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Observational Diagnostics of Gas in Protoplanetary Disks

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Abstract Protoplanetary disks are composed primarily of gas (99% of the mass). Nevertheless, relatively few observational constraints exist for the gas in disks. In this review, I discuss several observational diagnostics in the UV, optical, near-IR, mid-IR, and (sub)-mm wavelengths that have been employed to study the gas in the disks of young stellar objects. I concentrate in diagnostics that probe the inner 20 AU of the disk, the region where planets are expected to form. I discuss the potential and limitations of each gas tracer and present prospects for future research.

Keywords Protoplanetary disks · Observations · Gas · Spectroscopy

1 Introduction

At the time when giant planets form, the mass (99%) of the protoplanetary disk is dominated by gas. Dust is a minor constituent of the mass of the disk. Still, it dominates the opacity; consequently, it is much easier to observe. Therefore, most of the observational constraints of disks have been deduced from the study of dust emission (e.g., see chapter by Henning et al.). In contrast, direct observational constraints of the gas in the disk are relatively scarce. Nonetheless, to obtain direct information from the gas content of the disk is crucial for answering fundamental questions in planet formation such as: how long does the protoplanetary disk last?, how much material is available for forming giant planets?, how do the density and the temperature of the disk vary as a function of the radius?, what are the dynamics of the disk?

Although we have learned important insights from disks from dust observations (see for example the reviews by Henning 2006 and Natta et al. 2007), dust presents several limitations: (i) dust spectral features are broad; consequently, dust emission does not provide kinematical information; (ii) dust properties are expected to change during the planet

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formation process; therefore, quantities such as the gas-to-dust ratio (needed to derive the disk mass from dust continuum emission in the (sub)-mm) are expected to strongly vary with respect to the conditions of the Interstellar Medium (ISM). In addition, dust signatures are strongly related to dust size. In particular, as soon a dust particle reaches a size close to a decimeter it becomes practically “invisible”. For example, a crucial quantity such as the disk dissipation time scale is normally deduced from the decline of the fraction of the sources presenting near-IR (JHKL) excess in clusters of increasing ages (e.g., Haisch et al. 2001). In reality, the time scale that we want to constrain is not the time scale in which the small warm dust particles disappear from the surface layers in the inner disk, but the time scale in which the gas in the disk disappears.

In summary, independent information of the gas is crucial to understand protoplanetary disk structure and *combined studies of gas and dust in the disk are needed*. In particular, we are interested in deriving constraints for the inner disk, the region where the planets are expected to form ($R < 20$ AU). The observational study of the gas in the inner disk is a relatively new emerging topic. Only with the advent of ground-based high-spectral resolution infrared spectrographs and space-born infrared spectrographs has this research become possible.

The main tool used to study the gas in the disk is molecular spectroscopy. The gas in the disk is heated by collisions with dust, shocks or UV or X-rays from the central star. The heated molecules populate different rotational and vibrational levels and when they de-excite emission lines are produced. The key is that these emission lines have the imprint of the physical conditions of the gas where they originated. Important constraints can be derived from emission lines: (i) line ratios of different transitions constrain the excitation mechanism (shocks, UV or X-rays) and the temperature of the gas responsible of the emission; (ii) if the emitting gas is optically thin, then the measured line fluxes are proportionally related to the amount of molecules present; therefore, line fluxes can be used to derive column densities and gas masses; (iii) line shapes and spatial extend provide constraints on the size and geometry of emitting region as well as the dynamics of the emitting gas. Figure 1 displays a pedagogical example of how a line profile changes as a function of the inclination and size of the emitting region in the disk.

The line width and double peak separation depend on the inclination. The line profile wings depend on the innermost radius of the emission. For the interested reader, recent reviews by Najita et al. (2000, 2007a), Blake (2003) and Carr (2005) cover the subject of observational studies of gas in disks.

2 The Gas Emitting Region

An important element that one should always bear in mind when studying molecular emission from disks is the region where the emission observed is produced. As the disk has a radial and vertical temperature and density gradient (hotter closer to the star and higher in the disk, denser closer to the star and deeper in the disk) we need to have clear three concepts: (i) inner and outer disk, (ii) interior and surface layer, (iii) optical depth of the medium (i.e., optically thin or thick) and its wavelength and molecular species dependency.

The first concept is related to the distance of the central star (i.e., the radius) and the radial temperature gradient. Different gas tracers probe different radial regions of the disk. The hot and warm ($T \sim 100\text{--}2500$ K) *inner disk* ($R < 20$ AU) is traced by lines in the UV,

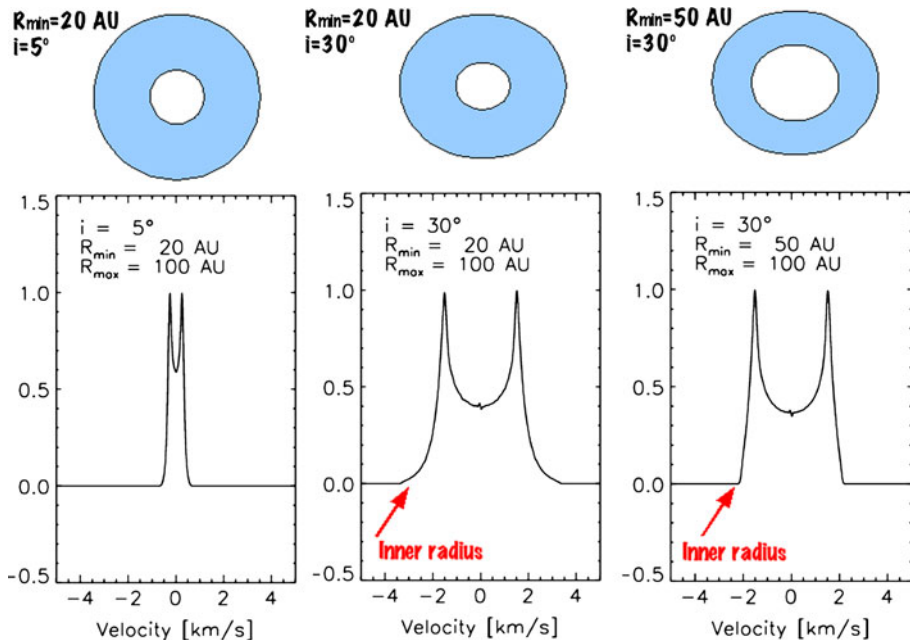


Fig. 1 Line shape, inclination and the emitting region of a disk in Keplerian rotation. The double peaked profile indicates emission from a rotating disk. The line width and double peak separation depend on the inclination of the disk. The line profile wings depend on the innermost radius of the emission. In this toy model, it is assumed that the intensity is constant as a function of the radius and a spectral resolution of 1 km/s

near- and mid-IR. The cold ($T < 100$ K) *outer disk* ($R > 20$ AU) is probed by lines in the (sub)-mm.

The second and third concepts are related to the vertical temperature and density gradient. As a first approximation, we can understand a protoplanetary disk at each radius as composed of two vertical layers: a dense colder *interior layer* and less dense hotter *surface layer* (Chiang and Goldreich 1997). At near-IR and mid-IR wavelengths (that probe $R < 20$ AU), the dust and gas in the interior layer are optically thick and the interior layer radiates as a black body (i.e., continuum equal to the blackbody level). Gas lines -and dust emission features- in the UV, near-IR and mid-IR arise from the optically thin surface layer of the inner disk. They are observed on top of the continuum of the interior layer. Emission is observed from the surface layer because the surface layer is hotter than the interior layer. The gas emission from the surface layer could be optically thin or optically thick depending on the gas density and the molecular species (for example CO emission is generally optically thick, and H_2 emission is optically thin). Optically thick gas lines from the surface layer of the inner disk are observable because the dust in the surface layer is optically thin.

At (sub)-mm wavelengths (that probe $R > 20$ AU), the dust become optically thin in the interior layer as well (i.e., continuum below the black-body level), and we can observe optically thick emission from -CO- gas from the interior layer on top of the optically thin dust continuum. Optically thin gas emission can be observed from other less abundant molecular species such as ^{13}CO . Figure 2 presents a cartoon of the structure of a disk and the observable properties of the medium.

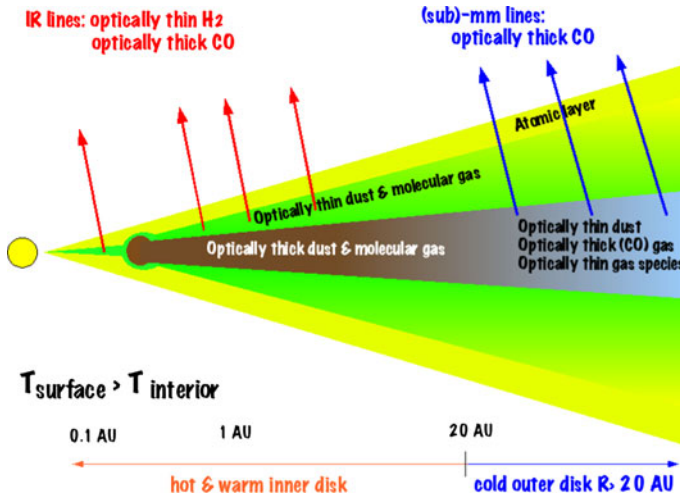


Fig. 2 Cartoon of the structure of an optically thick disk. The disk has a hot inner region ($R < 20$ AU) and a cold outer region ($R > 20$ AU). Near-IR and mid-IR diagnostics probe the inner disk, (sub)-mm diagnostics probe the outer disk. The disk has a vertical structure: a dense mid-plane and a hotter less dense surface layer. Near-IR and mid-IR gas and dust emission features originate in the optically thin surface layer of the inner disk. Near-IR and mid-IR continuum originates from the optically thick interior layer. At (sub)-mm wavelengths we observe line emission from optically thick CO gas and optically thin emission of cold dust located in the outer disk

In addition to the surface layer, in particular cases such as transitional disks¹ or disks in close binaries, gas emission lines (optically thin or thick depending on the gas density) are expected from the inner region of the disk when the dust is optically thin.

3 A Diversity of Gas Diagnostics

Given that the disk has a radial temperature gradient, different tracers are employed to probe the gas at each location in the disk. Figure 3 displays a summary of disks gas diagnostics. In the following sections, I will explain one by one each of them highlighting their strengths and limitations. I will follow a discussion inspired by the historical development of the field.

¹ Transitional disks are sources that do not display or display very weak near-IR excess but that have relatively normal mid-IR excess in their spectral energy distributions (SED). This is due to the lack of small hot dust particles radiating in the near-IR. This can be attributed to a hole in the disk (a physical gap, i.e., no gas and no dust), to a lack of dust particles in the inner disk (i.e., no dust, but gas is still present), or a change in the dust size (an opacity gap, i.e., gas and dust are still there but the dust is too large to radiate in the near-IR). Gaps could be produced either by a close binary, a low-mass companion (i.e., a giant planet), dust coagulation, or photoevaporation of the inner disk. For recent papers on transitional disks, see for example Calvet et al. (2005), Sicilia-Aguilar et al. (2006), Najita et al. (2007b), Pontoppidan et al. (2008) and Cieza et al. (2008).

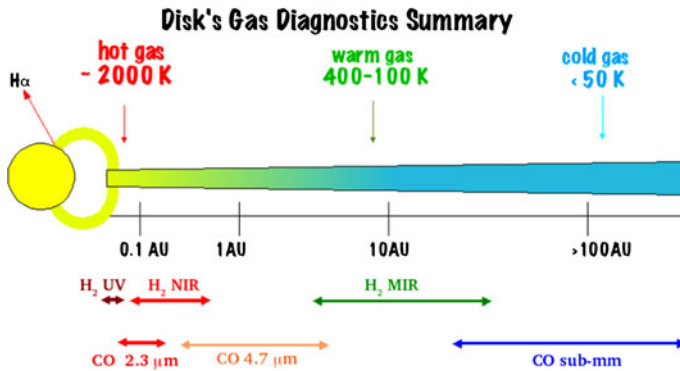


Fig. 3 Summary of disk gas diagnostics and the disk region that they probe

3.1 H α in Emission

Properly speaking H α in emission (6590 Å) from young stars does not trace the gas in the disk. However, since H α emission is one of the primary indicators of accretion of gas from the disk onto the star (e.g., Hartmann et al. 1994; Muzerolle et al. 1998b), H α is a robust indicator of a gaseous disk. In particular, when any other gas tracer fails, H α emission tells us unambiguously that there is gas.

Its main advantages are: (i) it is easy to observe (a small telescope with a medium resolution $R \sim 3000$ spectrograph can do it); (ii) it is a robust diagnostic; (iii) it can be studied in large samples of objects of diverse brightness in relatively short time.

Its main limitations are: (i) it does not provide information on the physical conditions of the gas in the disk (H α tells us that there is gas and allows us to deduce the accretion rate, but not much more); (ii) if the accretion rate is below $10^{-12} M_{\odot}$ /year, H α in emission is too weak to be observed; (iii) in low resolution spectra of late type stars (K and later), H α in emission from accretion can be confused with H α due to stellar activity (typically a line width higher than 100 km/s is required for inferring accretion). H α in emission allowed us to confirm that very low mass stars have disks, that relatively old objects still have gaseous disks, and that several transition disks still have gas in their inner disks (e.g., Sicilia-Aguilar et al. 2006).

Note that other H lines such as the weaker Br γ line in the near-IR have been used for deducing accretion rates -and the presence of a gaseous disk- in young stars (e.g., Najita et al. 1996a, Muzerolle et al. 1998a, Natta et al. 2006).

3.2 CO Overtone Emission at 2.3 μm

One of the earliest indicators of gas in a disk was the detection of CO overtone ($\Delta v = 2$) emission at 2.3 μm in T Tauri stars (Scoville et al. 1983; Geballe and Persson 1987; Carr 1989; Carr and Tokunaga 1992; Carr et al. 1993; Chandler 1993; Najita et al. 1996b). More recently Thi et al. (2005) reported CO 2.3 μm emission in the Herbig Ae/Be star 51 Oph (see also Berthoud et al. 2007 and Tatulli et al. 2008). CO bandhead emission traces very hot ($T > 2000$ K) and dense gas in the innermost part of the disk ($R < 0.1$ AU) in objects exhibiting high accretion. This line provided the first evidence of Keplerian rotation of gas in the inner disk of T Tauri stars. The CO band-head emission is characterized by a broad feature at 2.3 μm . Its particular shape can be modeled by the convolution of

$v = 2-0$ CO ro-vibrational emission lines at rest with the double peaked line profile characteristic of emission from a disk.

The main advantages of this diagnostic are: (i) it can be studied with a low resolution near-IR spectrographs and (ii) it traces the innermost part of the disk. The main disadvantage is that the densities and temperatures require to be very high to produce the emission. This is the main reason for why this line has been observed towards only a handful of objects. Finally, note that in general the CO overtone emission at $2.3 \mu\text{m}$ is optically thick emission. For the interested reader this diagnostic and its modeling is treated in detail in Carr et al. (1993).

3.3 CO (sub)-mm Emission and Other (sub)-mm Lines

Progress in the sensitivity of millimeter radio telescopes led to the detection in the early 1990s of pure rotational emission ($\Delta J = 1$) from cold CO from T Tauri stars (e.g., Weintraub et al. 1989; Koerner et al. 1993; Skrutskie et al. 1993; Beckwith and Sargent 1993; Guilloteau and Dutrey 1994). Those observations revealed the classical double peaked profile expected from gas rotating in Keplerian disk (see Fig. 1). The detections with single dish telescopes were followed by studies with millimeter interferometers that allowed to spatially resolve the emission in T Tauri stars (e.g., Dutrey et al. 1996; Guilloteau and Dutrey 1998; Dutrey et al. 1998) and Herbig Ae/Be stars (e.g., Mannings and Sargent 1997). In the particular case of Herbig Ae stars, millimeter interferometry observations of CO permitted to settle the controversy about the existence of circumstellar disks around these objects. Since then a multitude of studies in the (sub)-mm have been undertaken in protoplanetary disks thanks to development of sensitive millimeter and sub-mm arrays (e.g., Plateau de Bure, SMA, CARMA, see recent review by Dutrey et al. 2007). Progress has not only been done in tracing cold CO, but also in detecting many other molecules such as CN, HCN, HCO^+ , H_2CO , etc (e.g., Thi et al. 2004). These detections have opened the door to observational studies of chemistry in disks (e.g., review by Bergin et al. 2007).

The principal advantages of CO are: (i) CO is the second most abundant molecule after the H_2 . (ii) CO (sub)-mm emission is bright. These not trivial characteristics had allowed the survey of relatively large samples of young stars with disks (e.g., Dent et al. 2005, Andrews and Williams 2005), and have permitted the spatially resolved study of the disk structure in several objects (e.g., Piétu et al. 2007). The main limitation of CO emission and other gas tracers in the (sub)-mm is that they trace the cold gas in the outer part of the disk ($R > 20$ AU). Therefore, they are not suitable to trace the disk region ($R < 20$ AU) where planets are expected to form. Nonetheless, most of the mass of the disk is located in the cold outer part of the disk.

CO emission in the (sub)-mm has important limitations as tracer of gas mass: (i) cold CO is expected to freeze-out onto dust grain surfaces at low temperatures ($T < 20$ K) and high densities ($N \geq 10^5 \text{cm}^{-3}$); therefore, CO is expected to be depleted; (ii) CO emission can be optically thick. Both limitations introduce a large uncertainty on the conversion factor (up to a 1000) between the CO observed and the real amount of H_2 present in the outer disk. Typically, the ISM CO/H_2 conversion factor of 10^{-4} is used. However, this value is most likely incorrect for disks. The large uncertainty in the determination of mass of gas affects seriously the empirical estimation of the gas-to-dust ratio. Finally, note that there are sources which are known to have a disk—by the detection of IR & (sub)-mm excess and H α in emission, but, because of sensitivity limitations or depletion, we do not detect CO emission.

In the near future, significant progress is expected in the study of disks in the (sub)-mm domain thanks to the Atacama Large Millimeter/submillimeter Array (ALMA), which will start operations soon. ALMA will increase the sensitivity and spatial resolution by an order of magnitude with respect to those obtained with present facilities. In addition, the far-infrared space telescope HERSCHEL will allow the study of disks at frequencies which are impossible to observe from the ground. A detailed description of gas diagnostics in the (sub)-mm and chemistry in disks deserves a review in its own. For the interested reader, the reviews by Dutrey et al. (2007) and Bergin et al. (2007) cover these topics.

3.4 CO Emission Band at 4.7 μm

The advent of high-resolution ($R > 10000$) spectrographs in the near-IR opened the door to the study of the CO ro-vibrational emission band ($\Delta v = 1$) at 4.7 μm . CO emission at 4.7 μm probes the gas at temperatures ranging from hundred to thousand of degrees. This diagnostic is important because the gas at these temperatures is located in the terrestrial planet forming region of the disk ($R < 5$ AU). CO 4.7 μm emission from disks has been studied in T Tauri stars (e.g., Carr et al. 2001; Najita et al. 2003; Brittain et al. 2005, 2007b; Rettig et al. 2005; Brown et al. 2005), Herbig Ae/Be stars (e.g., Brittain et al. 2002, 2003, 2007a; Blake and Boogert 2004; Carmona et al. 2005; Goto et al. 2006; van der Plas et al. 2009) and in a growing number of transitional disks (Rettig et al. 2004; Salyk et al. 2007; Najita et al. 2008; Pontoppidan et al. 2008).

The detection of the CO band at 4.7 μm allowed in the first place to constrain the temperature of the gas by means of rotational diagrams. The gas temperatures observed varied from 100 to 1000 K and in a few cases up to 3000 K. In several sources, for example AB Aur (Brittain et al. 2003), the shape of the rotational diagram allowed to infer CO gas at two different temperatures. The shape of the CO lines was used to set constraints on the inclination of inner disks (e.g., Blake and Boogert 2004). In general, within the errors, the inclinations deduced from CO 4.7 μm emission are consistent with the inclinations derived from (sub)-mm observations (note that to derive the disk inclination, the CO emitting region needs to be assumed).

Modeling of the shape of the line profile allowed to estimate the innermost radius where the CO emission is produced (see Fig. 1). Najita et al. (2007a) found that the inner radius of the CO 4.7 μm emission in T Tauri stars extends inside the dust sublimation radius and, typically, inside the corotation radius too. Those authors compared the distribution of the inner radii deduced from the CO 4.7 μm lines and the distribution of the orbital radii of short period extrasolar planets. They found that both distributions are very similar (see Fig. 4). The gas required for giant planet migration was put in evidence by the CO fundamental transitions.

The most recent development has been to combine high spectral resolution with the enhanced spatial resolution provided by Adaptive Optics (AO). Goto et al. (2006) spatially resolved the CO $v = 2 - 1$ 4.7 μm emission from the Herbig Ae/Be star HD 141569 and measured an inner clearing of radius 11 ± 2 AU. Pontoppidan et al. (2008) and van der Plas et al. (2009) observed young stars with disks combining AO and very high spectral resolution ($R \sim 100000$). Those authors, employing the spectroastrometry technique, were able to measure the displacement of the PSF center as a function of wavelength in the line, and obtained robust evidence of emission from Keplerian disks (see Fig. 5). Pontoppidan et al. (2008) detected gas emission from the inner gaps of transitional disks (Sr 21, HD 135344B and TW Hya).

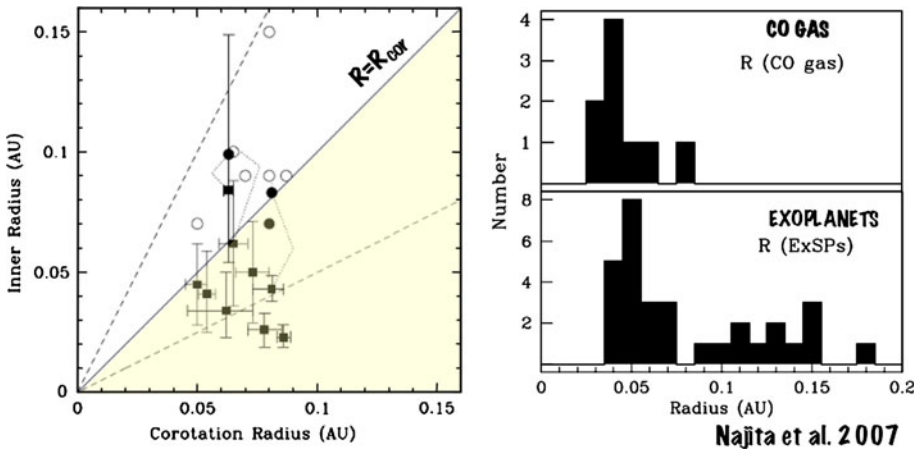


Fig. 4 *Left panel* Inner radius of CO fundamental emission at $4.7\ \mu\text{m}$ vs corotation radius of the sources. In black squares CO $4.7\ \mu\text{m}$ detections (Najita et al. 2007a), in filled circles the inner dust radius from near-IR interferometry (Akeson et al. 2005a, b.), in open circles R_{in} from SED modeling (Muzerolle et al. 2003). In several sources CO gas is present inside the corotation radius and inward the dust sublimation radius. *Right panel* Distributions of the gas inner radius from CO $4.7\ \mu\text{m}$ observations and the distribution of the semi-major axis of short period extrasolar planets. The minimum radius of both distributions is similar. Both figures are taken from the review from Najita et al. (2007a)

Besides the fact that CO $4.7\ \mu\text{m}$ emission probes the terrestrial planet forming region of the disk, one clear advantage of CO $4.7\ \mu\text{m}$ emission is that it is detectable in a large number of sources with present instrumentation. This opens the perspective for developing large surveys. For example, CO $4.7\ \mu\text{m}$ emission has been detected in a vast majority of Herbig Ae/Be stars that display excess $E(K - L) > 1$ (Brittain et al. 2007a). CO $4.7\ \mu\text{m}$ emission studies have in consequence an important potential for the future. A second advantage comes from the fact that several lines are observable at the same time in a single setup even with echelle spectrographs. This is important to make reliable rotational diagrams and to perform analyses involving the averaging of line profiles (i.e., determine R_{in} or the inclination).

The principal limitations of this diagnostic are: (i) it requires high-spectral resolution. Thus it is limited to relatively bright targets (for the moment stars fainter than $M = 10$ are challenging); (ii) observations in the M band are relatively time intensive and observations of telluric standard stars are required before or after the science observations; (iii) CO $4.7\ \mu\text{m}$ lines lie very close, if not inside CO atmospheric features. Hence, observations should be performed in an epoch such that the velocity shift due to the orbital motion of the Earth is maximized; (iv) one should keep in mind that CO $4.7\ \mu\text{m}$ emission does not trace in general (unless we see emission from a gap) the giant planet forming region of the disk ($R > 5\text{--}10\ \text{AU}$).

3.5 H₂ Emission from Disks

From previous sections, the reader perhaps realizes that principally CO has been discussed. The discussion started with CO at $2.3\ \mu\text{m}$, it was followed with CO in the (sub)-mm, and finally CO emission at $4.7\ \mu\text{m}$ was treated. But what about molecular hydrogen? H₂ is by far more abundant than CO (in the ISM H₂/CO is typically 10^4). Although H₂ is the

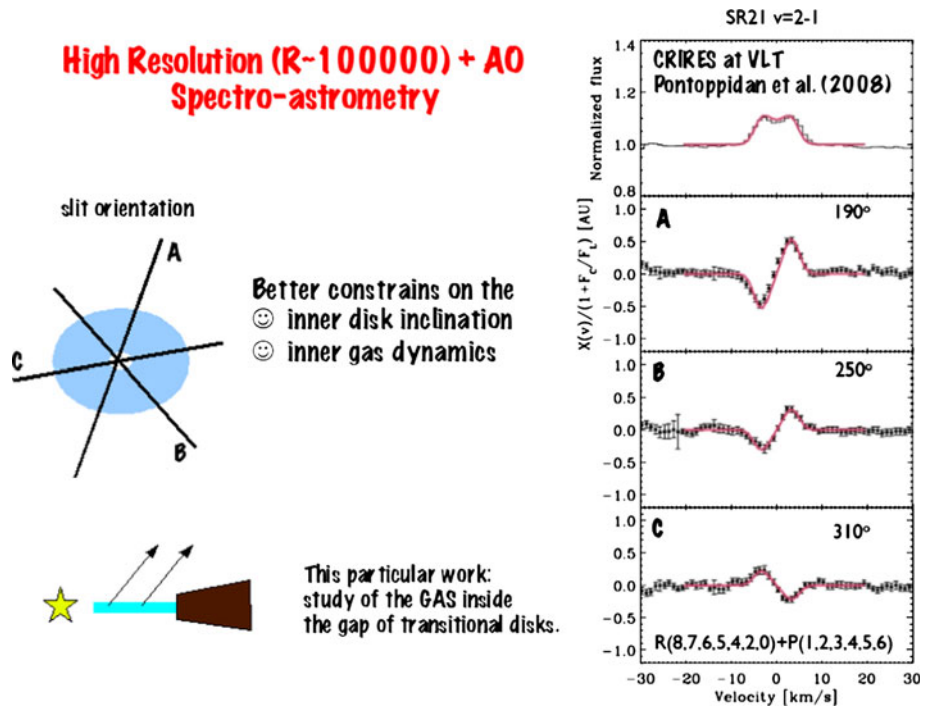


Fig. 5 Normalized flux and spectro-astrometric signal of the averaged CO $v = 2-1$ emission at $4.7 \mu\text{m}$ from the transition disk SR 21. Data in three slit orientations is displayed. In the bottom of the right panel, a detail of the transitions (R and P) employed for calculating the composite profile is shown. In all the panels the continuous line is a Keplerian disk model. The line shape and spectro-astrometric signal observed are consistent with CO gas in Keplerian rotation. Adapted from Pontoppidan et al. (2008)

principal constituent of the gas in the disk, it is very challenging to detect. This is due to the H_2 physical nature: H_2 is an homonuclear molecule that—in contrast to CO—has not permanent dipole moment. Its fundamental transitions are quadrupole in nature. Hence, their Einstein spontaneous emission coefficients are small and give rise to weak lines. In the context of circumstellar disks, one extra challenge is present. The weak H_2 lines should be detected on top of the strong dust continuum emission. Thus, high spectral resolution is a must to disentangle the weak lines. To complicate a little bit the life of astronomers, the energy levels of H_2 are widely spaced in energy (for example the first energy level starts at 510 K). That means that a dedicated observation is required for each H_2 line in order to construct rotational diagrams (note that in contrast, CO lines are closely spaced and several lines are observable within one observation set up). Moreover, since H_2 emission is produced in warm $T > 150$ K gas, H_2 emission can also originate from shocked gas in outflows and not in the disk (note that historically H_2 emission has been used to trace shocks). Finally, the mid-IR region is a challenging window to perform high-sensitivity observations from the ground.

Nevertheless, besides being the most abundant molecule, H_2 has some advantages: (i) H_2 is optically thin up to column densities of 10^{23} cm^{-2} ; thus, if the observed emission is thermal, we can derive direct constrains to the mass of the emitting gas; (ii) H_2 self-shields against photo-dissociation; (iii) H_2 traces the inner disk in the giant planet

formation region; (iv) the H_2 condensation temperature is 2 K. Hence, H_2 does not freeze onto dust grains surfaces -as happens with CO-; (v) the velocity shift of H_2 lines and their spatial extent allow to distinguish if the emission observed is from a disk or from an outflow.

To discuss the observations of H_2 emission in disks, I will start by addressing the near-IR ro-vibrational lines, later I will discuss the mid-IR pure rotational lines and finally I will discuss the H_2 electronic transition lines in the UV.

3.5.1 H_2 Ro-vibrational Emission at 2 μm

H_2 lines in the near-IR probe the inner disk from a fraction of AU up to a few AU. They trace gas at temperatures of 1000 K and higher. They are sensitive up to a few lunar masses of gas. H_2 near-IR emission arises from ro-vibrational transitions between the rotational levels (J) of the first and second vibrational states ($v = 1, 2$) and the rotational levels of the ground vibrational state ($v = 0$). Typical lines observed are the $v = 1-0$ S(1) line ($J = 3-1$) at 2.12 μm , the 1-0 S(0) line at 2.22 μm , and the 2-1 S(1) line at 2.24 μm .

The H_2 1-0 S(1) line was first observed in outflows in T Tau stars (e.g., Beckwith et al. 1978; van Langevelde et al. 1994). Only recently, H_2 1-0 S(1) quiescent emission (i.e., at the velocity of the star) from a disk was reported in the T Tauri star TW Hya (Weintraub et al. 2000). Later on Bary et al. (2002) detected the same line in the weak line T Tauri star²(WTTS) DoAr 21. After these initial studies, quiescent H_2 1-0 S(1) emission from T Tauri stars has been reported by Bary et al. (2003), Itoh et al. (2003), Weintraub et al. 2005, Ramsay Howat and Greaves (2007), Carmona et al. (2007, 2008a) and Bary et al. (2008). Carmona et al. (2007) detected for the first time the H_2 1-0 S(0) line in the disk of LkH α 264 and demonstrated that H_2 near-IR from disks originates in gas at temperatures around 1000 K.

In classical T Tauri stars (CTTS) H_2 near-IR lines are preferentially observed in objects that exhibit signatures of active accretion, that is, objects with large H α equivalent widths and strong UV excess (Carmona et al. 2007, Bary et al. 2008, see Fig. 6). In CTTS there is no apparent correlation between the X-ray luminosity, disk mass and the presence of the near-IR H_2 lines (Carmona et al. 2007). The H_2 1-0 S(1) line has been detected in a few WTTS (Bary et al. 2002, 2008, see Fig. 5). This indicates that a fraction of such objects still have a gaseous disk. The WTTS in which the H_2 1-0 S(1) line has been detected are sources exhibiting large X-ray luminosity (Bary et al. 2002, 2008, see Fig. 6).

H_2 near-IR lines have been observed in relatively old objects such as ECHAJ08843.3-7905 in the η Chamaleontis cluster (6 Myr, Ramsay Howat and Greaves 2007) and TW Hya (Bary et al. 2000) in the TW Hya association (8–10 Myr). H_2 lines have been detected in transitional disks in Chamaleon (Bary et al. 2008), and in the close binary star GV Tau (Doppmann et al. 2008). In the transitional disks in Chameleon in which H_2 near-IR emission has been observed, [Ne II] emission at 12 μm has been also detected by Spitzer (Bary et al. 2008). This suggests a common excitation mechanism for both lines (see Sect. 3.7).

The main strength of the H_2 lines in the near-IR lies in their ability to probe very small quantities of hot gas in the inner disk if the right excitation conditions are present (accretion, UV photons, X-rays). This strength can be exploited to search for gas in

² Weak-line T Tauri stars are stars that do not exhibit signatures of active accretion and that lack IR-excesses in their spectral energy distribution. They were discovered by X-ray studies of star-forming regions.

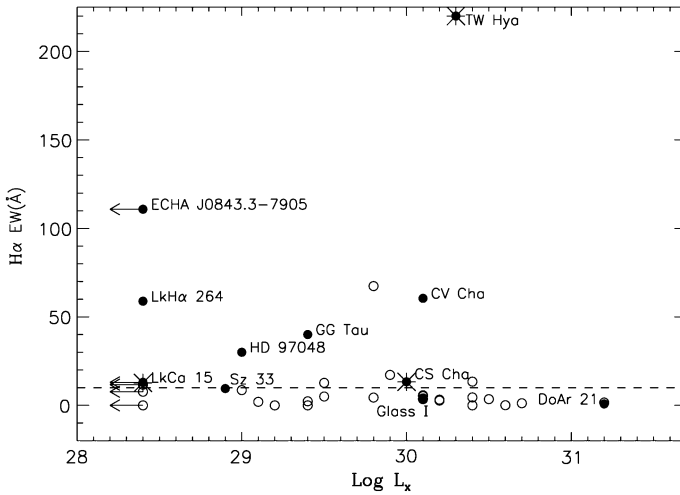


Fig. 6 $H\alpha$ Equivalent Width vs X-ray luminosity in CTTS and WTTS in which 1-0 H_2 S(1) emission at 2.12 micron has been detected. Filled circles represent detections, empty circles non-detections, left arrow upper limits in X-ray luminosity, asterisks transition disks. The boundary CTTS/WTTS is set represented by the horizontal dashed line at EW 10 Å. The probability of detecting H_2 in CTTS seems to be correlated with accretion signatures ($H\alpha$, UV excess). In WTTS H_2 emission is observed preferentially towards sources with high X-ray luminosity. Figure taken from Bary et al. (2008)

environments where other gas diagnostics give negative results (i.e., WTTS). In a similar way, non-detections allow to set stringent upper limits on the presence of hot gas in the inner disk (e.g., Carmona et al. 2007 found no evidence of H_2 emission in the debris disk 49 Cet, and constrained the mass in the inner most disk to be lower than a few lunar masses). Observationally, H_2 lines in the near-IR have the advantage that they are observed in the K band. The transmission of the atmosphere in the K band is relatively good; hence, H_2 lines in the near-IR can be searched in relatively faint objects with large telescopes. There is potential for performing large surveys for H_2 emission in the near-IR.

The main disadvantage of H_2 near-IR emission is that it is also produced by shocks in outflows. Thus, to reduce the risk of confusion with shocks, high spectral resolution observations with precision higher than 5 km/s and observations at high angular resolution with AO are needed. For the interested reader, Beck et al. (2008) and Gustafsson et al. (2008) present examples of H_2 integral field spectroscopy obtained with AO in T Tauri stars. In the sources observed by those authors, we can observe the contribution of outflow emission to the H_2 1-0 S(1) observed. Finally, note that near-IR H_2 only trace the hot H_2 in the innermost disk ($R < \text{few AU}$). Consequently, an additional limitation is that H_2 lines in the near-IR can *not* be used to derive the total disk mass or the gas mass in the giant planet forming region of the disk (note that most of the mass of the disk is in cold gas at $R > 20$ AU).

3.5.2 H_2 Pure-rotational Emission in the Mid-IR

H_2 pure-rotational emission in the mid-IR traces warm gas at temperatures generally from 150 up to 1000 K. Thus, H_2 mid-IR lines have the unique potential of tracing the gas in the giant planet formation region of the disk at $R > 2$ AU. With present sensitivities (5×10^{-15} erg s $^{-1}$ cm $^{-2}$) a few Earth masses of warm gas in sources at 140 pc can be probed.

H₂ mid-IR emission arises from transitions between the rotational levels ($\Delta J = 2$) of the ground vibrational state ($v = 0$). Typical lines searched are the $v = 0-0$ S(0) line ($J = 2-0$) at 28 μm (visible only from space), the 0-0 S(1) line at 17 μm , the 0-0 S(2) line at 12 μm and the 0-0 S(3) line at 9.6 μm .

Following the initial detection claims of H₂ 0-0 S(0) and 0-0 S(1) emission from observations with ISO³ (Thi et al. 2001), several ground-based (Richter et al. 2002; Sheret et al. 2003; Sako et al. 2005; Martin-Zaïdi et al. 2007, 2008b; Bitner et al. 2007, 2008; Carmona et al. 2008b) and space (Hollenbach et al. 2005; Pascucci et al. 2006; Lahuis et al. 2007) searches for H₂ mid-IR emission have been performed. ISO detections remain controversial, as all subsequent efforts do not confirm the high H₂ emission fluxes reported by Thi et al.

At the time of writing, positive detections of H₂ mid-IR emission have been reported only in a handful of objects: the Herbig Ae/Be stars AB Aur (Bitner et al. 2007) and HD 97048 (Martin-Zaïdi et al. 2007), and the T Tauri stars Sz 102, EC 74, EC 82, Ced_110_IRS6, EC92, ISO-Cha237 (Lahuis et al. 2007), DoAr 21, Elias 29, GSS 30. GV Tau N and H1 Tau (Bitner et al. 2008). In total, H₂ pure-rotational emission has been detected only in 13 young stars with disks from ~ 114 objects searched (here we exclude 14 ISO H₂ detections in 18 stars observed, and the searches in 16 optically thin disks of Hollenbach et al. 2005 and Pascucci et al. 2006). The main result of these searches are: (i) H₂ mid-IR emission is relatively rare ($\sim 11\%$ of the sources), and (ii) in the sources where the emission is detected, the gas is heated by an additional mechanism.

The numerous non detections can be understood in a first approximation under the frame of the Chiang and Goldreich (1997) two-layer model of an optically thick disk. In this model, only emission from the surface molecular layer of the disk is observed (the mid-plane is optically thick). Since the amount of gas in the surface layer is very small, if the dust and gas are at equal temperatures and the gas-to-ratio is equal to 100, then the expected thermal emission of H₂ from the surface layer is too weak to be detected ($\sim 10^{-16}$ – 10^{-17} erg s⁻¹ cm⁻², Carmona et al. 2008b). In the context of the two-layer model, the few detections can be explained if the temperature of the gas is allowed to be at twice the temperature of the dust and if the gas-to-dust ratio is larger than 1000 (Carmona et al. 2008b). This can occur under certain physical circumstances such as a high UV or X-ray radiation fields or if dust coagulates and sediments towards the mid-plane of the disk.

The two-layer model is just an approximation to the real structure of the disk; however, similar conclusions have been reached from more detailed modeling. Sophisticated models of H₂ emission from disks (Nomura et al. 2005, 2007) assuming typical X-ray and UV-fluxes from pre-main sequence stars predict flux levels below present detection limits (both in line flux and in the line contrast with the continuum). Models from optically thick disks with enhanced levels of UV and X-ray radiation (e.g., Gorti and Hollenbach 2008) can account for the H₂ fluxes reported. Finally, note that H₂ mid-IR emission has been reported up to the 0-0 S(9) line (indication that an extra source of heating is present) and that it has been observed in a few transitional disks (e.g., Sz 102) and in the WTTS DoAr 21 (Bitner et al. 2008).

In summary, H₂ mid-IR lines have the potential of tracing the gas in the giant planet forming region of the disk, but their main limitation is that they are too weak to be detected in a large number of sources. In addition, if the disks observed are optically thick, then mid-IR H₂ lines only trace the small amount of gas in the surface layer of the disk. Therefore, H₂ mid-IR lines in optically thick disks cannot be used to derive constraints in

³ Infrared Space Observatory.

the total disk mass. In the objects in which we are able to detect the emission, H₂ appears to be heated by an additional mechanism. In this case the LTE approximation is no longer valid and the H₂ masses derived can be overestimated.

H₂ mid-IR emission studies from the ground are so far limited to relatively bright sources with fluxes typically larger than 1 Jy. Future mid-IR infrared instrumentation such as high-resolution mid-IR spectrograph EXES in the airplane observatory SOFIA, and the mid-IR spectrograph MIRI in the James Webb Space Telescope (JWST) will increase the sensitivity and will allow the study of H₂ mid-IR emission in larger number of objects, in particular in CTTS.

3.5.3 H₂ Electronic Transitions in the UV

H₂ electronic transitions in the UV probe two kinds of gas: (i) in emission when the disk is seen face on, they trace highly excited gas at temperatures of a few thousand Kelvin ($R \ll 1$ AU). (ii) in absorption when the disk is seen close to edge-on, they probe colder gas at few hundred K. H₂ UV lines are observed in absorption against the bright continuum in hot stars or in emission lines (e.g., O VI at λ 1032–1038 Å) in cool stars. H₂ electronic transitions occur between the vibrational levels of the first (B) or the second (C) electronic states, and the ground vibrational level of the ground electronic state (X). Given the low transmission of the atmosphere at UV-wavelengths, H₂ UV transitions are studied primarily with space instrumentation (e.g., IUE, HST, FUSE).⁴

H₂ lines are excited by the far-UV (FUV) flux of the central star, or by shocked gas in outflows. Warm H₂ gas can absorb photons all over the FUV; consequently, a flat radiation field would excite a very large number of densely packed H₂ lines and a pseudocontinuum is produced. In the case of CTTS, the FUV flux is dominated by emission lines, in particular by Ly α . Hence, in CTTS, we observe principally Ly α -band (B-X) transitions. Nevertheless, Werner-band transitions (C-X) are observed as well.

H₂ electronic transitions have been searched towards T Tauri stars (Valenti et al. 2000; Errico et al. 2001; Ardila et al. 2002; Wilkinson et al. 2002; Herczeg et al. 2002, 2004, 2005, 2006; Walter et al. 2003; Bergin et al. 2004), Herbig Ae/Be stars (Roberge et al. 2001; Lecavelier des Etangs et al. 2003; Bouret et al. 2003; Grady et al. 2005; Martin et al. 2004; Martin-Zaïdi et al. 2005, 2008a), accreting Brown Dwarfs (Gizis et al. 2005) and in close to edge-on debris disks (β Pic, Lecavelier des Etangs et al. 2001; Martin-Zaïdi et al. 2008a; AU Mic, Roberge et al. 2005; France et al. 2007).

In the case of T Tauri stars, H₂ UV lines have been detected in several CTTS and in at least one WTTS (V836 Tau). Nonetheless, a large fraction of the H₂ detections in CTTS appears to be emission from outflows. The observed lines are blueshifted (e.g., Ardila et al. 2002) and/or spatially extended (e.g., Herczeg et al. 2006). So far, only in very few cases quiescent spatially unresolved H₂ emission in the UV has been reported. The most notable example is the T Tauri star TW Hya. In this source, the lines observed are excited by Ly α fluorescence. The emission is consistent with emission from the surface of a hot inner disk (Herczeg et al. 2002)

In the case of Herbig Ae/Be stars, H₂ UV lines have been studied mostly in absorption at 1032–1038 Å. Evidence for different origin/excitation for the lines is observed as function of the stellar mass. For the massive Herbig Be stars (spectral types B2 to B8), the H₂ lines are consistent with a photodissociation region (PDR) in large circumstellar envelopes

⁴ IUE: International Ultraviolet Explorer; HST: Hubble Space Telescope; FUSE: Far Ultraviolet Spectroscopic Explorer.

(Martin-Zaïdi 2008a). For Herbig Ae stars, the line of sight generally appears *not* to pass through the disk. The H₂ lines observed are consistent with warm gas in the circumstellar environment of the stars (e.g., an envelope in AB Aur, Roberge et al. 2001) or cold gas in the line of sight (e.g., HD 141569 Martin-Zaïdi et al. 2005). In Herbig Ae stars, the H₂ absorption lines are not consistent with PDR models (Martin-Zaïdi 2008a). In some cases, if the inclination and flaring of the disk are adequate, we may see a thin layer of a flared circumstellar disk (e.g., HD 100456 & HD 163296, Lecavelier des Etangs et al. 2003).

In the case of the debris disk β Pic, no strong H₂ lines either in emission or absorption have been detected. Only a marginal detection of the $J = 0$ H₂ line was reported (Lecavelier des Etangs et al. 2001). This was interpreted as evidence of lack of gas in the β Pic disk. In the case of AU Mic H₂ was not detected in absorption, but it was detected in emission. The estimated gas mass was of 10^{-4} – $10^{-6} M_{\text{earth}}$ (France et al. 2007).

The main advantage of the H₂ lines in the UV are: (i) if observed in emission, they can probe small amount of very hot gas ($T \sim 2500$ K) in the innermost part of the disk; (ii) if observed in absorption, they can trace small amounts of colder ($T \sim 50$ -hundreds of K) gas. H₂ lines in the UV have allowed us to unveil the presence of hot gas in the inner disk in WTTS and transitional disks.

Their main limitations are: (i) in most of the CTTS, the H₂ emission in the UV originates in outflows; (ii) in most of the Herbig Ae stars where H₂ has been observed in absorption, the probed gas is not in the disk, but instead in circumstellar ambient material or cold gas along the line of sight; (iii) absorption studies probe a narrow pencil-beam that limits its application in sources observed far from edge-on; (iv) in the case of detections in emission, the interpretation of the results (i.e., column densities) requires complex modeling based on the poorly constrained FUV field of the central star. Finally, uncertain conversion factors are needed to extrapolate the mass of gas probed to the total amount of gas in the disk.

3.6 [OI] Emission at 6300 Å

[OI] emission at 6300 Å is a tracer of atomic gas in the surface layers of flared disks. The line traces up to a 100 AU depending on the geometry of the disk. [OI] forbidden emission at 6300 Å is a diagnostic that started to be explored recently. It has been studied in a growing number of Herbig Ae/Be stars with high-resolution optical spectroscopy (Acke and van den Ancker 2005, 2006; van der Plas et al. 2008; Fedele et al. 2008). The majority of the studied sources display narrow (width < 50 km/s) single peaked profiles; however, several objects exhibit double-peaked profiles. In such objects, the low velocities with respect to the star's rest velocity, the symmetry of the features and the peak-to-peak separation are consistent with line emission from a circumstellar disk in Keplerian rotation.

The strength of the [OI] line appears to be strongly correlated with the SED shape of the sources (i.e., disk geometry). Following the SED classification scheme of Meeus et al. (2001), Acke et al. (2005) found that Herbig Ae/Be from group I (flared disks) exhibit a [OI] emission stronger than those of group II (self-shadowed disks). In addition, the feature was found to be absent in an important fraction (40%) of group II sources. Acke et al. found also that the [OI] luminosity is correlated to the PAH luminosity of the sources. Acke et al. proposed that the [OI] line arises from the photodissociation by UV radiation of OH and H₂O molecules in the surface layer of flared disks. The conclusions shown by Acke et al. require fractional OH abundance $\sim \epsilon(\text{OH}) 10^{-7}$ – 10^{-8} .

Based on the analysis of the [OI] emission line profile in HD 100546, Acke et al. (2006) found evidence of a gap present at 10 AU in HD 100546's disk. They suggested that such a

gap was likely induced by a planetary-mass companion of $20 M_J$ located at 6.5 AU. Temporal changes in the [OI] line profile were reported as well. Acke et al. concluded that such changes are related to inhomogeneities in the [OI] disk emitting region.

By analyzing the [OI] line, van der Plas et al. (2008) found evidence of the existence of a puffed-up inner rim followed by a shadow in HD 101412. Fedele et al. (2008) employed a combined analysis of the [OI] emission and mid-IR interferometry observations found evidence of different dust and gas vertical structure inside 2 AU in the disks of HD 101412 and HD 135344B. Fedele et al. interpreted their findings as the result of dust/gas decoupling in the inner disk. They suggested that they may exist an evolutionary sequence from flared disks to flat disks due to the combined action of gas-dust decoupling, grain growth, and dust settling.

[OI] emission at 6300 \AA has the advantage of being observable in the optical; therefore, statistical studies of large numbers of objects are possible at high-spectral resolution in the future. One limitation of the diagnostic is that [OI] emission can be produced by shocked gas in an outflow. Thus high spatial and spectral resolution observations are required to avoid confusion with emission from outflows.

3.7 [Ne II] Emission at $12.8 \mu\text{m}$

Recently, Pascucci et al. (2007) and Lahuis et al. (2007) reported the detection of [Ne II] $12.8 \mu\text{m}$ emission from T Tauri stars with Spitzer. Pascucci et al. (2007) detected the line in four out of six targets (all with faint mid-IR continuum with respect to classical T-Tauri stars of the same spectral type) and Lahuis et al. (2007) in 15 out of 76 T Tauri stars. These first detections were followed by ground-based detections in TW Hya by Herczeg et al. (2007). The [Ne II] line has been observed towards optically thick disks, as well as in the transitional disk GM Aur and the circumbinary disk CS Cha (Espaillat et al. 2007).

Given that neon cannot be ionized by photons with energies of less than 21.4 eV, the detection of [Ne II] emission from disks attracted the attention of the disk community. The [Ne II] line could provide evidence of higher energy photons irradiating the disk, in particular extreme-UV (EUV) photons (Gorti and Hollenbach 2008; Alexander 2008) or X-rays (Glassgold et al. 2007, Meijerink et al. 2008). Nonetheless, [Ne II] emission can be produced by shocked gas in outflows (e.g., Hollenbach and McKee 1989). At the present, it is not well constrained which of these scenarios is taking place. Spitzer's spatial and spectral resolution are too modest to distinguish between the different scenarios proposed.

Models of X-ray irradiated disks by Glassgold et al. (2007) predicted that the ionization fraction of neon is proportional to the square root of the X-ray luminosity. However, models by Meijerink et al. (2008) rather found that there is a linear proportionality between the [NeII] line luminosity and the X-ray luminosity. Pascucci et al. (2007) reported a tentative correlation between the [Ne II] and the X-ray luminosities. However, only about 30% of the sources with [Ne II] detections from Lahuis et al. (2007) are identified as X-ray sources (either due to the lack of X-ray emission, sensitivity limited X-ray searches, or object geometry).

In the UV model of Gorti and Hollenbach (2008), EUV photons from the stellar chromosphere and/or from accretion create a region similar to a HII region at the surface of the disk. The EUV are absorbed in the inner 10 AU of the disk, and a EUV photon luminosity $\sim 10^{41}$ erg/s would be able to produce detectable [NeII] line fluxes. But, in the EUV model, a stellar wind greater than $\sim 10^{-10} M_{\odot}/\text{year}$ could drastically reduce the UV-photons reaching the disk. Stellar winds of this magnitude correspond to typical CTTS accretion rates. Thus, lower [Ne II] luminosities are expected for CTTS stars simple due to

the accretion and the related wind rates. Nonetheless, several detections from Lahuis et al. (2007) are from CTTS.

In an alternative model, Alexander et al. (2008) suggested that the [Ne II] line is produced in a photoevaporating wind. Alexander et al. predicted broad (30–40 km/s) double peaked [Ne II] lines when the stars are viewed close to edge-on and narrower (~ 10 km/s), slightly blue-shifted lines when viewed face-on. High spatial and spectral resolution is required for testing this model.

In an additional scenario, high-velocity shocks can entrain ionized lines (e.g., Hollenbach and McKee 1989). Van den Ancker et al. (1999) detected [Ne II] emission in the ISO spectra of the T Tau triplet. This system contains three stars of which at least one is a strong X-ray source, as well as regions of shocked gas in the immediate vicinity. Due to the large beam ($27'' \times 15''$) it was not clear from where in the system the emission comes. Van den Ancker et al. proposed that the emission arose in J-type (dissociative) shocks resulting from the interaction of the outflow of T-Tau south with ambient material. T Tau exhibits a very high $L_{[\text{Ne II}]} / L_X$ ratio, hinting that processes other than X-ray irradiation are important. Recent high spectral and spatial resolution observations of the [Ne II] line in T Tau with the VLT spatially resolved the various components of the system (van Boekel et al. 2009). Van Boekel et al. found that the vast majority of the [Ne II] flux appeared to be associated with an outflow from T Tau S, and that only a small fraction (~ 5 –10%) of the [Ne II] emission was directly related to the X-ray bright Northern component. van Boekel et al. observations showed that if strong accretion/outflow activity is present, shocks were the main mechanism for producing [Ne II] emission in T Tau.

Finally, note that in three young stars that exhibit the *Spitzer* [Ne II] line, the H_2 1-0 S(1) line at $2.12 \mu\text{m}$ was detected as well: TW Hya (Bary et al. 2003), GM Aur (Shukla et al. 2003) and CS Cha (Bary et al. 2008). Bary et al. (2008) pointed out that simultaneous presence of the [Ne II] line and *quiescent* H_2 disk emission suggests a shared excitation mechanism of the gas in the disk by the central star's high-energy photons. The same high-energy photons that stimulate the [Ne II] emission could also produce the *quiescent* H_2 emission observed. However, as previously discussed, H_2 near-IR emission can be also produced by shocks. In such a case, objects displaying the [Ne II] lines, may show the H_2 near-IR emission velocity shifted or extended. In such objects, H_2 and [Ne II] emission will be produced by shocks. Spectrally and spatially resolved observations are required to test both scenarios.

In summary, [NeII] emission has the potential of unveiling the effects of X-ray or UV-ray in the surfaces of disks. But, since [NeII] emission can be produced by shocks, it is necessary to perform observations with higher spatial and spectral resolution to determine the dominant excitation mechanism. In addition, observations of larger samples are required to establish statistically meaningful correlations between the presence/strength of [NeII] emission and physical properties of the central star (i.e., spectral type, accretion rate, age, X-ray and UV-luminosity).

3.8 H_2O , C_2H_2 , HCN, OH Molecular Emission in the Near and Mid-IR

How water is transported to the surface of habitable planets is one fundamental and fascinating question in planet formation theory. Water and other simple organic molecules are expected to be abundant—in gas phase—in the inner regions of the disk ($R < 5$ AU). Nevertheless, observational measurements of water in the planet forming region of disks are relatively recent. First detections of hot water vapor were reported by Carr et al. (2004)

and Thi and Bik (2005) in the near-IR spectrum of young stellar objects exhibiting the 2.3 μm CO bandhead emission (e.g., SVS 13, DG Tau and 51 Oph).

The observed H_2O displays a characteristic excitation temperature of ~ 1500 K. Since this temperature is cooler than the temperature of the CO overtone emission (2500 K) the observed water emission should be produced in a region exterior to the CO 2.3 μm emitting region. Simultaneous modeling of the CO and steam emission revealed that the $\text{H}_2\text{O}/\text{CO}$ ratio is lower to that expected in chemical equilibrium (Carr et al. 2004). Physical processes other than equilibrium chemistry should be responsible of the measured H_2/CO abundances. Thi and Bik (2005) reproduced the H_2/CO abundance observed in 51 Oph with gas at 1,600 K and an enhanced UV field over gas density ratio.

These first detections of H_2O were followed by detections in the IR of simple molecules such as C_2H_2 and HCN. They were observed in absorption in the near-IR spectrum of the T Tauri binary GV Tau N (Gibb et al. 2007, 2008) and in absorption in the mid-IR spectrum of the low-mass young stellar object IRS 46 (Lahuis et al. 2006). The temperatures measured were of a few hundred K. The lines originate most likely in the inner disk ($R < 6$ AU) of the sources. However, there is also the possibility that they originate in a disk wind.

The high sensitivity reached with IR spectroscopy from space and ground-based high spectral resolution allowed the detection of emission of simple organic molecules from the terrestrial planet region of the disk ($R < 5$ AU). Carr and Najita (2008) reported the detection of HCN, C_2H_2 , CO_2 water vapor and OH emission in the Spitzer's mid-IR spectrum of the T Tauri star AA Tau. Modeling of the observed profiles indicates that the observed gas has temperatures from 500 to 900 K and is located within 0.5 and 3 AU. One important finding is that the abundances relative to CO found are much higher than those obtained from models of hot molecular cores, this suggests that substantial molecular synthesis occurs within the disk.

Salyk et al. (2008) reported the detection of H_2O emission at 3 μm and 10–20 μm and OH emission at 3 μm in the T Tauri stars AS 205a and DR Tau. They measured excitation temperatures of 1000 K. Based on the velocity wings of the lines, they concluded that the observed emission arises up to radius of 1 AU.

Mandell et al. (2008) found OH emission at 3 μm in the Herbig Ae stars AB Aur and MWC 758. Optically thin LTE models of the observed lines revealed excitation temperatures ~ 700 K and an OH emitting region extending up to 1 AU. The observed OH lines can be explained by collisional excitation models, and in the case of AB Aur by a UV fluorescence model too.

Pascucci et al. (2009) detected with Spitzer C_2H_2 and HCN at 7–14 μm in a large number of young stellar objects with disks. They found that the abundance of these simple organic molecules appears to be different between stars cooler than the Sun and sun-like stars.

The study of simple organic molecules in the near and mid-IR is growing. The main advantage of these diagnostics are: (i) they trace the gas in the terrestrial planet forming region of the disks, and (ii) they have the potential of constraining the chemical processes in this region. From the observational point of view, an additional advantage is that within a single observation set-up, multiple tracers are observable simultaneously. In addition, the fact that some of the lines are observable from the ground at 3 μm open the door to the study of a large number of objects at high spectral and spatial resolution.

One limitation of these gas tracers is that the interpretation of the observations generally requires complex modeling that involves: (i) assumptions in the structure of the inner disk; (ii) poorly constrained physical quantities (e.g., the UV field, inclination of the inner disk); and (iii) poorly constrained physical processes (e.g., excitation mechanisms, chemistry,

radial and vertical mixing in the disk). On the other hand, these limitations can become an advantage, because, even if observations can be interpreted with different models, observations can also rule out scenarios that are not consistent with the measurements. It is interesting that future observations of simple molecules in the inner disk could reveal a variety of disk chemistry until now unsuspected. Finally, note that in very short time Spitzer will not offer mid-IR spectroscopy anymore. However, future mid-IR spectrograph MIRI planned for JWST will be an ideal tool for this research.

4 Conclusion

In this contribution I have discussed several observational diagnostics that allow to study the gas in protoplanetary disks highlighting the strengths and limitation of each diagnostic. Here, I summarize important general points that one should bear in mind about observational constraints of gas in disks.

- Disks have a radial temperature structure; therefore, different gas diagnostics are employed for probing different regions of the disk. UV probes the hottest gas in the innermost disk ($R \ll 1$ AU, $T > 2000$ K), NIR and MIR probes hot and warm gas in the inner disk ($R \sim 0.1$ – 20 AU, $T \sim 100$ – 2000 K), (sub)-mm probes cold gas in the outer disk ($R > 20$ AU, $T \sim 20$ – 100 K). Note that disks have typical sizes of several hundreds of AU.
- To observe a line from gas (in emission or absorption) the dust in the medium where the line is produced must be optically thin at the observed wavelength, or the gas should be at a higher temperature than the dust.
- An optically thick disk has a vertical temperature structure. The surface layer is hotter than the interior mid-plane layer. The dust in the surface layer is optically thin, the dust in the interior layer (of the inner disk) is optically thick. In optically thick disks, hot and warm gas emission lines from the UV to the IR are produced in the surface layer. Note that the amount of mass in the surface layer is much smaller than the amount of mass in the interior layer. Gas lines in the IR probe only a limited amount of material. H_2 lines in the IR are optically thin. CO lines in the IR can be optically thick.
- Sub-mm lines trace only the cold outer regions of the disk at $R > 20$ AU. Planets usually are not expected to form at these distances. Still, most of the mass of the disk is at $R > 20$ AU.
- CO in the (sub)-mm is not a reliable disk gas mass tracer because (i) CO freezes onto dust grain surfaces, (ii) the CO/ H_2 conversion factor is unknown in disks (iii) the emission is likely optically thick.
- Be aware that so far we do not measure directly the mass of gas in disks. We deduce the disk mass from dust continuum emission in the (sub)-mm from cold dust in the outer disk ($R > 20$ AU). The deduced mass depends on the dust opacity, dust temperature and the dust-to-gas ratio assumed. The disk mass observed is from material located at $R > 50$ AU, and disk evolutionary models are typically of disks of $R < 50$ AU. The mass and surface density profiles of gas at $R < 20$ AU are poorly constrained from observations.
- Modeling is required for the interpretation of line observations. Conventional assumptions are that the observed gas is at LTE and is optically thin. The rotational diagrams employed for deducing the temperature of the observed gas make use of those two assumptions. To deduce the inner most radius of the observed emission (i.e., R_{in})

from line profile modeling, it is required to assume the disk inclination and the dependence of the intensity as a function of radius ($I(R)$). Inclinations are typically deduced from (sub)-mm imaging and extended to the inner disk. On the other hand, if we want to deduce independently the inclination (e.g., to search for evidence of warps) we need to assume (or calculate) R_{in} and $I(R)$.

- Most of the gas tracers (e.g., H_2 , $[\text{Ne II}]$) can be produced by shocked emission from outflows as well. High spectral/spatial resolution is required for determine whether the emission is observed at the velocity of the central star and whether it is spatially extended or not.
- Gas emission could be excited by collisions with dust grains, shocks and UV or X-rays. Line ratios are generally employed to discriminate between the different excitation mechanisms.
- Gas could be present in a disk even when dust emission is weak or not present. Gas emission lines have been observed in the inner regions of transitional disks and in several WTTS.
- The study of gas in disks acquired momentum with the advent of high-resolution ground IR spectrographs and high-sensitivity IR spectrographs in space.
- A new chapter in gas studies was recently written with the detection of emission of simple molecules in the inner disks.

At the beginning of the paper I highlighted some fundamental science questions that required direct observational constraints from the gas in the disk. To conclude, I would like to address them again from the actual state of the observational studies of gas in protoplanetary disks.

(i) *How long does the protoplanetary disk last?* In general terms, disk gas diagnostics are not detected when the signatures of the dust in the disk have disappeared. Thus, as a first approximation the gas in the disk disappears almost simultaneously with the signatures from small dust particles. Nonetheless, we should be aware of a few details: (a) with the exception of $\text{H}\alpha$ emission, there are many sources for which we know that they have a disk, but given sensitivity issues, we are not able to detect any gas tracer; (b) gas has been observed in several WTTS stars (e.g., H_2 in the UV and NIR), and in transitional disks (e.g., H_2 in the near-IR, CO at 4.7 μm , $[\text{Ne II}]$ at 12 μm); (c) unbiased surveys for hot/warm gas in a large sample of WTTS have yet not been performed; (d) surveys of $\text{H}\alpha$ at high spectral resolution need to be done in larger samples of WTTS in star-forming regions of different ages. If the accretion rate and spectral resolution are low, one can easily miss objects accreting gas at low accretion rates. In summary, an estimate of disk gas lifetime independent of dust is still required.

(ii) *How much material is available for forming giant planets?* On this aspect our hopes are fainter. Several surveys for H_2 emission in the MIR showed that the emission is observed only in a handful of objects, and that in these objects the gas is heated by an additional (to dust collisions) heating mechanism (UV, X-ray excitation). Although these results confirm our two-layer picture of the disk, in practice these results mean that we are blind to the disk's mid-plane and that we are unable to know directly how much mass is in the giant planet forming region of the disk. The good news are two fold: (a) in objects with data at several wavelengths, an educated guess can be found from modeling the surface density (see next point); (b) at some point the disk should become optically thin -by dust evolution- then we will be able to measure the gas mass.

(iii) *How do the density and temperature of the disk vary as a function of the radius?* There is a growing number of sources (e.g., TW Hya, AB Aur) for which we start to have

information from several gas tracers at wavelengths from the UV to the (sub)-mm. In such sources, we can attempt to constrain the disk structure employing a disk model aimed to fit all the available data. Therefore, at least for a handful of objects, by modeling multi-wavelength spectroscopy, we have the potential to constrain the density and temperature as a function of radius. However, we should always keep in mind that we observe emission from the disk's surface layer and that the mid-plane temperature and density will be deduced from the model. Hence, the final gas mass deduced will be model dependent.

(iv) *What are the dynamics of the disk?* In this aspect we had good news. To detect gas lines in the IR we commonly use the highest spectral resolution available. At the present, the resolution is sufficiently high to spectrally resolve the lines. This allows the modeling of the line shape; therefore, constraints in the dynamics of the emitting gas can be derived. Recently, with the combination of AO and high-resolution spectroscopy, it has been possible to spatially resolve gas disk emission directly or to spatially resolve the spectroastrometric signal with spectra taken at different slit orientations. So far the observed gas is consistent with gas in Keplerian rotation. This kind of studies should be extended in the future to a larger number of systems.

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