High angular resolution millimeter observations of circumstellar disks

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Abstract

In this lecture we review the properties of protoplanetary disks as derived from high angular resolution observations at millimeter wavelengths. We discuss how the combination of several different high angular resolution techniques allow us to probe different regions of the disk around young stellar objects and to derive the properties of the dust when combined with sophisticated disk models. The picture that emerges is that the dust in circumstellar disks surrounding pre-main sequence stars is in many cases significantly evolved compared to the dust in molecular clouds and the interstellar medium. It is however still difficult to derive a consistent picture and timeline for dust evolution in disks as the observations are still limited to small samples of objects.

We also review the evidence for and properties of disks around high-mass young stellar objects and the implications on their formation mechanisms. The study of massive YSOs is complicated by their short lifetimes and larger average distances. In most cases high angular resolution data at millimeter wavelengths are the only method to probe the structure of disks in these objects.

We provide a summary of the characteristics of available high angular resolution millimeter and submillimeter observatories. We also describe the characteristics of the ALMA observatory being constructed in the Chilean Andes. ALMA is going to be the world leading observatory at millimeter wavelengths in the coming decades, the project is now in its main construction phase with early science activities envisaged for 2010 and full science operations for 2012.

Key words:

Circumstellar disks are expected to form as a natural consequence of the star formation process, as high angular momentum material in the parent molecular core cannot fall directly onto the central star, but accumulates on a flattened structure perpendicular to the average original angular momentum of the prestellar core (Shu et al., 1987; Galli and Shu, 1993a,b). Indeed, observationally, disks are found to be present around most young stellar objects.

Disk-like structures are found around protostars of every mass, when sufficient angular resolution and sensitivity observations are available, from the lowest mass brown dwarf systems (Natta and Testi, 2001; Testi et al., 2002) to massive protostars (Cesaroni et al., 1997; Beltrán et al., 2005).

As detailed elsewhere in this book, disks play an essential role in the formation of stars as material looses angular momentum in the disk and is accreted onto the central forming star. When the central star is assembled and the main accretion phase is finished, it is within the circumstellar disk that planets are expected to be assembled. In fact, around many young pre-main sequence stars protoplanetary disks are detected. The presence of disks around TTauri like stars (TTS) and Herbig Ae/Be stars (HAeBe) was originally inferred from the presence of infrared excess in these systems and then eventually demonstrated through direct imaging at millimeter wavelengths (Sargent and Beckwith, 1991; Mannings and Sargent, 1997).

In this lecture, we primarily concentrate on high angular resolution observations of protoplanetary disks surrounding pre-main sequence intermediate-mass stars and high-mass (proto-)stars. We mainly concentrate on the unique capabilities offered by high angular resolution millimeter observations, but we also show examples of complementary observations obtained using many different techniques that have been discussed during this school, in particular adaptive optics assisted and infrared interferometry observations. We discuss how different observations allow us to probe the dust component of these disks, especially regarding the properties and evolution of the dust towards the first phases of the planetary formation process. Gas, and in particular molecular gas, is the main constituent of these disks and high angular resolution observations at various wavelengths are essential for our understanding of the kinematical, physical and chemical properties of the gaseous component of disks. We only briefly discuss this aspect here and refer to the recent review in Dutrey et al. (2007) for more details.

We have chosen the approach of giving a number of selected examples of observations of protoplanetary disks around intermediate mass stars, with the goal of illustrating the potential of different high angular resolution observations combined with detailed modeling. Most of the results we discuss here are similar to those obtained around lower mass TTauri-like systems. Due to lack of space, we do not discuss here observations of the earliest stages of disks in low- and intermediate-mass systems, but we limit our discussion to the high-mass case and how disks can be a probe of the formation mechanism of these objects. For the topics that we do not cover in these lectures, we refer the reader to the very good reviews in the volumes of the series Protostars and Planets.

1 Structure of circumstellar disks

1.1 Continuum emission

Some basic constraints on the structure of circumstellar disks can be derived modeling from their spectral energy distribution (SED). As a first approximation, the SED of a circumstellar disk can be modeled as the sum of the contribution of annuli, each emitting as a black body at a local temperature $T_d(r)$, where r is the distance from the central star. Under these assumptions the SED of a circumstellar disk can be written as:

$$F_\nu = \frac{\cos\theta}{D^2} \int_{r_i}^{r_o} B_\nu(T_d)(1 - e^{-\tau_\nu}) 2\pi r dr \qquad (1)$$

where B_ν is the Planck function and τ_ν is proportional to the dust opacity at the frequency ν and the dust surface density distribution. The local temperature at each radius is determined by the balance between cooling due to the emitted radiation and the heating. The two main heating sources are the direct radiation from the central star and the viscous dissipation. Both these processes predict temperature distributions $T_d \sim r^{-p}$ with $p = 0.75$ (see Natta, 2000, , for a detailed discussion).

These simple parametric models have been widely used to infer global properties of disks around young stars. The general result (Beckwith et al., 1990) has been that such models account well for overall shape of the observed SEDs in TTauri and HAeBe systems, but the temperature profile $T_d(r)$ has to fall off much more slowly than predicted by the simplistic models described above. To fit the observed data, the derived value of p is close to 0.5.

The most successful solution to this inconsistency is the class of disk models that include a *flaring* outer disk (Kenyon and Hartmann, 1987) and an optically thin disk atmosphere (Chiang and Goldreich, 1997). These models predict that the disk opening angle (or the ratio between the scale height and the radius) increases toward the outer disk. The grazing angle at which the stellar radiation impinges on the disk changes with radius allowing for an increase of the heating of the outer regions of the disk. The optically thin (to the disk radiation) atmosphere absorbs the stellar radiation and is warmer than the disk (optically thick) interior at the same radius.

These disk models have been extremely successful in explaining a number of observational properties of disks that range from the overall shape of the SED to the scattered light images of disks and emission spectral features. These are thus the reference models that are used as benchmark for the observations.

The disk structure predicted by these models has important implications on which regions of the disk are probed by different observational techniques.

Scattered light emission in the visible and near infrared are sensitive probes of the small dust grains population in the upper layers of the disk atmosphere, while emission in the mid infrared features of the silicates probe the emission of dust grains in the atmosphere. The disk midplane, which contains the bulk of the disk mass, can only be probed directly at millimeter and longer wavelengths, where the emission becomes optically thin.

1.2 Molecular gas emission

In the early phases of disk formation and evolution, i.e. up to the formation of planetary systems and before the formation of a debris disk, most of the disk mass is in molecular gas. The most abundant molecule, H_2, is very difficult to observe directly due to its molecular structure and the lack of low excitation emission lines. The next most abundant molecule is CO with an abundance of $\sim 10^{-4}$ compared to molecular hydrogen, with its non-zero dipole moment, this molecule has a number of low excitation rotational transitions that can be observed at millimeter wavelengths. All other molecules are much less abundant than CO and their observation is possible only in a limited number of objects with current millimeter interferometers.

These line observations are essential to study the disk kinematics, chemical composition and evolution. The reader is referred to Dutrey et al. (2007) for a detailed recent review of the subject. A detailed discussion on how to model and interpret millimeter interferometric observations of molecular gas in disks is given by Isella et al. (2007).

1.3 The disk atmosphere

The properties of dust grains and macro-molecules in the disk atmosphere can be probed indirectly by observing the scattered light emission from the central star or directly observing the emission features in the mid-infrared. By comparison with disk models, both observables also allow to constrain the geometrical structure of the disk atmosphere, such as the disk flaring.

In this lecture I will concentrate on the dust emission diagnostics and refer to Watson et al. (2007) for a recent review on the properties of disks derviced from scattered light images at various wavelengths.

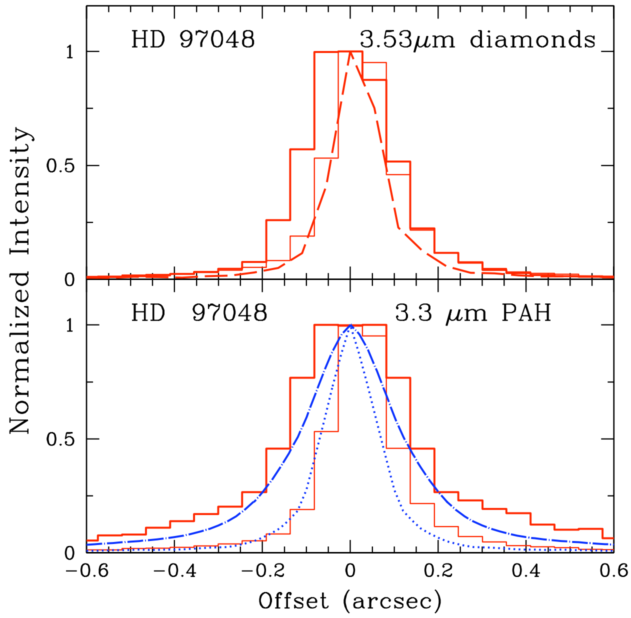

Fig. 1. NAOS/CONICA VLT observations of the 3.6μm "diamonds" and 3.3μm PAH features and the adjacent continuum in the HD 97048 intermediate mass system (Habart et al., 2006, 2004). The upper panel shows the intensity profile of the continuum subtracted diamond feature as a thick line histogram, the adjacent continuum profile as a thin histogram and the profile of an unresolved star as dashed line, the diamond emission is clearly resolved. In the bottom panel the PAH and continuum profiles are compared with disk model computations for the PAH line (dot-dashed) and the continuum (dotted). At the distance of this object, the horizontal scale correspond to ±100 AU from the star.

1.4 Diamonds and PAH

Very small dust particles and macro-molecules emit a rich spectrum of features in the mid-infrared, most of which have not been univocally identified so far. It is generally believed that the unidentified features at 3.3, 7.7-7.9, 8.6, 11.3, 12.7 μm are associated with transiently heated large Policyclic Aromatic Hydrocarbours (PAH). These have been widely detected in HAeBe systems Acke and van den Ancker (2004). The exact region of the system in which these are located has been debated for some time, until diffraction limited 10-12 μm observations with large telescopes (van Boekel et al., 2005) and adaptive optics assisted L-band spectroscopy have resolved the emission as predicted by flared disk models (Habart et al., 2006, 2004). In one system, HD97048 (see Fig. 1), an additional feature was detected and resolved at 3.6 μm, which is suggested to be associated with C-C stretch in diamond-like carbon grains.

The presence and abundance of these macro-molecules in the disk atmospheres

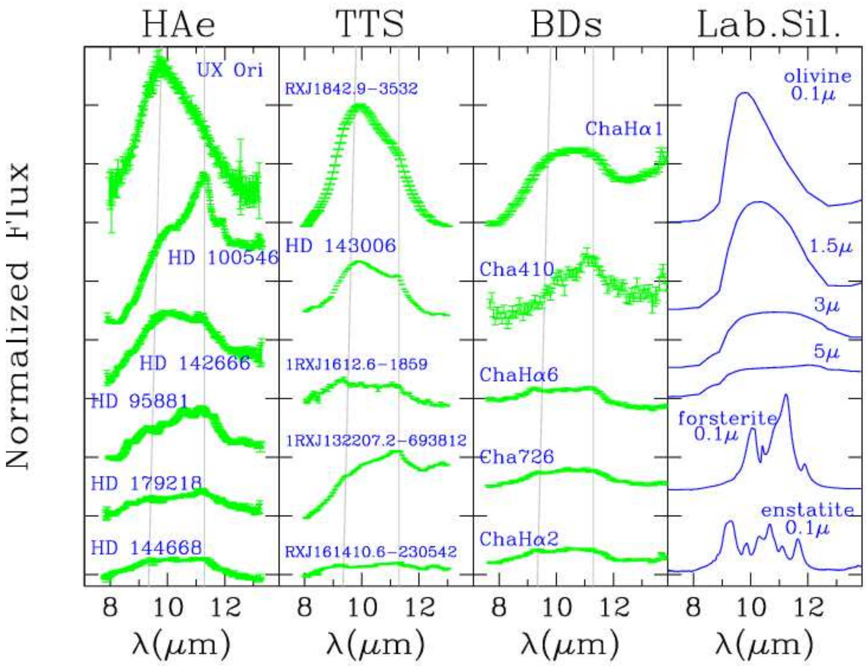

Fig. 2. Compilation of observations of silicates profiles in HAebe, TTS and BD systems and in the laboratory (adapted from Natta et al., 2007, and references therein).

has a strong impact on the gas heating and chemistry in the disk as they contribute to a significant fraction of the gas heating via the photoelectric effect. They may also affect the formation rate of molecular hydrogen on the grain surfaces. These grains need to be taken into account in most accurate disk models, however, one of the most serious limitation in doing this is that observations of these grains cannot probe the population in the disk interiors and models have to rely on assumptions on the abundance throughout the disk.

1.5 Silicates

Astronomical silicates have in the most prominent emission feature at 10 μm,. One of the successes of the flared disks models with atmosphere is the natural explanation for the emission observed in this feature in a large variety of circumstellar disks (Chiang and Goldreich, 1997). In recent years with high quality mid-infrared spectra becoming available first with ISO and more recently with Spitzer, it has been possible to attempt to understand the diversity of the profiles observed in various regions.

As reviewed in Natta et al. (2007), the modeling of silicate profiles in disks as well as comparison with laborato ry measurements can give indications on

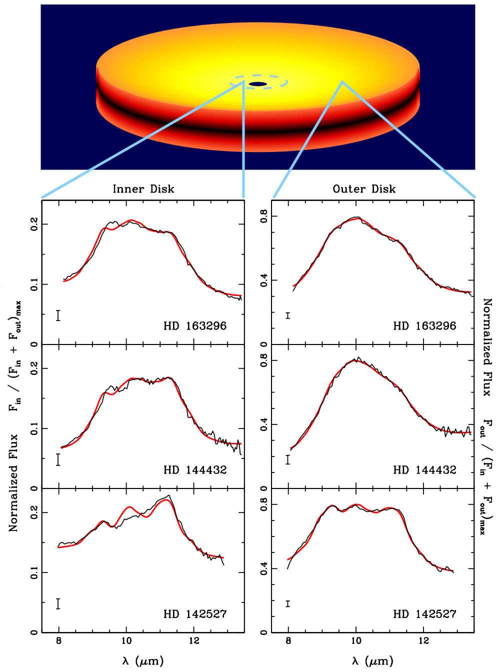

Fig. 3. VLTI/MIDI observations of the silicate profile in the three HAeBe systems HD163296, HD144432, and HD142527. In the top panel a flared disk is sketched, in the bottom panels the MIDI observations of the inner disks are compared with the emission from the outer disk derived by subtracting the interferometric spectrum from single telescope spectra (adapted from van Boekel et al., 2004).

the degree of "crystallinity" and on the size of the emitting particles.

The observed systems show a range of properties with grains similar to those present in the diffuse interstellar medium to grains that have undergone a significant processing, both in terms of crystallization and growth. It is still difficult to properly understand the zoo of properties observed, and in particular the expectation that dust processing evolves with time, i.e. with the age of the system, is still not evident from the current observations.

High angular resolution observations with the VLTI (see contribution from Malbet, this volume) allows to investigate the properties of the silicate profile as a function of the distance from the central star. In Figure 3 we show the results of van Boekel et al. (2004) who demonstrated that the dust in the inner regions of disks is more processed than in the outer region. This is consistent with the expectations that the evolution of dust is faster closer to the star (Gail, 2004).

2 The inner disk

In the previous section we have seen how high angular resolution observations allow us to probe the dust in the upper layers of the disks. The dust in the disk atmosphere is in many cases very evolved and large (up to a few microns), crystalline grains are found, especially in the inner regions of the disk atmospheres. The atmosphere of the disks, however, contains only a tiny fraction of the total disk mass, and the planet formation process is thought to occur on the disk midplane.

The disk midplane can only be probed at long wavelengths where the disk is optically thin, as we will discuss in Section 3, or at NIR wavelengths in the very inner regions of the system where the radiation from the central star photoevaporates the dust grains. The properties (size, geometry) of the inner edge of the disk are shaped by the properties of the dust grains and how they interact with the direct stellar radiation. The region of the disk where this process takes place is very close to the central star. For a typical HAe system, this region is less than one Astronomical Unit from the stellar photosphere. At the distance of the nearest star forming regions ($\sim 100-140$ pc), this correspond to an angular sizes of up to 10 milliarcsec. With the current generation of large telescopes, these sizes are beyond reach even with adaptive optics systems and need to be explored using near infrared interferometers.

The properties of the inner regions of the disk have been the subject of intense recent modeling efforts as observations of the SEDs of HAeBe systems and early near infrared interferometric observations had shown the possibility of the presence of an inner "puffed-up" edge (Dullemond et al., 2001; Monnier and Millan-Gabet, 2002). More recently Isella and Natta (2005) have produced a self consistent model of the inner regions of the disk, which naturally explains the size and shape of the inner edge of the disk in terms of the stellar photospheric parameters and the properties of the dust grains.The models were used by Isella et al. (2006) to interpret the visibilities observed with near infrared interferometers of several disks around young stellar objects (see Fig 4 for an example).

The combination of these advanced observational and modeling techniques has allowed to constrain the properties of dust grains on the disk midplane in the inner regions of a small sample of HAe systems. Isella et al. (2006) demonstrated that in almost all systems investigated, the observations are consistent with the presence of grains much larger than the ISM grains. The analysis of the near infrared data allow to set a minimum size of the order of $\sim 1\mu$m for the grains that dominate the population of dust in the inner disk. Very similar results were also obtained by Pontoppidan et al. (2007),

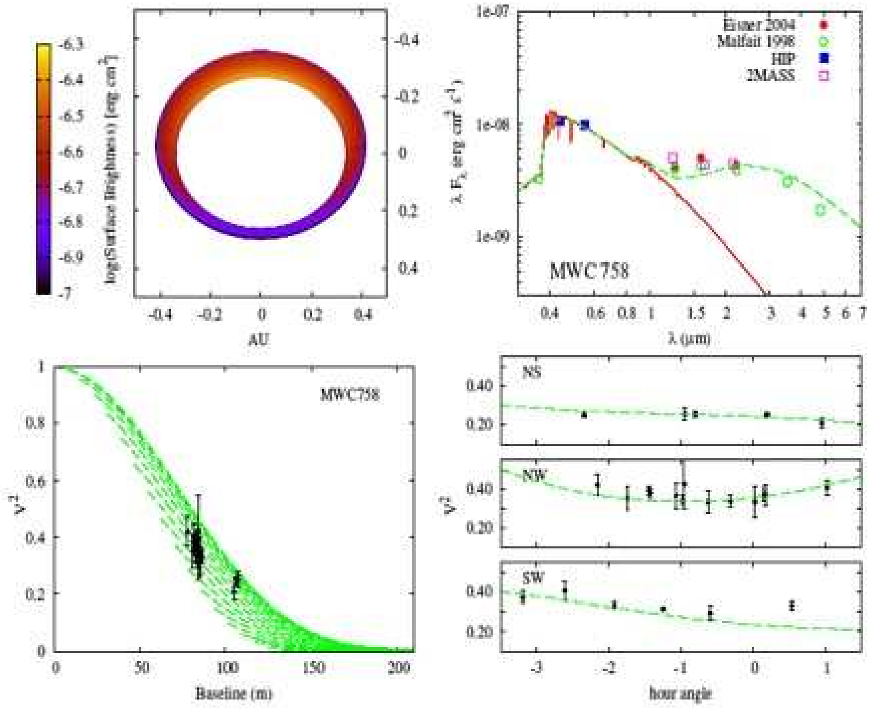

Fig. 4. The inner edge of the MWC758 disk. The top left panel shows the model image of the inner edge of the disk (following the models of Isella and Natta (2005); the top right panel shows the fit to the observed SED; the bottom panels show the fits to the visibility observations: visibility as a function of baseline length (left) and as a function of hour angle for the three PTI baselines (left). The figure has been adapted from Isella et al. (2006).

who modeled the disk around the UX Ori-type star VV Ser.

The availability of the AMBER instrument at the VLTI is expected to allow for a substantial improvement in the study of the inner disk in a large sample of intermediate mass pre-main sequence systems and possibly a number of TTauri systems. Thanks to its spectroscopic capabilities, AMBER will also allow a step forward in our understanding of the gaseous component on the inner disk and the relationship between disk and jet. Some initial experiments with AMBER (Malbet et al., 2007; Tatulli et al., 2007) have confirmed that in HAeBe stars the Brγ emission is not associated with the magnetosphere of the central star or inner gaseous disk, but with the base of the wind/jet. Moreover, the hydrogen recombination line observations have shown that the wind/jet is launched from a region of the disk similar or slightly more extended than the dusty inner disk rim (see Fig. 5 and Tatulli et al., 2007).

The study at high angular resolution of the hot gas in the inner regions of circumstellar disks is certainly an area where one can expect a lot of development in the coming years. As the VLTI system is becoming more stable and

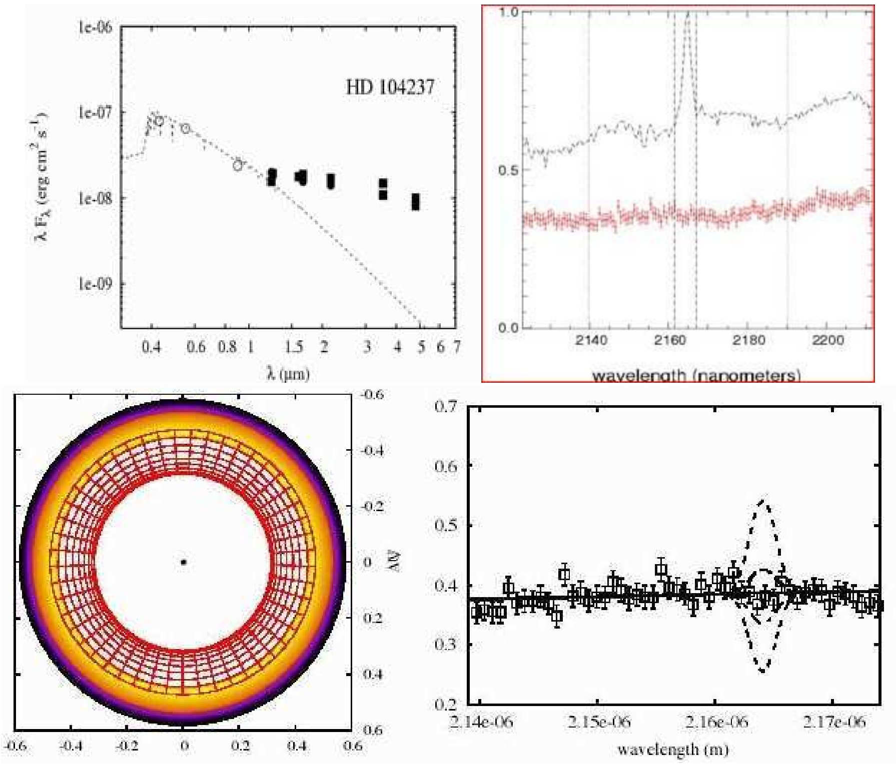

Fig. 5. AMBER/VLTI high angular resolution observations of the inner disk in the HD104237 HAe system. The top left panel shows the spectral energy distribution of the system, the near infrared excess exceeding the photospheric emission (dotted) is due to the disk inner rim; the top left panel shows the AMBER/VLTI total power spectrum (dashed) and interferometric differential visibilities (red points with error bars), which show *no variation* across the prominent Brγ line; in the bottom panels visibilities predicted by different models of the Brγ emitting regions are compared with the observed differential visibility. The models consistent with the observations predict an emitting region essentially coincident with the disk inner dusty rim (see schetch on the bottom left panel). The figure has been adapted from Tatulli et al. (2007).

sensitive, it will be possible to probe other lines such as the CO overtones longward of 2.93μm. In the meantime, the availability of sensitive high spectral resolution instruments in the near infrared at large telescopes has allowed the detection of the CO and H_2O emission from the inner regions of the disks (e.g. Blake and Boogert, 2004; Brittain et al., 2005, 2007; Salyk et al., 2007).

3 The disk midplane

While the study of the inner disk allows to probe the proprties of the dust grains in the midplane close to the central star, most of the disk mass which is in the midplane at large radii can only be probed at millimeter and longer wavelengths. At these wavelengths the disk becomes optically thin to its own radiation and we can observe the emission from the bulk of the solid material.

Assuming thermal emission from an isothermal, optically thin ensemble of dust, the observed flux at millimeter wavelengths can be written as:

$$F_\nu = \frac{1}{D^2}\, B_\nu(T_d)\, k_\nu M_d \qquad (2)$$

where T_d and M_d are the dust temperature and total mass, D is the distance to the observer, $B_\nu(T_d)$ the Planck function at the appropriate frequency and temperature and k_ν is the dust opacity per unit mass. At millimeter wavelengths the dust opacity as a function of frequency can be approximated with a power law $k_\nu \sim \nu^\beta$ and the Planck function can be well approximated by the Rayleigh-Jeans function, hence:

$$F_\nu \sim T_d\, M_d\, \nu^\alpha \qquad (3)$$

with $\alpha = 2+\beta$. This implies that the shape of the spectral energy distribution at millimeter wavelengths can be used to derive the dust opacity power law index β, while the total flux measured at a given wavelength is proportional to the product of temperature and mass.

The value of β depends on the type of dust grains in the ensemble: composition, shape, size, and combination of these. The mixture of grains that fits the properties of the interstellar medium correspond to a value of β close to two ($\alpha \sim 4$). If, however, the dust grains become much larger than the wavelength at which the fluxes are measured, then the dust opacity becomes grey (as only the geometrical cross section of the grains is relevant) and α value approaches 2 ($\beta = 0$). Even if the exact value of β depends on a variety of dust properties which are hard to constrain (see Fig. 6 for some examples of β computations for different properties of the grain population), the general result that a low value of β is only consistent with the presence of large grains is a solid one (see also Draine, 2006).

Obviously this is a powerful probe for the presence of very large grains in circumstellar disks as discussed in Beckwith and Sargent (1991) who carried on the first millimeter and submillimeter survey for grain growth in circumstellar disks. In practice, as already discussed in Beckwith and Sargent (1991), the situation is more complex, as disks are not isothermal ensembles of optically thin dust.

Even if the assumption of an average temperature, as discussed in Natta et al. (1997), is not a poor approximation of Eq.1 to give a rough estimate of the disk mass, to obtain an accurate determination of the value of β it is necessary

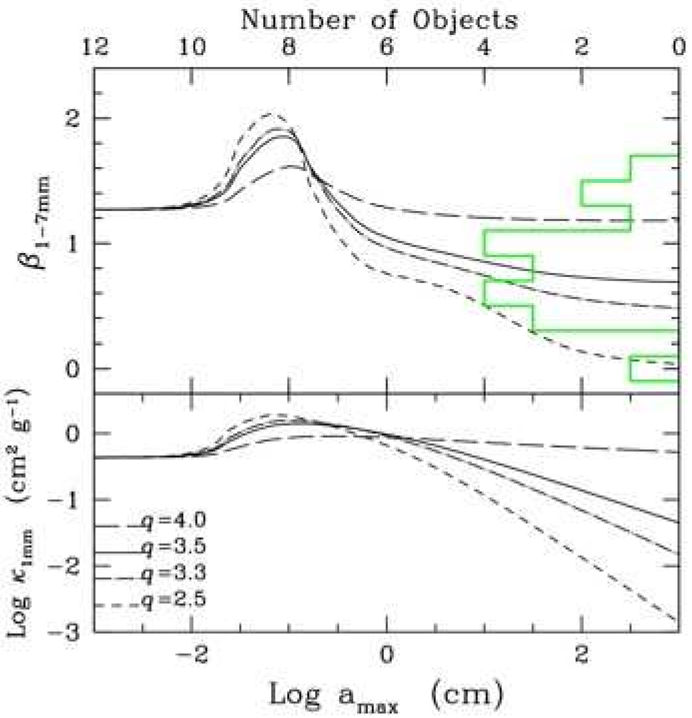

Fig. 6. Dust opacities per unit mass (bottom panel) and power law exponent (top panel) as a function of the maximum size for the dust grains and for various dust size distributions. The histogram on the right side of the top panel illustrates the values of the index beta measured in a sample of protoplanetary disks around TTauri and HAe stars. Adapted from Natta et al. (2007).

to use more sophisticated disk models that take into account the temperature profile and the presence of an optically thick inner region of the disk. As discussed in Testi et al. (2001) low values of α approaching 2 may be an indication of low values of β, hence grain growth, or may be the consequence of unexpectedly high optical depth disks (see Fig. 7).

To resolve these ambiguities in fitting proper disk models and deriving accurate values of β, it is necessary to resolve the disk emission at millimeter wavelengths. To achieve this it is necessary to obtain angular resolutions of the order of $\sim$1 arcsec or beter, corresponding to linear resolutions of the order of 100 AU in the nearest star forming regions. These angular resolutions at millimeter wavelengths can only be achieved by large radio interferometers. An example of such a study is that done on the CQ Tau system by Testi et al. (2003) (see also Fig. 8). The combination of the millimeter spectral index from 1 through 7 mm and high angular resolution VLA observations at this wavelength allow to obtain an accurate measurement of β and to derive the presence of very large (centimeter size) grains in the disk midplane. Even more convincing are the observations of Wilner et al. (2005) who detected the dust emission in the TW Hya system at wavelengths as long as 3.6cm.

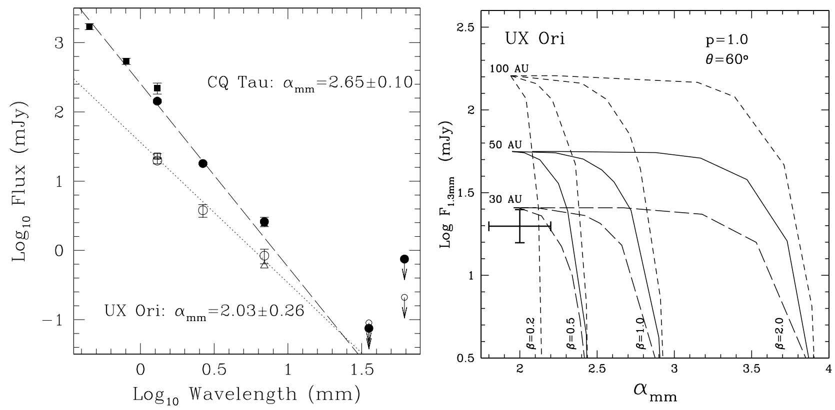

Fig. 7. Left panel: millimeter-centimeter wave spectral energy distribution of the UX Ori and CQ Tau systems; right panel: disk model families for the millimeter integrated flux and spectral index. For a given value of the dust opacity index β and disk radius, disk model predictions move along the lines depending on the total disk mass, the higher the mass the higher the mm flux until the disk becomes optically thick and the flux saturates. Low resolution observations that do not constrain the disk size are consistent with either large, mostly optically thin disks with low values of β or small, optically thick disks with any value of β. Adapted from Testi et al. (2001).

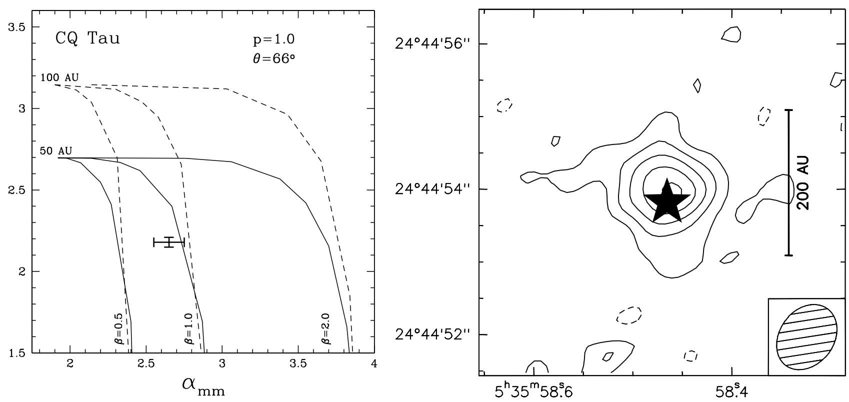

Fig. 8. Left panel: family of models as in Fig. 7 for CQ Tau; right panel: spatially resolved 7mm continuum VLA map of the disk surrounding CQ Tau. The resolved image allows to constrain the minimum disk radius and to restrict the families of models consistent with all the data, the result is that in the CQ Tau system the *average* value of β is well constrained to be ~ 0.6. Adapted from Testi et al. (2001) and Testi et al. (2003).

There is now a growing number of systems for which accurate measurements of β are available (see Natta et al., 2007, for a recent compilation). The sample studied so far is significantly biased as the goal of most of the searches was to identify systems with large grains (see e.g. Natta et al., 2004). So far all searches for correlations of the dust properties in the midplane with other properties of the system have not given convincing results. As an example, in Fig. 9 the run of β as a function of luminosity and age of the central star is

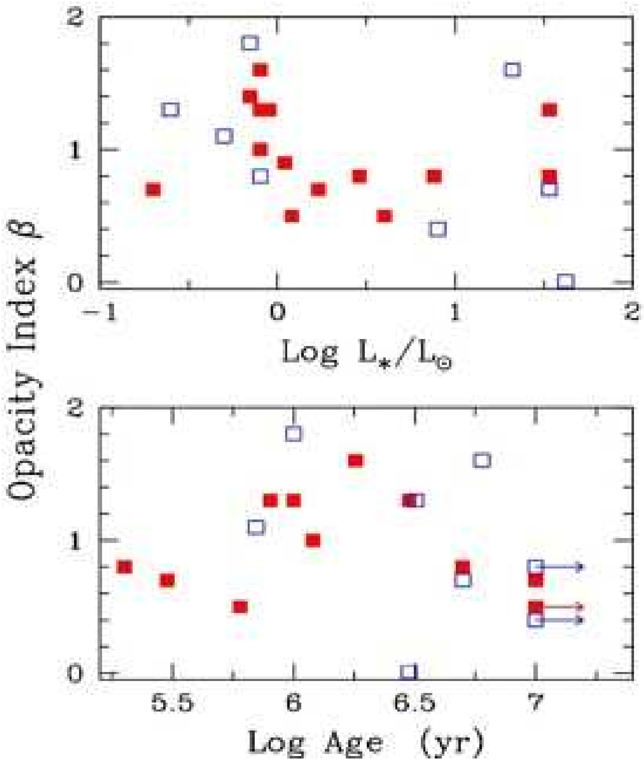

Fig. 9. Measured values of β as a function of luminosity (top panel) and age (bottom panel) of the central star. Adapted from Natta et al. (2007).

shown. No correlation is found contrary to the expectation that grain growth proceeds with the age of the system toward the planetary formation phase.

There are several explanations for this failure, the most obvious is that the samples studied so far are very small and biased for the trend to emerge. Obviously this is an area that needs improvement and surveys with current and future millimeter and radio interferometers are planned to this effect. There is however the more interesting alternative that the lack of (expected) correlation is due to some physical effect, such as the possibility that disks go through their evolution at different rates or that the growth to large particles may be a fast process occurring in the earliest stages of the system (prior to the stage we are observing now) and then the next step, the growth to planetesimals and planets, may be a much more difficult process that requires substantial time to occur.

4 Massive circumstellar disks

Due mainly to their scarcity, and their large distance, the number of massive young stellar objects (YSOs) studied in detail is still not enough to properly interpret the evolutionary scenario of how high-mass stars form (for a review of massive star formation, see e.g. Beuther et al., 2007). Their contraction timescale is short, and they produce a copious radiation already in early evolutionary stages that may inhibit the accretion process: when the kernel has reached a mass of ~ 8 $M_{\odot}$, the accretion timescale of the surrounding envelope and the contraction timescale of the kernel become comparable (Palla and Stahler, 1993). From this moment on, the radiation pressure and UV flux emitted by the kernel can disrupt the surrounding environment thus preventing further growth of the stellar mass (e.g., Wolfire and Cassinelli, 1987). As a consequence, no star with mass larger than 8 $M_{\odot}$ should ever form.

Theories have been proposed that overcome the radiation problem and lead to the formation of stars more massive than 8 $M_{\odot}$. Since massive stars never form isolated, a first scenario suggests that low-mass (proto)stars undergo physical collisions and merge, avoiding the problem of the radiation pressure (see for example Stahler et al., 2000). Other hypotheses (e.g., Yorke, 2004) essentially propose variations to the standard paradigm of star formation (Shu et al., 1987), and suggest that massive stars may form via accretion, but overcome the radiation problem by varying the dust properties (e.g., the dust absorption coefficient) or by non-spherical accretion (e.g., through a disk). A way to discriminate between the two hypotheses is the detection of a system outflow-disk in a massive young stellar object: well defined geometrical structures such as collimated jets and circumstellar disks are unlikely to survive a disruptive event as the merger of several low-mass protostars. Hence, the detection of circumstellar disks around more massive objects would have a strong impact on the theory of their formation. However, one has to look for outflows and disks in early evolutionary phases of massive YSOs (see discussion in next paragraph), and these studies present several observational biases that make the search for circumstellar disks in massive star forming region difficult. A recent review on disks around young O–B (proto)stars is presented by Cesaroni et al. (2007). For the nomenclature of this lecture, we use the term protostars, and equivalently massive young stellar objects, for sources that are still actively accreting, independent of whether they have started hydrogen burning or not.

As we discussed in the first part of this chapter, the presence of disks around young stellar objects is well established up to intermediate mass stars (few solar masses). A first attempt to investigate whether or not the accretion mechanism of star formation holds throughout the mass spectrum, the obvious step is thus to extend the searches for disks at higher stellar masses. Attempts to detect disks around young early B type stars give only upper limits, and one detection (Natta et al., 2000; Fuente et al., 2003, 2006). The result of these studies is that the masses of disks in early B young stars, if they exist, compared to the masses of the stars themselves are much lower than those typically found around lower mass stars. One possibility is that disks around more massive stars have shorter lifetimes than their low-mass counterparts, and that when they reach the ZAMS their disks are already dispersed. The other possibility is that intermediate and massive stars do not form through accretion. The main consequence of the studies on intermediate mass stars, and of their lack of detections of disks, is that searches for massive accretion disks should be done in earlier evolutionary phases, before the disks evaporate. Massive young stellar objects are very embedded, still surrounded by their infalling envelope, and cannot be observed at IR wavelengths, where extinction is high. On the other hand, these regions are transparent at cm and (sub)mm frequencies, where we know from studies of disks in low-mass stars that the bulk of the dust emission arises; and where molecules in the gas phase, which dominate the total mass of the disk emit (for a review, see Natta et al., 2007; Dutrey et al., 2007). Therefore, observations at (sub)mm wavelength are indeed an optimal way to study the property of massive accretion disks.

As mentioned above, studies of massive YSOs present several observational difficulties. First of all, massive stars have short lifetimes, and massive young stellar objects even shorter. Therefore, these objects are rare to find. As a consequence of their scarcity, massive (proto)stars are in general far away. Typical distances are of a few kpc or more, with a few exceptions like Orion and Cepheus A located at less than 1 kpc from the Sun. Moreover, massive stars form in clusters, making the study of isolated massive YSOs difficult. Molecular outflows have typical sizes up to several parsec, and are easy detectable even with radio single dish telescopes, whose typical resolution is of the order of $10''$ or larger ($> 30\,000$ AU at 3 kpc). Several observational studies have been carried out in the past to find molecular outflows originating from massive young stellar objects (e.g., Shepherd and Churchwell, 1996; Zhang et al., 2001; Beuther et al., 2002b). In the last few years, high angular resolution observations of CO at mm wavelengths revealed highly collimated outflows from early B type young stellar objects (Beuther et al., 2002a; Gibb et al., 2003; Su et al., 2004). Therefore, the next step towards the understanding of how massive stars form is the detection of circumstellar disks around high mass protostars.

Since the search for massive accretion disks is not easy, one has to select the best candidates for such observations. These are massive star forming regions where outflows have been already detected, and which show dense, compact cores, that are believed to harbour massive young stellar objects. These cores are commonly referred to as hot cores, and have sizes of 0.1 pc or less, high densities ($> 10^7$ cm^{-3}) and are warm (> 100 K) and luminous ($10^4 - 10^6$ L$_\odot$) (Cesaroni et al., 1994; Kurtz et al., 2000). The sign of a circumstellar disk hosted in such an environment would be a velocity gradient detected in a molecular line, which is perpendicular to the direction of the outflow and comes from the compact hot core at the center of the outflow. Ideal molecular tracers of disks are high excitation lines of rare molecular species, because emission from these transitions is confined to the innermost region around the protostar and have low optical depth, thus allowing studies of their line profiles. Molecules that have been often used to try to detect accretion disks in massive YSOs are NH_3, CH_3CN and $HCOOCH_3$. However, we still do not know which is the best molecular transition to study massive disks, since CH_3CN and NH_3 are not always suitable for this purpose, and $HCOOCH_3$ is observationally more difficult to tackle.

There are currently a few good candidates of massive circumstellar disks. The best studied example is hosted in the star forming region IRAS 20126+4104, at a distance of 1.7 kpc. High resolution observations of the region in several molecular tracers at mm wavelengths revealed that the source hosts a powerful parsec-scale molecular outflow (Wilking et al., 1990; Cesaroni et al., 1997), with a compact hot core detected in CH_3CN and other complex molecules (Cesaroni et al., 1997, 1999) at the geometrical center of the bipolar jet. The analysis of the CH_3CN emission reveals a velocity gradient along a linear structure perpendicular to the outflow. Imaging in CH_3CN, NH_3 and $C^{34}S$ (Zhang et al., 1998; Cesaroni et al., 1999, 2005) showed that the rotation is Keplerian. From the rotation curve, the stellar mass is between 7 and 24 $M_\odot$, depending on the linear scale sampled by the observations. The example of IRAS 20126+4104 is illustrated in Fig. 10 and 11. Another well studied massive disk candidate is in the star forming region G192.16–3.82, at 2 kpc distance, where Shepherd and Kurtz (1999) found a rotating structure, detected by a velocity gradient in $C^{18}O$, perpendicular to a molecular outflow. In this case, the estimated spectral type of the central star is B2.

Other candidate massive disks have been also reported in the literature (see e.g. Cesaroni et al., 2007; van der Tak et al., 2006). However, the interpretation of some of them is still controversial. Rotating disks in early B type young stellar objects have typical radii of several hundreds AU, and are less massive than their central objects ($M_\star \leq 10\ M_\odot$). Although the mass of the central object is usually derived through indirect methods, for example from the continuum Lyman flux at cm wavelengths (Panagia, 1973), and is therefore affected by large uncertainties, all candidate massive disks are found around early B type objects. This is probably an observational bias, since massive O type protostars are even rarer than early B type, and therefore on average more distant. In the last years, attempts have been made to study the inner region around O-type protostars. Two sources, G31.41+0.31 and G24.78+0.08 ($d \sim 8$ kpc), have been intensively studied at high spatial resolution by Beltrán et al. (2004, 2005). The results of these observations are similar to those found in early B type protostars: the authors detected velocity gradients in both sources (G24.78+0.08 consists of several cores, and three of them show a velocity gradient) in the rare molecular species CH_3CN. In all four cases (three in G24.78, one in G31.41) the velocity gradient is along a linear structure, roughly perpendicular to a molecular outflow. Beltrán et al. (2005) discuss the properties of the rotating structures in G31.41+0.31 and G24.78+0.08. Since these structures, which Cesaroni (2005b) refer to as *toroids*, are de-

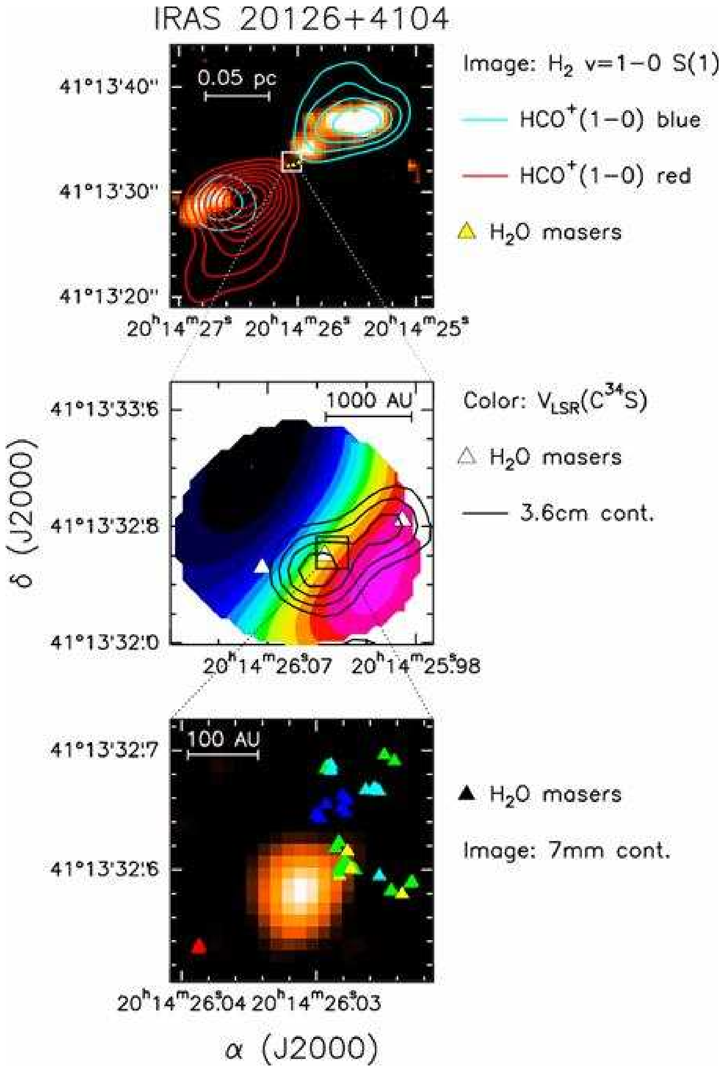

Fig. 10. The disk/outflow system in IRAS 20126+4104. Top: in color scale the H_2 line emission at 2.2μm; red and blue contours show the blue- and red-shifted HCO+ (1-0) emission in the bipolar outflow (Cesaroni et al., 1997). The yellow triangles mark the positions of the H_2O masers spots detected by Tofani et al. (1995). Middle: 3.6 cm continuum map (Hofner et al., 1999) overlaid on a map of the velocity measured in the $C^{34}S$ (5-4) line by (Cesaroni et al., 2005). Bottom: Distribution of the H_2O maser spots (Moscadelli et al., 2000, 2005) compared to a VLA map (image) of the 7 mm continuum emission (Hofner, pers. comm.). The grey scale of the spots ranges from white, for the most red-shifted spots, to black, for the most blue-shifted. The arrows denote the absolute proper motions of the spots, measured by Moscadelli et al. (2005).

tected also in other sources, their conclusions are general, and not valid only for G31.41+0.31 and G24.78+0.08. Toroids have radii of several thousands AU and masses of hundreds $M_{\odot}$. Their physical properties suggest that they are different objects in respects to the rotating disks detected in less luminous sources. Toroids are unstable against gravitational collapse, since their mass is

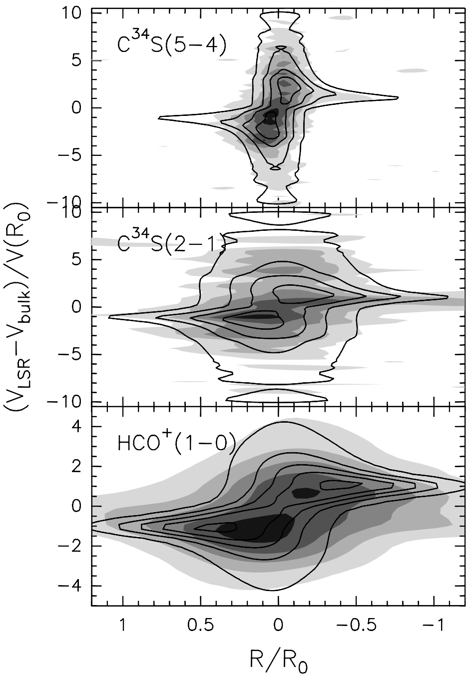

Fig. 11. Best-fit position-velocity plots along the disk plane, for $C^{34}S$(2-1) (top), $C^{34}S$(5-4) (middle) and HCO^+(1-0) (bottom). Contour levels are the same for the data and corresponding model and are drawn at 10, 30, 50, 70, and 90% of the data peak value. The best-fit models for $C^{34}S$(2-1) and $C^{34}S$(5-4) have been obtained with a 7 $M_\odot$ stellar mass, whereas the best-fit model of HCO^+(1-0) corresponds to a 12 $M_\odot$ mass (adapted from Cesaroni et al., 2005).

much larger than the dynamical mass needed for equilibrium, and they have accretion rates much larger than less luminous protostars. However, their nature is still not clear, although they likely host a cluster of protostars in their interior and may eventually fragment into smaller accretion disks around single objects (Cesaroni, 2005a). In agreement with this scenario is the detection of multiple continuum sources in G31.41+0.31, at the center of the toroid (see Fig. 26 of Beltrán et al., 2005).

5 The role of future cm and mm interferometers

In spite of the enormous progress made in the last decade in our understanding of circumstellar disks and their role in the formation of stars and planetary systems, as hinted throughout this chapter, considerable work is needed in several areas.

The dust properties and dust evolution in disks around low- and intermediate-mass stars are still very uncertain. Given that most of the disk masses are measured in the continuum and that the solid component of the disk is thought to play a key role in the formation of planetary cores, these two are also very uncertain (see e.g. the discussion in Dullemond et al., 2006; Natta et al., 2004, 2007). To advance in this area, the dust emission in the centimeter and (sub-)millimeter continuum has to be explored in more detail and in a more systematic fashion. On the observational side, this requires high angular resolution to resolve the disks and properly model them and high sensitivity to detect the weak emission at long wavelengths (see e.g. the discussion in Isella et al., 2007; Testi et al., 2001, 2003; Wilner et al., 2005; Hughes et al., 2007). With the current generation of arrays it is very difficult and time consuming to obtain adequate observations and the detailed studies are limited to a handful of bright and nearby systems. In the long term, the ultimate goal of these type of study would be the direct detection of the effect of a forming planetary body on the protoplanetary disk, this is definitely out of grasp with the current millimeter arrays, but possible at the highest frequency and spatial resolution offered by the Atacama Large Millimeter/submillimeter Array (Wolf, 2007).

Another area that is only poorly explored with current millimeter arrays is the chemistry and evolution of the molecular gas in protoplanetary disks. Current instruments are only able to detect the most abundant molecules in the most massive and gas rich disks. This is obviously an area in which ALMA will provide a major observational breakthrough (Dutrey et al., 2007).

Also in the discovery and study of disks surrounding massive protostars the next generation of radio interferometers will allow a major advancement compared with what is possible today. The most promising way to detect a circumstellar disk around a (proto)star is by studying the velocity field around it. To achieve such a detection, the observations must have high velocity resolution to resolve the line profile, and high spatial resolution to disentangle the red and blue emission of the disk. Typical linewidths for high-mass young stellar objects are of the order of a few km s^{-1}, while high velocity resolution ($\sim$ 0.1 km s^{-1}) is easily achieved at radio wavelengths. From low-mass star forming regions, we know that the sizes of circumstellar disks vary from a few hundred to tens of AU. Therefore, for an average massive young stellar object at 3 kpc, a resolution of $0.1''$ or less (corresponding to 300 AU) is needed to resolve a disk. However, current interferometers at cm and (sub)mm wavelengths are often limited to angular resolutions which are still coarse for these needs. The highest angular resolution reached today is with the Very Large Array (VLA) at 7 mm in the most extended configuration ($\sim 0.05''$), while (sub)mm observations are limited to a few hundred milliarcsecs. Finally, since there is still no unanimous consensus on the molecular species to use for such studies, broad bandwidth receivers are preferable, because they allow the simultaneous detection of several molecular transitions, each of them a potential disk tracers. Again, the present generation of receivers and correlators is often still inadequate for these purposes: usually, broad bandwidth observations are limited to low spectral resolution, while high resolution is attained on narrow bandwidths.

Table 1 summarises the characteristics of current interferometers and compairs them to those of the Atacama Millimeter Array (ALMA), and to the Expanded Very Large Array (EVLA). The advantages of the new generation of interferometers are essentially the higher sensitivity at high spatial resolution, which will allow regular observations at $0.1''$ scales, and the flexibility of the receivers and correlators, which will guarantee broad bandwith observations with high velocity resolution. ALMA, moreover, will work in the (sub)mm regime (see Fig. 12 for the frequency coverage of ALMA), which is the spectral window where most of the high energy rotational and vibrational transitions from molecules emit. These lines trace the innermost gas around protostars, where disks are hosted, and are therefore the best candidates for tracing the circumstellar material.

ALMA will be composed of 50 12 m antennas, and of an additional compact array of 7-m and 12-m antennas (Atacama Compact Array, ACA). It will located on Llano de Chajnantor in the Atacama desert of Chile, 5000 m above sea level, on what is considered one of the world's outstanding sites for submillimeter astronomy. A view of the site is given in Fig. 13. Figure 14 shows the altitude at which the atmospheric transmission becomes completely transparent as function of the wavelength, thus explaining the need of high altitude observations for the (sub)mm window. In Fig. 12, the atmospheric transmission at the ALMA observing bands is plotted for different weather conditions. Currently, the first American antenna, and three of the Japanese antennas are already in Chile. The first call for proposal is expected for 2010, when 16 antennas are scheduled to be on site, while the full operation of ALMA is scheduled for 2012.

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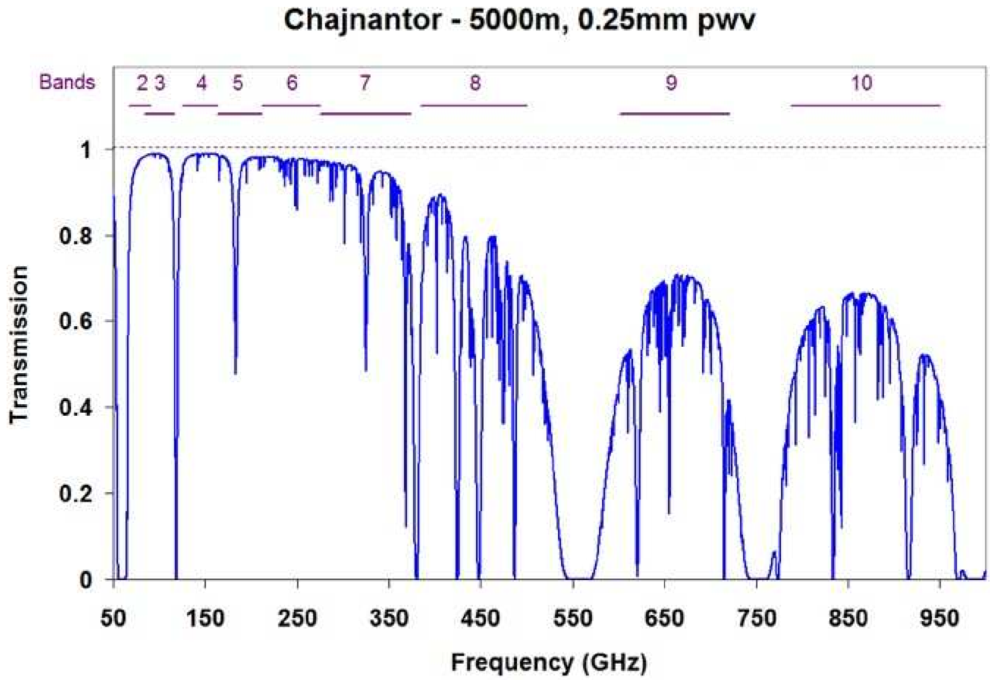

Fig. 12. Atmospheric transmission for Chajnantor in good (but not exceptional) weather conditions. The ALMA frequency bands from 2 through 10 are indicated at the top of the panel. At the time of writing, bands 3, 4, 6, 7, 8, and 9 are fully funded, six single polarization band 5 receivers have been funded through a contract with the European Commission FP6, band 10 is under development and a decision on whether to build this as part of the first phase of the project is under discussion, bands 1 and 2 are not currently funded.

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Fig. 13. Top: view of the ALMA site. Bottom: picture of the technical building at the Array Operations Site.

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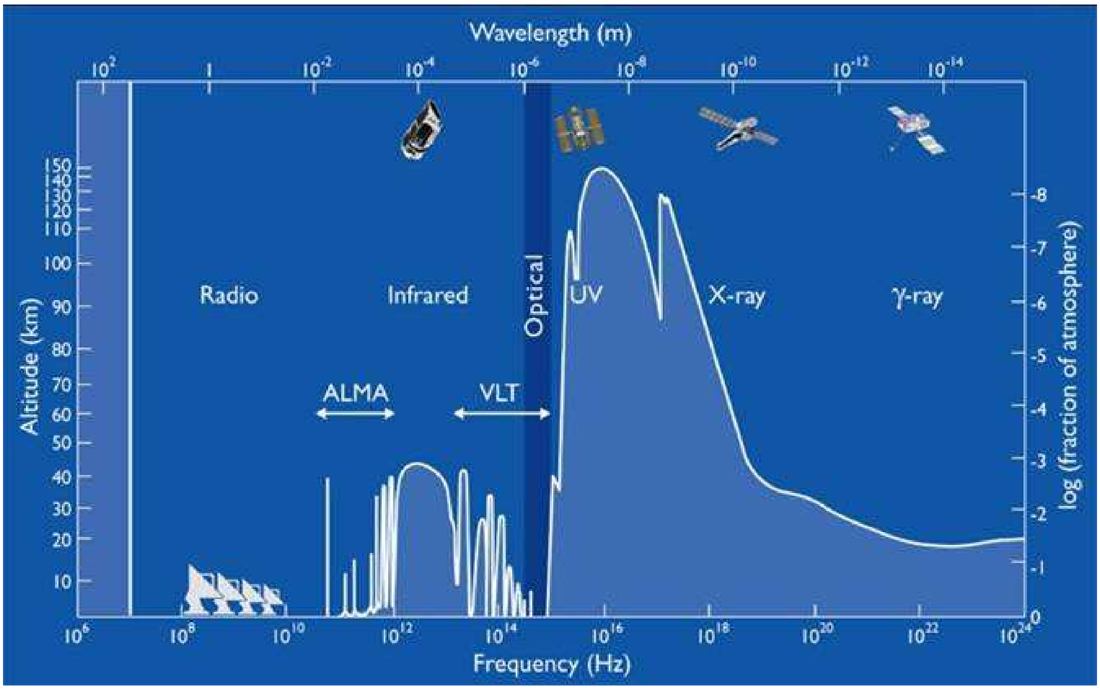

Fig. 14. Plot of the altitude at which the atmosphere becomes transparent as function of the wavelength.

Table 1
Summary of current cm-mm interferometers.

	Frequency coverage [GHz]	Angular resolution [″]	Spectral flexibility
	Current facilities		
VLA	$0.289 - 50^a$	$0.05 - 850$	no
ATCA	$1.25 - 106.0^a$	$0.5 - 6$	no
PdBI	$81 - 116,\ 201 - 244$	< 0.3	no
CARMA	$85 - 116,\ 215 - 270$	< 0.1	no
SMA	$180 - 900^a$	$< 0.7^b$	yes
Nobeyama	$85 - 237^a$	< 1	no
	Future facilities		
EVLA	$1.2 - 50$	< 0.01	yes
ALMA	$30 - 950^a$	$< 0.012^b$	yes

[a] not contiguesly

[b] at 345 GHz.

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