Structure and Evolution of Circumstellar Disks Around Young Stars: New Views from ISO *

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Abstract. A question central to understanding the origin of our solar system is: how do planets form in circumstellar disks around young stars? Because of the complex nature of the physical processes involved, multi–wavelength observations of large samples will be required in order to obtain a complete answer to this question. Surveys undertaken with ISO have helped to solve pieces of this puzzle in addition to uncovering new mysteries. We review a variety of studies aimed at understanding; i) the physical structure and composition of circumstellar disks commonly found surrounding young stellar objects; and ii) the evolution of circumstellar disks from the active accretion phase to post–planet building debris disks.

1 Introduction

The number of researchers involved in studies of circumstellar disks surrounding young stars has exploded in recent years – and with good reason! Discoveries of giant planets orbiting main sequence stars in the solar neighborhood, of planetary mass companions surrounding pulsars, and of brown dwarf companions to stellar mass objects have brought new urgency and interest in the search to understand the structure and evolution of circumstellar disks. In addition to their fundamental importance as the likely sites of planet formation, circumstellar accretion disks also play an important role in pre–main sequence evolution. Depending on their mass, accretion rates, and lifetimes, such disks could contribute significantly to building up the final mass of a solar type star. They also appear to play a crucial role in regulating stellar angular momentum during the early accretion phase. ISO, the first multi–mode infrared space observatory, devoted a significant fraction of time to object–oriented surveys of stars in order to study their circumstellar disks.

We begin with a review of what was known and unknown about circumstellar disks surrounding pre–main sequence stars when ISO was launched. In section 3, we discuss new results from ISO that shed light on the physical structure and composition of these disks. In section 4, we review several mid– and far–infrared surveys conducted with ISO focussed on the temporal

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evolution of the disks. Finally in section 5, we summarize these results and comment on progress that will be made in the coming years.

2 Properties of Circumstellar Disks

It is generally accepted that the formation of a circumstellar disk is a common outcome of the star formation process [7]. Observational evidence for the existence of these disks abounds. Many young stars exhibit infrared and millimeter excess emission indicating the presence of large amounts of circumstellar material. Yet in order to provide an optically–thin line of sight toward the central object, a flattened dust distribution is required [38]. Emission–line profiles observed toward young stars provided additional evidence. Red–shifted components of the bi–polar flow are thought to be occulted by a geometrically–thin, optically–thick disk resulting in blue–shifted line profiles [4]. In young stellar objects where the observed flux is dominated by accretion luminosity (e.g. FU Ori eruptive variables) one can observe kinematic signatures of rotation in absorption lines arising in the disk photosphere [53]. However the most compelling evidence comes from direct images of the disks themselves (Figure 1).

Based on these and other studies over the past 15 years, we have learned a great deal concerning the physical properties of disks. From sub–mm observa-
tions of optically–thin dust emission, estimates of total disk mass (gas+dust) range from $0.1 - 10^{-3} \text{ M}_\odot$ ([4]; [3]; and [13]). Based on direct images obtained with HST, modeling of spectral energy distributions, and millimeter wave observations of gas disks, sizes are estimated to range from $10 < r < 1000 \text{ AU}$. Finally, observations of UV/blue excess emission allow one to estimate accretion rates from the disk onto the star [16]. Recent estimates range from $10^{-9}$ to $10^{-7} \text{ M}_\odot \text{ yr}^{-1}$ for classical T Tauri stars and $\times 100$ greater for the FU Ori objects. There is a hint of decreasing accretion rate with age for T Tauri stars found in the Taurus–Auriga and Chamaeleon I complexes [21]. This is consistent with the pioneering studies of the frequency of near–infrared excess emission [50] as a function of stellar age. Near–IR excess emission (1–5 $\mu$m) traces dust emission at radii $< 0.1 \text{ AU}$ and there is a nearly 1:1 correlation between the presence of dust in the inner disk and spectroscopic signatures of accretion [20]. Recent studies which utilize larger statistically significant samples confirm that the timescale for dissipation of inner accretion disks is $< 30 \text{ Myr}$ [24]. Further, due to the small number of objects found to be evolving from optically–thick to optically–thin disks in the region 0.1–1.0 AU, it appears that the transition time is $< 10^6 \text{ yrs}$ [17]. Finally, there appears to be a connection between the presence/absence of an inner accretion disk and the evolution of stellar angular momentum [4]. This relationship can be understood in terms of a magnetospheric star–disk interaction [39].

Despite the tremendous explosion in our knowledge concerning circumstellar disks surrounding young stars, many fundamental questions remain unanswered. What physical processes control the energy budget as a function of radius in the disk? What is the chemical composition of the dust grains observed? Does the evolution of disks in the planet–forming regions from 0.1–10.0 AU differ from the evolution of the inner accretion disks? ISO has made fundamental contributions toward answering these questions as described below.

### 3 Physical Structure and Composition

Photometric observations obtained over a broad wavelength range can be a powerful diagnostic of the spatial distribution of circumstellar material. As the temperature of the circumstellar material decreases with radius, progressively longer wavelength emission traces larger radii in the disk (Figure 2). Utilizing the ISOPHOT instrument on–board ISO [30], Beckwith and collaborators set out to conduct a small survey of young star+disk systems in order to search for structure in the SEDs impossible to observe from the ground. They obtained multi–wavelength photometry with 13 filters from 4.9–160 $\mu$m for a sample of 14 objects in the Taurus–Auriga and Chamaeleon I dark clouds ($d \sim 150 \text{ pc}$). Preliminary results are presented in Figure 3 for a representative sample of objects compared to expected stellar SEDs as well as
a simple model of a geometrically–thin, optically–thick passive reprocessing disk seen face–on [46]. A few general trends are obvious from inspection of these data. First of all, several objects lack significant near–infrared excess emission suggesting the presence of inner holes in the circumstellar dust distribution [36]. An extreme example is CS Cha in which the disk appears to be evacuated to $> 0.1$ AU. Secondly, it appears that a standard reprocessing (or accretion disk) matches the SEDs between 2–10 $\mu$m. Finally, the observed SEDs are flatter and exhibit greater flux in the mid– and far–IR than simply blackbody disk models predict; an additional emission component is required. Similar conclusions have been reached from multi–wavelength study of the peculiar young star UX Ori [40] utilizing ISOPHOT.

**Fig. 2.** Schematic representation of an optically–thick, geometrically–thin circumstellar disk model. Viscous accretion and/or reprocessing of stellar photons results in a power–law temperature distribution in the disk [2]. Each radius corresponds to a unique blackbody temperature which is diagnosed using a specific range of wavelengths (see [6]).

What controls the energy budget in these circumstellar disks? For a disk dominated by the dissipation of accretion energy confined to the disk mid–plane, the disk should exhibit a decreasing temperature distribution away from the mid–plane which could produce absorption features in the disk photosphere as observed in the FU Ori objects. For a disk dominated by
reprocessing of stellar radiation, there should be a temperature inversion producing emission–lines in a hot, optically–thin disk atmosphere ([8]; [9] (CG97)). A pioneering mid–IR spectral survey of T Tauri star+disk systems [11] found several sources exhibiting 10 µm emission attributed to Si–O stretching modes. In order to investigate inner disk regions as well as understand the heating mechanisms which control disk structure, Natta, Meyer, and Beckwith [42] utilized the PHOT–S module of ISOPHOT, to conduct a low resolution spectrophotometric survey from 2.5–11.7 µm of a sub–set of the T Tauri sample sample described above (see also [17]). Each star in the sample of nine exhibited some evidence of a 10 µm emission feature. Using the simple flared–disk atmosphere model of CG97 and adopting a fiducial Si–O feature cross–section (σ_ν/σ_10), they fitted these data for the efficiency of converting stellar photons into silicate emission (ε = σ_10/σ_ν). The results of these fits are shown in Figure 4 where the 10 µm features are compared with the models. The CG97 models successfully reproduce the majority of
the observed spectra using a mixture of amorphous olivine and pyroxene grains with sizes < 1 µm. Combining these results with the SEDs described above suggests that disk atmospheres contribute significantly to the mid–and far–infrared fluxes observed in young star+disk systems.

![Fig. 4. Model fits to the observed spectra.](image)

Additional surveys undertaken with the SWS instrument on–board ISO have enabled us to ask new questions regarding the dust mineralogy and gas content of these disks. Moderate resolution ($R \sim 1500$) mid–infrared spectroscopy obtained for a sample of young intermediate mass Herbig Ae/Be stars, have revealed the presence of crystalline silicate features in three objects: HD 100546, HD 142527, and HD 179218 ([32]; [31]; and [52]). Similar features have been observed in the disk of β Pictoris [28] as well as in solar system comets [19]. These observations are intriguing because crystalline silicates are not observed in the diffuse interstellar medium. Thus their presence in the circumstellar material surrounding the Herbig stars suggests that amorphous silicate grains were transported into the inner disk region where they could be processed at temperatures > 1500 K. This, along with their observation at characteristic dust temperatures of ~ 300 K, suggests large–scale radial mixing in these disks (however see [37]). Finally, we note that...
pioneering observations have detected H$_2$ toward some young star+disk systems ($^{51}$; $^{14}$). The relative intensities of the S(0) and S(1) lines suggest gas temperatures of $\sim 100$ K and mass estimates $\sim 0.01$ $M_{\odot}$ comparable to the minimum mass solar nebula $^{22}$.

4 Temporal Evolution

While it appears that most young stars form accompanied by a circumstellar disk, it is not clear that all disks form planets. Several factors could play a crucial role in determining the fate of an accretion disk. It has been suggested that disks evolve more quickly around high mass stars ($M_*>1.0$ $M_{\odot}$) compared to low mass stars $^{41}$. Stellar companions can also effect the dynamical evolution of disk material $^{33}$. Finally, stellar environment can also play a role $^{23}$. Of course one would like to study disk evolution as a function of all these variables. Here we review the observed correlations of disk properties with time as studied from ISO surveys of stars in clusters with ages determined from evolutionary models as well as surveys of main sequence field stars of uncertain age.

Despite significant advances in our understanding of the evolution of inner accretion disks very little is known concerning the evolution of outer disks. At mid–infrared through sub–mm wavelengths (10–1000 $\mu$m) observations trace material between 0.1–10 AU. Several surveys have been conducted with ISOPHOT which have made significant contributions to our understanding of outer disks. Meyer et al. $^{35}$ observed between 10 and 30 stars in each of five separate clusters and associations at 25 and 60 $\mu$m tracing material in the terrestrial planet zone from 0.3–3.0 AU. This survey provides a complete census of optically–thick circumstellar disks at these wavelengths surrounding solar–type stars with ages 1–300 Myr. Despite being a factor of $\times 5$ more sensitive than IRAS at 60 $\mu$m, only four sources were detected with $SNR>3$ out of a sample of 97 stars. All of the sources detected were members of the Chamaeleon I dark cloud ($\tau<10$ Myr) including one transition object possessing a large hole in its inner disk. These results suggest that optically–thick outer disks dissipate, or coagulate into larger particles on timescales comparable to the cessation of accretion (c.f. $^{18}$; $^{26}$). A complementary survey undertaken by Spangler et al. $^{48}$, observed 300 stars in young clusters and the field at 60 and 90 $\mu$m spanning a similar age range. These authors analyze the data in terms of the fractional contribution of the far–infrared emission to the bolometric luminosity of the sources observed ($f=L_{FIR}/L_{bol}$). They plot the mean value of $f$ as a function of cluster age, and find a smooth variation from the youngest stars ($f>10^{-2}$ at ages $<10^7$ yrs) to the oldest stars in sample ($f\sim10^{-5}$ at ages $\sim10^9$ yrs). Presented in this way, the zodiacal dust disk (within 5 AU) would have a value of $f\sim10^{-7}$ for the 4.5 Gyr age of our solar system.
Fig. 5. Frequency of 60 µm detections as a function of cluster age for several star-forming regions observed by IRAS (triangles) and ISO (circles) [35]. Because the ISO observations are ×5 more sensitive than the IRAS survey, the triangles should be considered lower-limits when compared to the circles. It appears that optically-thick disks from 0.3-3.0 dissipate or coagulate into larger bodies on a timescale comparable to the termination of the main accretion phase in T Tauri disks.

Other relevant surveys include the study of intermediate mass members of the Ursa Major Stream (τ ~ 300 Myrs) [1]. One out of nine stars were detected consistent with a recent estimate of the frequency of IR excess among field main sequence stars [15]. Similar results based on a survey of 38 main sequence stars at 20 µm, tracing the inner-most annuli of these cool outer disks, have also been reported [15]. Finally, Habing et al. [18] present preliminary results concerning their survey of stars in the solar neighborhood. Improving on searches for “Vega phenomenon” objects in the IRAS database, this survey was sensitive to stellar photospheric emission for A–K stars out to a distance of 25 parsecs. Combining ISO observations with improved age estimates for their sample, they report the intriguing result that all stars younger than 300 Myr possess a detectable disk while no stars older than 400 Myr show IR excess emission at 60 µm. They interpret this result as evidence that the era of maximum bombardment documented in our own solar system is a common phenomena in the evolution of circumstellar disks.
5 Summary and Future Work

From this vast array of observational results, a coherent picture is emerging. Most young stars (50–100 %) possess active accretion disks during a significant portion of their PMS evolution. These disks appear to have masses comparable to the minimum mass solar nebula in both gas and dust. Structurally, they possess small inner holes (< 0.05 AU) and flare in their outer regions as expected from hydrostatic equilibrium. Although almost all disks that extend to within 0.1 AU of the stellar surface appear to be actively accreting, the energy budget of the outer regions are dominated by reprocessing of light from the central star. The active accretion phase lasts from 1–10 Myr in most systems, though it can persist longer. The time to transition from optically–thick to optically–thin within 1 AU lasts < 1 Myr. At the same time, outer disks appear to dissipate, or grow into larger bodies (with decreased mass opacity) rendering them optically–thin. The results of Meyer et al. [35] and Spangler et al. [48] appear to be consistent when comparing the frequency of detections in both surveys. Additional data are required in the crucial 10–30 Myr old range order to discern whether or not there is a gradual evolution of dust mass in small particles (a < 1 mm) with time, or an abrupt change in disk properties associated with the termination of accretion. Perhaps particle growth in circumstellar disks is inhibited during the active accretion phase? Similarly, further study of stars aged 100–500 Myr is necessary to follow–up the intriguing results of Habing et al. [18]. Is the era of maximum bombardment, thought to be associated with with planet formation, a common phase of dust disk evolution around solar–type stars?

Tremendous observational capabilities, both ground– and space–based, will focus on these problems in the coming decade. With continued improvement in instrumentation, the current generation of 6–10m class telescopes will continue to make astounding discoveries such as the dramatic images of the disk surrounding HR4796A [29; 27]. High resolution images obtained from the UV through the near–infrared with HST will have an on–going impact on studies of circumstellar disks [6]. Sub–millimeter telescopes (both single dish surveys and targeted observations with extant and future interferometric arrays) will provide data necessary to obtain a complete understanding of the evolution of dust mass and grain size in circumstellar disks [22]. SIRTF will enable a detailed census of faint debris disks in the solar neighborhood, as well as surveys of unprecedented sensitivity in nearby star–forming regions. SOFIA will prove very complementary to SIRTF, providing higher spatial and spectral resolution. Finally, both ALMA and NGST have as central to their science missions studies of circumstellar disk evolution and planet formation. With the renewed interest in the origins of stars and planets, future work is sure to provide answers to questions that surveys undertaken with ISO have played a key role in defining.

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