Thermal Structure of Protoplanetary Disks

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Abstract. We discuss results of models of the thermal structure of steady accretion disks, irradiated by their central stars, in which dust sublimation, growth and settling are taken into account. The models are constrained by comparison with different observations of Classical T Tauri Stars with ages between 1 and 10 million years. The implications of these models for the interpretation of planetary data are also discussed.

1. Introduction

The study of the early phases of circumstellar disks and planetary systems has boomed in recent years with the wealth of information provided by large ground-based telescopes and space missions. In addition to spectral $\dot{M} = 10^{-8} M_\odot$ yr$^{-1}$ energy distributions (SEDs) from the UV to millimeter (mm) and centimeter wavelengths, we are beginning to acquire information on the spatial distribution of the emission, as well as detailed spectra in the mid-infrared (mid-IR, between $\sim 3$ and 25 $\mu$m). The number of constraints imposed by observations has thus significantly increased, requiring an increase in the sophistication of the existing models to explain disk emission. The expectation is that by aiming to fit as many constraints as possible, a much better understanding of the intrinsic structure of the disk can be obtained. Nonetheless, these efforts are necessarily limited, as many factors complicate the calculations. For one thing, disks are accreting matter onto the star, and the mechanisms for which accretion proceeds are just beginning to be understood. In addition, the main heating mechanism in young disks around solar-mass stars is stellar irradiation, implying that dust particles, which are the main absorbers and emitters of radiation in the disk, play an essential role in determining the disk structure. We thus need to know the composition, size, and shape of the dust particles, in addition to their vertical and radial distribution. Given the diversity of characteristics of the solid particles, the task may seem overwhelming.

In this chapter, we describe results from modeling the protoplanetary disk structure taking into account key observational constraints, while making a number of approximations in order to facilitate the task. In section 2 we describe these approximations and
model calculations, and in section 3 we outline the representation used for the dust. In section 4 and section 5, we present results of disk structure inferred from comparisons with observations. In section 6 we focus on inferences for the structure and clearing of the inner disks. In section 7 we discuss thermal processing of solids. All these results are based primarily on the comparison of models with observations of Classical T Tauri stars (CTTS), which have masses of order \( \sim 0.1 - 2 \, M_\odot \), and which span a range of ages between \( \sim 1 \) and 10 Myr. In section 8 we compare the model predictions with inferences gleaned from the planetary materials data. Finally, in section 9 we summarize the main results.

2. Irradiated Accretion Disks

In optical wavelengths, CTTS emit more energy than expected from their photospheres according to their spectral type. This energy excess is thought to be accretion energy, released as matter from the disk falls into the gravitational potential well of the star. Evidence to support this hypothesis includes the profiles of emission lines which can be explained as resulting from the infall of matter channelled along stellar magnetic field lines (Muzerolle et al. 1998, 2001). Further, the SED of the energy excess is consistent with emission from the accretion shocks formed on the stellar surface as disk matter merges into the photosphere (Calvet & Gullbring 1998; Gullbring et al. 2001). The photospheric luminosity is \( L_\star \) and the excess luminosity, identified with accretion, is \( L_{\text{acc}} = GM_\star \dot{M}/R_\star \). From this excess luminosity, the mass accretion rate onto the star \( \dot{M} \) can be measured, given that the stellar mass and radius \( (M_\star, R_\star) \) are known from the star’s position in the HR diagram. The average mass accretion for 1 Myr old stars is \( \dot{M} = 10^{-8} M_\odot \text{ yr}^{-1} \) (Gullbring et al. 1998; Hartmann et al. 1998; White & Ghez 2001), however, there is evidence for an overall decrease of mass accretion rate with age, consistent with viscous evolution (Hartmann et al. 1998; Muzerolle et al. 2001; Calvet et al. 2004).

From the observation that the average accretion luminosity \( L_{\text{acc}} \) for 1 Myr old accreting stars is only about \( 0.1 L_\star \), it is inferred that the stellar irradiation is an important heating mechanism of protostellar disks. Models for a flat irradiated disk and a viscous non irradiated disk both have the same radial distribution of heating and thus both yield the same slope for the disk SED at IR wavelengths. In contrast, CTTS typically show a larger IR excess with a flatter slope than the one predicted by these disk models. Kenyon & Hartmann (1987, hereafter KH87) demonstrated that irradiated disks in hydrostatic equilibrium would be flared. This curvature increases the capture of stellar energy at large radii and naturally explains the SEDs of CTTS (KH87; Calvet et al. 1991, 1992; Chiang & Goldreich 1997; D’Alessio et al. 1998, 1999, 2001).

In recent years, models of circumstellar disks have been calculated at several levels. The most straightforward modeling assumes power laws in radius for the temperature \( T(R) \) (assuming that the disk is vertically isothermal) and mass column density \( \Sigma(R) \) (e.g., Beckwith et al. 1990). A second level of modeling assumes that the flared disks are heated only by stellar irradiation and calculates a temperature structure \( T(z, R) \), where \( z \) is the vertical coordinate. In this approximation, \( \Sigma(R) \) is still an arbitrary power law, with an adjustable coefficient and exponent (Chiang & Goldreich 1997; Dullemond et al. 2001). In a third level of modeling, the vertical structure equations are solved and \( \Sigma(R) \) is calculated consistently with the disk angular momentum flux, under the assumption of steady accretion; the main heating mechanisms
Figure 1. Monochromatic absorption coefficient for the dust mixture proposed by Pollack et al. (1994) shown at a temperature where water ice is sublimated, in order to emphasize the silicate features at 10 and 18 µm. The adopted grain size distributions are $n \sim a^{-p}$, with $p = 3.5$, $a_{\text{min}} = 0.005 \mu m$ and two different values of $a_{\text{max}} = 1 \mu m$ (solid line) and 1 mm (dotted line). The wavelength where CTTS have, typically, their photospheric maximum flux is marked with an arrow.

considered are viscous dissipation and stellar irradiation (D’Alessio et al. 1998, 1999, 2001, hereafter D01). The turbulent viscosity is calculated using the $\alpha$ prescription (Shakura & Sunyaev 1973), and $\alpha$ is assumed to be constant in the disk. These irradiated disk models predict that $\Sigma(R)$ is not strictly a power law, but can be approximated to one ($\Sigma(R) \propto 1/R$) at large distances from the star. This mass surface density is consistent with the one inferred from the radial distribution of brightness at millimetric wavelengths for some well studied disks (e.g., Wilner et al. 2000).

In the following sections we discuss disk models of the third kind. In this, we show how the temperature of irradiated accretion disks depends on dust and disk properties.

3. Dust Properties

As demonstrated by KH87, the shape of the disk surface determines the amount of energy it can capture from a central source and thus its heating; the more flared the surface, the hotter the disk. In turn, the shape of this surface is determined by the ability of the dust in the disk upper layers to absorb the incident radiation. Quantitatively, this surface can be defined as the place where the mean radial optical depth to the incident radiation is unity. Thus, the properties of the dust at the upper layers and in particular its
opacity at short (X-rays to near-IR) wavelengths where the star and the shock emission are maxima, are the key parameters determining the heating and the resulting SEDs of disks.

A mixture of silicates, organics, water ice, and troilite is chosen by D01 to represent the dust in disks, following Pollack et al. (1994). The opacity of this mixture is calculated using the Mie theory, assuming that the grains are compact segregated spheres of size \( a \), with a size distribution \( n(a)da = a^{-p} da \) between \( a_{\text{min}} \) and \( a_{\text{max}} \) (cf. D01 for details). Each component has a different sublimation temperature, the silicates being the ones that survive closer to the star. Figure 1 illustrates an important property noticed by D01. As \( a_{\text{max}} \) increases for a fixed mass of dust and all other parameters constant, more solid mass is trapped in larger grains. As a result, the opacity at short wavelengths decreases, which has the direct effect of making the disk surface less flared and thus decreasing the heating of the disk. At the same time, the opacity at long wavelengths increases, making the disk brighter at these wavelengths (cf. D01).

4. Temperature Profiles for Disks with Uniform Distribution of Gas and Dust

A first series of irradiated accretion disk models have been calculated under the assumption that dust and gas are well mixed and uniformly distributed in the disk, i.e., the same dust-to-gas mass ratio and grain size distribution is assumed for the whole disk (D01; D'Alessio et al. 2005b). A result of these calculations is that substantial grain growth (to maximum sizes \( a_{\text{max}} \sim 1 \text{ mm} \)) is required to explain the median SED of the CTTS in Taurus; although the large spread of fluxes around the median implies a large diversity of the dust properties in the population.

Figure 2 shows vertical temperature profiles at representative radii, 1 AU and 100 AU, in a disk model with a typical mass accretion rate of \( \dot{M} = 10^{-8} M_\odot \text{yr}^{-1} \) and stellar parameters of a 1 Myr old star with 0.8 \( M_\odot \). These profiles are calculated for two values of the maximum dust radius, \( a_{\text{max}} = 1 \text{ \mu m} \), close to an interstellar medium distribution, and \( a_{\text{max}} = 1 \text{ mm} \), which reproduces the Taurus median SED. The lower panel shows the radial dependence of the Rosseland mean optical depth, which corresponds to the optical depth to the local radiation. The temperature of the upper layers in all cases is high, as those layers are directly heated by the stellar radiation. As we proceed to deeper layers in the disk, the temperature decreases as the stellar flux is deposited in the atmosphere and reprocessed to longer wavelengths. The direct incident flux becomes negligible at 2 - 3 times the gas scale height, above the disk midplane. This height corresponds roughly to what we have called the disk irradiation surface. At large radii, where the disk is optically thin to its own radiation, the temperature near the midplane is constant with height, maintained by the reprocessed flux reaching those layers. In contrast, in the optically thick inner radii, negative temperature gradients are required to diffuse outward the energy deposited by viscous dissipation.

Temperatures in the disk decrease as more solid mass is located in larger grains, i.e. as \( a_{\text{max}} \) increases in our representation, as shown in Figure 2. Again, this is a direct result of the fact that as the number of small grains decreases less incident radiation is captured, since the small grains are the most effective absorbers at short wavelengths.

These calculations assume that the dust and gas are in thermal equilibrium. This assumption breaks down in the uppermost layers, specially at large distances from the star (Glassgold et al. 2004, and in this volume; Jonkheid et al. 2004; Kamp & Dullemond 2004). However, close to and below the disk surface where the incident radiation
Figure 2. Upper and middle panels: Temperature profiles at $R = 1$ AU and $R = 100$ AU for disks with $\dot{M} = 10^{-8} M_\odot \text{yr}^{-1}$, $\alpha = 0.01$, and two grain mixtures. The abscissa is the vertical coordinate $z$ in units of the local scale height; the scale height is given in each case. Lower panel: Rosseland mean optical depth as a function of disk radius. Left column: mixture with $a_{\text{max}} = 1 \mu m$, right column: $a_{\text{max}} = 1 \text{mm}$, both with $p = 3.5$. In all models shown in this contribution, the stellar properties are: $T_* = 4070$, $R_* = 1.86 R_\odot$, $L_* = 0.79 L_\odot$, $M_* = 0.8 M_\odot$, and $a_{\text{min}} = 0.005 \mu m$. 
is deposited, densities are high enough to assure the validity of this equality (Kamp & Dullemond 2004).

Figure 3 shows the radial dependence of the temperature at the midplane in the inner disk for several values of the mass accretion rate. Values are shown again for two dust mixtures with \( a_{\text{max}} = 1 \mu m \) and \( a_{\text{max}} = 1 \) mm. Temperatures increase with mass accretion rate, as viscous dissipation increases. They decrease as \( a_{\text{max}} \) increases, but the decrease is less pronounced for the higher mass accretion rates, where viscous dissipation begins to dominate the heating. A similar midplane temperature radial distribution for the inner disk was found by Boss (1996, 1998) for disks heated by turbulent viscous dissipation.

Figure 4 shows the dependence of midplane temperatures in the inner disk on two other parameters: the exponent \( p \) of the grain size distribution and the viscosity parameter \( \alpha \). As shown in the left panel, as \( p \) decreases, more solid mass is trapped into larger grains, and the temperature drops. On the other hand, the midplane temperature increases as \( \alpha \) gets smaller, as shown in the right panel of Figure 4. As \( \alpha \) decreases for a fixed mass accretion rate, the surface density, \( \Sigma \propto M/\alpha \), and thus the optical depth increase. As a result, there is more energy trapping and the midplane temperature increases. However, if there is a “dead zone” at the midplane of the inner disk, where the magneto-rotational instability is not present to drive the accretion (as proposed by Gammie 1996; and in Gammie & Johnson, this volume), then the larger surface density of the material accumulating in this zone would make the midplane colder, as less reprocessed energy from the upper layers can reach the deeper regions and less viscous dissipation (or no viscous dissipation at all) would contribute to the heating of the dead zone.

As the star ages its mass accretion rate decreases, as mentioned in section 2. At early evolutionary phases, when the star+disk system is still actively receiving mass from the infalling envelope, disk mass accretion rates are higher than the average value for 1 Myr old CTTS (\( \sim 10^{-8} M_\odot \text{yr}^{-1} \), see section 2) For instance, typical mass accretion rates in “quiescent” periods are \( \dot{M} \sim 10^{-7} M_\odot \text{yr}^{-1} \) (Muzerolle et al. 1998; for another view, see White & Hillenbrand 2004). On the other hand, episodic increases
Figure 4. Left panel: Midplane temperature for two values of the exponent of the grain size distribution, $p = 3.5$ (solid line) and $p = 2.5$ (dashed line). Right panel: Midplane temperature for two values of the viscosity parameter, $\alpha = 0.01$ (solid line) and $\alpha = 0.001$ (dashed line). The models have $\dot{M} = 10^{-8} M_\odot \text{yr}^{-1}$ and $a_{\text{max}} = 1$ mm.

of the mass accretion rate up to $\dot{M} \sim 10^{-4} M_\odot \text{yr}^{-1}$ due to disk instabilities (FU Ori eruptions) can occur at these early phases (Calvet, Hartmann, & Strom 2001; Hartmann, this volume). At later evolutionary phases, stars which are still accreting at 10 Myr have $\dot{M} \leq 10^{-9} M_\odot \text{yr}^{-1}$ (Hartmann et al. 1998; Muzerolle et al. 2001; Calvet et al. 2005).

For heuristic purposes, we may attempt to estimate the expected evolution of physical quantities at the disk midplane, taking into account the observed decrease of accretion rate with age, including the observational spread. Figure 5 shows the evolution of the midplane temperature and pressure, calculated assuming a fixed viscosity parameter and a grain size distribution. We show values for two locations in the disk: 0.4 AU, representative of the innermost disk regions, just outside the dust sublimation temperature (see section 6), and 1 AU. It can be seen that in the first few million years, the innermost disk regions can be hot and dense enough to sustain significant thermal processing ($T \geq 1000$ K). On the other hand, only at ages $\leq 1$ Myr may some thermal processing occur at 1 AU and for ages greater than a few Myr, most of the disk is too cold for processing solids. Similar midplane temperatures as those shown in Figure 5 were obtained by Woolum & Cassen (1999) for disks surrounding $< 1$ Myr T-Tauri stars, based on astronomical data (disk masses, sizes, surface temperatures and accretion rates) available at the time, and ignoring considerations of detailed dust characteristics.

5. Effects of Dust Settling on Temperature Profiles

Theories of dust evolution predict that as time passes, dust particles collide, stick to each other, grow and settle toward the midplane (Weidenschilling 1997). Observational evidence supports these theories. The overall SEDs of CTTS are consistent with substantial grain growth (D01; Chiang et al. 2001). In particular, the slope of the SED of some CTTS observed in submm/mm wavelengths is well explained if the dust grains have maximum sizes around mm (Beckwith & Sargent 1991; Miyake & Nakagawa 1993; D01). On the other hand, the presence of the 10 $\mu$m silicate feature in emission
Figure 5. Left panel: Evolution of the midplane temperature at two locations in the disk: 0.4 AU, that is, the region just outside the dust sublimation temperature (§6), and 1 AU. These evolutionary paths have been estimated from the observed decrease of mass accretion rate with age (Hartmann et al. 1998; Muzerolle et al. 2001; Calvet et al. 2005). Right panel: Corresponding decrease of the pressure at the midplane. Models are calculated for $\alpha = 0.01$ and $a_{\text{max}} = 1$ mm.

(Natta, Meyer, & Beckwith 2000; Honda et al. 2003; Forrest et al. 2004) indicates that a substantial population of small grains should be present in the disk upper atmosphere. Moreover, since this spectral feature is washed out in grain mixtures with $a_{\text{max}}$ greater than a few microns (c.f., Figure 1), there should be no big grains at the disk upper atmosphere. Dust settling provides a natural explanation for the apparently contradictory observations. The silicate emission feature forms in the upper atmospheric hot layers of the optically thick disk; on the other hand, the continuum at wavelengths longer than the mid-IR arises from deeper regions. As grains settle, a population of small grains is left behind in the upper layers (Weidenschilling 1997; Dullemond & Dominik 2004, 2005) and it can produce the emission features; but since the dust-to-gas mass ratio of these small atmospheric grains is much smaller than the standard interstellar medium value, the incident radiation can penetrate deeper. In this case, the disk surface is lower and intercepts less incident radiation than a disk with an interstellar dust-to-gas mass ratio of small grains at every height. This lower surface produces the continuum and, in particular, the large grains near the mid-plane are responsible for the submm-mm SED.

Comparison of observations with disk models including dust settling can yield information on the degree of settling in protostellar disks. Figure 6 shows the SEDs for disk models with different degrees of settling. These models have been calculated assuming that two grain populations, characterized by very different values of $a_{\text{max}}$, co-exist in the disk, with height-dependent abundances (D’Alessio et al. 2005c). The small grains mostly populate the upper regions. The parameter $\epsilon$, which characterizes the different SEDs in Figure 6, is given by

$$\epsilon = \frac{\zeta_{\text{small}}}{\zeta_{\text{std}}}$$

where $\zeta_{\text{small}}$ is the depleted dust-to-gas mass ratio of the small grains in the upper layers and $\zeta_{\text{std}}$ is the standard dust-to-gas mass ratio in the interstellar medium. Thus,
Figure 6. SEDs of disk models with different degrees of settling given by $\epsilon = 0.001, 0.01, 0.1$ and 1 (from bottom to top). We also show the contribution of the stellar photosphere (for a star with $T_\ast = 4000$ K, $R_\ast = 2 R_\odot$), the contribution of the wall at the dust sublimation radius (which is taken to be the same for the four disk models in order to facilitate the comparison). The disk has a mass accretion rate $M = 10^{-8} M_\odot yr^{-1}$ and a viscosity parameter $\alpha = 0.01$. Its dust has abundances and optical constants from Pollack et al. (1994), which is characterized by a large fraction of water ice. In these models, the upper layers have dust with $a_{\text{max}} = 0.25 \mu m$ and close to the midplane, $a_{\text{max}} = 1 \text{ mm}$ (D’Alessio et al. 2005c).

the degree of settling increases as $\epsilon$ decreases. The big grains are located closer to the midplane with a dust-to-gas mass ratio consistent with the depletion of the upper layers, under the assumption that the vertically integrated dust-to-gas mass ratio is conserved at each radius (see D’Alessio et al. 2005c for details).

As the depletion in the upper layers increases, i.e., as $\epsilon$ decreases, the slope of the mid-IR SED (3-25 $\mu$m) becomes steeper (i.e., shows less excess). This results from less absorption of stellar radiation in the upper layers as small grains become more scarce. At the same time, the silicate feature is always in emission in these models. The mid-IR region of the SED is thus perfect for estimating the degree of settling. In contrast, emission in the millimeter range, where grain growth is usually tested, is mostly optically thin and probes regions near the midplane of the outer disk (> 50 AU). The mid-IR spectra of CTTS had not been observed in detail until recently and few inferences could be made from the IRAS (InfraRed Astronomical Satellite) fluxes measured at wide spectral bands centered at 12, 25, 60 and 100 $\mu$m. The situation
has now changed radically, as spectra obtained with the IRS spectrograph on board of Spitzer, which cover the 5 - 40 µm wavelength region are becoming available. These spectra offer for the first time the possibility of probing the planet forming region of the disk, the inner tens of AU, to determine the amount of dust settling in these regions. Analysis of the first IRS spectra of CTTS in Taurus shows that most disks in Taurus have a degree of settling corresponding to \( \epsilon = 0.01 \) to 0.001, in our representation, i.e., a dust-to-gas mass ratio of the small grains at the upper layers equal to 1 and 0.1 % of the standard value, respectively (Furlan et al. 2005; D’Alessio et al. 2005c).

The left panel of Figure 7 shows how the disk midplane temperature decreases when the degree of dust settling increases (i.e., \( \epsilon \) decreases). The right panel of Figure 7, showing the vertical temperature profile at 1 AU, illustrates also this effect and helps to explain the reason. In the model for \( \epsilon = 1 \), the dust is uniformly distributed within the disk and the temperature profile is similar to those in Figure 2. As the degree of depletion of the upper layers increases, the opacity of the small grains decreases, and less stellar radiation is absorbed by the disk (because its surface is lower, intercepting less stellar radiative flux). In addition, the total mean optical depth of the disk decreases, so that the midplane becomes more and more isothermal, resembling the profiles for the optically thin regions in Figure 2. Thus, as dust settles, the midplane becomes colder in addition to having a higher dust-to-gas mass ratio, which may have important implications for the subsequent evolution of solids. These implications remain to be explored.
6. The Inner Disk. Structure and Clearing

In recent years, it has become accepted that there is a sharp transition between the inner gaseous disk where dust is sublimated and the outer disk, where dust co-exists with the gas. In old modeling efforts, the disk was supposed to be illuminated sideways by the star. Since the cross-section to the stellar radiation was tilted relative to the incoming rays, the capture of stellar radiation was low. However, because the upper layers were hotter, even in those models, there were regions where dust had sublimated in the uppermost levels, although dust existed further down into the disk. This was not a stable situation. The reason for this is that stellar radiation could penetrate through the dust-free layers, heating up the dust beneath and forcing it to sublimate. This would continue until a radius at which the temperature achieved by the dust was equal to the dust sublimation temperature. The dust outside this radius could survive, while the one inside could not. Thus, a sharp transition between gas and gas+dust is established at this radius, the dust sublimation radius, which is given by

\[ R_{\text{sub}} = \left[ \frac{L_\star + L_{\text{acc}}}{16\pi\sigma_R} \left( \frac{2 + \frac{\kappa_i}{\kappa_d}}{T_{\text{sub}}^2} \right) \right]^{1/2} \]

(Muzerolle et al. 2003; D’Alessio et al. 2004), where \( T_{\text{sub}} \) is the dust sublimation temperature, \( \kappa_i \) and \( \kappa_d \) are opacities at wavelengths characteristic of the incident and disk radiation, respectively, and the rest of the symbols have the standard meaning.

Inside this radius, which for typical parameters is \( \geq 9R_\star \), the disk is gaseous, and extends inward until it is truncated by the stellar magnetosphere at \( \sim 3-5R_\star \).

The existence of this sharp transition, sometimes called “wall” or “rim”, was first proposed for the Herbig Ae/Be stars (HAeBe stars, Tuthill et al. 2001; Natta et al. 2001; Dullemond et al. 2001). In particular, Natta et al. (2001) proposed that emission from this sharp dust wall, frontally illuminated by the star, could explain the peculiar SED of the HAeBe stars in the near-IR, i.e., from 0.8 to 3 \( \mu \)m (Hillenbrand et al. 1994). Further calculations showed that for the mass accretion rates expected for the HAeBe stars, the inner gas disk was optically thin and the wall could indeed be frontally illuminated (Muzerolle et al. 2004). Blackbody-like excesses in the near-IR corresponding to \( T_{\text{sub}} \sim 1400K \) (see Figure 6 as an example of a model of the wall’s SED), identifiable with emission from the wall were later discovered in the lower mass and less luminous CTTS (Muzerolle et al. 2003). In this case, the wall emission correlates with the total luminosity of the source, i.e., \( L_{\text{acc}} + L_\star \), suggesting that for high mass accretion rate objects, not only is the wall heated by the central star, but also by the emission of the accretion shocks at the stellar surface.

The existence of the wall at the dust destruction radius has been fully confirmed by interferometric measurements (Millan-Gabet et al. 1999; Monnier & Millan-Gabet 2002; Eisner et al. 2004). The interferometric measurements for HAeBe stars yielded sizes which were consistent with the dust sublimation temperatures for the corresponding stellar luminosities, with \( T_{\text{sub}} = 1000K - 1400K \) (Monnier et al. 2005). Interferometric measurements have proved more difficult for the less luminous CTTS; nonetheless, Colavita et al. (2003) obtained a size consistent with dust sublimation for a high accretion rate object (Muzerolle et al. 2003).

Dust settling is expected to proceed faster in the inner disk (Weidenschilling 1997). However, details of the theories are uncertain and it is important to look at the observations for guidance. Until recently, this could not be done. But as observations in
the mid-IR become available, information on the conditions in the inner disk is rapidly being gathered.

The near-IR (0.8-3 \( \mu m \)) emission in CTTS is due to the sum of the emission of the wall at the dust sublimation radius and of the disk. The latter is small compared to the first one, since the dust disk starts at \( R_{\text{sub}} \), except at very low or very high inclinations, where the wall emission is minimized for geometrical reasons. Since the wall emission is essentially that of a black body at \( T_{\text{sub}} \) times the solid angle subtended by the wall, and \( R_{\text{sub}} \) can be estimated from \( L_\star \) and \( L_{\text{acc}} \), measurements of this emission give us estimates of the height of the wall, and thus of potential dust settling in the inner disk.

For small grains, the height of the wall is expected to be \( \sim 4 \) times the local gas scale height, which is consistent with values determined for HAeBe stars (Dullemond et al. 2001) and CTTS (Muzerolle et al. 2003). However, observations of 3-5 Myr old stars in Ori OB 1 (Calvet et al. 2005) and especially Spitzer observations of 3 Myr old objects in Tr 37 (Sicilia-Aguilar et al. 2005) reveal a large number of disks with substantial flux deficits in the near-IR relative to the median fluxes of the 1 Myr old Taurus objects, while the flux deficit is smaller at longer wavelengths. These observations point to a general evolution of the dust; as disks age, the dust settles toward the midplane, at a faster pace in inner regions, in general agreement with dust evolution theories.

However, there are objects where this steady evolution has been stopped. In these objects, the near-IR emission excess is very small, while there is a rapid increase of flux in the mid-IR, to levels higher than the median of Taurus. The first objects of this class were found in the 10 Myr old TW Hya association (Jayawardhana et al. 1999). Detailed analysis of one of these objects, TW Hya, revealed that the sharp increase in flux was due to a wall frontally illuminated by the star located at \( \sim 4 \) AU, which was identified with the inner edge of a disk. The left panel of Figure 8 shows the IRS spectrum of this object (Calvet et al. 2002; Uchida et al. 2004). As TW Hya is accreting mass onto the star, an inner disk is still present, containing only a small amount of small dust (Calvet et al. 2002; Uchida et al. 2004), which gives rise to the strong silicate feature in emission. Several objects with these characteristics have now been identified in the 1 Myr Taurus population (Rice et al. 2003; Bergin et al. 2004), and it has been proposed that a planet has formed in the disk, creating a gap which allows the illumination of the edge of the outer disk. On determining cold temperatures at the midplane of T-Tauri stars at 1 Myr, Woolum & Cassen (1999) concluded that planetesimals must exist at such locations in the disk at that age. Now even planets are posited!

Very recently, an object has been discovered in Taurus where the inner disk has already dissipated although a significant outer disk is still present. The SED of this object, CoKu Tau 4, is shown in the right panel of Figure 8 (Forrest et al. 2004; D’Alessio et al. 2005a); the silicate feature in this case is weak and arises in the wall, located at \( \sim 10 \) AU from the central star (D’Alessio et al. 2005a).

7. Thermal Processing of Solids

Spectral information of young low mass stars in the mid-IR is difficult to obtain from the ground; until recently, it only existed for a handful of objects, the brightest ones of the class (Sitko et al. 2000; Weinberger et al. 2002; Honda et al. 2003). Some indication of grain growth and/or crystalline structure from the profile of the 10 \( \mu m \) silicate feature existed, but IRS observations have significantly changed the situation.
IRS spectra cover not only the 10 µm feature, but also the region around \( \sim 20 \) µm, providing more constraints for a better identification of the compounds present.

Analysis of the first observations indicates that crystalline materials exist in abundances larger than identified in the ISM, even in the disks of 1 Myr old stars (Forrest et al. 2004; Uchida et al. 2004). The presence of crystalline material indicates that processing of the essentially amorphous ISM material has taken place. This processing generally requires temperatures \( \geq 1000 \) K. The possibility that such processing could occur in energetic collisional events cannot be dismissed; collisions must be pervasive. However, if such processing temperatures were achieved globally, they are expected to occur only in the innermost disks of the youngest objects. But it is difficult to see how processed material avoided being accreted onto the star if it was created only at early epochs. Material could in principle be processed near the inner disk wall heated at \( T_{\text{sub}} \) (Wood 2004), but still it would need to move outward to explain the presence of crystalline features on the broad 10 µm silicate band. In any event, detailed modeling of the observations in the near future will provide insight on the radial extent of the silicate compounds.

In this regard, the transitional disks discussed in §6 provide interesting information on the distribution of the crystalline materials in the inner disks. A significant degree of crystallinity is found in transitional disks of the 10 Myr TW Hya association (Uchida et al. 2004), and in other transitional disks in the younger Taurus population. The region where this material forms is within \( \sim 6 \) AU from the star. In contrast, only pristine material akin the ISM, without any significant amount of processing, is found at the edge of the disk in CoKu Tau 4, located at \( \sim 10 \) AU. Analysis of this small sample suggests that thermal processing is confined to the inner few AU of the disks; these analyses will be refined as studies of much larger numbers of transitional disks become available.
8. The Connection with the Record from Planetary Materials

Theoretical models for the thermal structure of protoplanetary disks have come a long way from the early days when globally hot temperatures were predicted (Cameron 1962; Cameron & Pine 1973). Improvements have come with both theoretical and observational advances, many of which have been noted here. It is interesting to ask what the record from planetary materials might have to contribute.

Early on, the isotopic homogeneity of planetary materials was used to argue that the solar nebula must have been globally hot in order to vaporize all accreted solids so that efficient homogenization could be achieved in the gas phase (e.g., Kerridge 1993). This picture was challenged with the identification of isotopically anomalous grains in a wide variety of primitive meteorites (Anders & Zinner 1993; Ott 1993; Huss & Lewis 1995). More recently, some of these types of grains have been confidently identified with formation in specific stellar environments prior to their incorporation in the solar nebula. The existence of pre-solar grains suggests that either the solar nebula was never globally hot, so that the grains could have been sequestered in a cool region of the nebula, or that they were added to the nebula after the hot epoch. The wide distribution of pre-solar grains in a variety of meteorite types has been used to argue for the former.

Chemical arguments have been made for global temperatures as high as silicate vaporization temperatures (see e.g. Palme & Boynton 1993; Woolum & Cassen 1999 for summaries). For example, chondritic meteorites exhibit volatility-correlated elemental depletions, relative to average solar system abundances, regardless of the geochemical behavior of the element. These data have been interpreted in terms of incomplete gas to dust condensation in a nebula cooling from silicate vaporization temperatures to about 650 K (Wasson & Chou 1974; Palme et. al. 1988). Cassen (1996, 2001) has devised theoretical models of nebula evolution which achieve such depletions with progressive condensation of the moderately volatile elements while the nebula gas is being dissipated.

Further, primitive meteorites (chondrites) contain components, such as superrefractory, calcium-aluminum-rich inclusions (CAIs) and chondrules, which attest to high temperatures. For example, the rare earth element abundance patterns in CAIs yield estimates of temperatures exceeding ~ 1550 K (Boynton 1975, 1978; Boynton et. al. 1980; Palme et. al. 1982). However, these data need not imply high global temperatures, since both CAIs and chondrules appear to have cooled much more rapidly than the nebula could have cooled. These temperatures must have been achieved in local, high energy events in which the nebula gas is being dissipated.

Chondrites are the oldest objects for which dates have been obtained, and with a Pb-absolute age of 4567.2 ± 0.6 Myr, CAIs are the oldest components of these primitive samples (Amelin et. al. 2002; Kita et al. 2004). Relative to CAIs, chondrules appear to have formed, starting ~ 1 Myr later and spanning an interval of 1-3 million years (Kita et. al. 2000; Kita et al., this volume; Tachibana et. al. 2003; Mostefaoui et. al. 2002; McKeegan et al. 2000). A significant age span is even found for chondrules extracted from a single unequilibrated ordinary chondrite meteorite. None of the models for chondrule formation have won a true consensus, although nebula shocks (Desch & Connolly 2002, and references therein) and the X-wind model (Shu et al. 1996) have emerged as the leading contenders. Shocks and the X-wind model require the production of chondrules prior to the dissipation of the nebula, and, in this, there is no conflict with the estimated lifetimes of protoplanetary disks. Disk lifetimes of ~10
Myr are inferred astronomically (Haisch et al. 2001) and from the record in planetary materials (Podosek & Cassen 1994).

The problem with the X-wind model, pointed out by Muzerolle et al. (2003), is that temperatures in the inner disk during the X-wind epoch appear to be too high to permit solids to reach the X-wind launching point. The few million year span in chondrule formation ages also seems a problem for the X-wind model. The shock model of Desch & Connolly (2002) seems more appealing. They argue that shock waves generated by gravitational instabilities in the protoplanetary disk are sufficient to provide the shock speed and gas density needed to produce chondrules. They also calculate cooling rates which are consistent with those inferred from chondrule data and predict a positive correlation between the concentration of chondrules and the cooling rate of chondrules. The latter appears consistent with the unusually high frequency of rapidly cooled chondrules among the population of compound chondrules, which must have formed in regions of high chondrule density. The enhanced remanent magnetization measured for chondrules, relative to the bulk chondritic values, is also consistent with their calculated shock compression of magnetic field lines, provided the lines are oriented parallel to the shock front. The key issue in this model is whether it can be established that the solar protoplanetary disk was indeed gravitationally unstable. Current modeling efforts suggest that disks in the CTTS phase are globally gravitationally stable. However, in the dead zone, where the ionization fraction is not enough to sustain the magneto-rotational instability that is accepted as the ultimate mechanism responsible for the accretion, material can accumulate and become locally gravitationally unstable (see Gammie & Johnson, this volume). We speculate that the dead zone might host chondrule formation.

The fact that chondrule ages from a single meteorite also span more than a million years is a surprise given the interpretation of some meteorite data, which suggest a more rapid accumulation of primitive solids. Wood (1985) argued that chondrules, CAIs and matrix began to accrete promptly, probably in less than one orbital period following the formation of CAIs and chondrules. He based this on two observations: 1) the striking morphological differences between carbonaceous chondrite subtypes which have virtually identical major element compositions, and 2) the Fe/Si compositional complementarity between distinct structural components (matrix vs. chondrules plus CAIs) of carbonaceous chondrites, which have essentially solar bulk composition. In the first, the argument was based on the CV3 and CO3 carbonaceous chondrites. The second, stronger argument was based only on data from the C2 carbonaceous chondrites. Since then Kong & Palme (1999) and Klerner & Palme (1999) have demonstrated compositional complementarity for the CR and CV carbonaceous chondrites. Perhaps the carbonaceous chondrites were indeed promptly accreted, but, for some reason, the ordinary chondrites, from which the spread in chondrule ages are derived, were not.

Planetesimal accumulation models also imply accumulation times much shorter than the spread in chondrule ages. The models achieve 1 km sizes in $10^4$ yr timescales (Weidenschilling 1988) and asteroidal sizes (100 km) by runaway accretion in $10^5$ yr timescales (Wetherill & Stewart 1993; Kokubo & Ida 1996; Weidenschilling et al. 1997; Kortenkamp & Wetherill 1998). The possibility that planets already exist in $\sim1$ Myr disks, as indicated by the presence of gaps, would suggest that the resolution of the conundrum posed by the span in chondrule ages will lie in devising schemes by which chondrules, mm sized objects, can be stored for millions of years in the terrestrial region and, thus, saved from their fate of drifting into the sun. Perhaps chondrules
were rapidly accumulated into bodies large enough to decouple from the gas and were subsequently mixed with younger, later accumulated, bodies in the collisional events which must have been prevalent in that epoch.

The rapid accumulation predicted for solar system solids also poses a problem for explaining the existence of undifferentiated volatile rich primitive meteorites. Since $^{26}$Al was introduced live into the solar system (Russell et. al. 1996; MacPherson et al. 1995, and references therein), bodies growing significantly larger than a km in size would be expected to melt if they formed contemporaneously with CAIs. There are meteorite types, like the HEDs and some irons, which are igneous in origin, and, for example, Lugmair & Shukolyukov (1998) have determined that the HED parent body melted and differentiated within 1 Myr of CAI formation. However, parent bodies of the primitive meteorites (chondrites, which were never melted and at most were only mildly metamorphosed) are inferred to have reached 100 km sizes (Miyamoto et al 1981; Grimm & McSween 1989; Bennett & McSween 1996). Woolum & Cassen (1999) discuss this problem and possible resolutions. In particular, they posit that the resolution might lie in the nature of runaway accretion. While runaway accretion may be responsible for building large bodies rapidly, it requires a very large number of much smaller bodies. For example, results from unpublished data provided by Weidenschilling indicate that while a Vesta-sized body (250 km) can form in $\sim$1 Myr, the median-mass objects are only $\sim$7.5 km in size, which would provide a large reservoir of smaller, unmelted bodies. Whether these smaller bodies would subsequently reside in bodies of the size inferred for chondrite parent bodies remains an open question.

Another problem arising in our current understanding of the thermal structure of protoplanetary disks is the fact that very cool temperatures are predicted for the terrestrial region during the planet-building epoch, temperatures which would allow the condensation of water ice. Why then is the inner solar system so dry? Cuzzi & Zahnle (2004) suggest that the water content of the inner solar system was determined by the competition of water ice migrating inward on meter-sized bodies and the loss by outward diffusion of water vapor. Rapid growth of bodies in the cooler regions beyond the terrestrial zone promotes depletion in the terrestrial zone by cold trapping (Stevenson & Lunine, 1988; Cyr et al., 1998; Cuzzi & Zahnle, 2004). What is not clear is whether cold trapping can be efficient enough to account for the severe depletion of water in the terrestrial planets.

Many of the outstanding problems may soon be resolved with analyses of IRS spectra as they become available. A wealth of new data is anticipated, and from the planetary perspective, it will be critical to attempt observations of the very youngest pre-main sequence stars.

9. Summary

Models of steady viscous accretion disks irradiated by their central stars show that only disks with very high mass accretion rates ($\geq 10^{-6} M_{\odot}yr^{-1}$) have silicates sublimated at 1 AU. These high mass accretion rates are not observed in 1-10 million years old Classical T Tauri Stars, and probably are only possible in very embedded young disks, still actively accreting from their parental core. Disks with more typical values of CTTS mass accretion rates (e.g., $10^{-8} M_{\odot}yr^{-1}$) have midplane temperatures higher than 1000 K, only in the innermost regions, $< 0.4$ AU, and only during the first few million years.
The peculiar near-IR SEDs and resolved images or visibilities of HAe stars and CTTS are consistent with the idea that there is a sharp transition at the dust sublimation radius, where a dusty wall (the inner edge of the outer disk with gas+dust) receives radiation from the star and from the accretion shocks at the stellar surface. The observations show that the temperature of such a wall is 1000-1400 K, which can be identified with the sublimation temperature of silicates. With ISO and Spitzer IRS different crystalline components of silicates have been identified, and correlations with other disk properties are being investigated.

More evolved disks show a substantial clearing of their inner zones, which is thought to be produced by one or more planets. Mid-Infrared spectra of a couple of these transitional objects obtained with Spitzer IRS suggest that crystalline material is found at $R < 6$ AU, and pristine material is found for $R > 10$ AU. More observations and modeling of these objects will help to understand the spatial distribution of dust processing. The midplane temperature at the disks’ innermost regions depends on $\dot{M}$, $\alpha$ and grain size distribution. Observations with ALMA will provide the first direct information on the midplane of the inner disk.

Evidence from meteoritic material suggests that the inner solar nebula might have been globally hot, with temperatures as high as silicate vaporization temperatures. However, there were certainly vast regions of the nebula beyond the asteroid belt which were never hot, and so could have been the source of pre-solar grains and other unprocessed solids. CAIs and chondrules were probably formed in local high energy events involving temperatures higher than the silicate melting temperature. The X-wind model for the production of chondrules seems to be inconsistent with the observations of the near IR excess in CTTS, which have been interpreted as implying that the dust sublimation radius is $\sim 9 R_\star$. This is significantly further out than the X-wind launching point, $\sim 3 R_\star$, and so solids would not be expected to survive to the solar proximity required by the X-wind model. The alternative model developed for the production of chondrules, involving nebula shocks, is thus favored. The span in ages determined for chondrules from a single meteorite was not expected, based on some meteoritic data and on planetesimal accumulation models, both of which suggest accumulation times much shorter than the measured span in chondrule ages. There are still many open issues, but it is anticipated that IRS spectra from Spitzer may resolve at least some of these, and from the planetary prospective, it will be most important to target IRS spectra from the very youngest pre-main sequence stars.

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