

2.1.4. Chandra

A research in the data archive⁵ revealed that AX J1910.7+0917 was also twice observed by the ACIS telescope on-board *Chandra* (Garmire et al. 2003). The first of these observations (ID. 117) was performed on 2001 July 8 and lasted for 54 ks. AX J1910.7+0917 was serendipitously observed in the ACIS-I2 chip, but not detected. Unfortunately, the analysis of this observation revealed the presence of a large number of poorly illuminated columns on the ACIS-I2 chip (most likely a read-out problem), and therefore we did not consider this observation in our subsequent analysis. In the second observation (ID. 9615), performed on 2008 May 31 and lasting 1.65 ks, AX J1910.7+0917 was observed in the FOV of the ACIS-S3 chip, but not detected.

We derived from these data an upper limit on the source X-ray flux by using both the task⁶ available within the

⁴ See the ASCA ABC guide at <http://heasarc.gsfc.nasa.gov/docs/asca/abc/abc.html>.

⁵ <http://heasarc.gsfc.nasa.gov/>.

⁶ See the on-line thread: [http://cxc.harvard.edu/ciao/threads/aprates/\\$\protect\kern-.1667em\relax\index.html\#netcts](http://cxc.harvard.edu/ciao/threads/aprates/$\protect\kern-.1667em\relax\index.html\#netcts).

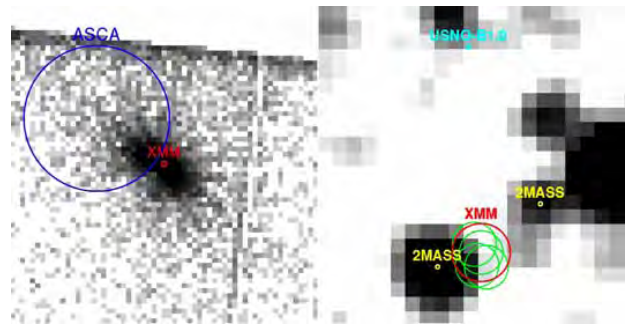


Fig. 6. *XMM-Newton* (left) and infrared (2MASS, *J* band, right) image of the region around AX J1910.7+0917. We show the error circles (green) associated with the determined positions in the 2 *XMM-Newton* observations for the *Epic-pn* and *Epic-MOS2* cameras, and the best adopted source position (red circle, error 2'' at 90% c.l.). We also show in blue the previously determined ASCA position (only slightly outside the *XMM-Newton* error circle) and the closest 2MASS and USNO-B1.0 counterparts discussed in Sect. 2.1.5 (see the electronic version of the paper for the colored picture).

package (v.4.2) and by building a fluxed image of the ACIS-S3 chip⁷. The first method allowed us to derive a 68% c.l. upper limit on the source count rate of 0.012 cts/s (0.5–7 keV), which corresponds to a 1–10 keV X-ray flux of 4.0×10^{-13} erg/cm²/s (we used the online tool⁸ and assumed a PL model with $\Gamma = 1.4$ and $N_H = 4.8 \times 10^{22}$ cm⁻² to be consistent with the other upper limits derived, see Sect. 2.1.3). The second method permits us to directly calculate the energy flux in units of erg/cm²/s for each event in the selected *Chandra* chip, taking into account the quantum efficiency and effective area as well. With this method we estimated a 3σ upper limit on the source X-ray flux of 5.4×10^{-13} erg/cm²/s (0.5–7 keV) energy band, compatible with the limit derived with the first method.

2.1.5. Counterparts of AX J1910.7+0917

We used the improved source position found from the *XMM-Newton* data to search for an infrared and/or optical counterpart to AX J1910.7+0917. In Fig. 6 we show the *XMM-Newton* FOV around AX J1910.7+0917, and the corresponding 2MASS image (Skrutskie et al. 2006). The four determined positions in the *XMM-Newton* observations (green circles) and the best adopted source position (red circle, error 2'' at 90% c.l.) are also shown. We found only one likely counterpart, 2MASS J19104360+0916291, which partly lies within the *XMM-Newton* error circle and has $J = 15.044 \pm 0.030$, $H = 13.000 \pm 0.022$, and $K = 11.808 \pm 0.023$. No cataloged optical counterparts were found within the *XMM-Newton* error circle. The closest object in the USNO-B1.0 catalog is shown in the figure but because of the relatively large separation from AX J1910.7+0917, it is very unlikely that it is associated with AX J1910.7+0917. We note that the lack of a clear optical counterpart is compatible with the high absorption in the direction of the source measured from the *XMM-Newton* observations (see Sect. 2.1.2). We also queried the FIRST Survey and the NVSS catalogs in search for a radio counterpart, but did not find any obvious candidate.

⁷ See the on-line thread: <http://cxc.harvard.edu/ciao/threads/eff2evt>.

⁸ <http://heasarc.nasa.gov/Tools/w3pimms.html>

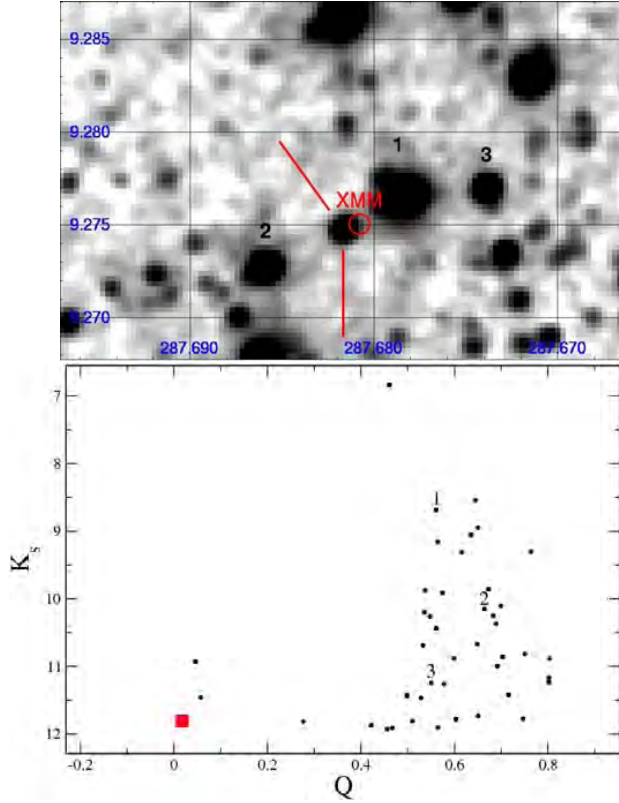


Fig. 7. Top: 2MASS image (K band, coordinates in Right Ascension and Declination) of the FOV around AX J1910.7+0917. The best-determined *XMM-Newton* position is marked in red, and a few nearby potential IR candidates are also displayed. Bottom: Plot of Q vs. K_s magnitudes for the 2MASS stars around the XMM position (see text for details). The square represents the likely IR counterpart to AX J1910.7+0917. Some of the nearby potential candidates are also shown.

To investigate the nature of the possible IR counterpart found above for AX J1910.7+0917 in more detail, we applied the analysis described in [Negueruela & Schurch \(2007\)](#) to the objects in the FOV of 2MASS J19104360+0916291. For each star represented in Fig. 7 we used 2MASS photometric data to obtain the values of their J , H , and K . Then, we calculated the quantity $Q = (J - H) - 1.70(H - K_s)$ for each object (here $K_s = K$) and plotted these values as a function of K_s in the bottom panel of Fig. 7. According to [Negueruela & Schurch \(2007\)](#), the objects characterized by $K_s \lesssim 11$ and $Q \lesssim 0.2$ are promising supergiant candidates. Even though this method does not provide a secure classification, it suggests that the nature of the source 2MASS J19104360+0916291 (red square in Fig. 7) would be compatible with being a supergiant star. We discuss this aspect further in Sect. 4.

3. New *INTEGRAL* sources

In the IBIS/ISGRI FOV around AX J1910.7+0917, we found three new sources that had previously remained undetected. These appeared to be the only excesses found independently both in the OSA9.0 mosaic and the mosaic obtained with the *software* ([Segreto et al. 2008, 2010](#)). A summary of the properties of the sources is given in Table 2. There we report

Table 2. Newly discovered *INTEGRAL* sources around AX J1910.7+0917.

Name	RA (deg)	Dec (deg)	Err. (')	Det. ^a (σ)	Counts ^b	Exp. ^c (Ms)
IGR J19173+0747	289.349	7.785	2.1	10.0	0.15 ± 0.02	3.0
IGR J19294+1327	292.367	13.459	3.4	6.8	0.12 ± 0.02	2.1
IGR J19149+1036	288.73 ^d	10.61 ^d	1.0 ^d	$\sim 20^d$	$\sim 0.3^d$	2.6

Notes. (a) Detection significance in the IBIS/ISGRI mosaic (17–80 keV); (b) the count rates in cts/s estimated from the ISGRI mosaic. In this energy band 1 mCrab = 0.28 cts/s; (c) effective exposure time; (d) these values are affected by large systematic uncertainties related to the presence of GRS 1915-105.

the best values of the detection significance, source position, and the associated errors. The sources were named according to the standard *INTEGRAL* convention. A mosaic containing all the new sources is shown in Fig. 1.

We report in Table 2 only a first-order approximation for the values of IGR J19149+1036 because it is relatively close ($\lesssim 20$ arcmin) to the brighter object GRS 1915-105 and a precise determination of the degree of contamination would require a much more detailed analysis. We note, though, that the inferred source position is coincident with the *Einstein* source 2E 1912.5+1031. For IGR J19173+0747 and IGR J19294+1327, we performed a spectral analysis. For IGR J19173+0747, the ISGRI spectrum was well described by a power-law model with $\Gamma = 3.3^{+0.9}_{-0.7}$ ($\chi^2_{\text{red}}/\text{d.o.f.} = 0.3/5$) and flux of $F_{20-40 \text{ keV}} = 5.6 \times 10^{-12} \text{ erg/cm}^2/\text{s}$. A similar analysis for IGR J19294+1327 gave $\Gamma = 2.6^{+0.8}_{-0.7}$, $F_{20-40 \text{ keV}} = 6.5 \times 10^{-12} \text{ erg/cm}^2/\text{s}$ and $\chi^2_{\text{red}}/\text{d.o.f.} = 0.4/4$.

3.1. *Swift*/XRT follow-up of the newly discovered sources

Following the discovery of the three new sources reported in the previous section, we asked for follow-up observations (PI L. Stella) in the soft X-ray domain with *Swift*/XRT (0.3–10 keV; [Gehrels et al. 2004](#)). At the time of writing, only the follow-up observations in the direction of IGR J19173+0747 and IGR J19294+1327 were carried out. In order to search for the X-ray counterpart of these two sources, we used the best-determined positions and errors in Table 2. We processed all the *Swift*/XRT data with the *and* the latest calibration files available (caldb v.20091130). All observations were performed in photon-counting mode (PC). Filtering and screening criteria were applied by using *(Heasoft v.6.9)*. We extracted source and background light curves and spectra by selecting event grades of 0–12 for the PC mode, and created the exposure maps for each observation through the task. We rebinned each spectrum where possible to have at least 20 photons per bin and used the latest spectral redistribution matrices available in the *calibration database* (v.011). Ancillary response files, accounting for different extraction regions, vignetting and PSF corrections, were generated with the task. For each of the two sources, we determined an improved source position by using the task.

3.1.1. IGR J19173+0747

IGR J19173+0747 was observed by *Swift*/XRT starting on 2010 February 22 at 08:07:00, for a total exposure time of 6 ks. An image of the source is shown in Fig. 8. Inside the *INTEGRAL* error circle there is only one soft X-ray source.

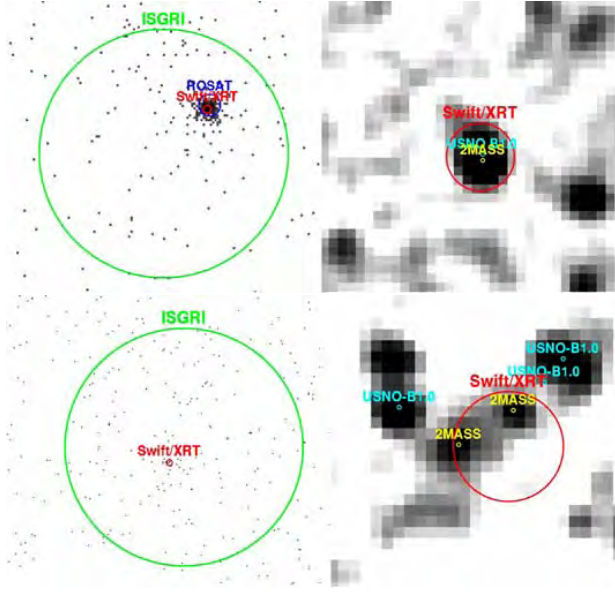


Fig. 8. *Swift*/XRT observations of the newly discovered *INTEGRAL* sources. *Top:* IGR J19173+0747. In this case only one soft X-ray source is found in *Swift*/XRT within the ISGRI error circle. We show on the right the 2MASS infrared image (*J* band) together with the *Swift*/XRT error circle and the position of the IR and optical counterpart. A positionally coincident *ROSAT* source is also shown. *Bottom:* for IGR J19294+1327 only one very faint soft X-ray excess has been found in the *Swift*/XRT observation ($S/N = 3.7$). Within the assumed XRT error circle there are two possible IR candidates, but no optical counterpart has been found (see the electronic version of the paper for the colored image).

The spectrum of the source could be well fitted by an absorbed power-law model. We estimated a PL photon index of $\Gamma = 0.6 \pm 0.2$ and obtained an upper limit on the absorption column density of $N_H < 6 \times 10^{21} \text{ cm}^{-2}$ (90% c.l.). The corresponding flux is $(6^{+1.0}_{-1.5}) \times 10^{-12} \text{ erg/cm}^2/\text{s}$ (0.5–10 keV). Extrapolating this flux to the 20–40 keV band would predict a much higher flux ($\sim 2.8 \times 10^{-11} \text{ erg/cm}^2/\text{s}$) than the one observed with *IBIS*/ISGRI ($5.6 \times 10^{-12} \text{ erg/cm}^2/\text{s}$, see Sect. 3). This, together with the different photon index derived in the two energy ranges, suggests a break in the spectrum at energies between 10 and 20 keV, or alternatively a variability of the source. We obtained a refined source position at $\alpha_{J2000} = 19^{\text{h}}17^{\text{m}}20^{\text{s}}.8$ and $\delta_{J2000} = 07^{\circ}47'51''.1$, with an associated uncertainty of 3.8 arcsec (90% c.l.). This position is consistent with that of the *ROSAT* source 1RXS J191720.6+074755 (Voges et al. 1999). The count rate of the source is $0.04 \pm 0.01 \text{ cts/s}$ in the 0.1–2.4 keV band. By assuming the spectral shape determined above, we checked with the online tool that the *ROSAT* countrate would correspond to a flux compatible with that of *Swift*/XRT. Inside the *Swift*/XRT error circle we found only one possible NIR and optical counterpart. The NIR counterpart is 2MASS J19172078+0747506, characterized by $J = 13.945 \pm 0.031$, $H = 13.520 \pm 0.030$, and $K = 13.311 \pm 0.043$. The optical counterpart is USNO-B1.0 0977-0532587 ($R1 = 15.46$, $B1 = 16.91$, $R2 = 14.99$, $B2 = 16.14$, $I = 14.78$). We queried the FIRST Survey and the NVSS catalogs in search for a radio counterpart, but did not find any obvious candidate.

3.1.2. IGR J19294+1327

IGR J19294+1327 was observed by *Swift*/XRT twice, on 2010 February 22 beginning at 23:59:01 and on 2010 February 26 beginning at 10:16:01. The total exposure time was 7.4 ks. In the *Swift*/XRT FOV only one very faint X-ray source is visible within the ISGRI error circle ($S/N = 3.7$, see Fig. 8). Given the relatively low S/N ratio, other observations are needed to confirm this detection. Assuming that this is the real counterpart of the *INTEGRAL* source, we estimated its best position at $\alpha_{J2000} = 19^{\text{h}}29^{\text{m}}29^{\text{s}}.80$ and $\delta_{J2000} = 13^{\circ}27'05''.44$ (associated error of 5.0 arcsec). The estimated source count rate was $(4.0 \pm 1.1) \times 10^{-3} \text{ cts/s}$, corresponding to an X-ray flux of $3 \times 10^{-13} \text{ erg/cm}^2/\text{s}$ (0.3–10 keV, we assumed $N_H = 7.1 \times 10^{21} \text{ cm}^{-2}$, and $\Gamma = 1.5$). This low flux, compared to that measured in the 20–40 keV band, suggests that either the source is intrinsically very faint in the 0.3–10 keV range, or that it is a strongly variable source. Within the *Swift*/XRT error circle we found the two possible NIR counterparts 2MASS J19292976+1327087 ($J = 16.075 \pm 0.143$, $H = 15.187 \pm 0.150$, $K = 14.761 \pm 0.133$) and 2MASS J19293011+1327056 ($J = 16.018 \pm 0.137$, $H = 14.725 \pm 0.119$, $K = 13.803 \pm 0.101$). No cataloged optical or radio counterpart was found at these positions.

4. Discussion and conclusions

We reported on the analysis of all available X-ray observations carried out with *INTEGRAL*, *XMM-Newton*, *Chandra*, and *ASCA* that included AX J1910.7+0917 in the instruments' FOVs. The information we could extract from these data showed that in the soft X-ray energy band (0.5–10 keV) the source is clearly variable. The highest dynamic range in the X-ray flux we could investigate with all available observations and instruments is ≥ 60 (see Table 1). The highest flux was recorded during the *XMM-Newton* observations, which also provided an improved source position and the first detailed characterization of the spectrum of the source. In the *XMM-Newton* data, AX J1910.7+0917 appeared to be variable on a relatively short timescale (hundreds of seconds) and the 0.5–10 keV X-ray spectrum could be well fitted with an absorbed power-law model. In the second available *XMM-Newton* observation, we also found that an iron line was required to fit the spectrum of the source. The centroid of the line is at $\sim 6.4 \text{ keV}$, consistent with fluorescence origin from cold iron (likely due to iron material in a ionization state not higher than Fe XX). The absorption column density measured in the different X-ray observations showed only minor changes and remained always much higher than that expected in the direction of the source ($\sim 1.5 \times 10^{22} \text{ cm}^{-2}$). The power-law photon index was constant (to within the errors) in all data we analyzed. In the hard X-ray energy band (17–80 keV) the source was characterized by a mean X-ray flux of a few $10^{-12} \text{ erg/cm}^2/\text{s}$. No evidence was found in the *XMM-Newton* and *INTEGRAL* data for a coherent periodicity that could be associated with the spin period of a neutron star hosted in this system or an orbital period. The improved X-ray position obtained thanks to the *XMM-Newton* observations also allowed us to search for possible counterparts in different energy bands (optical, infrared, radio). In Sect. 2.1.5 we suggested a possible association between AX J1910.7+0917 and the object 2MASS J19104360+0916291, which is the closest classified object to the *XMM-Newton* position. No obvious counterpart in the optical and radio band could be identified.

The available X-ray data on AX J1910.7+0917 do not allow for an unambiguous classification of this source. Its position, relatively close to the Galactic plane, favors the

hypothesis of a Galactic source, and we discuss below a few different possibilities. A relevant feature for investigating the nature of AX J1910.7+0917 is the iron line visible in the *XMM-Newton* observations. The width and the centroid of the line are compatible with a fluorescence origin and thus suggest that AX J1910.7+0917 is likely part of a binary system. Similar iron lines are indeed unlikely to appear in the X-ray spectra of isolated compact objects and magnetars (see, e.g. Mereghetti 2008). The apparent lack of intrinsic broadening would also argue against AX J1910.7+0917 being a low-mass X-ray binary (Bhattacharyya & Strohmayer 2007, and references therein). Among the different subclasses of cataclysmic variables (for a review see Warner 1995, and references therein), polar systems are hardly detected in the ISGRI energy band. Furthermore, for these systems a variability in flux of order ~ 60 is uncommon. Similar arguments apply to the intermediate polar case. These sources sometimes display emission above 20 keV, but they are known to be generally persistent objects in the soft energy band (0.5–10 keV). We also suggest that the X-ray properties of AX J1910.7+0917 are not compatible with those of novae sources (Warner 1995). A more likely possibility is that AX J1910.7+0917 is a new member of the high-mass X-ray binaries (HMXB) discovered by *INTEGRAL*. According to this interpretation, the iron line observed in the *XMM-Newton* spectrum could originate from irradiation of cold iron in the wind of a massive companion. The analysis conducted in Sect. 2.1.5 on the nature of the possible IR counterpart to AX J1910.7+0917 and the low Galactic latitude of the source would also support this interpretation. However, the association of AX J1910.7+0917 with the class of the HMXBs would still face some difficulties. Among the different subclasses of HMXBs observed by *INTEGRAL*, neither the classical supergiants (see e.g., Walter et al. 2006) nor the SFXT (Sguera et al. 2005) have a behavior fully compatible with that of AX J1910.7+0917. On the one hand, the variability in the X-ray flux reported in Table 1 for the different observations available clearly shows that AX J1910.7+0917 is not a persistent source as expected for the classical supergiant HMXBs. On the other hand, the non detection in the ISGRI data of some bright and short flares typical of the SFXT sources argues against this interpretation. Another possibility is that AX J1910.7+0917 is a Be X-ray binary, and the *XMM-Newton* observation luckily caught the source during an outburst. According to this interpretation we would expect a somewhat higher flux during this period in the *INTEGRAL* observations of AX J1910.7+0917. We checked that no simultaneous *INTEGRAL* and *XMM-Newton* observations were available, and in the closest ISGRI data (obtained about 7 days before and after the *XMM-Newton* observations) AX J1910.7+0917 was detected with a count rate compatible with the average one. We concluded that if the high flux measured in the *XMM-Newton* data corresponded to an outburst, then this should have lasted less than 10 days. This could still be compatible with the durations of the outbursts observed from Be systems. Extrapolating the *XMM-Newton* spectrum in the ISGRI energy band (17–80 keV), we estimated that a similar bright event should correspond to an ISGRI count rate of 1.5–2 cts/s. We searched for similar events in all available ISGRI data by using a 5-day binned lightcurve and found no evidence for such bursts. During the 2200 days spanned by the ISGRI data the source was effectively monitored for approximately 415 days.

This suggests that AX J1910.7+0917 should spend $<80\%$ of the time in the bright X-ray state observed by *XMM-Newton*. Additional pointed observations in X-rays with *XMM-Newton* and *Chandra*, as well as follow-up observations in different energy bands, are required in order to firmly establish the nature of AX J1910.7+0917.

Besides carrying out a detailed study of AX J1910.7+0917 in X-rays, we also report the discovery of three new hard X-ray sources in the IBIS/ISGRI FOV around AX J1910.7+0917. These sources were independently detected with the OSAv9.0 and the *SAO* software (Segreto, priv. comm.) and are the only excesses appearing in both the mosaics extracted around AX J1910.7+0917 with the two software packages. As we showed in Sect. 3, a detailed study of 2E1912.5+1031 could not be carried out because of the likely contamination in the *INTEGRAL* data by the bright source GRS 1915-105 and the lack of proper follow-up with *Swift*. A more refined analysis of this source will be reported elsewhere. For the two new *INTEGRAL* sources IGR J19173+0747 and IGR J19294+1327, we identified a counterpart in the soft X-ray energy band (0.3–10 keV) thanks to dedicated *Swift* observations (see Sect. 3), and searched for possible cataloged optical and infrared counterparts. However, owing to the relative faintness of the sources in the hard X-ray band ($<10^{11}$ erg/cm²/s in the 17–80 keV band) and the short exposure time of the *Swift*/XRT observations, a clear classification of the two sources is still premature, and other observations are required in order to determine their nature.

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Conclusions and future prospects

About 70 years after their discovery, AGN are still a very hot topic in extragalactic astronomy, as witnessed by the extremely large amount of yearly publications on the subject (~ 1500 only in 2010). In particular, several key questions regarding their nature and evolution still need to be clearly (or completely) answered:

- What is the relation between the host galaxy and its SMBH? We have seen in Sect. 5.1 that there must exist some sort of connection between the two, maybe related to the mechanical ejection of matter from the AGN, but still very little is known about it. Besides, what is the relation between the AGN and starbursts? Does the SMBH terminate the star formation? Or is it rather star formation that drives the evolution of the AGN?
- How do AGN evolve with time? What can they teach us about the evolution of the Universe? We know that star formation in galaxies and AGN evolution proceed on parallel tracks (Sect. 4), with the high luminosity objects evolving faster than the lower luminosity ones, but current observations are not able to observe a large number of objects at high redshift ($z > 3$). Long-exposure X-ray surveys are an extremely powerful tool to constrain the evolution of AGN, as demonstrated in these last years by the studies of the *Chandra* and *XMM-Newton* deep fields. In the next years, the new generation X-ray satellites as *eROSITA* and *NuSTAR* will certainly largely improve our knowledge on this subjects.
- What is the role of AGN in shaping the CXB? We know nowadays with large confidence that they are the main contributors to the X-ray background (Sect. 4), but in which proportion do different classes contribute to it? Is there really a population of hidden and heavily absorbed AGN? We have seen that population synthesis models of the CXB still struggle to well explain its spectral shape, due to the lack of good constraints on some parameters, in particular the Compton reflection amplitude (see Sect. 4.4). The launch of *NuSTAR*, few months from now, will without doubt provide much better constraints on the fraction of heavily obscured (and reflection-dominated) sources. This new mission is in fact expected to be able to resolve $\sim 50\%$ of the CXB in the 10–40 keV band, i.e. around its peak.
- X-ray spectra of AGN have been found in the last 10 years to be more difficult to explain than previously thought (Sect. 5). While part of this spectral complexity is surely due to the presence of extremely complex multi-phase outflows, a considerable portion of it might be due to relativistic effects close to the SMBH (i.e. light bending), or to clumpy neutral material in the line of sight. However, the relative influence of these two contributions on the spectra of AGN (for instance in the creation of the red wing of iron $K\alpha$ line) must still be assessed. Moreover, the soft and recently discovered hard excess still lack a complete self-consistent explanation (although several models have been proposed), and will need higher quality observations to be fully understood. The launch of *ASTRO-H*, with its X-ray calorimeter and extremely high signal-to-noise ratio, will surely shed light on the subject. Moreover its broad-band capabilities

will allow to obtain accurate constraints on the energy of the cutoff and on the reflection parameter R , key parameters for the development of realistic synthesis models of the CXB.

- We have seen in Chapter 8 that the actual formulation of the unified model of AGN fails to explain many important features, as the decrease of the fraction of absorbed sources with the luminosity, the existence of Seyfert 2s without a BLR, and the existence of intrinsic differences between different classes (e.g., different star formation rates). In my PhD work, I concentrated on the study of the average emission of different types of Seyfert galaxies at hard X-rays, an ideal energy band to test the unified model. In our work we confirmed the existence of significant differences between more and less obscured objects, possibly related to different amplitudes of the reflection component. Broad band X-ray studies of Seyfert 2s using facilities as *Suzaku* at first, and then *ASTRO-H*, will provide a clear insight on the structure of the absorber/reflector in these objects. The unified model is very likely a simplification of a much more complex situation, as it is clearly evident from IR studies of the putative molecular torus, which points towards a much more intricate picture. Moreover, the existence of NLS1s (small black hole masses, high accretion rates) and LINERs (large black hole masses, low accretion rates), show that a single extrinsic parameter (i.e. the orientation with respect to a torus) is not enough to provide a complete explanation to the AGN phenomenon. The accretion rate has probably a very important role, as does the black hole mass, but it is likely not the only physical parameter needed to self-consistently explain all the characteristics of AGN. The accretion modes might also play an important role, but due to the current observational limits, so far it has been impossible to discern between different models. The discovery of a new class of AGN, the buried Sy2s (Sect. 8.7), has shown that there is still much to understand about the structure of the absorbers. Being this component possibly directly related to the apparent fraction of reflected emission observed, it might have a key role in the modeling of the CXB.

The advent of the new X-ray missions will make the next decade an extremely exciting period for the study of the physics and evolution of AGN, and likely many of the above questions will find an answer, although as often happens in science, probably rising as many new ones.

Appendix A

List of Publications

2007

- Beckmann, V., **Ricci, C.**, Beck, M., et al. 2007, *GRB 070707 - a long GRB detected with INTEGRAL*, GCN 6605
- Beckmann, V., **Ricci, C.**, Beck, M., et al. 2007, *GRB 070707 - a long GRB detected with INTEGRAL*, GCN 6606

2008

- **Ricci, C.**, Beckmann, V., Carmona, A., et al. 2008, *Localization of the hard X-ray transient IGR J17062-6143*, ATel 1840
- **Ricci, C.**, Soldi, S., Beckmann, V., et al. 2008, *IGR J17375-3022: a new hard X-ray transient detected by INTEGRAL*, ATel 1781
- **Ricci, C.**, Caballero-Garcia, M., Beckmann, V., et al. 2008, *H1743-322 in stable outburst phase*, ATel 1779

2009

- **Ricci, C.**, Beckmann, V., Audard, M., et al. 2009, *Multi-zone warm and cold clumpy absorbers in 3 Seyfert galaxies*, proceedings IAU Symposium No. 287
- Beckmann, V., Soldi, S., **Ricci, C.**, et al. 2009, *The second INTEGRAL AGN catalogue*, A&A 505, 417
- Beckmann, V., **Ricci, C.**, Soldi, S. 2010, *Fermi detected blazars seen by INTEGRAL*, 2009 Fermi Symposium, eConf, Proceedings C091122

2010

- Beckmann, V., Soldi, S., **Ricci, C.**, et al. 2010, *The unified scheme seen with INTEGRAL detected AGN*, proceedings of the Bologna 2009 X-ray conference
- Beckmann, V., **Ricci, C.**, Soldi, S., et al. 2010, *Lessons learnt from INTEGRAL AGN*, proceedings of the INTEGRAL Workshop Otranto 2009
- **Ricci, C.**, Beckmann, V., Audard, M. & Courvoisier T. J.-L. 2010, *Multi-zone warm and cold absorbers in 3 Seyfert galaxies*, A&A 518, 47
- Lenain, J.-P., **Ricci, C.**, Turler, M., et al. 2010, *Seyfert 2 galaxies in the GeV band: jets and starburst*, A&A 524, 72

- **Ricci, C.**, Beckmann, V., Audard, M. & Courvoisier T. J.-L. 2010, *Multi-zone warm and cold absorbers in 3 Seyfert galaxies*, A&A 518, 47
- Lenain, J.-P., **Ricci, C.**, Turler, M., et al. 2010, *Seyfert 2 galaxies in the GeV band: jets and starburst*, A&A 524, 72

2011

- Pavan, L.; Bozzo, E.; Ferrigno, C.; **Ricci, C.**, et al. 2011, *Study of the X-ray/gamma source AX J1910.7+0917 and three newly discovered INTEGRAL sources*, proceedings of the 8th INTEGRAL Workshop
- **Ricci, C.**, Walter, R., Courvoisier, J.T.-L., 2011, *INTEGRAL and the Unified Model of AGN*, proceedings of the 8th INTEGRAL Workshop
- Lenain, J.P.L., **Ricci, C.**, Turler, M., Dorner, D., Walter, R., 2011, *Seyfert 2 galaxies in the GeV band: jets and starburst*, Proceedings of the 25th Texas Symposium
- S. Soldi, V. Beckmann, N. Gehrels, Lubinski, P., **Ricci, C.**, Walter, R., 2011, *Compton processes in the bright AGN MCG+8-11-11*, proceedings of the 8th INTEGRAL Workshop
- **Ricci, C.**, Walter, R., Courvoisier T. J.-L. & Paltani, S. 2011, *Reflection in Seyfert Galaxies and the Unified Model of AGN*, A&A 532, 102
- Pavan, L., Bozzo, E., Ferrigno, C., **Ricci, C.**, Manousakis, A., Walter, R., Stella, L., 2011, *AX J1910.7+0917 and three newly discovered INTEGRAL sources*, A&A 526, 122

Appendix B

Glossary

- **ACIS** – Advanced CCD Imaging Spectrometer
- **ACS** – Anti-Coincidence Shield
- **ADAF** – Advection-Dominated Accretion Flow
- **AGILE** – Astrorivelatore Gamma a Immagini Leggero
- **AGN** – Active Galactic Nuclei
- **ASCA** – Advanced Satellite for Cosmology and Astrophysics
- **BAL QSO** – Broad Absorption Line Quasar
- **BAT** – Burst Alert gamma-ray Telescope
- **BGO** – Bismuth Germanate Oxide
- **BLR** – Broad Line Region
- **BLRG** – Broad Line Radio Galaxy
- **BLS1** – Broad line Seyfert 1
- **CCD** – Charge-Coupled Devices
- **CDFN** – Chandra Deep Field North
- **CDFS** – Chandra Deep Field South
- **CIB** – Cosmic Infrared Background
- **CMB** – Cosmic Microwave Background
- **COB** – Cosmic Optical Background
- **COBE** – Cosmic Background Explorer
- **CT AGN** – Compton Thick AGN
- **CXB** – Cosmic X-ray Background
- **EGRET** – Energetic Gamma-Ray Experiment Telescope
- **EMSS** – Extended Medium Sensitivity Survey
- **EPIC** – European Photon Imaging Camera
- **ESA** – European Space Agency
- **ESO** – European Southern Observatory
- **EXOSAT** – European Space Agency’s X-ray Observatory
- **FCFOV** – Fully Coded Field of View
- **FIR** – Far InfraRed
- **FIRAS** – Far InfraRed Absolute Spectrometer
- **FOV** – Field of View

- **FR I** – Fanaroff-Riley Type I
- **FR II** – Fanaroff-Riley Type II
- **FSRQ** – Flat-Spectrum Radio Quasar
- **FWHM** – Full Width at Half Maximum
- **GBM** – Gamma-ray Burst Monitor
- **GRB** – Gamma-Ray Burst
- **GSO** – Gadolinium Silicate
- **HBL** – High-Frequency Peaked BL Lac
- **HEAO** – High-Energy Astronomy Observatory
- **HEG** – High Energy Grating
- **HESS** – High Energy Stereoscopic System
- **HETG** – High Energy Transmission Grating
- **HRC** – High Resolution Camera
- **HST** – Hubble Space Telescope
- **HXD** – Hard X-ray Detector
- **IBIS** – Imager on Board the INTEGRAL Satellite
- **IBL** – Intermediate-Frequency Peaked BL Lac
- **INTEGRAL** – INTErnational Gamma-Ray Astrophysics Laboratory
- **IRAS** – Infrared Astronomical Satellite
- **ISDC** – Data Center for Astrophysics
- **ISGRI** – INTEGRAL Soft Gamma-Ray Instrument
- **ISOC** – INTEGRAL Science Operations Center
- **ISO** – Infrared Space Observatory
- **JEM-X** – Joint European Monitor in the X-rays
- **KN** – Klein-Nishina
- **LAT** – Large Area Telescope
- **LBL** – Low-Frequency Peaked BL Lac
- **LDDE** – Luminosity-Dependent Density Evolution
- **LETG** – Low Energy Transmission Grating
- **LINER** – Low-Ionization Nuclear Emission-line Region
- **MEG** – Medium Energy Grating
- **MOC** – Mission Operations Center
- **MOS** – Metal Oxide Semi-conductor
- **MURA** – Modified Uniformly Redundant Array
- **NAL QSO** – Narrow Absorption Line Quasar
- **NASA** – National Aeronautics and Space Administration
- **NLR** – Narrow Line Region
- **NLRG** – Narrow Line Radio Galaxy

- **NLS1** – Narrow line Seyfert 1
- **OGS** – Operations Ground Segment
- **OMC** – Optical Monitoring Camera
- **OM** – Optical/UV Monitor Telescope
- **OVV** – Optically Violent Variable
- **PAH** – Polycyclic Aromatic Hydrocarbon
- **PCA** – Principal Component Analysis
- **PCFOV** – Partially Coded Field of View
- **PN** – p-type/n-type semiconductor
- **PSD** – Power Spectral Density
- **RGS** – Reflection Grating Spectrometer
- **RXTE** – Rossi X-ray Timing Explorer
- **SED** – Spectral Energy Distribution
- **SGS** – Science Ground Segment
- **SMBH** – Supermassive Black Hole
- **SPI** – Spectrometer on Board INTEGRAL
- **SSC** – Synchrotron Self-Compton
- **SSRQ** – Steep-Spectrum Radio Quasar
- **Sy** – Seyfert galaxy
- **UTA** – Unresolved Transition Array
- **UVOT** – UV/Optical Telescope
- **XIS** – X-ray Imaging Spectrometer
- **XLF** – X-ray Luminosity Function
- **XMM-Newton** – X-ray Multi-mirror Mission Newton
- **XRT** – X-Ray Telescope

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