The Universe under the Microscope – Astrophysics at High Angular Resolution IOP Publishing
Journal of Physics: Conference Series **131** (2008) 012018 doi:10.1088/1742-6596/131/1/012018

Structure and evolution of protoplanetary disks

Cornelis Dullemond, Yaroslav Pavlyuchenkov
Max Planck Institut für Astronomie, Heidelberg, Germany
E-mail: `dullemon@mpia.de`

Daniel Apai
Stewart Observatory, Tucson, USA

Klaus Pontoppidan
Cal Tech, Pasadena, USA

Abstract. We present here a few thoughts on how high-angular resolution observations can give clues to some properties of protoplanetary disks that are fundamental to theories of planet formation. High-angular resolution infrared spectroscopy, either with a large single mirror telescope, or by using infrared interferometry, allows us to probe the abundance of thermally processed dust in the disk as a function of distance to the star. We show that this radial abundance profile can give information about the early evolution of the protoplanetary disk as well as about the nature of the turbulence. Since turbulence is one of the main ingredients in theories of planet formation, this latter result is particularly important. We also show that Nature itself provides an interesting way to perform high-angular resolution observations with intermediate-angular resolution telescopes: if a disk has a (nearly) edge-on orientation and is located in a low-density ambient dusty medium, the disk casts a shadow into this medium, as it blocks the starlight in equatorial direction. We argue how these shadows can be used to characterize the dust in the disk.

1. Introduction

The major advances in observational studies of the circumstellar disks surrounding pre-main-sequence stars have enormously supported the picture that these disks are the birthplaces of planets and planetary systems. Infrared and millimeter observations of such disks have given strong indications that dust aggregation is taking place in these disks, i.e. that the very first steps on the long road from dust to planets have been taken in these environments (see e.g. [1] for a review). Moreover, it has been recently announced that, by using radial velocity measurements, the first planetary mass companion has been found around a star that still features a gas-rich circumstellar disk [2]. If confirmed, this is the first direct evidence of the formation of a planet in a gas-rich circumstellar disk around a young star, and it would justify the fact that for many years astronomers have called these observed disks “protoplanetary disks”. Since the question how our own solar system, and the many “extra-solar systems” that have been discovered since 1995, have been formed is one of the crucial questions about our own existence, the study of such disks is of utmost importance.

Observational techniques to study these disks have improved dramatically over the past 15 years. Yet, it is still a major challenge to get enough spatial resolution to really study details of processes happening in these disks. Most of the information we have today of protoplanetary disks as a class of objects still comes from unresolved observations. The Spitzer Space Telescope has observed a very large number of T Tauri stars, their slightly more massive cousins, the Herbig Ae stars as well as their considerably less massive siblings, the Brown Dwards, using infrared spectropscopy (see e.g. [3–6]). Using these spectra it is possible to infer the properties of the solid material in the disk, and hence how far it is along the path of growth to larger bodies, as well as information about the thermal history of this matter. Spitzer has given a large number of such high quality spectra, and has made a meaningful statistical analysis possible. But Spitzer does not even nearly have sufficient angular resolution to spatially resolve these disks. So what one observes is the average properties of the dust throughout the disk. It is hard to analyze such data in terms of theoretical models of dust evolution because of the lack of spatial information. For some bright sources, however, it is possible to obtain spatial information about the dust content of these disks. For instance, with the MIDI instrument on the Very Large Telescope one can perform mid-infrared interferometry measurements. This makes it possible to observationaly separate mid infrared spectra into an "inner disk spectrum", emitted inward of about 2 AU from the central star and an "outer disk spectrum", emitted outward of 2 AU [7]. Using different baselines it is in principle possible to "scan" the disk from inside out, obtaining mid-infrared spectra as a function of radius. As I will argue in this chapter, this may provide interesting clues to the nature of turbulence in disks and to the very early formation history of disks. I will also argue that in addition to new instrumentation to obtain ever higher spatial resolution in our observations, there is another hitherto little used method of studying the inner regions of protoplanetary disks: a magnifying effect that nature gives us for free in some rare instances where the disk is at a nearly edge-on configuration with the observer. This will be also discussed here in this chapter.

2. Disk formation and evolution: how it thermally affects the dust

From our own solar system we know that the primitive material from which asteroidal and cometary bodies were formed 4.5 billion years ago has undergone at least one, but often more than one event of heating since it entered the protosolar nebula from the interstellar medium. The nature of this/these heating event(s) is still hotly debated, both in the meteoritic and cometary community as well as in the astronomical community. In the latter community the study of thermal processing of dust in protoplanetary disks is relatively new. The first indications that the dust in many protoplanetary disks is different from the interstellar dust came from ISO observations [8] and ground based N-band spectroscopy [9; 10]. In these observations, and in a host of more recent observations with Spitzer and a number of ground based telescopes, the flattened multi-spike shape of the 10 μm feature of silicates indicated that at least a considerable fraction of the dust that is observed has a crystalline (rocky) mineralogical structure. The dust in the interstellar medium is mostly of amorphous (glassy) structure [11; 12], so evidently something must have happend after the dust entered the disk to change the amorphous dust into crystalline dust. This requires the dust to have undergone a heating event up to at least 800 K after which it is being slowly cooled back to the temperature at which it is currently observed. High temperatures are most readily found close to the star, so this region is the most likely origin of crystals. Indeed, the VLT MIDI interferometric observations of [7] show that the dust in protoplanetary disks is clearly more crystalline close to the star than further out. However, it also clearly showed that even at relatively large distances from the star some of the dust is of crystalline nature. If we believe in the picture that these grains were crystallized close to the star, then there must be a process that transports this dust outward. Since most disks are known to accrete, and hence have a systematic inward stream of mass, this means that these grains must have been able to "swim upstream" against the flow of matter to the locations they are found now. Turbulent mixing may provide such a mechanism [13; 14], but the efficiency of this depends strongly on the nature of the turbulence, as we shall demonstrate below. Perhaps a more efficient mechanism is related to the realization long ago that the radial motion of gas in an accreting disk may vary as a function of height: As [15] found out, in an accretion disk the matter in the surface layers indeed flows inward, but the matter in the midplane tends to flow outward. The net accretion rate is the difference of the inward flow to the outward flow. If this is indeed what happens in turbulent accretion disks, then thermally processed minerals can be easily and efficiently transported to large radii, and a small residual vertical mixing between the inward movig surface layer and the outward moving midplane layer then transports some crystals to the surface where they can be osberved [16].

However, if we go back in time to the very early phases of the evolution of the disk, when it was still being fed by infalling matter from the collapsing envelope, we may expect yet another mechanism for transporting matter outward, in addition to the mixing and layered inflow-outflow: the disk spreading mechanism [17].

In our simple model of disk formation and evolution we model the evolution of the surface density of the disk$\Sigma(r,t)$ as a function of time. We assume that the disk is continually fed by matter from the infalling envelope, yielding a source term in the continuity equation for$\Sigma(r,t)$ which we denote as $\sigma(r,t)$. The standard equation for the evolution of the surface density profile is then (see [18]):

$$\frac{\partial\Sigma}{\partial t} - \frac{3}{r}\frac{\partial}{\partial r}\left[\sqrt{r}\frac{\partial}{\partial r}\left(\Sigma\nu\sqrt{r}\right)\right] = \sigma \tag{1}$$

where ν is the effective viscosity of the disk, which is likely due to magneto-rotational turbulence. It is typically written in terms of the α-prescription: $\nu = \alpha c_s^2/\Omega_K$, where $c_s = \sqrt{k_BT/\mu m_p}$ is the isothermal sound speed of the disk at that radius,$\Omega_K = \sqrt{GM_*/r^3}$ is the Kepler frequency, and α is a tuning parameter typically taken to be $\alpha = 0.01$. For the infall rate $\sigma(r,t)$ we take a simple recipe created from a combination of the Shu model [19] for obtaining the accretion rate of the envelope onto the disk and the Ulrich model [20] for how this matter is distributed over the disk surface. Details are described in [17] and [21] (see also [22]).

In Fig. 1-Left the evolution of the surface density is shown for a model with initial cloud mass of $2.5M_\odot$, and rotation rate of $\Omega = 1\times10^{-14}\mathrm{s}^{-1}$. The star that is formed is a Herbig Ae star with an assumed effective temperature $T_* = 10,000$ K and luminosity $L_* = 50\ \mathrm{L}_\odot$. The infall phase lasts about 1 Myr. As one can see from the figure, during this time the disk is continually fed with fresh material, keeping the surface density inward of about 20 AU roughly constant. But during this time the disk is clearly spreading beyond this radius, and even after the infall has stopped and the disk mass decays the disk is still spreading. In the model we present here we do not include effects of photoevaporation, which certainly may affect the long term evolution of the disk. This will be done in near-future work.

In any case, it is clear that the spreading of the disk continuously pushes material toward larger radii, while at the same time most of the matter that falls onto the disk is conveyed to the star. During the infall phase the stagnation point, the radius separating the inflowing disk material and the outflowing disk material, is close to the centrifugal radius of the infalling matter. The centrifugal radius is the radius within which most of the infalling matter falls onto the disk. This radius increases with time according to the Ulrich model for a rigidly rotating core, and the stagnation point increases with it. So what happens is that most of the matter that falls onto the star is rapidly transported onto the star while some is pushed outward to absorb the angular momentum that the accreting matter is losing.

Once the infall phase is over, and the disk becomes visible to the observer and not enshrouded anymore by infalling the envelope material, the disk continues to accrete, albeit at a lower rate. This accretion still pushes the outer regions of the disk outward, as angular momentum still needs

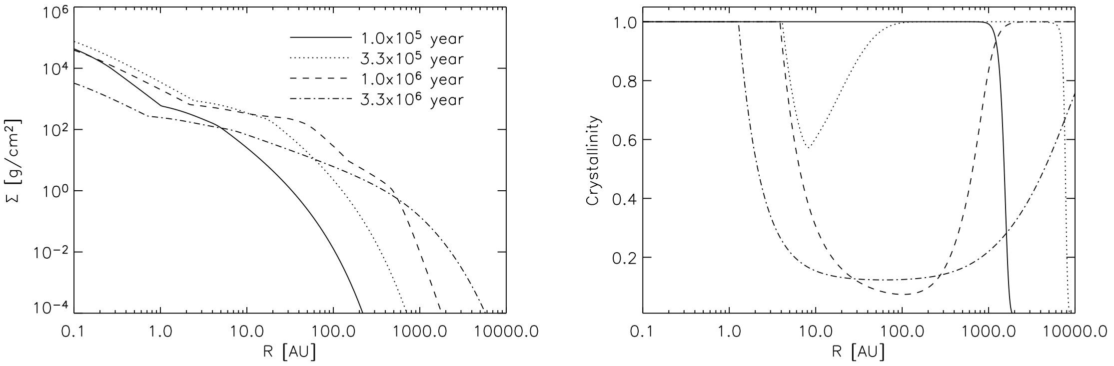

Figure 1. Left: The surface density as a function of radius for different times after the onset of the collapse of the parent molecular cloud core. Right: The crystallinity of dust (fraction of dust that is thermally processed) as a function of radius for different times.

to be absorbed to continue the accretion process. The stagnation point now moves outward slower than before, but it moves outward faster than the disk material. In other words, the stagnation point overtakes the matter. This means that a package of gas that initially is pushed outward will at some point be overtaken by the stagnation point and start moving inward again and accrete onto the star. The further out the gas package is at the end of the infall phase, the longer it moves outward before it turns around and move inward again, and hence the further out it reaches before turning back.

The critical idea here is that if the angular momentum of the parent molecular cloud core is low, then most matter falls onto the disk close to the star, and gets thermally processed. Some of this matter is then pushed toward large radii, and this matter makes up what is later identified as the "protoplanetary disk". In Fig. 1-Right one sees that in such a case all the matter in the disk is initially thermally processed (the dust is crystalline), even the matter that ends up far away from the star. Only shortly before the end of the infall phase, in this particular model, the disk has cooled down enough around 10 AU that new material entering the disk at that location is not immediately turned into crystalline material. In this late phase of infall the disk is replenished with amorphous material. Had the rotation rate of the parent cloud been slower, then this late phase of amorphous replenishment may not have taken place and all the disk would have been thermally processed. For larger rotation rate of the parent cloud less of the disk material would have been processed, since more material falls onto the colder outer disk regions.

In the picture we sketch here (see Fig. 2) the degree of processing of the dust in the disk as seen at a few Myr after the onset of the collapse of the parent cloud core, depends on the parameters of the parent cloud core. Therefore, the degree of crystallinity we observe may tell us something about the evolutionary history of the disk.

3. The nature of the turbulence in the disk

In the previous section we saw that the average crystallinity of the disk is, in our model, set by the history of the disk. But as seen in Fig. 1-Right there is also a well-defined slope of the crystallinity curve as it drops from 1 down to ∼0.2, and this slope steepness does not change with time (only the location of the slope changes). This is a result of radial mixing [13; 14]. What it says is that in addition to the redistribution of crystals through disk spreading there is still the more familiar radial mixing process operating in the disk. The reason why this affects

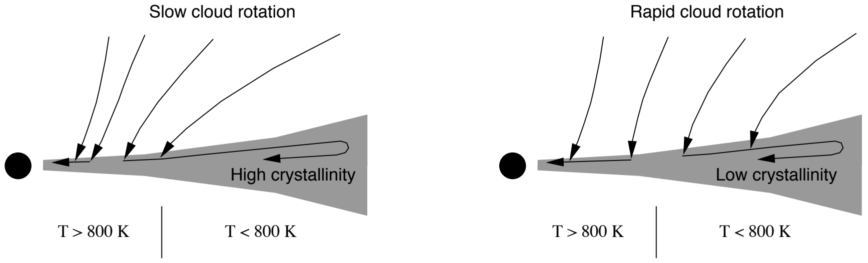

Figure 2. Cartoon of how the angular momentum of the infalling matter affects the crystallinity of the resulting disk. Left: low angular momentum of parent cloud. Right: high angular momentum of parent cloud.

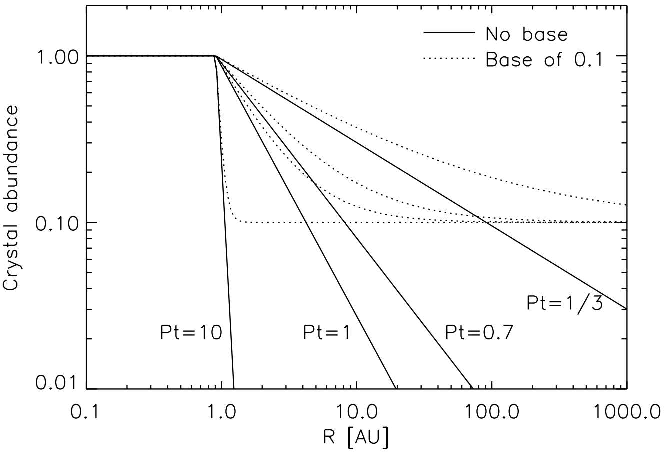

Figure 3. The abundance of crystals (thermally processed dust) as a function of radius in the disk for several different ratios Pt=D/ν. The base value is the value of the crystallinity inherited from the early phases of disk evolution (see Section 2).

the results is that inward of about 1 to 3 AU the disk is warm enough to crystallize all the dust, even long after the infall phase. So even in the late phases there is a continuous new production of crystals in the very inner disk regions, and radial mixing will mix them outward. The slope of the outward mixing depends, however, on the nature of the turbulence. It was described by [23] that a contaminant being injected into the disk at some location and at a constant rate, will swim upstream due to turbulent mixing, but its abundance will naturally decay with distance upstream. The resulting abundance of this contaminant will follow a powerlaw which can be computed analytically [24], see Fig. 3. In this paper it was investigated whether it is possible to measure this powerlaw slope and thus learn about the nature of the turbulence. The idea is that the slope depends uniquely on the ratio of the turbulent viscosity coefficient ν and the turbulent mixing coefficient D. It does *not* depend on the strength of the turbulent mixing D alone. If one disk has strong mixing and strong accretion (large D and ν) and another has weak mixing and weak accretion (small D and ν) they can still both have the same slope of the crystallinity as long as their ratio D/ν is the same. So by measuring the slope one can determine the *nature* of the turbulence instead of its strength. This ratio Pt=D/ν is an important parameter for

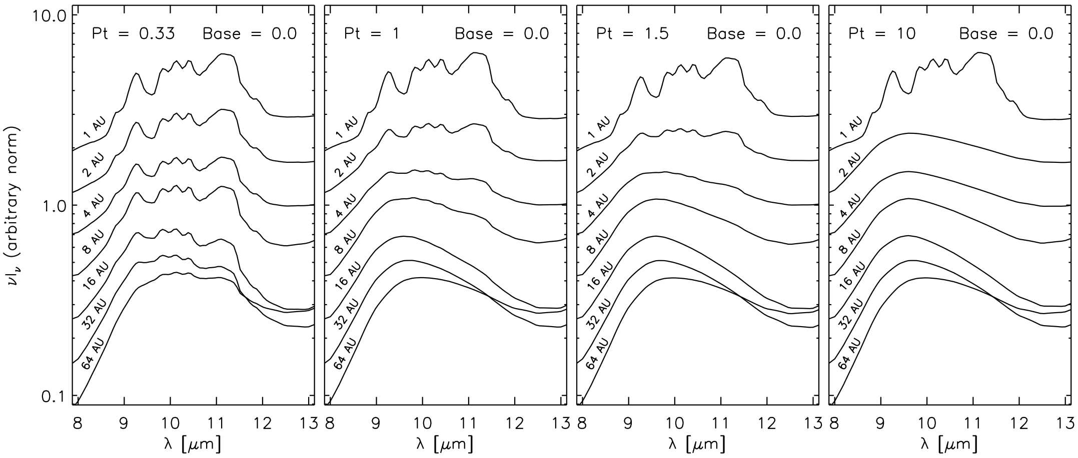

Figure 4. Local disk mid-infrared spectra as a function of radial coordinate r. In practice one does not measure such spectra with an interferometer: instead one measures "correlated spectra" and "uncorrelated spectra". But with some effort and sufficient baselines these can be translated into local spectra. The main issue here is that one can see that depending on the ratio of mixing and viscosity Pt= D/ν the change of the spectra as a function of radius are different.

theories of planet formation[1]. In Fig. 4 it is shown how the local (spatially resolved) N-band spectrum of a disk looks at different radii, for four different values of Pt. It shows that while it may be difficult to make very accurate "measurements" of Pt, it is certainly possible to find hints of the rough value of Pt in measurements using mid-infrared interferometry measurements with e.g. MIDI.

4. Near-edge-on disks as magnifying glasses

Now let us switch to a very different kind of high-angular resolution observation, one than can be made with low-angular resolution instrumentation. The idea is to let Nature magnify our object of interest for us. The mechanism operates if a spatially unresolved disk source is embedded in an environment of low density dusty ambient gas, for instance the material of the giant molecular cloud in which the star+disk source resides, and if this disk is edge-on or nearly edge-on. Radiation from the star can now light up this circumstellar material as scattered light in the optical and/or near infrared, or as emission from quantum heated grains/molecules such as polycyclic aromatic hydrocarbons (PAHs). The size of this emitting region can be tens to hundreds times as large as the radius of the disk, and this glow can therefore, if bright enough, be clearly observed and spatially resolved by telescopes such as Spitzer or the ISAAC instrument on the VLT. In the absense of a disk and assuming the ambient matter to be either spherically symmetric around the star or homogeneous, this glow will be a spherically symmetric nebula around the star with a brightness that drops as a powerlaw steeper than or equal to R^{-1}. If, however, a (nearly) edge-on, but spatially unresolved, disk is placed around this star, then this disk blocks the stellar light in (near-) equatorial direction, and hence there will be a wedge-like shadow in the surrounding reflection/PAH-excitation nebula. This wedge will extend out to very large distances from the star, basically out to the radius where the brightness of the otherwise

---

[1] Here we use the symbol Pt, the Prandtl number, for the ratio of *mass* diffusion over viscosity. Originally the Prandtl number was defined as the *heat* diffusion over viscosity. The mass diffusion over viscosity is also sometimes called the Schmidt number, but also this definition is not always unique.

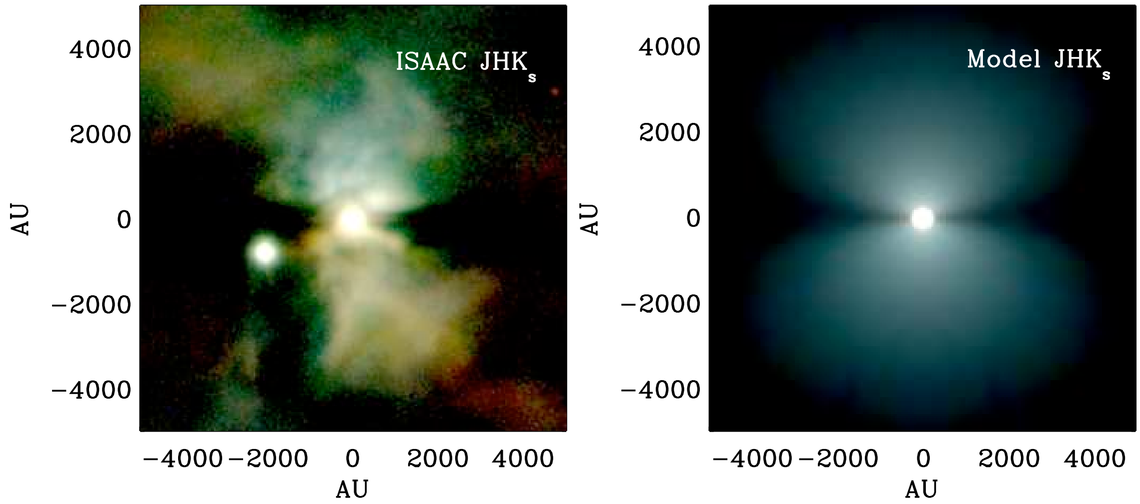

Figure 5. The reflection nebula around the source CK 3 in Serpens, JHK$_s$ color composite. Left: observations with VLT ISAAC. Right: model of projection. In the model the disk is too small to be spatially resolved, but the wedge-like shadow is seen.

spherical nebulosity will drop below the background brightness. In this way even a tiny disk of, say, 10 AU size can cast a shadow that is 10,000 AU in radius. We studied this effect in two papers: [25] for a scattered light reflection nebulae surrounding two stars star and [26] for a PAH nebula around the star VV Serpens. For the source CK3 in Serpens we show in Figure 5 the observed image and the model image.

What does this tell us scientifically? The depth of the shadow, i.e. how black is the shadow wedge, tells us about the optical depth of the disk through the midplane at the relevant stellar wavelengths, if this is lower than a few. For optically very thick disks scattered light off the disk surface and/or of the ambient medium itself can “fill in” part of the shadowed wedge. This is, however, expected to be a rather weak effect, meaning that one cannot expect to fill the shadow in by, say, 50%. If the shadow is very shallow then there might be one or more other sources of photons which are outside of the system and hence do not experience shadowing by the disk. Another way to fill in the shadow is simply foreground emission.

Now suppose we have a rather deeply shadowed wedge in a nebula around a star. By studying the sharpness of the shadow we can derive constraints on the optical depth of the disk. The idea is this: Les us measure the optical depth τ of stellar radiation (for scattering: the wavelength at which you observe, while for PAHs: the wavelength of the PAH-exciting radiation) along a radially outward pointing ray from the star out to infinity at a given angle with the midplane of the disk ϕ (where $\phi = 0$ means a ray along the midplane and $\phi = \pi/2$ means a ray along the polar axis). Now plot this optical depth as a function of ϕ. For a marginally optically thick disk the function $\exp(-\tau(\phi))$, which indicates the depth of the shadow, will be a function that gradually goes from some low value at $\phi = 0$ to $\phi = 1$ for $\phi \gg 0$. The shadow wedge will therefore have fuzzy edges. If, on the other hand, the disk is very optically thick then the function $\exp(-\tau(\phi))$ will have value 0 near the midplane and then rapidly rises to 1 at some angle $\phi > 0$. The resulting shadow will be sharp. The sharpness of the shadow of the wedge is therefore a measure of the optical depth of the disk, or in other words of the amount of small opacity-bearing dust grains still in the disk. In fact, this often can then be contrasted to the infrared spectrum from the source. If the disk is expected to be very optically thick because of a sharp edge of its wedge-like shadow, then in the infrared spectrum we would expect to find for instance the 10 μm silicate feature in absorption. As shown in [25] this combination can put severe constraints on the disk model. In that paper we found that for the source CK3 the relative sharpness of the wedge required optical depths that were not small enough to prevent the 10 μm feature to go in absorption. The infrared spectrum, however, showed clearly a strong feature in emission. This severely limited our options for parameters, and in fact a perfect fit was not even possible and we are still left with this unsolved puzzle. If the wedge would have been of a truly large disk seen nearly edge-on then this problem would, however, not be easily solved either.

5. Conclusions

In this chapter we have presented two issues. First, we show that the observable levels of crystallinity of the dust in disks can tell something about the history of these disks as well as about the nature of the turbulence in the disk. For both high spatial resolution observations are necessary that make it possible to measure the abundance of crystals at different locations in the disk. Infrared interferometry in the mid-infrared is ideal for this. Secondly we show that, in certain special circumstances, Nature itself provides us with an interesting magnifying glass: the projections of nearly edge-on disks into their surroundings. The study of these wedge-like projections can lead to interesting information about the optical depth of the disk, which is linked to the question how much of the dust is still present in the disk and if the planet formation process has already ended or not.

References

[1] Natta A, Testi L, Calvet N, Henning T, Waters R and Wilner D 2007 *Protostars and Planets V* ed Reipurth B, Jewitt D and Keil K pp 767–781

[2] Setiawan J, Henning T, Launhardt R, Müller A, Weise P and Kürster M 2008 *Nature* **451** 38–41

[3] Furlan E, Hartmann L, Calvet N, D'Alessio P, Franco-Hernández R, Forrest W J, Watson D M, Uchida K I, Sargent B, Green J D, Keller L D and Herter T L 2006 *ApJS* **165** 568–605 (*Preprint* `arXiv:astro-ph/0608038`)

[4] Kessler-Silacci J, Augereau J C, Dullemond C P, Geers V, Lahuis F, Evans N J, van Dishoeck E F, Blake G A, Boogert A C A, Brown J, Jørgensen J K, Knez C and Pontoppidan K M 2006 *ApJ* **639** 275–291

[5] Bouwman J, Henning T, Hillenbrand L A, Meyer M R, Pascucci I, Carpenter J, Hines D, Kim J S, Silverstone M D, Hollenbach D and Wolf S 2008 *ArXiv e-prints* **802** (*Preprint* `0802.3033`)

[6] Sicilia-Aguilar A, Hartmann L W, Watson D, Bohac C, Henning T and Bouwman J 2007 *ApJ* **659** 1637–1660 (*Preprint* `arXiv:astro-ph/0701321`)

[7] van Boekel R, Min M, Leinert C and Waters L B F M e a 2004 *Nature* **432** 479–482

[8] Bouwman J, de Koter A, van den Ancker M E and Waters L B F M 2000 *A&A* **360** 213–226

[9] Honda M, Kataza H, Okamoto Y K, Miyata T, Yamashita T, Sako S, Takubo S and Onaka T 2003 *ApJL* **585** L59–L63

[10] Meeus G, Sterzik M, Bouwman J and Natta A 2003 *A&A* **409** L25–L29

[11] Kemper F, Vriend W J and Tielens A G G M 2004 *ApJ* **609** 826–837

[12] Kemper F, Vriend W J and Tielens A G G M 2005 *ApJ* **633** 534–534

[13] Gail H P 2001 *A&A* **378** 192–213

[14] Bockelée-Morvan D, Gautier D, Hersant F, Huré J M and Robert F 2002 *A&A* **384** 1107–1118

[15] Urpin V A 1984 *Soviet Astronomy* **28** 50–+

[16] Keller C and Gail H P 2004 *A&A* **415** 1177–1185

[17] Dullemond C P, Apai D and Walch S 2006 *ApJL* **640** L67–L70

[18] Lynden-Bell D and Pringle J E 1974 *MNRAS* **168** 603–637

[19] Shu F H 1977 *ApJ* **214** 488–497

[20] Ulrich R K 1976 *ApJ* **210** 377–391

[21] Dullemond C P, Natta A and Testi L 2006 *ApJL* **645** L69–L72 (*Preprint* `astro-ph/0605336`)

[22] Hueso R and Guillot T 2005 *A&A* **442** 703–725

[23] Clarke C J and Pringle J E 1988 *MNRAS* **235** 365–373

[24] Pavlyuchenkov Y and Dullemond C P 2007 *A&A* **471** 833–840 (*Preprint* `arXiv:0706.2614`)

[25] Pontoppidan K M and Dullemond C P 2005 *A&A* **435** 595–610 (*Preprint* `arXiv:astro-ph/0502103`)

[26] Pontoppidan K M, Dullemond C P, Blake G A, Evans II N J, Geers V C, Harvey P M and Spiesman W 2007 *ApJ* **656** 991–1000 (*Preprint* `arXiv:astro-ph/0610385`)