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Circumstellar Material in the Context of the Formation of Planetary Systems

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Abstract: Selected questions in the field of circumstellar material seen in the context of planet formation and evolution that can be addressed with future interferometers, operating in the optical to mid-infrared wavelength range, are discussed in this article. Corresponding constraints and minimum requirements that have to be met in order to perform these observations are derived.

1 Introduction

Circumstellar disks are considered to be a natural outcome of the protostellar evolution, at least in the case of low to medium mass T Tauri and Herbig Ae/Be stars (e.g., Adams, Lada, & Shu 1987). The disks provide the material and environment from and in which planets are expected to be formed (e.g., Lissauer 1993). Thus, if one wants to investigate how planets may be found in these disks one has to consider the evolution of both circumstellar disks and the planets therein. During the last two decades a detailed picture of the large-scale evolution of the circumstellar environment – in particular the circumstellar disk – has been worked out. The planet formation process, however, is in major parts still under discussion – mainly due to the lack of adequate constraints from observations. Thus, the search for signatures of planet formation and planets themselves in circumstellar disks is important in order to confirm or to rule out existing hypotheses on planet formation scenarios.

An example that underlines the importance of high-resolution observations for tracing the earliest stage of planet formation, namely the growth of submicron-sized dust grains to (sub)millimeter particles, are observations of the Butterfly star IRAS 04302+2247 in Taurus (Wolf, Padgett, & Stapelfeldt 2003 and references therein). Using high-resolution near-infrared scattered light images of the circumstellar envelope obtained with the Hubble Space Telescope (HST) in combination with millimeter maps that spatially resolve the dust reemission from the circumstellar disk, different dust evolution scenarios in the environment of this young stellar object (Class I) have been revealed. Based on the comparison with radiative transfer simulations it has been shown that the dust grains in the circumstellar envelope of this source are still comparable with those of the interstellar medium, while the grains in the much denser circumstellar disk have already grown by up to 2 - 3 orders of magnitude.

However, the above example also illustrates the strong need for higher-resolution observations, preferentially (interferometric) imaging. While the angular resolution of existing observatories / instruments, such as the HST or the Very Large Telescope (VLT), is sufficient to study

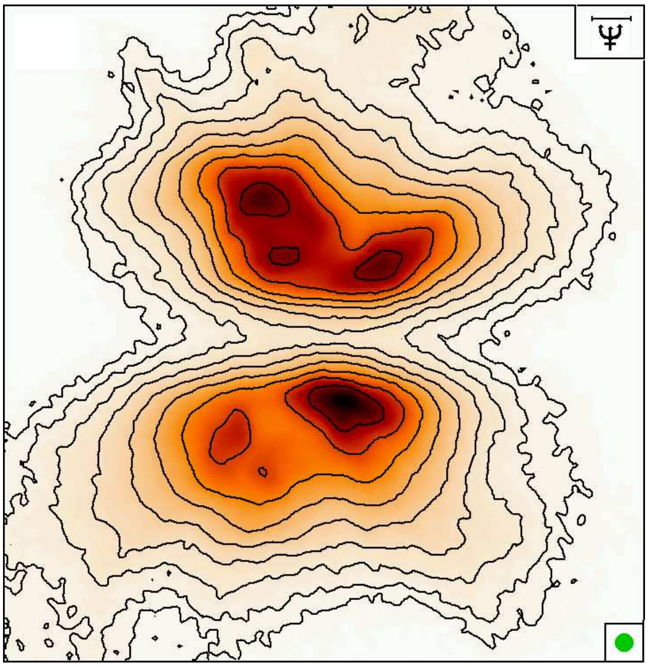

Figure 1: Illustration of the need for high angular resolution interferometry in the field of planet formation research. The image shows the "Butterfly star" (IRAS 04302+2247) in Taurus, observed with the Hubble Space Telescope using the near-infrared camera NICMOS. Under the assumption of a distance of 140 pc, the side length of the images amounts to 900 AU. The scale in the upper right edge shows the angular diameter of Neptune's orbit if it was in the distance of the Butterfly star ($\approx$60 AU corresponding to $\approx$429 mas in a distance of 140 pc).
[The contour lines mark steps of 0.5 mag. The lowest contour line corresponds to a level of 1.4σ, where σ is the standard deviation of the background noise. The filled circle in the lower right edge of the image represents the full width half maximum of the point spread function. — based on Wolf et al. 2003]

large-scale (global) properties of circumstellar disks, a significantly higher angular resolution is required in order to study the formation of planets and planetary systems. Given the typical size of circumstellar disks of $\approx$ 100 AU to 1000 AU, their typical angular diameter in nearby rich star-forming regions of low-mass stars (such as Taurus, Lupus, Ophiuchus, Coronae Australis, Chamaeleon, etc.) amounts to a fraction of an arcsecond to a few arcseconds. The planet formation, however, is expected to occur on size scales which are about one to two orders of magnitude smaller (the diameter of the Mercury / Earth / Jupiter orbit amounts to 5 mas / 14 mas / 74 mas; see Fig. 1 for illustration).

According to the longest baselines of the Very Large Telescope Interferometer (VLTI), maximum angular resolutions of $\approx$ 1 - 2 mas / 10 - 20 mas can be achieved in the near-infrared (e.g., with AMBER) and mid-infrared (e.g., with MIDI), respectively. As it will be pointed out in Sect. 3 in more detail, an increase of the angular resolution by about one to two orders of magnitude is required to study the innermost disk region. When performing interferometric observations with these high angular resolutions, one has to be aware of the fact that the central star can not necessarily be considered as a point source: T Tauri and Herbig Ae/Be stars are expected to have typical radii of $\approx$ 2-3 solar radii. Thus, their angular diameter at typical distances of potential targets amounts to $\approx$0.2 mas / 0.02 mas (in a distance of 100 pc and 1 kpc, respectively).

This article is structured as follows: In Sect. 2 a list of questions concerning the circumstellar matter and planet formation is compiled. The investigation of these problems would strongly benefit from high-resolution interferometric observations. In the subsequent Sect. 3, a few selected questions are then discussed in more detail. Finally, a summary of the discussed requirements of next-generation optical to mid-infrared interferometers is provided in Sect. 4.

2 Catalog of Questions

As briefly discussed in the introduction, high-resolution interferometric observations would be not only helpful, but are required in order to study the planet formation process, e.g., for the verification of predictions derived from theoretical / numerical models (see Sect. 3). In the following, a selection of questions related to both the star and planet formation process is compiled. This compilation is by no means complete, but is intended to illustrate how the investigation of the complex process of star and planet formation can be broken down to particular questions that may be addressed with next-generation interferometers.

1. Circumstellar Disks: Star formation
    - How does the accretion process onto the central star evolve with time?
    - How do large-scale (molecular) outflows and jets form? How do they get collimated? Where is exactly their origin?
    - Which role do magnetic fields play? Are they coupled to the disk? Are they important for the accretion process onto the star, e.g. by accretion through magnetospheric funnel flows?
    - How are the gas and dust distributed on large scales in the disk (radially, vertically; azimuthal structures?)?
    - Which role do stellar and disk winds play?
    - What are the structure and geometry of the accreting protostar? How is the star interacting with its surrounding circumstellar disk?
    - How do disks interact with one another in young multiple stellar systems?
    - Do young massive stars have circumstellar disks?

2. Circumstellar Disk: Planet formation
    - How does the size distribution and chemical composition of the dust evolve?
    - How does the structure of circumstellar disks evolve?
    - Do circumstellar disks show signs of the possible planet formation process or even of the existence of already formed planets (gaps; large-scale spiral structures induced by the planet; planetary accretion)?
    - What are the conditions for planet formation in binary or multiple stellar systems? What is the influence of very close (sub)stellar binaries on the circumstellar disk?
    - Is planet formation possible in the environment of massive stars?

3 Selected Science Cases in Detail

In this section, selected potential science cases for future optical / mid-infrared interferometers are discussed in more detail. Since the observable quantities of a circumstellar disk strongly depend on the evolutionary state of the disk, the discussion is separated into two parts: young circumstellar disks (Sect. 3.1) and debris disks (Sect. 3.2). For this reason, a brief comparison between both "types" of circumstellar disk is given before:

Protoplanetary disks have been imaged from the near-infrared to the millimeter range around numerous low-mass young stellar objects (T Tauri stars, e.g., Dutrey et al. 1994, 1998; Burrows et al. 1996; see, e.g., Beckwith 1999 for an overview), intermediate-mass young stellar objects (Herbig Ae/Be stars, e.g., Mannings & Sargent 1997, 2000), and possibly around a massive star (Fontani et al. 2004). Circumstellar disks evolve from a gas-dominated state (mainly traced with millimeter interferometers), to so-called "debris disks". In contrast to young circumstellar disks, debris disks are solar system sized dust disks produced as by-products of collisions between asteroid-like bodies and the activity of comets left over from the planet formation process. In the case of our solar system, the debris of Jupiter-family short-period comets and colliding asteroids represents the dominant source of zodiacal dust located inside the Jupiter orbit. A second belt of dust is located beyond the orbit of Neptune (e.g., Dermott et al. 1992; Liou, Dermott, & Xu 1995). Besides the solar system, optical to mid-infrared images of β Pic and AU Mic (e.g., Kalas & Jewitt 1995; Weinberger, Becklin, & Zuckerman 2003, Kalas et al. 2004) and (sub)millimeter images of Vega, Fomalhaut, ϵ Eri, and β Pic (Holland et al. 1998; Greaves et al. 1998, Liseau et al. 20003) have revealed spatially resolved debris disks which were first inferred from observations of infrared flux excesses above photospheric values with the Infrared Astronomical Satellite (IRAS). Based on studies with the Infrared Space Observatory (ISO), the disk fraction is thought to decrease significantly with age, amounting to much less than 10% for stars with ages $\geq$ 1Gyr (e.g., Spangler et al. 2001; see also Habing et al. 2001, Greaves et al. 2004; Dominik & Decin 2003). Planetary debris disks are assumed to represent the almost final stage of the circumstellar disk evolution process, i.e., they are the evolutionary products of ongoing or completed planet formation.

In contrast to optically thick young circumstellar disks around Herbig Ae/Be and T Tauri stars with spatial structures dominated by gas dynamics, the much lower optical depth and lower gas-to-dust mass ratio in debris disks (Zuckerman, Forveille, & Kastner 1995; Dent et al. 1995; Artymowicz & Clampin 1997; Liseau & Artymowicz 1998; Greaves, Coulson, & Holland 2000; Lecavelier et al. 2001) let the stellar radiation − in addition to gravity − be responsible for the disk structure. Besides, fragmentation becomes a typical outcome of particle collisions, because relative velocities of grains are no longer damped by gas. The Poynting-Robertson effect, radiation pressure, collisions, and gravitational stirring by embedded planets are all important in determining the dust population and disk structure (Liou & Zook 1999; Grady et al. 2000; Moro-Martín & Malhotra 2002). Similar to T Tauri-like disks, however, embedded planets may alter the debris disk structure substantially, although through different physical processes (e.g., Gor'kavyi et al. 1997; Kenyon & Bromley 2001). While planets may open gaps in gas-dominated young circumstellar disks (e.g., Bryden et al. 1999, 2000; Kley 2000), they create large-scale resonance structures, warps, and asymmetries in debris disks. Clumpy structures due to planetary resonances can be formed either by dust created outside the planet's orbit which migrates inwards into the resonances (Dermott et al. 1994; Kuchner & Holman 2003) or by the planet having migrated outward thus trapping the parent planetesimals of the dust into the resonances (Wyatt 2003).

Similar to T Tauri disks, circumstellar disks at the late stage of their evolution appear to show a large range of possible radii, typically in the range of about 100 AU to several hundred AU. So far, scattered light images and spectral energy distributions (SEDs) revealed radii of 80 AU (ϵEri), 120 AU (Vega), 125 AU (HR 4796), 185 AU (Fomalhaut) and even 1000 AU in the case of the disk around β Pic (see Vidal-Madjar et al. 1998; Dent et al. 2000; Greaves, Mannings, & Holland 2000b; Holland et al. 2003). However, the observed scattered light images and near/mid-infrared SEDs of debris disks are mainly determined by the small grain component in the disk, while larger grains with radii of several tens of micron and larger can be more efficiently found by (sub)millimeter measurements. One has to take into account that the abundance and spatial distribution of the small grain component depends on the location of dust sources and the likelihood of collisional events. Since these parameters are not necessarily correlated with the actual disk size, submillimeter/millimeter measurements are required to trace larger grains which are less affected by the radiation pressure and Poynting-Robertson effect.

Since the mass of small grains in debris disks and therefore the thermal dust reemission from these disks are much smaller than in the case of T Tauri disks, only a very limited sample of observations exists so far. However, because of the high sensitivity of the mid-infrared detectors aboard the Spitzer Space Telescope a substantial increase in the total number and in the specific information about debris disks is expected until 2005 (cf. Meyer et al. 2004).

Although debris disks represent a rich source of information about the formation and evolution of planetary systems, they also impose problems on the observations of exoplanetary systems. First, the zodiacal light of our own solar system has a potential serious impact on the ability of infrared / submillimeter ground- and space-based observatories to detect and study their targets. It is attributed to the scattering of sunlight in the UV to near-IR, and – important for mid-IR observations – the thermal dust reemission in the mid to far-IR. At infrared wavelengths from approximately 1μm, the signal from the zodiacal light is a major contributor to the diffuse sky brightness and dominates the mid-IR sky in nearly all directions, except for very low galactic latitudes (Gurfil et al. 2002).

Second, the exozodiacal dust disk around a target star, even at solar level, will likely be the dominant signal originating from the extrasolar system. In the case of a solar system twin, its overall flux over the first 5 AU is about 400 times larger than the emission of the Earth at 10μm. Although the factor reduces to a few tens after partial rejection by usage of a nulling interferometer, one still has to make sure that the exo-zodiacal signature will not mimic planetary signals such as would be the case if the disk is significantly clumpy (as almost always found in the outer regions of debris disk – e.g., Holland et al. 1998; Greaves et al. 1998; Holland et al. 2003). If the origin of this clumpiness is in perturbations of planets, then detecting clumps can help to pinpoint those planets (e.g., Wyatt 2003). In this context one has to be aware that collisionally regenerated debris disks are also intrinsically clumpy because dust created by collisions between large planetesimals starts out in a clumpy dust distribution (Wyatt & Dent 2002). As stated earlier, ongoing and planned observations of large debris disk candidate samples with the Spitzer Space Telescope are expected to provide this information within the coming year/s.

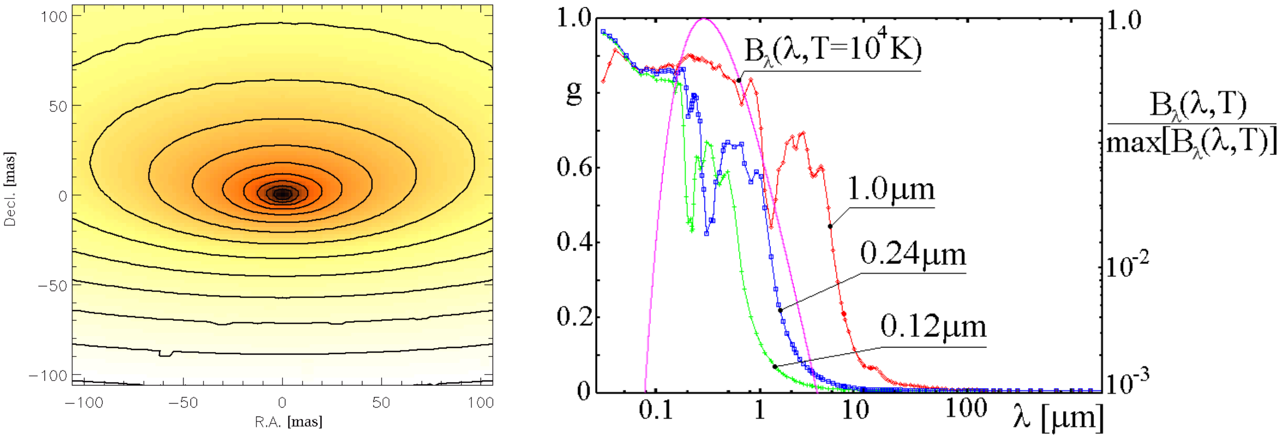

Figure 2: *Left:* Simulated 10μm intensity map of the inner 30AU×30AU region of a circumstellar T Tauri disk in an assumed distance of 140 pc; inclination angle: 60°. Due to the flared surface of the disk, the overlayed iso-intensity contour lines are clearly not centered on the star. *Right:* Stellar photospheric SED of a Herbig Ae star vs. the wavelength-dependence of the scattering parameter g for different grain sizes, resulting in a dependence of the efficiency to transport radiation in the upper layers of circumstellar disks. *[from Wolf 2001]*

3.1 Science Cases: Young circumstellar disks

1. Inner Disk structure: General Parameters

Description:

While two-beam interferometers allow to derive the “mean” disk size and the approximate inclination of a circumstellar disk, multi-beam interferometers are required to allow to consider that circumstellar disks which are not seen exactly face-on do show a brightness profile which cannot be described by iso-brightness contours, which are centered on the location of the central star (and thus not allowing to use point-symmetric models; see Fig. 2[left] for illustration).

Scattered light images, to be obtained in the optical to near-infrared wavelength range, allow to trace the surface structure of the disk and thus the degree of flaring and possible (sub)structures in the disk surface profile (see also the discussion of subsequent science cases in this section). From mid-infrared observations, the radial temperature profile of the hot dust on the disk surface and the inner disk rim can be derived. In turn, this profile will provide valuable information about the radial and vertical structure of the disk, about the importance of viscous and accretion heating (in addition to the stellar heating) and thus on the interior density structure in the - possibly - planet-forming region of the disk.

Goals / Parameters to be determined:

- Surface density profile (flaring, substructures) and temperature profile in the inner disk region (∼ 10 AU)
- Conclusions about the interior physical conditions (e.g., density, temperature, gas dynamics) and processes (e.g., accretion, magnetic fields, grain growth)
- Is the optical / near-infrared variability of the flux and polarization observed in numerous young stars linked to processes or the structure of the innermost disk region?

- How do jets / outflows influence the inner disk structure (and vice versa)?

Requirements:

- Angular resolution: 0.1 – 1 mas (in order to resolve ∼ 0.1 AU structures in nearby star-forming regions, i.e., in Taurus with a distance of ∼ 140 pc)
- Wavelength range: optical / near-infrared / mid-infrared
- Imaging (i.e., measurement of the phase in order to allow image reconstruction); visibility measurements alone are not sufficient

2. Dust grain growth in the inner circumstellar disk

Description:
The most reliable conclusions about grain growth - as the first stage of planet formation - are based on the millimeter slope in the SED of circumstellar disks (Beckwith et al. 1990) and more recently on images of dust disks provided by millimeter arrays (e.g., Butterfly star: Wolf et al. 2003; CQ Tau: Testi et al. 2003). These images clearly reveal grain growth up to particles of mm/(cm) size. What is clearly missing, however, are *a)* observational constraints on the region, where dust grain growth is presumably fastest (first qualitative results have been obtained with MIDI, based on a detailed analysis of the profile of the 10μm silicate feature, Leinert et al. 2004), and *b)* a detailed knowledge of the vertical disk structure.

First approach:
A particular feature of the infrared spectra of young circumstellar disks is the silicate band in the region from 8 to 13μm. The band originates from the stretching mode of the Si-O bond of silicate minerals like olivine ($[Mg,Fe]_2SiO_4$), forsterite (Mg_2SiO_4), enstatite ($MgSiO_3$) and silica (SiO_2). The silicate feature observed in T Tauri stars appears in emission as well as in absorption (Cohen & Witteborn 1985). Silicate emission is assumed to emerge from a warm, optically thin disk layer (“disk atmosphere”) which is heated by the radiation of the central star (Chiang & Goldreich 1997; Natta et al. 2000). Honda et al. (2003) showed that crystalline silicates are present in T Tauri stars, indicating substantial grain processing. In the 8-13 μm spectra of some T Tauri stars (e.g., AK Sco, Haro 1-16, CR Cha) a strong silicate emission with a peak near 9.8 μm is visible. In other cases (e.g., Ru Lup, DR Tau, HBC 639), the silicate emission is weaker and the profile looks more like a plateau (Przygodda et al. 2003). It is known that the shape of the band is strongly affected by the chemical composition and in particular by the size of the dust grains (Henning et al. 1995; Bouwman et al. 2001). Spatially resolved spectroscopy in the inner ∼ 10 AU in the 8-13 μm atmospheric window will therefore allow to trace the expected strong radial dependence of dust grain growth.

Second approach:
Images both in the optical / near-infrared as well as in the mid-infrared can help to constrain the grain size. First, the efficiency of forward-scattering of stellar light – and therefore the appearance of the inner disk at those wavelengths – strongly depends on the grain size. To illustrate this dependency, the significant change of the scattering parameter of dust grains in the sub-micron to micron size regime in the wavelength range of stellar emission is shown in Fig. 2[right]. Furthermore, the forward vs. backward-scattering behavior of dust grains determines – together with the dust density structure – the innermost temperature gradient in

the disk. Depending on the dust opacity, mid-infrared images showing the reprocessed radiation will also help to constrain the dust grain size.

Goals / Parameters to be determined:

- Grain size distribution in the upper layers of circumstellar disks
- Radial dependence of the grain size and thus constraints on grain growth (grain size: submicron – several micron, according to the wavelength range of the observations)

Requirements:

- Wavelength range: optical / near-infrared / mid-infrared
- Angular resolution: $\sim 1\,\mathrm{mas}$
- Medium spectral resolution in the mid-infrared (R $\sim$ 1000, in order to resolve dust absorption and / or thermal reemission features of amorphous and crystalline dust grains)

3. Chemical evolution of the dust phase

Description:

Protostellar and protoplanetary accretion disks are believed to be in a state of vigorous turbulence during the early stages of their evolution. If the carrier gas of a turbulent flow, such as a young circumstellar disk, has a spatially inhomogeneous composition with respect to its main and/or tracer constituents, turbulence induces a spatial diffusion of the components which tends to eliminate any spatial concentration gradients. The interplay between radial mixing process in protoplanetary accretion disks with processes leading to the destruction or modification of the extinction properties of abundant dust species has significant consequences for the properties of the disk.

As pointed out by Morfill (1983), the spatial diffusion is of importance for the composition of the material in a protoplanetary accretion disk if the turbulent part of the disk connects regions with widely different temperatures. Chemical and physical processes in warm and hot disk regions locally change the structure, properties, and chemical composition of the various dust components. Turbulent mixing then carries such material into cold regions of the disk where it is mixed with freshly accreted material from the parent molecular cloud. Furthermore, certain dust components (e.g., carbon grains) are vapourised in the hot parts of the disk and the vapours are mixed outwards by turbulent diffusion and recondense in cooler parts of the disk.

Diffusion: Protoplanetary accretion disks are unstable against convection throughout most parts of the disk at least during the first million years after their formation, ranging from the hot inner zone out to $\sim$20AU or even more (see, e.g., Ruden & Lin 1986; D'Alessio et al. 1998). Furthermore, the disk is likely to be unstable against production of shear driven turbulence (Dubrulle 1993). For this reason, turbulent flows exist in a protoplanetary accretion disks.

Carbon combustion: Carbon dust is a highly absorbing material and thus determines the temperature structure in protostellar disks. A realistic description of the properties of accretion disks therefore requires the determination of the true spatial distribution of this dust component within the disk. A considerable modification of the abundance of carbon dust in cold parts of the disk by carbon destruction in the warm inner region of the disk and turbulent radial mixing of this material into the cold outer parts of the disk is therefore expected (Gail 2001).

Annealing of Silicate: In a region of the disk where the midplane temperature exceeds activation of internal rearrangement processes in the lattice lead to the development of a crystalline lattice structure (annealing; Duschl et al. 1996; Gail 1998). Since amorphous and crystalline silicate have drastically different extinction properties, the process of annealing has strong implications for the structure of the protoplanetary disk. If turbulent mixing processes transport crystallized silicate dust from the warm inner disk into the outer disk regions, the dust opacity in that region is reduced. Therefore, it is important to account for the annealing and mixing process if the structure of a protoplanetary disk is calculated.

Goals / Parameters to be determined:

- Test of predictions concerning dust annealing, thermal combustion, and radial mixing within the inner ≈ 10 AU of circumstellar disks, i.e., via investigation of the spatial distribution of amorphous vs. crystalline silicates
- Determination of the spatial distribution of chemically different dust grain species

Requirements:

- Angular resolution: 0.1 – 1 mas
- Medium spectral resolution in the mid-infrared wavelength range (in order to resolve solid-state dust features of both amorphous and crystalline species)

4. Inner Disk Clearing

Description:
According to the temperature and luminosity of the central star, the sublimation radius for dust grains is in the order of 0.1 - 1.0 AU (T Tauri - Herbig Ae/Be stars). However, in contrast to these values, a significantly larger inner dust disk radius of $\sim$4 AU has been measured in the 10 Myr old protoplanetary disk around TW Hydrae (Calvet et al. 2002; another example: GM Aurigae – see Koerner, Sargent, & Beckwith 1993; Rice et al. 2003). This “inner hole” is characterized by a depletion of at least the population of small dust grains which are responsible for the near to mid-infrared flux. The confirmation of this indirectly (via SED modeling) determined gap with a radius of $\sim$4 AU, as well as the test of other disks for the existence / non-existence of similar gaps will provide valuable constraints on the evolution of the planet-forming region and thus on the process of planet formation itself.

Goals / Parameters to be determined:

- Inner disk radius of young circumstellar disks
- Is the existence / size of an enlarged inner disk radius correlated with other disk parameters (such as the age / evolutionary state, disk mass, etc.)?

Requirements:

- Angular resolution: 0.1 – 1 mas

- Visibility measurements sufficient

5. Density Inhomogeneities

Description:

The inner region of circumstellar disks is expected - but not yet proven - to show large-scale (sub-AU to AU sized) density fluctuations / inhomogeneities. The most prominent examples are predicted long-lived anti-cyclonic vortices in which an increased density of dust grains may undergo an accelerated growth process - the first step towards planet formation (Klahr & Bodenheimer 2003; see Fig. 3 for an illustration of the observability with submillimeter interferometers). Locally increased densities and the resulting locally increased disk scale height have direct impact on the heating of the disk by the central star and are expected to show up as local brightness variation (due to increased absorption / shadowing effects) in mid-infrared images.

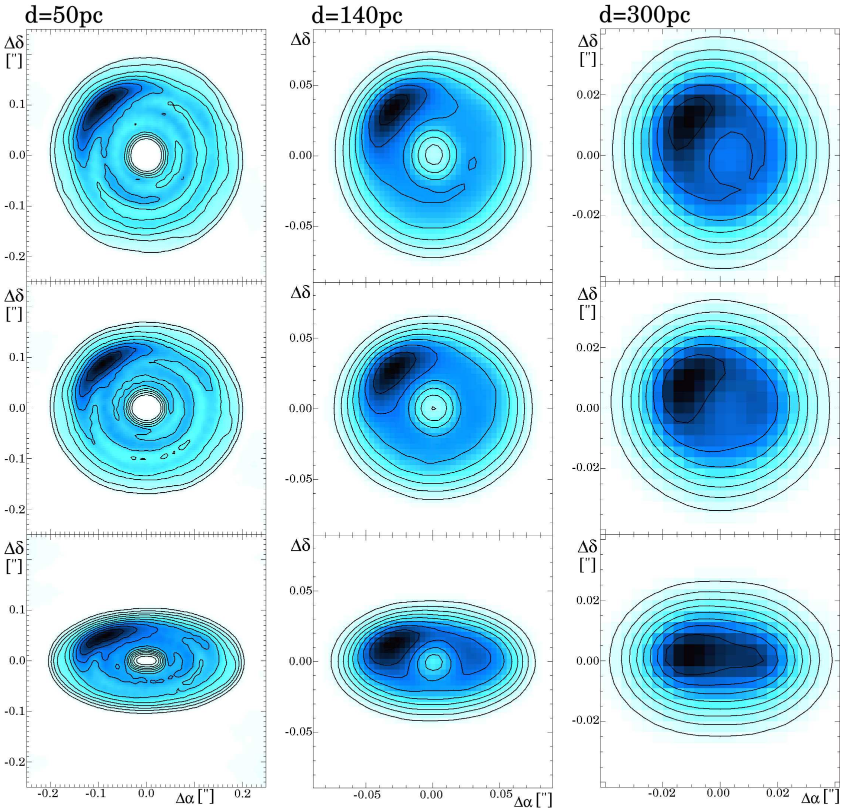

Figure 3: Large-scale anti-cyclonic vortices, resulting from a global baroclinic instability, as pre-cursors of planet formation in protoplanetary disks. The images represent simulations of observations with the Atacama Large Millimeter Array (ALMA): Reconstructed maps of a circumstellar disk with a vortex with an increased dust density seen under inclinations of i=0° (face-on; upper row), 30° (middle row), and 60° (lower row). Distances of 50 pc, 140 pc, and 300 pc are considered. Observing frequency ν=900 GHz; total integration time: 2 h. The contour lines mark steps of 2.0 mJy/beam$^{(1)}$ and 1.5 mJy/beam$^{(2)}$ in the case of d=50 pc$^{(1)}$, 140 pc$^{(1)}$ and 300 pc$^{(2)}$, respectively. *[from Wolf & Klahr 2002]*

Goals / Parameters to be determined:

- Search for large-scale localized dust concentrations in circumstellar disks, in particular in the potential planet-forming region

Requirements:

- Angular resolution: $\sim 1\,\mathrm{mas}$
- Wavelength range: (optical?) / near-infrared / mid-infrared
- Imaging

6. Gaps and Spiral Waves induced by planets

Description:
Once (proto-)planets have been formed, they may significantly alter the surface density profile of the disk and thus cause signatures in the disk that are much easier to find than the planets themselves. The appearance and type of these signatures depend on the mass and orbit of the planet, but even more on the evolutionary stage of the circumstellar disk. During recent years, numerical simulations studying planet-disk interactions have shown that planets may cause characteristic large-scale signatures in the disk density distributions. The most important of these signatures are gaps and spiral density waves in young circumstellar disks (e.g., Bryden et al. 1999; Kley 1999; Lubow, Seibert, & Artymowicz 1999; Kley, D'Angelo, & Henning 2001; Bate et al. 2003; Winters, Balbus, & Hawley 2003; Nelson & Papaloizou 2003). The gap, which is located along the orbit of the planet, may extend up to several astronomical units in width, depending on the mass of the planet and the hydrodynamic properties of the disk. The gas accretion on the planet can continue to planet masses of the order of $10\,\mathrm{M_{Jupiter}}$, at which point tidal forces are sufficiently strong to prevent flow into the gap. The simulations also show that only planets with masses $> 0.1\,\mathrm{M_{Jupiter}}$ produce significant perturbations in the disk's surface density (Bate et al. 2003). However, Paardekooper & Mellema (2004) found that for typical disk masses (e.g., $0.01\,M_{\mathrm{sun}}$ within 100 AU) the strong spiral shocks near the planet are able to decouple the larger particles (0.1 mm) from the gas. This leads to the formation of an annular gap in the dust, even if there is no gap in the gas density. Because the opacity at millimeter wavelengths is dominated by these larger particles, the signatures of low-mass planets in disks can be stronger than previously thought. The minimum mass for a planet to open a gap this way was found to be $0.05\,M_{\mathrm{Jupiter}}$ for 1 mm particles.

Wolf et al. (2002) demonstrated, that high-resolution imaging with the Atacama Large Millimeter Array (ALMA) will allow to map these gaps for sufficiently large planets in the submillimeter wavelength range. Fig. 4 demonstrates that a sufficiently cleared gap can also be found with mid-infrared interferometric observations.

Protoplanets also launch spiral waves in the disk. It is not clear, however, whether these waves are diffused and dissipated in the presence of turbulence (e.g., Nelson & Papaloizou 2003). High-resolution scattered light images in the optical / near-infrared wavelength range can be used to answer this question and therefore to discuss the degree of turbulence in disks and underlying physical properties of the disk material (see Fig. 5).

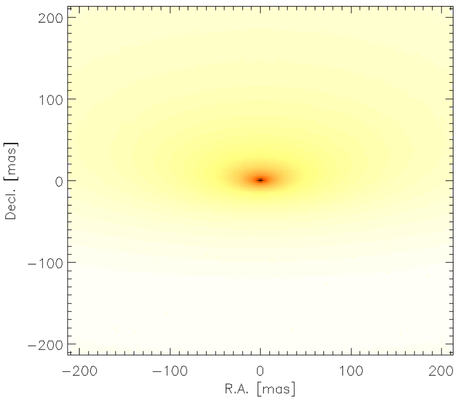

Figure 4: Simulated 10μm images of a circumstellar disk around a T Tauri star without (left) and with (right) a 4 AU gap in a distance of 4 AU from the central star. Disk inclination: 60° (for comparison: 0° = face-on); assumed distance: 140 pc.

Based on hydrodynamical simulations, D'Angelo, Henning, & Kley (2002) found smaller-scale spirals in the vicinity of the planet that are detached from the main ones: Along these small spirals the gas orbits the planet, representing a circumplanetary disk (see also Lubow, Seibert, & Artymowicz 1999). Wolf & D'Angelo (2005) then predicted that the hot region in the proximity of a young planet, along with the gap, could indeed be detected and mapped with the Atacama Large Millimeter Array in the case of nearby circumstellar disks (d<100 pc) in approximate face-on orientation. Wolf & Klahr (in prep.) could show that the hot dust in the local, accretion-dominated environment of the planet could indeed be observed also at shorter wavelengths, namely in the mid-infrared wavelength range (see Fig. 6).

Goals / Parameters to be determined:

- Verification of the predictions for the process of giant planet formation: Searching for gaps induced by giant planets in circumstellar disks (location, width, degree of clearing)
- Analysis of the possible structure in the surface brightness distribution (spiral waves?)
- Analysis of the planetary accretion region (spatial structure, temperature distribution)

Requirements:

- Angular resolution: ~ 0.1 − 1 mas
- Wavelength range: (optical) / near-infrared / mid-infrared
- Imaging

7. Circumstellar disks in binary systems

Description:

During recent years, near-infrared imaging and high-resolution observations yielded conclusive evidence that most (if not all) low-mass stars are born in binary and multiple stellar systems

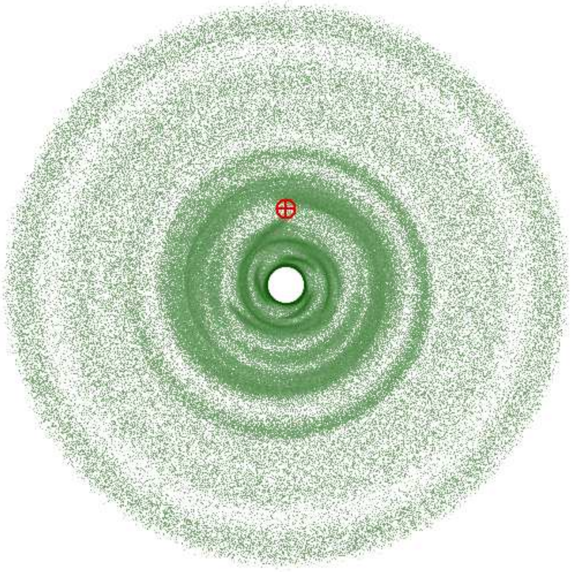

Figure 5: Simulated K band image of an inner young circumstellar disk (radius 19.7 AU) with an embedded Jupiter-mass planet at a distance of 5.2 AU, showing the scattering of the stellar radiation (solar-mass star) on the surface (structures) of the disk. The spiral density pattern is clearly visible, in contrast to the gap which is less pronounced in this wavelength range. The small circle marks the position of the planet. *[from Wolf & Klahr, in prep.]*

(Simon et al. 1995; Ghez et al. 1997; Leinert et al. 1997; Köhler & Leinert 1998). This finding suggests that binary formation is the rule and the birth of single stars the exception. However, the formation and survival of binary systems obviously depend upon environmental conditions (Bouvier et al. 1997). High-resolution interferometry will allow to explore this most prominent mode of star formation for low-to-intermediate mass stars. In particular, these measurements will allow to prove predictions about the occurrence of circumstellar instead of or in combination with circumbinary disks.

What are the predictions(?): Bate & Bonnell (1997) studied the disk formation process in accreting protobinary systems and established criteria for the formation of circumstellar and circumbinary disks. They found, that if a protobinary system accretes only gas with low specific angular momentum after its formation, the primary will have a circumstellar disk, but the secondary may not. The reverse is not true: if a circumstellar disk is formed around the secondary, the primary will also have a disk. Concerning circumbinary disks, Bate (2000) predicted that closer binary systems are more likely to have circumbinary disks than wider systems with the same total mass. Furthermore, if massive and low-mass binary systems form via the same process, the massive binaries are more likely to have circumbinary disks than low-mass binaries of the same separation.

Goals / Parameters to be determined:

- Distribution of circumstellar matter / disk material in binary systems
- Formation of circumstellar vs. circumbinary disks
- Conditions for planet formation (disks in) in binary / multiple systems

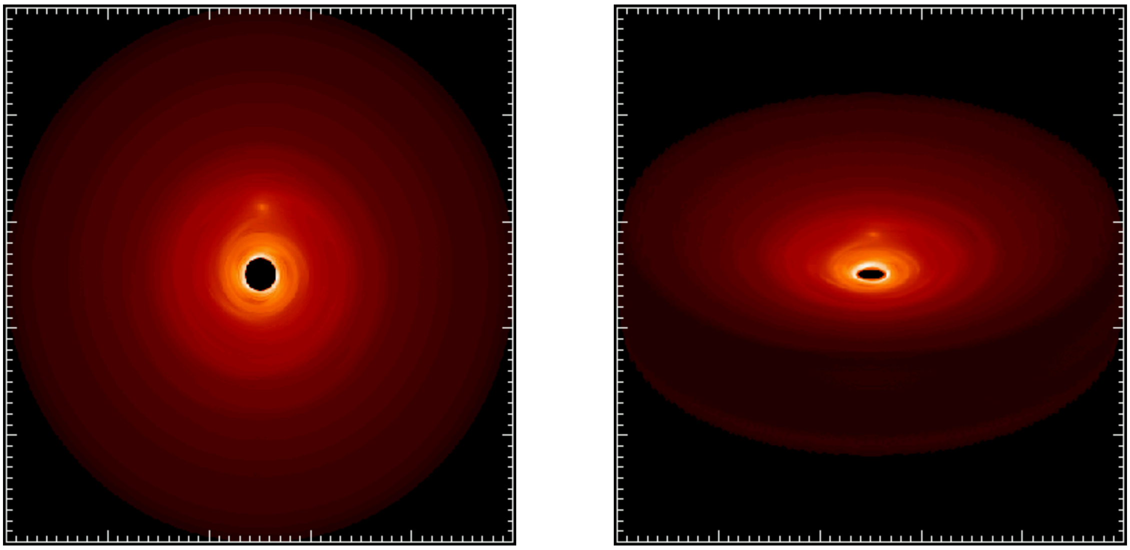

Figure 6: Simulated 10 μm images of the configuration discussed in Fig. 5, seen under an inclination of 0° (left) and 60° (right), respectively. The region of hot dust around the planet is clearly visible. *[from Wolf & Klahr, in prep.]*

Requirements:

- Angular resolution: $\sim 1 - 10$ mas
- Wavelength range: optical / near-infrared / mid-infrared
- Imaging

8. Massive star formation

Description:
Young high-mass stars ($M_\star > 10\,M_{\rm sun}$) are relatively rare in our Galaxy and tend to be more distant than low–mass young stellar objects. While several prominent low–mass star forming regions can be found at distances of 150 – 300 parsecs from the Sun, most of the currently active high–mass star–forming regions are located at distances beyond 1 kpc (a number of high-mass star formation regions can be found in distances of 3 to 7 kpc). Furthermore, massive stars tend to form in very opaque and highly clustered environments. Our understanding of the formation of high-mass stars is therefore significantly lagging behind that of the low-mass counterparts.

Goals / Parameters to be determined:

- Comparison of low and high-mass star formation
- Existence of circumstellar disks (structure?), Jets, Outflows
- Possibility of planet formation in the environment of massive stars?
- Binarity / Multiplicity of young high-mass stars

Requirements:

- Angular resolution: ∼ 1 mas
  (However, in order to investigate structures of similar size as in the case of low-mass young stellar objects, a resolution of 0.01 - 0.1 mas would be required.)
- Wavelength range: mid-infrared
- Imaging (investigations of the nearby high-mass star forming region in Orion have revealed a very complex structure of the environment of young massive stars)

3.2 Science cases: Debris disks

1. Inner Disk Clearing

Description:
In several prominent debris disks inner cavities have been found: β Pic (inner radius: 20 AU), HR 4796A (30-50 AU), ϵ Eri (50 AU), Vega (80 AU), Fomalhaut (125 AU), and CoKu Tau 4 – e.g., Dent et al. 2000; Greaves, Mannings, & Holland 2000b; Wilner et al. 2002; Holland et al. 2003, and Quillen et al. 2004. Taking into account the physical processes responsible for the spatial dust density distribution in debris disks, scattering of particles by massive planets is assumed to be the major effect in explaining these large inner holes: dust grains drifting inwards due to the Poynting-Robertson effect are likely to be scattered into larger orbits resulting in a lower dust number density within the planet's orbit. Clearing the inner disk results in a loss of warm dust which is mainly responsible for the near/mid-infrared shape of the SED. With increasing gap size, the emission spectrum is shifted toward longer wavelengths and the mid-infrared flux is reduced. Thus, short-wavelength observations (i.e., in the visual wavelength range) seem to be more promising in general than mid-infrared observations.

Goals / Parameters to be determined:

- Innermost radius of debris disks (concerning small dust grains, i.e., those which can be traced by visual to mid-infrared measurements)
- Are there further radii at which the dust density has a discontinuous distribution in radial direction (due to several embedded planets)? Which are the resulting orbital elements and masses of possible planets in debris disks?

Requirements:

- Angular resolution: ∼ 1 mas
- Wavelength range: optical / near-infrared / (mid-infrared)
- Imaging; Visibility measurements
- Spectroscopy, medium resolution (dust features)

2. Characteristic density pattern: Planets

Description:

In evolved, optically thin debris disks, planets are expected to produce (1) an asymmetric resonant dust belt with one or more clumps, intermittent with one or a few off-center cavities, and (2) a central cavity void of dust via resonances and gravitational scattering (Ozernoy et al. 2000, Liou & Zook 1999). The resulting characteristic density patterns are expected to provide the strongest indirect hints on the existence of planets in these disks (e.g., Ozernoy et al. 2000 - Fig. 1). Kuchner & Holman (2003) pointed out that four basic resonant structures probably represent the range of high-contrast resonant structures a planet with eccentricity < 0.6 can create in a disk of dust released on low eccentric orbits: (i) A ring with a gap at the location of the planet, (ii) a smooth ring, (iii) a clumpy eccentric ring, and (iv) an offset ring plus a pair of clumps. The appearance / dominance of one of these structures mainly depends on the mass of the planet and the eccentricity of its orbit.

Indeed, several debris disks around nearby main-sequence stars show structures and asymmetries that are considered to result from planetary perturbations (Holland et al. 1998, 2003; Schneider et al. 1999; Koerner, Sargent, & Ostroff 2001). A prominent example is the debris disk around Vega which shows two dominating emission peaks / density enhancements (Holland et al. 1998, Wilner et al. 2002). However, images tracing the thermal dust reemission with higher angular resolution are required to verify this hypothesis. Alternatively, high-resolution scattered-light images could be used.

Another example in the case of which the possible influence of a planet on the disk structure has been discussed is the β Pictoris disk. The dust disk, seen nearly edge-on, extends to at least a distance of 1000 AU from the central star (Zuckerman & Becklin 1993, Holland et al. 1998, Dent et al. 2000, Pantin, Lagage, & Artymowicz 1997). The Northeast and Southwest extensions of the dust disk have been found to be asymmetric in scattered light as well as in thermal emission. This warp is assumed to be caused by a giant planet on an inclined orbit that gravitationally perturbs the dust disk (Augereau et al. 2001, Mouillet et al. 1997; see also Lubow & Ogilvie 2001).

Goals / Parameters to be determined:

- Orbital elements and masses of planets in debris disks

Requirements:

- Angular resolution: 0.1 – 10 mas
- Wavelength range: optical / near-infrared
- Imaging

4 Conclusions

Next generation optical to mid-infrared interferometers that yield an angular resolution which is by at least 1 - 2 orders of magnitude higher than that of existing interferometers (such as the VLTI or the Keck Interferometer), will allow to study the circumstellar environment on size scales which allow to trace and to investigate the process of planet formation. Beside the question about the angular resolution, the selected science cases discussed in the previous sections provide a number of constraints / minimum requirements for such interferometers which are briefly summarized in the following:

Wavelength coverage

Optical to mid-infrared wavelengths range (including the 8-13μm atmospheric window) in order to trace both, the light scattered on the disk surface and the reemission of thermal dust radiation.
[This coverage will allow to constrain the geometry of the disk (inner few AU), the chemical composition / structure (amorphous vs. crystalline) and size of the dust grains and thus the evolutionary stage of the dust.]

Angular Resolution

$\sim 0.1 - 1\,\mathrm{mas}$ in the optical to mid-infrared wavelength range.
[This corresponds to a spatial resolution of $< 0.1\,AU$ *in nearby low-mass star-forming regions. Goal: Qualitatively new constraints on planet formation scenarios.]*

Spectral Resolution

~ 1000 (comparable, e.g., to the ISO Short-Wavelength Spectrometer).
[This spectral resolution will allow to resolve not only broad-band dust absorption / emission features, but also crystalline dust features and PAH features. Given the above wavelength coverage and angular resolution, the spatial distribution of different dust species in the planet-forming region of circumstellar disks can be studied.]

Contrast / Sensitivity

Given the lack of spatially resolved observations of the inner $\sim 10\,\mathrm{AU}$ over the above wavelength range, constraints can be derived from disk modeling only. Corresponding to the above angular resolution and typical near to mid-infrared fluxes of circumstellar disks, the sensitivities in the $\sim 1 - 10\,\mathrm{mJy}$ range must be aimed for. However, preparatory studies with first and second generation VLTI interferometers, such as AMBER (Astronomical Multiple Beam Recombiner) and MIDI (Mid-Infrared Interferometric Instrument) could provide better constraints based on observations of nearby objects (distance $< 100\,\mathrm{pc}$).

Imaging capability

Strongly recommended.
[Since next-generation interferometers – due to their aspired high angular resolution – will trace structures that cannot be verified directly using other observations / imaging techniques, comparisons with models would represent the only possible strategy to analyze these data. However, given the restricted amount of information contained in visibilities alone (without the phase

information), their analysis would – as often applied – rely on two-dimensional models with rotation symmetry. This approach, which is only justified by large-scale (if at all existent) symmetries of the considered objects, is expected to be strongly misleading on the smaller size scales investigated, while in some cases these models can even simply be proven wrong.]

Several of the presented science cases require a combination of both high angular resolution ($\sim 0.1\,\mathrm{mas}$) and large-scale maps ($\sim 1\,\mathrm{arcsec} \times 1\,\mathrm{arcsec}$) in order to trace systematic structures in disks (e.g., spiral waves).

Field of view

a) $\sim 1000\,\mathrm{mas}$ *[e.g., for mapping large-scale patterns (such as density waves), etc.]*

b) $\sim 100\,\mathrm{mas}$ *[e.g., for mapping the inner circumstellar disk]*

c) $\sim 1 - 10\,\mathrm{mas}$ *[e.g., for mapping the circumplanetary environment]*

Polarization

This observing mode allows to derive additional, independent constraints for the dust grain properties (grain size, chemical composition, large-scale grain alignment). However, polarization measurements are considered to be of second-order importance after imaging and spectroscopy.

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