The Observation of Circumstellar Disks: Dust and Gas Components

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Abstract. Since the 1990’s, protoplanetary disks and planetary disks have been intensively observed from the optical to the millimetre wavelength and many models have been developed to investigate their gas and dust properties and dynamics. These studies remain empirical and rely on poor statistics with only a few well known objects. However, the late phases of the stellar formation are among the most critical for the formation of planetary systems. Therefore, we believe it is timely to tentatively summarize the observed properties of circumstellar disks around young stars from the protoplanetary to the planetary phases.

Our main concern is to present the physical properties considered as observationally robust and to show their main physical differences associated to an evolutionary scheme. We also describe areas still poorly understood such as how protoplanetary disks disappear to lead to planetary disks and eventually planets.

1. Introduction

Before the 1980’s, the existence of protoplanetary disks of gas and dust around stars similar to the young Sun (4.5 billion years ago) was inferred from the theory of stellar formation (e.g. Shakura & Sunyaev 1973), the knowledge of our own planetary system and dedicated models of the Proto-Solar Nebula. The discovery of the first bipolar outflow in L1551 in 1980 drastically changed the view of the stellar formation. In the meantime, optical polarimetric observations by Elsasser & Staude (1978) revealed the existence of elongated and flattened circumstellar dust material around some Pre-Main-Sequence (PMS) stars such as the low-mass TTauri stars.

The TTauri are understood to be analogs to the Sun when it was about $10^6$ years old. A few years later, observations from the InfraRed Astronomical Satellite (IRAS) found significant infrared (IR) excesses around many TTauri stars, showing the existence of cold circumstellar dust (Rucinski 1985). More surprisingly, IRAS also show the existence of weak IR excess around Main-Sequence (MS) stars such as Vega, ε Eridani or β Pictoris (Aumann et al. 1984). These exciting discoveries motivated several groups to model the Spectral Energy Distribution (SED) of TTauri stars (e.g. Adams et al. 1987) and Vega-like stars (Harper et al. 1984).

On one hand, for PMS stars, the emerging scenario was the confirmation of the existence circumstellar disks orbiting the TTauri stars, the gas and dust being residual from the molecular cloud which formed the central star (Shu et al. 1987). Since such disks contain enough gas ($H_2$) to allow, in theory, formation of giant planets, they are often called “protoplanetary” disks. During this phase, the dust emission is optically thick in the Near-IR (NIR) and the central young star still accretes from its disk. Such disks are also naturally called accretion disks.

On the other hand, images of β Pictoris by Smith & Terrile (1984) demonstrated that Vega-type stars or old PMS stars can also be surrounded by optically thin dusty disks. These disks were called “debris” disks or later “planetary” disks because planetesimals should be present and indirect evidence of planets was found in some of them (β Pic).

In this chapter, we review the current observational knowledge of circumstellar disks from the domain of the UV to the millimeter (mm). We discuss in Sections 2 and 3 the properties of protoplanetary disks found around young low-mass (TTauri) and intermediate-mass (Herbig AeBe) stars. In section 4, we summarize the properties of transition disks which have still some gas component but also have almost optically thin dust emission in the NIR, objects which are thought to be in the phase of dissipating their primary gas and dust. We present the properties of optically thin dust disks orbiting old PMS, Zero-Age-Main-Sequence (ZAMS) or Vega-type stars, such as the β Pic debris disk in Section 5. We conclude by reviewing future instruments and their interest for studying such objects.
2. Protoplanetary disks: The T Tauri stars

Following the standard classification (see Chapter 4.2.4), T Tauri stars typically present the SEDs of Class II objects.

Evidence for disk features around these young stars comes principally from the following observational considerations:

1. A flat and geometrically thin distribution account for the SED (produced by the dust emission) from the optical to the mm (including the IR excess) because the extinction towards most T Tauri stars is very low.

2. In the 1990’s, adaptive optics (AO) systems on ground-based telescopes and the Hubble Space Telescope (HST) started to image these disks. Dust grains at the disk surface scatter the stellar light, revealing the disk geometry of circumstellar material as in the case of HH30 (Fig. 4).

3. Large millimeter arrays such as OVRO or the IRAM interferometers clearly demonstrate by mapping the CO J=1-0 and J=2-1 line emission from the gas that the circumstellar material has a flattened structure and is in Keplerian rotation.

Most T Tauri stars form in binary or multiple systems (Mathieu et al. 2000) and many observational results show that binarity strongly affects the dust and gas distribution as a result of tidal truncations. The material can be in a circumbinary ring as in the GG Tau disk (Dutrey et al. 1994) or confined in small, truncated, circumstellar disks. However, for simplicity, we will focus here on properties of disks encountered around stars known as single.

2.1. Mass Accretion rates

T Tauri stars with IR excess usually present optical emission lines (e.g. Edwards et al. 1994). Studies of these lines reveal that the stars are still accreting ejecting material from their disk even if the main ejection/accretion phase is over (see Chapter 4). When they present strong Hα emission lines (equivalent linewidth $W_{Hα} \geq 10 \, \text{Å}$), they are called Classical Line T Tauri stars (CTTs).

Observations show that the mass accretion rate (and also the mass ejection rate) decreases from the protostars to the Class III phases by several order of magnitudes (Hartmann et al. 1998, Chapter 4). Despite the uncertainties resulting from the various observational methods and tracers used for measuring both rates, there is a clear correlation between mass loss and mass accretion. Typical values for the mass accretion rate of a few $10^{-5} \, M_\odot/yr$ are found for Class 0 objects while T Tauri stars have lower values around $10^{-8} \, M_\odot/yr$. Some protostars such as the FU Orionis objects even exhibit episodic outbursts with accretion rates as high as a few $10^{-4} \, M_\odot/yr$ (Hartman & Kenyon 1996). Assuming a mass accretion rate of $\sim 10^{-8} \, M_\odot/yr$, a T Tauri star of 0.5 $M_\odot$ would accrete only $0.01 \, M_\odot$ in 1 Myr. Hence, most of the accretion must occur in the protostellar phase.

2.2. Modelling the Spectral Energy Distribution

Global properties of disks can be inferred from the SED but, due to the lack of angular resolution, the results are strongly model dependent and there is usually no unique solution. Moreover many stars are binaries and SEDs are not always individually resolved, leading to possible misinterpretations.

Small dust particles (of radius $a$) are efficient absorbers of wavelengths radiation with $\lambda \leq a$. In equilibrium between heating and cooling they re-emit at longer wavelengths a continuous spectrum which closely resembles a thermal spectrum. At short wavelengths, the scattering of the stellar light by dust grains can dominate the spectrum, the limit between the scattering and the thermal regimes being around $\sim 3 - 5 \mu$m. Very close to the star, ($\sim 0.1 - 5$ AUs) the temperature is high enough ($\sim 500 - 10000$ K) and the NIR/optical continuum can be dominated by the thermal emission of very hot grains.

Spectral Energy Distributions can be reproduced by models of disks (e.g., Pringle 1981, Hartman 1998) which assume that i) the disk is reprocessing the stellar light (passive disk) or ii) the disk is heated by viscous dissipation (active disk). In both models, since there is no vertical flow, the motions are circular and remain Keplerian ($v(r) = \sqrt{GM_*/r}$, where $M_*$ is the stellar mass). As a consequence the disk, in hydrostatic equilibrium, is geometrically thin with $H << r$ where $H$ is the disk scale height. For viscous disks, the viscosity $\nu$ is usually expressed by the so-called $\alpha$ parameter linked to $v$ by $\nu = \alpha c_s H$ where $c_s$ is the sound speed. The accretion remains subsonic with $v/r \sim \alpha c_s H/r << c_s$ and $\alpha \sim 0.01$.

Chiang & Goldreich (1997) have also developed a model of passive disk where the optically thin upper layer of the disk is super-heated above the blackbody equilibrium temperature by the stellar light impinging the disk which produces a kind of disk atmosphere. Both viscous heating and super-heated layers seem to be necessary to properly take into account the observations (D’Alessio et al. 1998, 1999).

Many observers interpret the SEDs assuming that the disk is geometrically thin with simple power law dependencies versus radius for the surface density ($\Sigma(r) = \Sigma_0 (r/r_0)^{-p}$) and the temperature ($T_k(r) = T_0 (r/r_0)^{-q}$). This in case, there is no assumption about the origin of the heating mechanism, and the results are compared to more sophisticated models similar to those described above.

Dust disks are usually optically thick up to $\lambda \sim 100 - 200 \mu$m, allowing us to trace the disk temperature. In active disks as in passive geometrically thin disks, the radial dependence of the temperature follows $T_k(r) \propto r^{-0.75}$. Beckwith et al. (1990) have found that typical temperature laws encountered in T Tauri disks are more likely given by $\propto r^{-0.65 - 0.75}$. However Kenyon & Hartman (1987) have shown that for a flaring disk, the temperature profile should be as shallow as $q = 0.5$, closer to the observed values.

2.3. The dust content

Longward of $\sim 100 \mu$m wavelength, the dust emission becomes optically thin. Observations, at these wavelengths, are well explained by a dust absorption coefficient following $\kappa_\nu = \nu$.
$\kappa_\nu (\nu/10^{12}\text{Hz})^\beta$ with $\beta \simeq 0.5 - 1$ and $\kappa_o = 0.1 \text{cm}^2\text{g}^{-1}$ of gas + dust (with a gas to dust ratio of 100, Beckwith et al. 1990). The spectral index is significantly lower than in molecular clouds where $\beta \simeq 2$. Compared to values found in molecular clouds, both $\beta$ and $\kappa_o$ show that a significant fraction of the grains have evolved and started to aggregate (Henning & Stognienko 1996, Beckwith et al. 2000), grains may even have fractal structures (Wright 1987). Dust encountered in protoplanetary disks seems to be a mixture of silicate and amorphous carbon covered by icy mantles (Pollack et al. 1994). The exact composition is poorly known, recent VLT observations of broad-band absorption features in the NIR start to put quantitative constrains on solid species located on grain mantles such as CO or H$_2$O (Dartois et al. 2002, Thi et al. 2002). These results also confirm that many molecules may have condensed from gas phase on grains (see also Section 2.4 and 3) in the cold ($\sim 20 - 15 \text{K}$) outer part of the disk. Very close to the star, the dust mantles may be significantly different since the disk is hotter ($\sim 1000 \text{K}$ at 0.1 AU).

Optical/NIR interferometry is a powerful tool to trace the very inner disk. Monnier & Millan-Gabet (2002) have observed several disks around TTauri and Herbig Ae/Be stars. They found that the observed inner disk sizes ($r_{in} \sim 0.1 \text{AU}$) of TTauri stars are consistent with the presence of an optically thin cavity for a NIR emission arising from silicate grains of sizes $\alpha \geq 0.5 - 1 \mu\text{m}$ and which are heated close to their temperature of sublimation.

At NIR and optical wavelengths, small dust particles also scatter the stellar light impinging the disk surface, producing reflection nebulas imaged by optical telescopes. Fig.4 shows, in false color, the HH30 disk seen edge-on which appears as a dark lane. The star ejects a jet perpendicular to the disk plane and is highly obscured by the material along the line-of-sight (visual extinction up to $A_{\nu} \geq 30 \text{mag}$). Only the disk surface or atmosphere (Chiang & Goldreich 1997) is seen. Due to the high opacity, these data cannot allow us to estimate the dust mass distribution without making a priori (or external) assumptions about the vertical distribution. However, grains of typical size around $\alpha \sim 0.05 - 1 \mu\text{m}$ are responsible for scattering (Close et al. 1998, Mac Cabe et al. 2002). Since forward scattering is easier to produce than the backward scattering (e.g., GG Tau, Roddier et al. 1996), the disk inclination usually provides simple explanation for the observed brightness asymmetry.

Estimating the gas and dust mass of these disks is done by several methods (see also Section 2.4) but is quite uncertain. Analyzing the SEDs in the optically thin part of the spectrum leads to TTauri disk masses (gas+dust) ranging from 0.1 to 0.001 $M_{\odot}$ (Beckwith et al. 1990). These determinations suffer from many uncertainties such as the value of $\kappa_o$ and the gas-to-dust ratio which is usually assumed to have its interstellar value of 100. Moreover, the inner part of the disk is still optically thick (up to radii of $\sim 10 - 30 \text{AU}$ at 3mm). Resolved images of the thermal dust emission obtained with mm arrays allow a separation of possible opacity and spectral index effects. This procedure also estimates the surface density radial profile $\Sigma(r) = \Sigma_0(r/r_0)^{-p}$. Typical values of $p$ are around $1 - 1.5$ (Dutrey et al. 1996). Such low values imply that the reservoir of the mass is in the outer disk traced by sub-mm images. Assuming a single surface density distribution from 0.1 to 500 AU, a disk with $p = 1$ has only 10% of its mass located within $r = 10 \text{AU}$ while with $p = 1.9$, the same disk has 50% of its mass within the same radius.

In summary, a significant fraction of the grains in protoplanetary disks appears to be more evolved than in molecular clouds and coagulation processes have already started. The vertical dust distribution is however not yet constrained. Moreover, observations at a given frequency are mainly sensitive to grains of size $\alpha \leq \text{a few } \lambda$ (absorption or diffusion cross-sections cannot significantly exceed the geometrical cross-section, even for more complex grain features and aggregates, Pollack et al. 1994, Krügel & Siebermorgen 1994). Only multi-wavelength analysis of resolved images, from the optical to the cm domains, should allow to conclude about the dust sedimentation. Estimating the mass of the disks remains difficult. However, continuum mm images suggest that the reservoir of mass is located at large distance $r \geq 30 - 50 \text{ AU}$. Using a gas-to-dust ratio of 100, analyzes of the dust emission indicate that the total (dust+gas) disk masses are in the range 0.001 to 0.1 $M_{\odot}$.

2.4. The Gas Content

In protoplanetary disks, molecular abundances are defined with respect to H$_2$ since this is the main (gas) component and the gas-to-dust ratio, which is not yet measured, is assumed to be 100, as in the molecular clouds. Several groups (Thi et al. 2001, Richter et al. 2002) have recently started direct investigation of H$_2$ (which only possesses quadrupolar moment) but the most-used tracer of the gas phase remains CO.

Carbon monoxide is the most abundant molecule after molecular hydrogen. Its first rotation lines are observable with current mm interferometers allowing astronomers to trace the properties of outer gas disks. Current sensitivity of mm arrays is limited and does not allow the observation of CO lines for $r \leq 30 - 50 \text{AU}$. Since the density is very high ($n(\text{H}_2) \geq 10^6 \text{cm}^{-3}$), the J=1-0 and J=2-1 CO lines are thermalized by collision with H$_2$ in the whole disk. Hence, a simple model of Keplerian disk assuming LTE conditions is sufficient to derive the CO disk properties (Dutrey et al. 1994). CO maps reveal that disks are in Keplerian rotation (Koerner et al. 1993) and that many disks in Taurus-Auriga clouds are large with typical radii $R_{out} \simeq 300 - 800 \text{AU}$ (see Simon et al. 2000, their Fig.1). Comparing resolved CO maps to disk models by performing a $\chi^2$ minimization of the disk parameters (Guilloteau & Dutrey 1998, see their Fig.1) provides very useful information about the density and temperature distributions. The temperature radial profiles deduced from $^{12}\text{CO}$ images are consistent with stellar heating in flared disks and the turbulence appears to be small, less than 0.1 km.s$^{-1}$ (Dutrey et al. 2004). Since the $^{12}\text{CO}$ and $^{13}\text{CO}$ J=1-0 and J=2-1 have different opacities, they sample different disk layers. A global analysis of these lines permits one to derive the vertical temperature gradient. Dartois et al. 2003 have shown that in the DM Tau disk, the “CO disk surface”, traced by $^{12}\text{CO}$, is located around $\sim 3\mathcal{H}$ above the disk mid-plane, the $^{13}\text{CO}$ J=2-1
samples material at about 1 AU while J=1-0 is representative of the disk mid-plane. They also deduce a vertical kinetic gradient which is in agreement with disk models (e.g. D'Alessio et al. 1999), the mid-plane is cooler (∼ 13 K) than the CO disk surface (∼ 30 K at 100 AU). This appears in the region of the disk where the dust is still optically thick to the stellar radiation while it is already optically thin to its own emission, around r ∼ 50 – 200 AU in the DM Tau case. Beyond r ≥ 200 AU where the dust becomes optically thin to both processes, the temperature profile appears isothermal vertically.

A significant fraction of the DM Tau disk has a temperature below the CO freeze out point (17 K) but there remains enough CO in the gas phase to allow the J=2-1 line of the main isotopologue to be optically thick. The chemical behavior of molecules and coupling between gas and dust are poorly known. There have only been a few attempts to survey many molecules in protoplanetary disks (Dutrey et al. 1997, Kastner et al. 1997, Zadelhoff et al. 2001). Today, in addition to 13CO and C18O, only the more abundant species after the carbon monoxide are detectable, like HCO+, CS, HCN, CN, HNC, H2CO, C2H and DC2O. By studying the excitation conditions of the various transitions observed in the DM Tau disk, Dutrey et al. (1997) deduced molecular abundances indicating large depletion factors, ranging from 5 for CO to 100 for H2CO and HCN, with respect to the abundances in the TMC1 cloud. They also directly measured the H2 density; the total disk mass they estimated is a factor 7 smaller than the total mass measured from the thermal dust emission. Both results suffer from several uncertainties, only a more detailed analysis will allow one to conclude that the gas-to-dust ratio is lower than 100, even if such a behavior is expected.

Due to limited sensitivity, the chemistry of the gas phase in the inner disk is poorly constrained (Najita et al. 2000). Models of nebulae irradiated by stellar radiation, including X ray emission, suggest a complex chemistry (Glassgold et al. 1997), even at relatively large radii (r ≥ 50 AU, Najita et al. 2001).

Fig 1 summarizes the observable properties of a protoplanetary disk encountered around a TTauri star of 0.5 M⊙ and located at a distance of 150 pc.

2.5. Illustration through HH 30

The HH 30 observations, shown Fig 2, give one of the most complete pictures of the material surrounding a PMS star. Optical and mm observations are clearly tracing the same physical object. In Fig 2 the HH30 dust disk observed in the optical by the HST (Burrows et al. 1996) is close to edge-on and appears as a dark lane, only the disk surface or atmosphere is bright. The jet emission is also seen, perpendicular to the disk plane. Pety et al. (2003) have superimposed in contours to this image the blueshifted and redshifted integrated emission (with respect to the systemic velocity) of the 13CO J=2-1 line in the disk. The CO disk extends as far as the dust disk and the velocity gradient is along the major disk axis, as expected for rotation. 12CO J=2-1 emission is also observed within the jet (extreme velocity). In the HH 30 case the low angular resolution of the data does not allow one to separate between the 12CO J=2-1 emission associated to the outflow, the cloud and the disk. This is a common problem which cannot be fully solved by current interferometric observations. Selecting sources which are located in a region devoid of CO emission of the molecular cloud minimizes the confusion.

Since the disk is seen edge-on, the vertical distribution can be estimated from the optical observations of the dust (Burrows et al. 1996). The results are somewhat model dependent but one can conclude that the disk is pressure supported (dominated by the central star) with the best fit given by H(r) ∝ r1.45. The authors estimate the surface density law to be Σ(r) ∝ 1/r and the disk mass ∼ 6.10^{-5} M⊙. CO observations reveal that the disk is in Keplerian rotation around a central star of mass 0.5 M⊙ and has an outer radius of R_out = 440 AU. Interestingly, this is in agreement with the best fit of the optical data which gives R_out ∼ 400 AU.

2.6. Proplyds

The disks we described have so far are found in low-mass star forming regions such as the Taurus-Auriga clouds. Physical properties of disks surrounding low mass-stars born inside...
3. Disks around intermediate-mass stars: The Herbig Ae/Be stars

With masses in the range 2-8 $M_\odot$, Herbig Ae/Be (HAeBe) stars, massive counterparts of TTauri stars, are the progenitors of A and B Main Sequence stars. Since they are more luminous and massive than the TTauri stars, the surrounding material is submitted to stronger UV and optical stellar flux.

Several Herbig Ae stars are isolated but located in nearby star forming regions (Taurus, R Oph); their observed properties can be directly compared with those of TTauri stars. This is not the case for Herbig Be stars because most of them are located at larger and uncertain distance ($D \geq 500-800$ pc). Therefore, we will discuss in this section mainly isolated Herbig Ae stars.

Like TTauri stars, SEDs of HAeBe stars exhibit strong IR excesses. Optical and NIR observations (Grady et al. 1999) reveal that many of these objects are surrounded by large reflection nebulae (e.g. more than 1000 AU large for the A0 star AB Auriga) revealing envelopes or halos (Leinert et al. 2001). There is however now clear evidences that Herbig Ae stars are also surrounded by disks. In particular, resolved CO maps from mm arrays reveal that the circumstellar material is also in Keplerian rotation (e.g. MWC480, an A4 star: Manning et al. 1997 and HD 34282, an A0 star: Pietu et al. 2003). Millimetre continuum surveys also suggest that the total surrounding mass may have a tendency to increase with the stellar mass (see Natta et al. 2000, Fig.1). So far, one of the more massive Keplerian disk ($\sim 0.11 M_\odot$) has been found around an A0 Herbig Ae star: HD 34282 (Pietu et al. 2003).

Since the medium is hotter than for TTauri stars, one would expect different behavior and in particular a rich chemistry. The limited sensitivity at present of molecular surveys at mm wavelengths does not allow one to distinguish significant differences and outer disks ($r \geq 50$ AU) of Herbig Ae stars appears similar to "cold" outer disks found around TTauri stars.

However, most of the differences should appear in the warm material, closer to the star. Optical/NIR interferometric observations by Monnier & Millan-Gabet (2002) revealed that the observed inner radius of disks is usually larger for HAeBe stars than for TTauri stars. This is understood in term of truncation by dust sublimation close to the star. They also found that grain sizes are about similar for TTauri and HAeBe stars. Dullemond et al. (2001) have shown that direct irradiation of Herbig Ae disks at their inner radius can explain the bump observed at IR wavelengths in the SEDs of Herbig Ae stars. In a few cases, as for HD 100546, direct detection of H$_2$ with FUSE (Lecavelier et al. 2003) reveals the existence of warm ($T \sim 500$ K) molecular gas close to the star ($r \sim 0.5 - 1$ AU).

The fact that HAeBe stars are hotter has also favored the use of ISO to characterize the geometry and the dust composition of the disk close to the star. Bouwman et al. (2000) have performed a detailed spectroscopic study from 2 to 200 $\mu$m of the circumstellar material surrounding AB Auriga (A0) and HD 163296 (A1). Their analysis of the SEDs, assuming an optically thin dust model, has revealed the existence of both hot ($T \sim 1000$ K) and cold ($T \sim 100$, most of the mass) dust components while the NIR emission at 2$\mu$m can be explained the presence of metallic iron grains. As in TTauri disks, substantial grain growth has occurred, with grain size up to $\sim 0.1-1$ mm. It is also important to note that comparisons of the ISO spectrum of the Herbig Ae star HD 100546 with those of the comet Hale-Bopp have revealed many similarities (Waelfken et al. 1999).

3.1. MWC 480: similarities and differences with a TTauri disk

MWC 480 is located at $D = 140$ pc, in Auriga cloud. CO observations by Manning et al. (1997) have revealed that the surrounding disk is in Keplerian rotation around an A4 star (Simon et al. 2000). The disk is large ($R_{\text{out}} \sim 600$ AU) and inclined by about $35^\circ$ along the line of sight. The stellar mass is around $\sim 2 M_\odot$. The temperature deduced from the optically thick $^{12}$CO J=2-1 line (which probes about 3 scale heights above the disk mid-plane) is $T \sim 60$ K at $R = 100$ AU, this is significantly larger than the temperature of $\sim 30$ K found for TTauri disks using the same tracer. Interestingly, the disk is not detected in the NIR in scattered light. From the non-detection, Augereau et al. (2001a) have deduced that either the dust emission at 1.6 $\mu$m is too optically thin to be detected or there is a blob of optically thick material close to the star which hides the outer disk to the stellar radiation. Knowledge of the disk scale height is required to decide between these possibilities.

The existence of such blobs is also favored by SED models of several Herbig Ae stars (Meeus et al. 2001, their Fig.8).

NIR and CO/mm detections are not necessarily linked; the TTauri DM Tau has the best known disk at mm wavelengths but the disk was only recently detected in the NIR by performing deep integration with the HST (Grady et al. 2003). Keeping in mind, the MWC480 disk appears very similar to a TTauri disk, at least for the outer part ($r \geq 50$ AU).

3.2. The UX Ori phenomenon

Some HAeBe stars, such as UX Orionis, have a very complex spectroscopic, photometric and polarimetric variability which has been, in some cases, monitored for years. The variability has usually a short periodicity of order $\sim 1$ year and can be as deep as two magnitudes in the V band.

It is very tempting to link this phenomenon to planetary formation; the variability could be caused by clumps of material (such as clouds of "proto comets"), located in the very inner disk and orbiting the star. Natta & Whitney (2000) have developed a model in which a screen of dust sporadically obscures the star, this happens when the disk is tilted by about $45^\circ - 68^\circ$ along the line of sight. One clearly needs more sensitive multi-
wavelength data at high angular resolution on a large sample of Herbig Ae stars to distinguish among the various models.

4. From Protoplanetary to Planetary Disks

On one side, one finds massive *gaseous* protoplanetary disks surrounding T Tauri and Herbig Ae stars and on the other, one finds *dusty* protoplanetary disks around young MS stars. A natural question is then: *are there disks in an intermediate state and if so, what are their observational characteristics?*

Limited in sensitivity by current telescopes, we know only a few examples of objects which can be considered as “transitional disks.”

4.1. The surprising case of BP Tau

BP Tau is often considered as the prototype of CTTS. It has a high accretion rate of $\sim 3 \times 10^{-8} M_\odot/yr$ from its circumstellar disk which produces its strong excess emission in the ultraviolet, visible and NIR (Gullbring et al. 1998). It is also very young ($6 \times 10^4$ yr, Gullbring et al. 1998). Despite these strong CTTS characteristics, its mm properties are very different than those of other T Tauri stars surrounded by CO disks.

Recent CO J=2-1 and continuum at 1.3mm images from the IRAM array have revealed a weak and small CO and dust disk (Simon et al. 2000). With a radius of about $\sim 120$ AU, the disk is small and is in Keplerian rotation around a $(1.3 \pm 0.2)/(D/140pc) M_\odot$ mass star. A deeper analysis of these CO J=2-1 data (Dutrey et al. 2003) also shows that the J=2-1 transition is marginally optically thin, contrary to what is observed in other TTauri disks. The disk mass, estimated from the mm continuum emission by assuming a gas-to-dust ratio of 100, is very small $1.2 \times 10^{-3} M_\odot$, a factor 10 below the minimum initial mass of the Solar Nebula, for comparison. By reference to the mass deduced from the continuum, the CO depletion factor can be estimated; this leads to a factor as high as $\sim 150$ with respect to H$_2$. Even taking into account possible uncertainties such as a lower gas-to-dust ratio or a higher value for the dust absorption coefficient, the CO depletion remains high compared to other CO disks. Finally, the kinetic temperature derived from the CO data is also relatively high, about $\sim 50$ K at 100 AU.

Both the relatively high temperature and the low disk mass suggest that a significant fraction of the disk might be superheated (above the black body temperature) similarly to a disk atmosphere (e.g. Chiang & Goldreich 1997, see also Section 2). With reasonable assumptions for the dust grain properties and surface density, one can then estimate the fraction of small grains ($a \approx 0.1 \mu m$) still present in the disk to reach in the visible $\tau_V = 1$ at the disk mid-plane. Since it corresponds to a total mass of small grains of about 10% of the total mass of dust ($1.2 \times 10^{-5} M_\odot$) derived from the mm continuum data, this is not incompatible with the current data but should be confirmed by optical and NIR observations.

It is also interesting that the CO content of BP Tau is too high to result from evaporation of proto-comets (Falling Evaporating Body or FEB model, see also Section 5 where ). Considering the total number of CO molecules in the disk and the CO evaporation rate of an active comet such as Hale-Bopp, a few times $10^{11}$ large comets similar to Hale-Bopp would be simultaneously required to explain the amount of CO gas present in the BP Tau disk. This is well above the number of FEBs falling on $\beta$ Pic per year (a few hundred).

Taken together, the unusual mm properties suggest that BP Tau may be a transient object in the phase of clearing its outer disk.

4.2. The ambiguous case of HD 141569

HD 141569 is a B9 star located at $\sim$100 pc. The position of the star close to the ZAMS in the HR diagram and the presence of an IR circumstellar excess lead many authors to classify it an HAeBe star. This was reinforced by the presence of circumstellar gas latter on detected by Zuckerman et al. (1995) and by the identification of emission features tentatively attributed to PAH (Sylvester & Skinner 1996 and ref. therein) which are frequently observed in SEDs of HAeBe (e.g. Meeus et al., 2001). But, the lack of excess in the NIR, the lack of photometric variability, the faint intrinsic measured polarimetry (Yudin 2000), and importantly, the low disk to star luminosity ratio ($8.4 \times 10^{-5}$) rather correspond to the description of a Vega-like star. Both HAeBe and Vega-like classes show a large spread of ages. With an age of 5 Myr (Weinberger et al. 2000), HD 141569 falls at the common edge of the two categories.

HD 141569 is among the few stars showing a spatially resolved optically thin dust disk in the NIR. Contrary to the $\beta$ Pictoris disk, the inclination of the HD 141569 disk on the line of sight offers the opportunity to investigate both the radial and azimuthal profiles of the dust surface density in great detail. Using coronagraphic techniques, the HST identified a complex dust structure seen in scattered light of about ten times our Kuiper Belt size ($\sim 500$ AU) (Augereau et al., 1999). Mid-IR thermal emission observations only partly compensate the lack of constraints on the innermost regions ($<1''=100$ AU) masked by the HST coronagraph (Fisher et al., 2000). Both data help to sketch out the overall dust distribution as summarized in Fig.4 from March et al. (2002). The dust appears depleted inside $\sim 150$ AU compared to the outer regions. The outer disk has a complex shape dominated by two non-axisymmetrical and not accurately concentric wide annuli at 200 and 325 AU (Mouillet et al., 2001), respectively. Interestingly, the furthest ring is made of grains smaller than the blow-out size limit which theoretically points out on the presence of cold gas in the outer disk (Boccaletti et al., 2003). Surprisingly, an arc radially thin but azimuthally extended over $\sim 90^\circ$, is located at about 250 AU, precisely between the two major ring-like structures. These informations on the disk morphology are very valuable because they indicate the impact of internal (planets?) and/or external gravitational perturbations (stellar companions?, Augereau & Papaloizou 2003a).

The detection of a substantial amount of cold gas associated with an optically thin dust disk is also unusual (Zuckerman et al., 1995). Recent millimetre interferometric observations of HD 141569 reveal the gaseous counterpart of
the extended disk resolved in scattered light (Augereau et al. 2004, Fig. 3). The CO gas in rotation shows a velocity gradient consistent with the major axis of the optical disk. Interestingly, hot gas (CO) is also detected by high resolution mid-IR spectroscopy revealing the gaseous content of the inner disk (Brittain & Rettig 2002), at a few tens of AU’s from the stars.

The HD 141569 disk possesses NIR properties close to those of the β Pic disk and also Mid-IR and mm properties close to those of an Herbig Ae disk; as such it seems reasonable to consider it as a transition disk.

4.3. The puzzle of Weak Line TTauri Stars

Weak Line TTauri stars (wTTs) have a SED which presents a weak IR excess and unlike to CTTs, they do not exhibit strong optical emission lines (with $W_{H\alpha} \leq 10$ Å). As such, they are usually considered as the evolved counterpart of the CTTs stars and are classified as class III objects surrounded by optically thin NIR disk (of a few $\sim 10^5$ yr).

However, several studies show that a significant fraction of the wTTs have ages of same order than those of CTTs (Stahler & Walter 1993, Grosso et al. 2000). Among them, one interesting example is the case of V836 Tau: this star presents the optical properties of wTTs star and in the meantime its mm characteristics are very similar to those of BP Tau since it is also surrounded by a compact CO disk (Duvert et al. 2000). Its observed properties are very similar to those of the BP Tau disk. More recently, Bary et al. (2002) have reported H$_2$ detection around DOAr 21, a wTT located in ρ Oph which is even more puzzling.

We have only a few examples of transition disks and each of them exhibits very different properties which are also depending on the observational approach (optical versus mm/submm observations). This clearly demonstrates that only multi-wavelengths studies can allow to retrieve the physical properties of these objects. The scenario by which massive disks dissipate and may form planets is poorly constrained today.

5. Planetary Disks

Since the lifetime of massive protoplanetary disks is observed to be less than a few $\sim 10^7$ years, we a priori should not expect disk structure beyond that age. As circumstellar disks evolve, their mass decreases. When the disks dissipate, the material become less bright, less dense and apparently more difficult to detect. IR excess detection of material around nearby main sequence stars (Auman et al. 1984) leads to the conclusion that the lifetime of the thin disks is longer than that of massive disks. The time spent at these late stages being longer, gives the opportunity to detect evolved disks in the solar neighborhood (less than $\sim 100$ parsecs) around stars older than few $10^7$ years. These disks are less dense than protoplanetary disks, but their proximity allows us to observe them in great detail. The disks seen around main sequence stars are now believed to be the visible part of more massive systems in which most of the mass is kept in the form of planetesimals and even planets. There, planetary formation is either at the end or already finished (Lagrange et al. 2000).

The duration of the “planetary disk” phenomenon is so long (see below) that obviously they are by nature not the remaining material of the protoplanetary disks. It is now clear that these “planetary disks” has been replenished with material from a pre-existing reservoir. As we will see below, the basic process needed to sustain these disks is based on the release of dust and/or gas by colliding asteroids and/or by evaporating planetesimals. These disks are thus also described as ‘debris disks’ or ‘second generation disks’.

5.1. Dust in Planetary disks

First detected by IRAS through its infrared excess, the dust component of planetary disks is the easiest part to detect. The spectral energy distribution of main sequence stars with circumstellar material shows infrared excess above $\sim 10\mu$m from which it is possible to have some indication on the dust size, spatial distribution, total mass or simply information on the fraction of stars harboring such planetary disks (Backman & Paresce 1993). More recent ISO surveys of nearby stars show that about 20% of the stars have infrared excess attributed to circumstellar material (Dominik 1999) with typical lifetime of about 400 million years (Habing et al., 1999, 2001).

For an extremely small fraction of these disks, it is possible to image the dust. These images are produced by the scattered light at visible wavelengths, or by images of the infrared thermal emission of the warm part of the disk at 10 or 20 μm. The first historical image of such disk was the image of the disk of β Pictoris obtained with coronographic observations of the scattered light (Smith & Terrile 1984). Imaging is difficult; indeed β Pic remained the only disk imaged (see e.g. Lecavelier des Etangs et al., 1993; Kalas & Jewitt, 1995; Mouillet et al., 1997a; Heap et al. 2000) until the late 90’s when new instruments allowed observers to image few other disks by the detection of the scattered light (Schneider et al., 1999; Fig. 4) or by the detection of the thermal emission in the infrared (around HR 4796; Jawardhana et al., 1998; Koerner et al., 1998) or in the sub-millimeter (images of Vega, Fomalhaut and β Pic have been obtained by Holland et al., 1998, and of ε Eridani by Greaves et al., 1998).
Kalas & Jewitt 1995). Images revealed unexpected properties, like the presence of a break at ~120 AU in the radial distribution of the dust, the warp of the disk plane, and various asymmetries. All asymmetric features are often attributed to gravitational perturbation of massive bodies such as Jupiter-mass planets (Lecavelier des Etangs et al., 1996; Lecavelier des Etangs, 1997b; Augereau et al., 2001).

The most intriguing characteristic of the inner part of the β Pic disk is the so-called ‘warp’, which consists of a change of the inclination of the mid-plane of the disk inside about 80 AU. This warp is explained by the presence of a planet on an inclined orbit with the same inclination as the tilt of the inner disk (Mouillet et al., 1997b). The measured warp distance allows to constrain $M_p \times D_p^2$ where $M_p$ and $D_p$ are the mass and the distance of the perturbing planet. In the case of β Pic we have $M_p \times D_p^2 \approx 2 \times 10^{-3} M_\odot (10 \text{AU})^2 (t/10^7 \text{yr})^{-1}$. If the age of the system is $t \sim 2 \times 10^7$ years (Barrado y Navascues et al. 1999), then a Jupiter mass planet at 10 AU and inclined by 5 degrees from the disk plane can easily explain the observed warp.

Similarly, in the case of HR 4796, sharp truncation of the ring structure is observed (Fig. 4; Schneider et al., 1999). The presence of a ring is expected to shed light on the physical phenomena occurring at typical places where planets are supposed to form. However there is still not a general agreement on the interpretation of this truncation which could be produced by the gravitational perturbations of a planet (e.g., Wyatt et al., 1999) or by drag of the dust by the gas component of the disk (Klahr & Lin, 2001; Takeushi & Artymowicz, 2001).

A key point concerning disks around main sequence stars is that the dust life-time is shorter than the age of these systems (see Fig. 8 p.206, Artymowicz, 1997). In the β Pic disk, dust particles are destroyed by collisions between grains which produce submicronic debris quickly eliminated by the radiation pressure. In the less dense disks like the e Eri ring (Greaves et al., 1998), the Pointing-Robertson drag is the dominant process which also eliminates the dust on time-scale shorter than the disk age. As the dust life-time is very short, one must consider that the observed dust is continuously resupplied (Backman & Paresce 1993). It is generally thought that the “debris” disks are substantial disks of colliding planetesimals (see Backman et al. 1995 for an analogy with collision in the Solar system Kuiper belt). These disks can thus be considered as the signature of complete planetary systems which, like our own Solar system, contain interplanetary dust, asteroid-like kilometer-sized bodies, and, probably, comets and planets. The visible part of these disks is only the fraction of material having the largest cross section, showing the presence of invisible but more massive objects.

5.2. Gas disks around main sequence stars

Although apparently more difficult to interpret, the gas component of the planetary disks gives the opportunity of the most detailed modeling of circumstellar processes. In particular, the β Pic spectroscopic variability is now well explained in many details by the evaporation of cometary objects close to the star (see Sect. 5.3).

In contrary to emission from more massive disks, emission lines from the gaseous planetary disks are, in most cases, below the detection limit of current instruments. Molecular transitions at millimeter wavelengths are too faint to be detected. They give only upper limits on the gas content (Dent et al. 1995, Liseau 1999). Detections of infrared emission of $H_2$ at 17 and 28 µm have been claimed with ISO around main sequence stars (Thi et al., 2001a, 2001b). However these detections have been challenged by ground based observations at 17 µm which show no detection with three times better sensitivity (Richter et al., 2002). FUSE observations also showed that if the ISO detection of $H_2$ emission around β Pic is real, then this $H_2$ is not distributed widely throughout the disk (Lecavelier des Etangs et al., 2001). The HST detection of $Fe \ II$ emission lines in the disk of β Pic is marginal and still to be confirmed (Lecavelier des Etangs et al. 2000). Finally, the only strong detection of emission from the gaseous component in a planetary disk has been performed by Olofsson et al. (2001). With high-resolution spectroscopy of the β Pic disk, they clearly detected the resonantly scattered sodium emission through the Na I doublet line at 5990 and 5996 Å. The gas can be traced from less than 30 AU to at least 140 AU from the central star. Unfortunately, this observation remains unique. This definitely opens a new field of observation with an original technique.

Although emission spectroscopy of tenuous gas disks is difficult, absorption spectroscopy is much more sensitive. In planetary disks seen nearly edge-on, the central star can be used as a continuum source, and the detection of absorption lines offers the opportunity to scrutinize the gaseous content in details.

Few months after the discovery of the dust disk around β Pic, its gaseous counterpart was discovered through the Ca II absorption lines (see Fig. 5; Hobbbs et al., 1985; Vidal-Madjar et al., 1986). Because one absorbing component is seen identically in all observations and at the same radial velocity as the star (20 km s$^{-1}$), it is named the “stable” gas component. This stable gas is composed of small amounts of neutral sodium and...
iron, as well as large amounts of singly ionized species like Ca II, Fe II, Mg II, Mn II, Al II. The overall composition is close to solar (Lagrange et al. 1998). Ultraviolet spectroscopy leads to the detection of two very peculiar elements: C I and the CO molecule, which both have short life-time. In the other hand, the OH molecule was not detected with a relatively tight upper limit (Vidal–Madjar et al. 1994). The numerous electronic transitions of CO in the ultraviolet give constrains on the column density, temperature (∼ 20 K) and a very unusual isotopic ratio $^{12}$CO/$^{13}$CO=15±2 (Jolly et al., 1998; Roberge et al., 2000).

Circumstellar gas signatures similar to the β Pic ones are also seen around some other main sequence stars. It should be noticed however that in the rare cases where a Ca II (or e.g., Fe IIi) line at the star radial velocity has been detected toward other stars like HR 10, these stars have been identified because they also show either spectral variability, or the presence of over-ionized species, or redshifted optically thick absorption lines. This lack of detection of only the circumstellar absorption at the systemic velocity may be due to possible confusion with the interstellar medium. The first main sequence star discovered to have a very similar spectroscopic behavior as β Pic is HR 10 (Lagrange et al. 1990). This star shows variable redshifted or blueshifted absorption lines (Lagrange et al., 1990; Welsh et al., 1998), and a central component seems relatively stable. Very highly excited levels of Fe II have been detected, proving that the gas is not interstellar but circumstellar. Redshifted optically thick lines of Mg II have also been detected and interpreted as small clouds of excited gas falling toward the star (Lecavelier et al., 1998).

51 Oph is an interesting case because circumstellar dust is present simultaneously with the gas: 51 Oph presents a complex system with dusty infrared excess due to cold dust, silicates emission features, absorption lines by overionized species (Grady & Silvis 1993), Fe II at excited levels, abnormal Mg II ratio, and finally a possible detection of C I in the circumstellar gas (Lecavelier des Etangs et al., 1997b). Links between these gas and dust features have still to be understood.

5.3. The β Pic disk: a cometary disk

The β Pic disk has certainly been the most fruitful for surprises and discoveries. In addition to the gaseous stable component, variable absorption features have been detected and surveyed since 1984 (Fig. 5). Slowly variable features are most of the time confined to one or two components redshifted by 10 to 30 km s$^{-1}$ relative to the star. Although such structures seem to be changing in both velocity and strength (by about ± 10 km s$^{-1}$ and large factors in strength), they nevertheless remain very comparable during few consecutive hours, often from one day to the next and even sometime over weeks.

Some other components present strong variability, in particular in the Mg II and Al III lines. These components are also observed in the Ca II and Fe II line as weak and broad absorptions spread over few tens of km s$^{-1}$. The changes are observed on very short time scale, hours or even less. These features are mostly strongly redshifted, with shifts that could reach 300 to 400 km s$^{-1}$. These highly varying features were detected only in ionized species, including highly (over-)ionized ones like Al III and C IV completely unexpected in such a relatively “cool” stellar environment. The rapid changes make these features difficult to track.

These spectral variations are interpreted with a scenario of star-grazing comets. The presence of strong redshifted ionized gas is difficult to understand, since the very high radiation pressure should expel it very quickly. The variable absorption lines are almost always redshifted, although blueshifted ones would have been expected. The gas must then be injected with very high inward radial velocity. There is only one simple way to produce this situation, namely the evaporation of grains moving toward the star. Since the radiation pressure acts on grains, they must be injected with high velocity, through the evaporation from more massive bodies for which the gravitation is much larger that the radiation force. This model has been developed in great detail (Beust et al. 1990, 1991a, 1991b), and can be summarized by ‘evaporation of star-grazing comets’. Indeed, the strong variability in the circumstellar lines of the ionized elements like Fe II, Al III, C IV and Mg II is now at-

![Image](image-url)
tributed to the evaporation of kilometer size, “cometary-like” bodies falling toward the star: this is the Falling Evaporating Bodies (FEB) scenario. The over-ionized variable species Al III and C IV cannot be produced by photoionization, but Beust and Tagger (1993) showed that they can be formed by collisional ionization in the coma surrounding these Falling Evaporating Bodies.

Among the different phenomena that can be explained by this model, one can stress on the observation of abnormal ratio in doublet lines. For example, although the Mg II doublet has an intrinsic oscillator strength ratio of two, the measured ratio is exactly one, even for unsaturated lines (Vidal-Madjar et al. 1994). This proves that the absorbing gas cloud is optically thick (ratio equals to one) but does not cover the total stellar disk (lines are not saturated). This behavior is directly explained by the FEB model which produces clumpiness of the absorbing clouds (Beust et al. 1989). Similar ratios have also been detected in redshifted absorptions toward other β Pic-like stars.

With several hundreds of FEBs per year, the frequency is several orders of magnitudes higher than that of sungrazing comets in the solar system. Planetary perturbations are thought to be the process responsible. Direct scattering by close encounters with a massive planet does not seem to be efficient unless the planet eccentricity is very high (Beust et al. 1991b). Beust & Morbidelli (1996) proposed a generic model based on a mean-motion resonance with a single massive planet on a moderately eccentric orbit (e ≃ 0.05). Indeed, a test particle trapped in the 4:1 resonance with such a planet becomes star-grazing after ≃ 10000 planetary revolutions. This model explains not only the preferred infall direction but also the radial velocity-distance relation observed in the FEBs.

Many other stars show redshifted absorption lines (HR 2174, 2 And, etc.). All these detections of redshifted absorption lines raise the question of the explanation for the quasi-absence of blueshifted events. In the β Pic case, it is believed that the orbits of the star-grazing comets present always about the same angle to the observer (because the gas is seen in absorption against the stellar continuum in an edge-on disk). However, when observed on several stars, some blueshifted orientation should be expected. Given the very impressive fit between the β Pic observations and the FEB model, it is likely that the β Pic FEB phenomenon is somehow particular and that other stars present either real “infall” on the star or their evaporating bodies may be generally destroyed before they reach the periastron (Grinin et al. 1996). In the last case, the process needed to put these bodies on very eccentric orbits in less than one orbital time-scale remains to be found.

Another class of cometary-like object might also be present around β Pic. Collision of planetesimals are believed to continuously resupply most of the dusty disks around main sequence stars. In the case of β Pic, a significant part of the disk can be also produced by the evaporation of kilometer-sized bodies located at several tens of AU from the central star (Lecavelier des Etangs et al. 1996). Indeed, in the β Pic disk, CO evaporates below 120 AU from the star. If bodies enter that region, they start to evaporate and eject dust particles. These particles are subsequently spread outward in the whole disk by the radiation pressure. The distribution of their eccentric orbits gives a dust surface density similar to one observed around β Pic. This alternative scenario for the production of dust in the β Pic disk easily explains any asymmetry even at large distances, because a planet in the inner disk can have influence on the distribution of nearby parent bodies producing the dust spread outward (Lecavelier des Etangs, 1998).

The observed CO/dust ratio is another argument in favor of this scenario. An important characteristic of the β Pic disk is the presence of cold CO and C I (Vidal-Madjar et al. 1994, Roberge et al. 2000). CO and C I are destroyed by ultraviolet interstellar photons (extreme UV flux from the star is negligible). Like the dust, they have lifetime shorter than the age of the star (tCO-tCI≈200 years). A mechanism must replenish CO with a mass rate of $\dot{M}_{CO} \approx 10^{11}$kg s$^{-1}$. The corresponding dust/CO supplying rate is $M_{dust}/\dot{M}_{CO} \approx 1$. This is very similar to the dust/CO ratio in the material supplied by evaporation in the solar system. This provides an indication that the β Pic dust disk could be supplied by evaporating bodies orbiting at several tens of AU from the star like Chiron evaporates at dozen AU from the Sun.

5.4. Towards a global picture

Disks around main sequence stars are probably related to the presence of young planetary systems in a phase of strong activity. They show that the planetary systems are still active and evolve after their formation.

There are still many unknowns. This new field of astronomy is still a collection of different objects which do not correspond to an evolutionary scheme. A global picture is still to be built. It is clear that the extremely numerous names to qualify these disks which we selected to call the "planetary disks", show that there is not an unique understanding of the phenomenon. Some authors refer to "Vega phenomenon", often to qualify the infrared excess. "β Pic phenomenon" is even more confusing regarding the number of different phenomena observed around that star. "Kuiper-disk", "cometary disk", or alternatively "debris disk" refer to evidence concerning the different origins of these disks. It is not yet clear if the many pieces shown here correspond to the same puzzle. New observations and theoretical works will be needed to solve these issues in the next decade.

6. Observations in Future

The examples given in the previous sections clearly demonstrate that the frontier between the different classes of objects is not well constrained, partly because the statistics is still too poor to provide a quantitative understanding of some of the observed properties. Since very few disks have been resolved so far it remains very speculative to derive a timescale and a detailed evolutionary scheme from protoplanetary to planetary disks. Moreover, concerning the protoplanetary phase, our understanding is crudely limited to the cold outer disks ($r \geq 50$ AU).

Throughout this chapter, the several examples also show that only multi-wavelength studies of the observational proper-
ties will allow astronomers to properly incorporate in models the physical processes in action.

6.1. Challenge for protoplanetary / transition disks

In protoplanetary disks, most of the material lies in the relatively cold outer part of the disks. Hence, resolved sub-mm observations, obtained with large mm arrays such as ALMA, will provide the best tool to investigate this reservoir of mass ($r > 20 - 50$ AU). In particular, ALMA will observe large samples, allowing statistics on disk properties and frequency. Of course, to study the hotter inner disk, where planets form ($0.1 \geq r \geq 10$ AU), optical, NIR and Mid-IR interferometry techniques are required. As soon as they will be able to produce images (even with a few baseline numbers), instruments such as AMBER and MIDI on the VLTI or OHANA will add to our understanding of the dust properties and composition. Images (or a reasonable $uv$ coverage) are required to decide between all the existing models of dust disks, in particular they should allow us to disentangle between geometry, temperature and opacity effects. Fig.6 summarizes which part of disk can be investigated depending on the instrument in use. A combination similar of “ALMA & VLTI” would be very efficient to sample the global disk properties. A necessary step to understand how planets form is to view gaps created by protoplanets. For this purpose images are definitely required either at sub-mm or NIR wavelengths. In its large configuration, ALMA will have baselines up to 14 km, providing an angular resolution of $\approx 0.03''$ (or 4 AU at the Taurus distance) at $\lambda = 1.3\mu$m. Hydrodynamics coupled to radiative transfer simulations of the dust emission at 350 GHz by Wolf et al. (2002) show that ALMA will be able to resolve out a gap created by a proto-Jupiter and located at 5 AU from a star at D=150 pc. Concerning the gas content, in spectral lines near $\lambda = 1.3$mm, ALMA will be about 30 times more sensitive than the IRAM array and quantitative chemical studies could begin. Multi-transitions analysis would even allow observers to measure abundance gradients in the disk. Protoplanetary disks are indeed H$_2$ disks and direct investigation of the H$_2$ distribution and mass remains the more direct way to study how protoplanetary disks dissipate. This domain will strongly benefit from satellites such as SIRTF and JWST. Finally, the knowledge of protoplanetary disks is today biased by sensitivity and we image only the brighter disks. Disk clearing is poorly constrained. The ALMA sensitivity will allow to image in the sub-mm domain many other objects similar to BP Tau and even optically thin dust disks in the NIR.

6.2. Challenge for planetary disks

By extrapolation from ISO results on the occurrence of debris disks around MS stars and according to the Hipparcos catalogue, one can predict $\sim 10^2$ and $\sim 10^3$ planetary dust disks around (hypothetical) stars younger than about 0.5 Gyr within 20 pc and 50 pc radii of the Sun respectively. These stars are close enough to be not limited by angular resolution considerations but their disks are simply too tenuous to have a chance to be detected with current instruments. This points up a crucial need for an enhancement in sensitivity combined with high angular resolution techniques. Precise disks shapes, fine structures and asymmetries as revealed by imaging may indeed be signposts of undetected gravitational companions such as planets perturbing the underlying disk of km-sized bodies that release the observed short-lived dust.

The observational techniques discussed below are summarized in Fig.7. In the NIR, high contrast imaging with single aperture telescopes is required to detect faint dust disks very close to a bright star. For instance new generations of adaptive optics systems and new concepts of coronographic masks are under study with the prime goal of being able to detect faint objects from the ground, ideally down to planets (e.g. VLT/Planet Finder). At these wavelengths but also in the mid-IR, the innermost regions of planetary disks will nevertheless remain unreachable without the help of interferometry (e.g. KeckI and VLTI). Resolving the material within the very first AU around young MS stars and ultimately producing images by NIR and mid-IR interferometry are attractive challenges in the near future. In the mid-IR, single aperture telescopes suffer an unavoidable decrease of the spatial resolution. The predominant gain at these wavelengths will mostly come from future spaced-based telescopes, especially the 6-m JWST and SIRTF with increases of two or three orders of magnitudes in detection thresholds. While current high resolution imagers in the mid-IR are limited to disks around close-by stars younger than a few 10 Myr, JWST/MIRI should resolved debris disks around Gyr old A-type stars at 50 pc. In the mm, ALMA will permit the detection of an unresolved (but optically thin) clump of dust of $10^{-2} M_{\oplus}$ orbiting a star up to 100 pc from us in one hour of observing time (see also “ALMA science case”).

Gas will also certainly concentrate more and more observational efforts in order to provide a better understanding of its timescales and dissipation processes. Since the gas content of young planetary disks is yet badly constrained, anticipating

**Fig. 6.** This montage summarizes the observable properties of a protoplanetary disk encountered around a TTauri star located at 150 pc. This illustrates which region of the disk is sampled depending on the telescope in use.

![Figure 6](image-url)
future results might be very speculative. However, the ALMA sensitivity would allow to detect, in 1 hour of observing time, a CO column density of a few $10^{12} \text{cm}^{-2}$ in a beam of 2.5″ (planetary disks are close to us hence angularly extended) assuming a linewidth of 3 km/s. This is well below the CO column density of $10^{13}\text{cm}^{-2}$ detected by Vidal-Madjar et al. (1994) in β Pic. Depending on the gas geometry, the distance and the evolutionary status of the disk, ALMA would allow astronomers to put some important constrains on various gas model distributions in planetary disks.

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