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SPITZER OBSERVATIONS OF CIRCUMSTELLAR DISKS

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Abstract.
Thanks to its very high sensitivity, the Spitzer Space Telescope is revisiting many of the questions on circumstellar dust disks evolution raised by previous space-based infrared observatories, in particular IRAS and ISO. I review in this paper recent Spitzer results on disks around young stars, including disk dissipation time-scale estimates, the identification of wTTS with disks, and the finding of transition disks. I will then summarize some of the results on dust mineralogy in T Tauri disks obtained as part of the "Core to Disks" (c2d) Legacy Project.

1 The Spitzer Space Telescope, and its impact on circumstellar disks study

The Space Infrared Telescope Facility (SIRTF) project has been in the books for more than 20 years. Late August 2003, after several delays, SIRTF was finally launched from Cape Canaveral into an Earth-trailing heliocentric orbit. SIRTF was then renamed the Spitzer Space Telescope (SST), in honor of the late Dr. Lyman Spitzer Jr. Less than 4 months after the launch, just before Christmas 2003, the first scientifically validated results were released. Spitzer was ready to start operations.

Wide field, broadband imaging can be obtained with Spitzer using the Infrared Array Camera (IRAC) and the Multiband Imaging Photometer for Spitzer (MIPS). IRAC is a four-channel camera that provides simultaneous 5.2×5.2 arcminutes images at 3.6, 4.5, 5.8, and 8 μm. MIPS, on the other hand, provides imaging and photometry capabilities in broad spectral bands centered at 24, 70, and 160 μm. In addition, MIPS has a low resolution spectroscopy mode from 55 to 95 μm. Finally, the Infrared Spectrograph (IRS) provides the SST with low and moderate resolution spectroscopic capabilities from 5.2 to 38.0 μm.

The high sensisitivity of Spitzer makes it unique. At 24 μm for instance, the SST is about 1000 times more sensitive than IRAS was at 25 μm. While the spectroscopic mode of ISO was limited to bright sources of a few Jy at around 10 μm, low resolution spectra of objects as faint as a few mJy can be obtained with the SST/IRS instrument. This improved sensitivity has many consequences in the field of circumstellar disks. Distant star forming regions are now reachable with the SST. Dust disks around very low-mass stars can be detected, allowing statistically meaningful comparisons between disks around early- and late-type stars. Spitzer is thus revisiting the main issues on dust disks evolution previously raised with the IRAS and ISO satellites.

I review in the following some of the recent Spitzer results related to disks evolution: disk frequency as a function of age (Sec. 2), disk properties around weak-line T Tauri stars (Sec. 3), identification of transition disks (Sec. 4), and dust evolution (Sec. 5). In this paper, I will neither discuss the PAHs in disks (see Habart, these proceedings, and Geers et al., 2006), nor disks around Main Sequence stars (debris disks) which would deserve a separate review.

2 Disk dissipation time-scale

Statistics on the dust and gas dissipation time-scales in the planet forming regions of disks are essential to constrain planet formation theories. JHKL near-infared excesses above the disk photosphere serve to trace hot

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Name	Age [Myr]	Disk Fraction [%]	Reference
NGC 7129	1	54±14	Gutermuth et al. (2004)
IC 348	2–3	50±6	Lada et al. (2006)
Tr 37	4	48	Sicilia-Aguilar et al. (2006)
Eta Cha	5–9	40	Megeath et al. (2005)
NGC 7160	10	4	Sicilia-Aguilar et al. (2006)
NGC 2547	25	0 (Spec. Type<K), 7 (ST>K)	Young et al. (2004)

Table 1. Fractions of stars with IRAC excesses due to hot dust in the planet forming regions of disks.

dust located at a few AU from the star. Ground-based studies of star forming regions of various ages showed that the dust in the internal disk dissipates in about 5–10 Myr (see Hillenbrand 2005 for a review).

Spitzer observations expand former ground-based studies to larger wavelengths. IRAC observations (3.6–8 μm) of several star forming regions aged between 1 Myr to 30 Myr confirm the general conclusion obtained in the JHKL-bands : the dust in the inner regions of circumstellar disks dissipates in less than 10 Myr (see Table 1). But thanks to the Spitzer sensitivity, Lada et al. (2006) could perform an interesting comparison of the disk fraction towards solar mass stars in IC 348 (2–3 Myr), to the disk fraction towards lower and higher mass stars. In IC 348, solar-mass stars show the highest disk occurrence (47±12%), while 28±5% of the lower- and 11±8% of the higher- mass stars, only, possess excesses consistent with dust in the inner regions of disks. These studies, nevertheless, do not tell anything about the gas content in the first few AU from the star, and hence on the remaining amount of gas that could accrete on planetary embryos.

3 Weak-line T Tauri stars

Weak-line T Tauri stars (wTTS) are X-ray emitters showing no evidence for accretion. They are thought to be T Tauri stars at an advance stage of evolution. Indeed, none of the wTTS show infrared excess in the JHKL and IRAS bands, indicating no disk. Nevertheless, the sensitivity-limited studies of these objects may have missed several, though dissipated compared to classical T Tauri stars, dust disks.

Deep IRAC and MIPS images have revealed infrared excesses due to the thermal emission of dust grains towards a significant fraction of wTTS. Lada et al. (2006) find that 36% of the wTTS in the IC 348 cloud show infrared excesses consistent with dust disks. Cieza et al. (2006) studied 230 wTTS in the Ophiuchus and Lupus clouds, and find a disk occurrence of 22%. But a third study of 83 off-cloud wTTS by Padgett et al. (2006) does not seem to confirm the Lada and Cieza high disk fractions. Padgett et al. (2006) conclude that only 6% of the wTTS in their sample show infrared excesses. The difference in disk fraction between on- and off-cloud could be related to the cloud history. For instance, the low disk fraction in the Padgett et al. (2006) off-cloud sample could be due to a contamination with older stars. Disk identification criteria also slightly differ from a study to an other and may explain some of the differences found between the Cieza and Lada studies. Cieza et al. (2006) note that the idenfication of a weak IRAC excess required careful consideration of the photometric uncertainties involved (i.p. extinction).

Despite the high sensitivity of Spitzer, a majority of wTTS do no show evidence for circumstellar dust. Cieza et al. (2006) used the IRAC fluxes and the MIPS 24 and 70 μm upper limits to derive the maximum encompased dust mass as a function of the distance from the star for wTTS in the Lupus and Ophiuchus clouds For each star, they calculated 15000 Spectral Energy Distributions (SEDs) by varying the grain and surface density properties. Less than $10^{-4}\,M_\oplus$ of dust must reside within 10 AU from the wTTS, and less than $10^{-5}\,M_\oplus$ within 1 AU (Fig. 1). Therefore, the inner regions of these wTTS are extremely dust-depleted, although the actual reason for this depletion is not known. One can speculate that planet formation occured already, which would explain the lack of hot dust, but alternative scenario are, at this level of interpretation, equally probable.

4 Transition disks

While disk dissipation statistically occurs in about 5–10 Myr in a cloud, the transition timescale for any individual object is much shorter. Cieza et al. (2006) estimate that the transition timescale from optically thick to

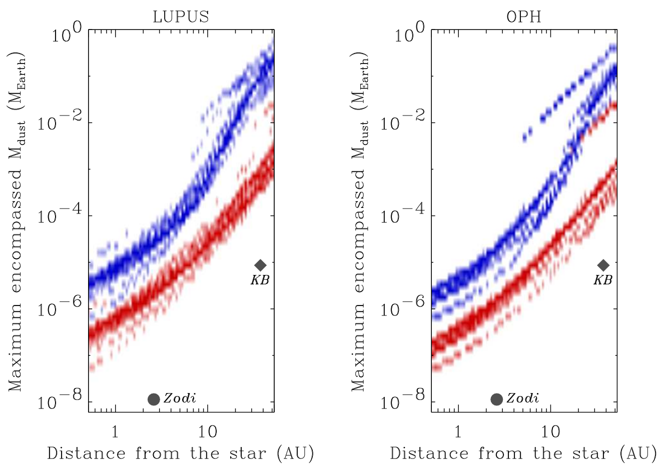

Fig. 1. Maximum encompassed dust mass as a function of the distance from the star for the Lupus and Ophiuchus clouds (respectively left and right panels). The red (lower) area correponds to mass upper limits when minimum grain sizes $a_{\rm min}$ between $0.05\,\mu$m and $0.5\,\mu$m are considered, while the blue (upper) area corresponds to $10\,\mu\text{m} < a_{\rm min} < 100\,\mu$m. Masses have been calculated assuming a -3.5 power-law differential grain size distribution, and a maximum grain size of 1.3 mm.

optically thin disks may be as short as 0.4 Myr. Because this dissipation process is fast, finding transition disks around solar-like stars has awaited the arrival of Spitzer. Schematically, transition disks have almost purely photospheric SEDs until about $\lambda = 10\,\mu$m, indicative of a dust-poor inner disk, and an optically thick external disk responsible for the SED longward $\sim 10\,\mu$m.

The wTTS Co-Ku Tau/4 is the most popular representative of this class of objects. The Spitzer IRS spectrum has been assuming an optically thick disk whith an inner hole of about 10 AU in radius (d'Alessio et al. 2005). DM Tau is an other good example. The shape of its IRS SED points toward a *dust* hole of about 3 AU in radius (Calvet et al. 2005). But contrary to Co-Ku Tau/4, DM Tau shows accretion signatures consistent with a classical T Tauri star. Therefore, the dust-depleted region of DM Tau must not be gas-depleted. Whether these dust holes are related to the disk photoevaporation, or to planet formation is currently being debated.

5 Dust evolution

The silicate dust grains that are incorporated into disks around young stars are sub-micronic and amorphous. The presence of crystalline silicates in some Solar System comets indicate that these ISM-like grains have been processed during the Solar System infancy, and incorporated into large solid bodies before the circum-solar disk dissipated. Crystalline silicates likely form close to the star through thermal annealing. Therefore, the degree of crystallinity of the silicates, an their presence at large distances from the star, is thought to be related to radial and vertical mixing processes in disks, for instance due to turbulence, settling, winds, ... (see also Gounelle 2006, Djouadi 2006, these proceedings). Before Spitzer, spectroscopic studies of silicate infrared emission features from disks were focused on intermediate mass (Herbig Ae/Be) stars, with observations of solar mass stars limited to the $10\,\mu$m region from the ground. Out of the 46 Herbig Ae/Be stars obserbed with ISO, 24% show clear evidence for crystalline grains (Acke & van den Ancker, 2004).

While T Tauri stars were too faint for ISO, 5–35 μm infrared spectroscopy of T Tauri stars can routinely be done with the Spitzer IRS instrument. As part of the "c2d" Spitzer Legacy Program (Evans et al. 2003), infrared spectra of more than 100 solar-mass T Tauri stars were obtained. I will focus in the following on the results we obtained from these observations, and published in Kessler-Silacci et al. (2006a). From the analysis of a sub-sample of 40 stars, we could show that the emission at 10 and 20 μm from amorphous silicates dominates the spectra of most T Tauri disks observed. A large fraction of the features are weak and flat, consistent with the presence of micron-sized grains in the inner disk regions (Fig. 2). Moreover, half of the spectra show crystalline silicate features near 28 and 33 μm, in surprising contrast with the 10 μm ground-based studies indicating crystalline emission from very few T Tauris.

The Spitzer/IRS observations indicate significant processing of the silicates in disks when compared to interstellar grains. But interestingly, no correlation is found between the degree of dust evolution and the stellar age. Similarily, no correlation could be found between the degree of grain processing and the mass accretion rate. Dust evolution appears, nevertheless, to be related to the spectral type. A and B-type stars show more centrally peaked 10 μm features than M-type stars. This can be understood if the silicate features probe different regions of the disk depending on the stellar luminosity, and if the grain properties depend on

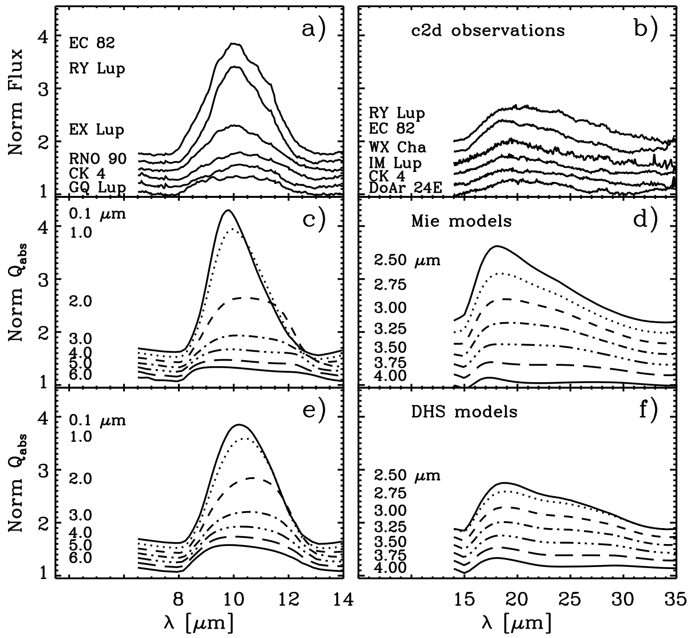

Fig. 2. Evidence of grain growth in the Si-O stretching and O-Si-O bending mode features (resp., 10 μm and 20 μm features), after Kessler-Silacci et al. (2006). The top panels show the observed normalized spectra in the *a*) 10 μm and *b*) 20 μm regions for subsamples of the c2d sources. The bottom two panels show the normalized absorption efficiencies (Q_{abs}) for models of spherical grains of amorphous olivines with various grain sizes calculated for the 10 μm and 20 μm regions. Models of filled homogeneous spheres calculated using Mie theory are shown in *c*) and *d*) and models of hollow spheres calculated using DHS theory (Min et al. 2005) are shown in *e*) and *f*). Spectra in all panels have been artificially shifted along the y-axis by a constant value as a function of wavelength, such that the spectrum of each source could be seen more clearly. The minimum of each normalized spectra was 1.0 prior to adding these constants.

the distance to the star (due for instance to settling, crystallization, radial mixing, ...). For a typical TTauri star, the 10 μm silicate emission arises from a region between ∼0.1 AU and ∼1AU, while it arises from a region between ∼0.5 AU and ∼50AU for A/B-type stars (Kessler-Silacci et al., 2006b, submitted to ApJL).

6 Conclusion

Thanks to its high sensitivity, Spitzer can probe the inner regions of numerous disks around young solar-like stars. Transition disks, as well as disks around wTTS could be identified. Although not discussed in this short (an incomplete) review, Spitzer has furthemore confirmed that even young Brown Dwarfs can harbor circumtellar disks, and that the dust could also been processed around these low-temperature objects. Mid-IR spectroscopy of many T Tauri disks allows for the first time thorough studies of the dust mineralogy in the circumstellar environment of young solar-like stars. These first results are only a small fraction of what will be the Spitzer legacy, and they constitute the starting point of new modeling efforts currently under development.

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