Evolution and Dispersal of Protoplanetary Disks

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Abstract. Multiwavelength studies of evolved protoplanetary disks around solar-type and low-mass stars reveal a general trend of changes in the IR excesses, accretion rates, and silicate features, suggesting grain growth/settling, photoevaporation, and maybe the formation of planetesimals and planets. Nevertheless, within the average-behavior picture of disk evolution, we observe strong variations between individuals, that may be related to different initial conditions, different environments, and the presence of companions.

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MULTIWAVELENGTH OBSERVATIONS OF DISKS

The evolution of accretion disks around solar-type and low-mass stars (T Tauri stars, TTS) and the way protoplanetary disks disperse are crucial to understand planet formation. Optically thick disks are very common at the ages of 1 Myr and rare at ages $>$10 Myr [1, 2, 3]. Most planet formation must therefore occur within 1-10 Myr, which sets important constraints to the formation mechanisms. Nevertheless, some objects lose their disks before 1 Myr, while some others are actively accreting at 10 Myr age. The accretion rates and IR excesses decrease with time [4, 5, 6], but the individual differences for similar objects at a given age are large. Clusters and associations offer a large number of members that share average age, metallicity, and distance, being an ideal target to study disk evolution and to explore the reasons of the individual variations and their effects on planet formation.

An optically thick, geometrically thin disk composed of dust (1%) and gas (99%) typically extends from few stellar radii up to 100-300 AU. The optically thick dusty disk produces an excess emission over the stellar photosphere at IR, submillimeter, and millimeter wavelengths. Although most of the dust is "hidden" into the optically thick continuum, the thermal inversion in the optically thin, warm, upper layers of the disk (disk atmosphere) produces emission features in the mid-IR [7], especially from silicate grains. The dust sublimates at $\sim$1400 K, so the innermost part of the disk contains only hot gas, detectable via the near-IR emission of gas molecules [8]. The gas is channeled onto the star via magnetospheric accretion [9], producing characteristic UV excesses and velocity-broadened emission lines (especially Hα). Even if most disks are located too far to spatially resolve their structure, observations at different wavelengths allow to spectrally resolve the different parts of the disk. Multiwavelength data also reveal disk evolution: The initially small ($\sim$0.1μm), ISM-like, amorphous

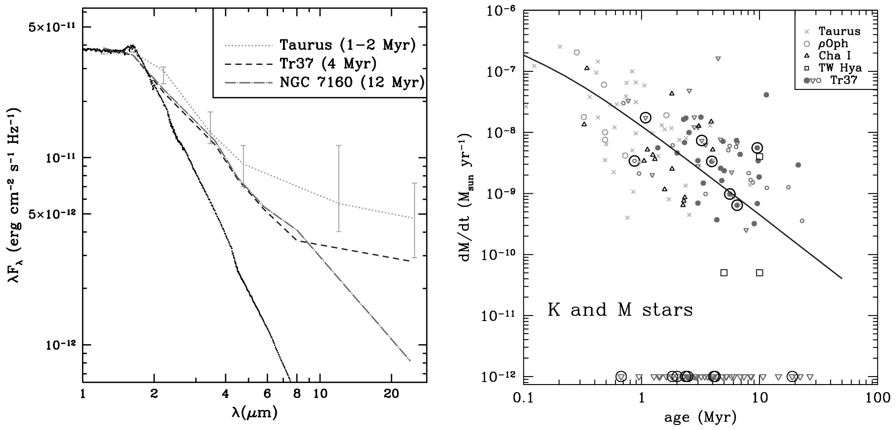

FIGURE 1. Time evolution of the median SED compared to photospheric emission (left), and accretion rates vs. age compared to viscous evolution (right), for K-M stars. TO are marked with large circles.

silicate grains agglomerate into larger aggregates, and some of them are processed into crystalline grains. Grain growth and disk evolution are expected to occur faster in the innermost disk [10]. The complexity of disk evolution requires therefore a combination of multiwavelength observations: optical observations to characterize the central star (spectral type, age, mass, radius), IR observations to reveal the inner disk (0.1-30 AU) and dust characteristics, UV data and optical photometry to study the presence of accretion, and millimeter data to study the bulk of the disk mass and grain growth.

EVOLUTION OF THE IR EXCESS

The Spitzer Space Telescope has been one of the most important tools to study the presence of protoplanetary disks. The IRAC and MIPS instruments have mapped large areas in young clusters at 3.6-8μm and 24-70 μm, respectively, for which the disk excess emission over the photospheric levels is much larger than in the ground-based JHKL bands. While the JHKL colors are sensitive to the innermost disk and inner rim ($<$0.1 AU), Spitzer reveals the emission coming from regions located at $\sim$0.1-20 AU from the star (depending on the spectral type). Covering a larger distance range led to the identification of the "transition" objects (TO) with inner opacity holes (small or zero near-IR excess, but mid-IR colors consistent with optically thick disks). Although in young regions most of the disks have JHK excesses, 20% or more of the disks in clusters aged $>$4 Myr have photospheric JHK colors, despite showing optically thick accretion disks at longer wavelengths, so observations at $\lambda > 3\mu$m are very important.

For solar-type stars, the comparison of clusters with different ages reveals a significant variation the median near-IR emission with age. Fig. 1 (left) displays the typical spectral energy distribution (SED) for three young regions: 1-2 Myr-old Taurus [11, 12], 4 Myr-old Tr 37 [2], and 12 Myr-old NGC 7160 [2]. The innermost SED slopes in Tr 37 and NGC 7160 are close to the slope of an optically thick, geometrically thin disk ($\lambda F_\lambda \sim \lambda^{-4/3}$; [13]). This suggests strong coagulation/settling progressing with time

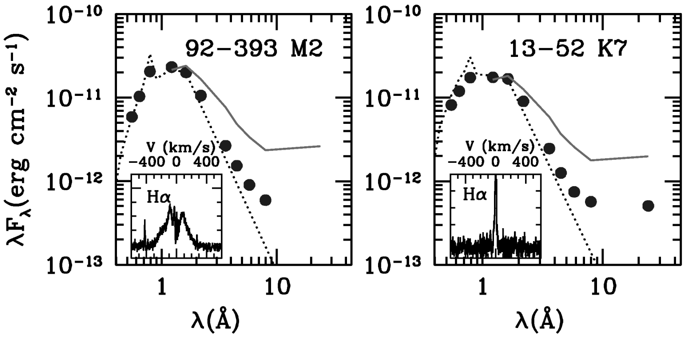

FIGURE 2. Accreting (left) and non-accreting (right) TO in the 4 Myr-old Tr 37 cluster. The median disk SED and photospheres are displayed for comparison.

and a faster evolution in the inner regions, as predicted by Hayashi et al. [10]. The disk fraction varies from ∼80% in Taurus, down to ∼45% at 4 Myr age in Tr 37, and <5% in NGC 7160 at 12 Myr age. Therefore, about half of the disks disappear within the first ∼ 5 Myr, but a few disks are able to survive for a very long time.

TO represent ∼5-10% of the disks in Taurus and Tr 37. The small relative numbers suggested that the rest of the disk should dissipate very fast (∼10^5-10^6 yr) once the inner disk develops a hole [2, 12], which is consistent with the scenarios of photoevaporation [14, 15] and inner disk clearing by planet formation [16]. Nevertheless, there are other possibilities to produce inner holes that have not been fully explored, like the presence of close binary companions [17], which reduces substantially the disk lifetime [18].

ACCRETION: PARALLEL GAS AND DUST EVOLUTION?

The gas accretion onto the surface of the star produces an UV excess that correlates with the accretion rate [19]. We derived accretion rates ($\dot{M}$) from U band photometry for the solar-type stars (K0-M2) in the clusters Tr 37 and NGC 7160 using data from the FLWO, Calar Alto, and the MPIA-Königstuhl [20, 21]. High resolution Hα spectroscopy of the Tr 37 members (Hectochelle/MMT) was used to identify objects with $\dot{M}$<10^{-10} $M_\odot$/yr, which do not produce significant U band excess, and to set strong limits to objects without Hα broadening ($\dot{M}$<10^{-12} $M_\odot$/yr; [6]). Comparing the accretion rates in Tr 37 and NGC 7160 (which has only 1 accreting object) with those measured in younger regions (Fig. 1 right), we find a decrease with time consistent with the evolution of a viscous disk [4], suggesting *parallel evolution* of the dust (IR excess) and the accretion rates (Fig. 1).

Despite the global parallel decrease in IR excess and $\dot{M}$, individual cases show a large spread in both IR disk emission and accretion. We find that ∼50% of the TO are still accreting (Fig. 2). Their accretion rates, although typically low (<10^{-9} $M_\odot$/yr), do not significantly differ from the accretion rates of normal disks in these evolved clusters (10^{-9} $M_\odot$/yr in average, Fig. 1 right). Photoevaporation predicts the opening of holes once the accretion through the disk drops below a certain limit (10^{-9}-10^{-10} $M_\odot$/yr; [14, 15]). The presence of TO with average accretion rates and normal disks with very

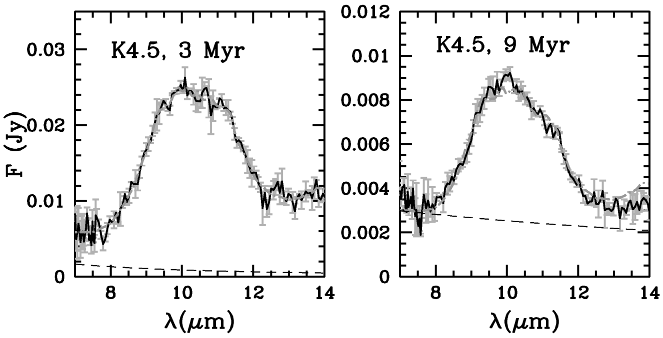

FIGURE 3. Silicate feature for two K4.5 stars with different ages. The youngest one presents larger grains (~2.5 vs. ~0.2μm), while the silicates of the oldest are closer to ISM dust.

low $\dot{M}$ suggests that photoevaporation may not be always effective. We also observe stars with no disks and no accretion at all ages. This, together with the large spread in $\dot{M}$ for any given age and mass (~2 orders of magnitude) suggest that there are many other parameters, in addition to viscous evolution, important for disk dissipation. The initial mass of the disk and the star, environment, presence of binaries, and ongoing planet formation may be responsible for at least part of the large diversity of behaviors.

DUST MINERALOGY IN THE DISK ATMOSPHERE

The silicate emission feature at 8-12μm (Fig. 3) traces the small (~0.1-6 μm), warm (~150-450 K) silicate grains in the optically thin disk atmosphere. This is only a very small part of the whole dust content in the disk, but it provides information about dust processing, grain growth, and formation of crystalline silicates. It is also sensitive to the turbulence in the disk, and the presence of crystalline grains in regions colder than the temperatures required for annealing can be used to test the transport/mixing in the disk.

Disk models and laboratory measurements of the optical constants of the different materials [22, 23, 24, 25, 26] are needed to extract the information about grain size, composition, and solid state from the optically thin silicate feature. The first models assumed one or two temperatures for the disk and silicate [27]. Recent detailed models apply a continuous distribution of temperatures (Two Layer Temperature Distribution; [28]), which is a more physical approximation to the real disk. The data reveal that the warm disk atmospheres are composed by amorphous and crystalline grains, with crystallinity fractions ranging from zero to ~ 80% [27, 28, 29, 30, 31, 32]. The main grain components are amorphous grains with olivine and pyroxene compositions and crystalline forsterite, enstatite, and silica. The grain sizes vary from ISM values (~0.1μm) to several microns, and there are objects without 10μm emission whose disk atmospheres must be dominated by large grains (>6μm; [29, 32]).

As in the case of IR excesses and $\dot{M}$, there is a large variety of silicate features for objects with similar ages and spectral types. Although the existence of large and crystalline grains is a sign of evolution compared to ISM dust, it is not possible to correlate the evolutionary state of a disk with the size or crystallinity of its grains, as

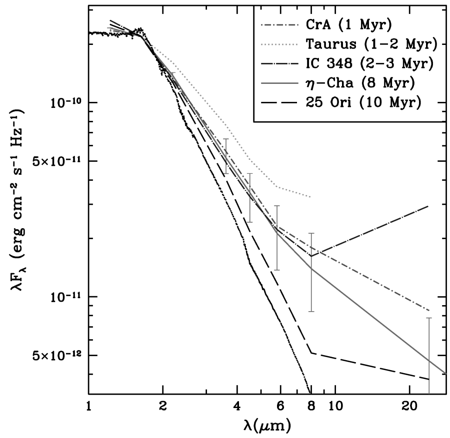

FIGURE 4. Median SED for M0-M8 stars in clusters with different ages. The quartiles are shown for the η Cha cluster, being similar in the other cases ([32] and references therein).

the presence of grains in the disk atmosphere depends rather on the turbulence/$\dot{M}$ in the disk than on the age of the system [29, 33]. Strongly processed grains are already found in objects with ages $\sim$1 Myr and some very old disks display silicate features very similar to the small, amorphous ISM grains (Fig. 3). Nevertheless, the effect of sedimentation on the silicate feature is not yet clear [34].

AGE, MASS, ENVIRONMENT, AND INITIAL CONDITIONS

The diversity of objects suggests that many parameters, in addition to age, affect disk evolution. The presence of close-in binaries is known to produce inner holes in the disks [17] and to reduce the disk lifetime [18]. The mass of the star and the mass of the disk may also affect the morphology, structure, and evolution of the disk [35].

Exploring the disks around low-mass objects (spectral types M0-M8), we find significant differences. The SEDs of disks around M-type stars and brown dwarfs differ from solar-type SEDs (Fig. 1, 4; [32]). The time evolution is not evident for M-type SEDs, for which the slopes at $\lambda < 6\mu$m are very close to optically thick, geometrically thin disks at any age (Fig. 4). The fraction of TO is also higher for M-type stars than for solar-type stars: In the 1 Myr-old Coronet cluster and the 8 Myr-old η Cha cluster, $>$50% of the disks around M-type stars are TO [21, 32]. The large fractions of TO at very different ages suggest TO lifetimes comparable to the lifetimes of normal disks. In such cases, disks with inner holes would not be in a rapid, "transitional" phase between Class II and Class III objects, but may have been caused by different processes (initial conditions, binaries) and may be "transition-like" structures since their formation. The variety of TO and their properties (accretion, hole size) point to multiple different mechanisms to open holes, not always related to time evolution nor to planet formation, and probably dependent on the masses of the star and disk. The effect of the cluster environment (photoevaporation by nearby OB stars, triggered star formation, formation in quiescent low-mass star-forming clouds, etc.) may be also important in determining the disk fate.

CONCLUSIONS

- The complexity and diversity of protoplanetary disks reveal that disk evolution cannot be understood without multiwavelength observations.
- IR excess and accretion rates decrease with age in a *parallel* way, but $\dot{M}$ and the SED shape vary largely for objects with similar ages and spectral types. TO with and without accretion and “normal" disks with very low $\dot{M}$ do exist.
- The silicate feature cannot be used as a proxy for evolution. The presence of large grains in the disk atmosphere is related to high turbulence levels/accretion rates in the disk rather than to the age or the degree of global dust evolution.
- “Transition” objects can be produced by various processes not always related to evolution, and may have sometimes lifetimes comparable to normal disk lifetimes.

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