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PROBING THE INNER ACCRETION DISK USING SPITZER C2D MID-INFRARED SPECTRA

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Abstract.
Mid-infrared emission from silicates grains around young stars arises from the inner disks regions (at distances smaller than a few AU), and can serve to probe the dust content and disk structure close to the inner disk edge. We obtained more than a hundred of Spitzer/IRS spectra in a 5-35 μm range, as part of the Cores to Disks (c2d) Legacy Program. The sample consists of mostly Class II objects (T Tauri) and they all show silicate emission features. In addition, a large fraction of them ($\sim$ 80%, Olofsson et al. in prep) show at least one crystalline silicate feature which could be attributed to crystalline Mg-rich silicates (forsterite or enstatite) or other crystalline components (diopside, etc). A statistical study, led by Kessler-Silacci et al. (2006, 2007), evidenced a correlation between the spectral type of the central star and the silicate grain size. This correlation finds an explanation considering the illumination from the star (the 10 μm emission zone is closer to the star for less luminous sources; less than a tenth of AU for a star luminosity smaller than $\sim 0.01 L_\odot$) and by the fact that the grains are, on average, expected to be larger at smaller radii. These results were obtained using the CGPlus two-layer disk model, therefore only geometrical considerations were studied. Future modelling including more details of grain coagulation, thermal processing and accretion events will be needed to strengthen this study. But the complexity of such modelling is beyond the scope of this poster.

1 Introduction

Silicates are observed in the interstellar medium (ISM) and in many Solar System objects such as comets. They are also present in the Earth mantle where they appear mostly in the form of olivine. Modeling and observations show that dust in the ISM is mainly composed of small ($< 1\mu m$), amorphous silicate grains, while infrared observations of some solar system comets clearly reveal significant fractions of crystalline silicates. In the solar nebula, silicates have then been processed before being incorporated into large bodies. It is therefore expected that modification of the dust chemical composition and lattice structure of silicates will also happen in circumstellar disks around young stars. Mid-infrared spectroscopy is a valuable tool to study silicate grains originating from the inner regions of circumstellar (accretion) disks. For example, grain growth can be derived using the $\sim$ 10 μm amorphous silicate feature (Kessler-Silacci et al., 2006). Furthermore, evidence of crystalline silicate emission features in disks around Herbig AeBe (HAEBE), T Tauri stars (TTs), but also low-mass stars and brown dwarves ((BDs, Merín et al., 2007) is also found using mid-IR spectroscopy. The most efficient process for crystallization of silicate grains is thermal annealing, that takes place in the inner regions of the disk, close to the central object. The instruments onboard the Spitzer Science Telescope enables us to probe those regions in disks: at 10 μm, the emission typically comes from the inner 10 AU for HAEBE, $<$ 1 AU for TTs, and $<$ 0.01 AU for BDs. The great sensitivity of Spitzer allows to study the very planet-forming regions

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Module	Wavelengths (μm)	Spectral resolution
Short-Low (SL)	5.2-14.5	60-127
Short-High (SH)	9.9-19.6	$\sim$ 600
Long-Low (LL)	14.0-38.0	60-127
Long-High (LH)	18.7-37.2	$\sim$ 600

Table 1. Characteristics of the four Spitzer IRS modules

in young disks around a great variety of stars. We present in the following, some results from the c2d Spitzer legacy program 'From Molecular Clouds to Planets-Forming Disks' (Evans et al., 2003) that aims at studying grain properties and inner disk regions around young stars.

2 Observations with the Infrared Spectrograph (IRS)

The IRS instrument onboard Spitzer was used to expand early spectroscopic studies of HAEBE with the Infrared Space Observatory (ISO), and of a few TTs observed from the ground in the $\lambda \sim 10\,\mu$m atmospheric window. A large sample of disks around low-mass and solar-mass stars has been observed. All the data presented here are part of the c2d program. The spectrograph is composed of four differents modules that enable a wavelength coverage from 5 to 37 μm (see Table.1). A total of 115 stars have been observed with IRS and our sample is mainly composed of TTs (72 out of 115) but also includes some HAEBE (9 out of 115), BDs (11) and 23 unclassified stars. This sample is distributed along several clouds (Perseus, Taurus, Chamaleon, Ophicius, Lupus and Serpens).

3 Silicate emission features

3.1 Dependency on stellar luminosity

It is now clear that the connection between the silicate emission strength and shape found by van Boekel et al. (2003) is seen in a large sample of stars, from HAEBE to TTs and BDs Kessler-Silacci et al. (2006, 2007). This correlation is apparent in Fig.1 (*left panel*) from Kessler-Silacci et al. (2007), showing the "grain size indicator" ($y-$axis) versus the stellar luminosity. Even if the exact relation between the grain size and $(S_{11.3}/S_{9.8})/S_{peak}^{10\mu m}$ may depend on the grain shape and composition, an inverse correlation appears between the grain size and the stellar luminosity. Brown dwarves have larger $(S_{11.3}/S_{9.8})/S_{peak}^{10\mu m}$ than T Tauri stars, which have larger $(S_{11.3}/S_{9.8})/S_{peak}^{10\mu m}$ than HAEBE (meaning that BDs have, in average, flatter silicates features than TTs). To explain this correlation Kessler-Silacci et al. (2006) postulated that the 10 μm feature probes different regions depending on the central object, with smaller grains at larger distances around more luminous stars (see Sec. 4).

3.2 Crystallinity

Our sample contains sources with strong crystalline silicate features (see e.g. the brown dwarf ISO-ChaII 54, Fig.1, *middle panel*). Spectra with no silicate crystalline features in fact represent a minority (24 out 115, or $\sim$ 21%, Olofsson et al. in prep). Many spectra only show one or two feature(s), mainly the forsterite features at 11.3 and at 33.6 μm. Several other components can also be identified, especially enstatite, but also possibly diopside, magnetite and FeS. Some of those features are very frequent in the spectra, such as the Mg-rich silicate complex at around 23.5 μm (resulting from a blend of enstatite - 23.0 and 24.5 μm - and forsterite - 23.8 μm - features), and the other one around 28μm (forsterite at 27.6 and enstatite at 28.2 μm). These results indicate that crystallization commonly occurs in disks, even around very low-mass stars and BDs.

Crystallization of amorphous silicates via thermal annealing requires that the grains are heated at relatively high temperatures (above 800 K). Those temperatures can only be reached close to the central object (typically 0.1 AU for a TTs, and 0.7 AU for an HAEBE). But several studies of TTs and HAEBE disks showed that crystalline grains are also present at larger radii. Several scenarii can explain this migration. The most favored one is the vertical and radial mixing due to turbulence in the disk. Another possibility was explored by Keller & Gail (2004). They explain that while the surface layers are accreting inward, the midplane is moving outward,

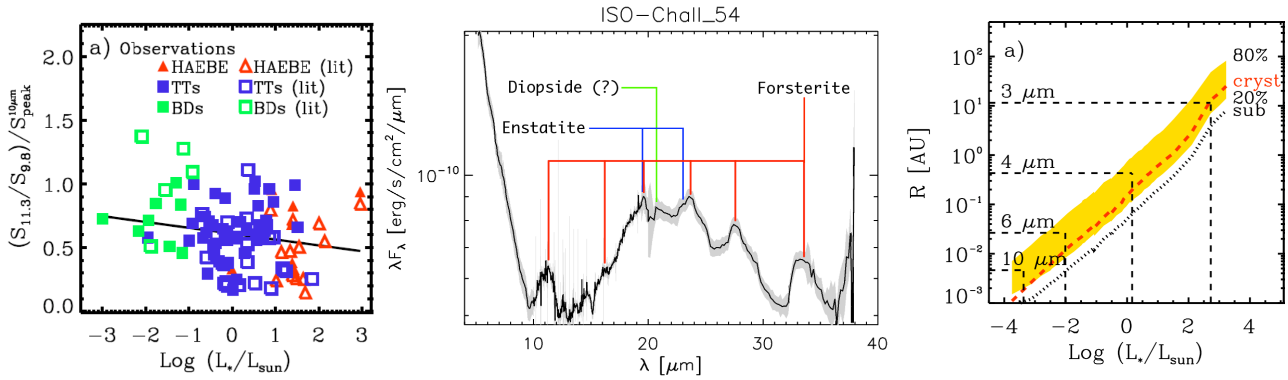

Fig. 1. *Left:* "Grain size" versus stellar luminosity. Peaked silicate features show up toward the right of the plot and flat features show up toward the left. Green squares are brown dwarfs with $M_{\odot} < 75\ M_{Jup}$. Blue squares are low-mass stars with $M_{\odot} > 75\ M_{Jup}$. Red triangles are HAEBE stars. Filled symbols are from the Spitzer c2d sample. Open symbols are from van Boekel et al. (2003); Przygodda et al. (2003); Kessler-Silacci et al. (2005); Apai et al. (2005). *Middle:* IRS spectrum of ISO ChaII 54, in λF_{λ} versus λ, with crystalline forsterite features (dot-dashed lines) at 11.3, 16.2, 19.7, 23.8, 27.6 and 33 μm and crystalline enstatite features (dashed lines) at 19.6 and 23.0 μm. The 20.6 μm feature is attributed to diopside (Olofsson et al. in prep). References for the features are : Koike et al. (2000) ;Molster et al. (2002). *Right:* Radius probed by 10 μm feature as a function of stellar luminosity. The yellow solid region shows the radii contributing 20-80% of the 10 μm emission for flared disks. The black dotted and red dashed lines show the radii corresponding to T = 1500 K and T = 800 K, above which temperature silicates will sublimate and crystallize via annealing, respectively

transporting crystalline silicates at the same time. Finally, winds may also contribute to dust transportation (Shu et al., 1995). Silicate grains, and in particular crystalline silicates, may then enable us to quantify the efficiency of these theories.

But these scenarii can hardly explain the crystallinity fraction found for several objects, such as the bordeline brown dwarf SST-Lup3-1 studied by Merín et al. (2007). They found a crystallinity fraction between 15 and 33%. How can such a low-mass star ($M \sim 0.1 M_{\odot}$, $L \sim 0.081 L_{\odot}$) produce a that large fraction of crystalline grains? The regions where the temperature is warm enough to trigger thermal annealing are greatly reduced. Merín et al. (2007) also found crystalline signatures arising from the 3-5 AU region, indicating that an efficient transport of the grains took place in the disk. Therefore the study of silicate grains raises many questions on accretion disks around low-mass stars.

4 Silicate emission zone

To better understand the correlation between grain size and the stellar luminosity, Kessler-Silacci et al. (2007) modeled disks around stars with a luminosity range from $\sim 10^{-4} - 10^{4} L_{\odot}$, using the CGPLUS 2-layer disk model of Dullemond et al. (2001). The idea was to determine the distance of the 10 μm emission zone (the region that contribute to the 10μm emission) as a function of the stellar luminosity. The model assumes vertical hydrostatic equilibrium, resulting in a flared disk structure. Dust grains present in the optically-thin layer re-radiate half of the stellar luminosity down into the disk and contribute to the temperature regulation. The other half is emitted away from the disk and can be observed as optically thin emission from the disk.

In order to evaluate the 10 μm emission zone, Kessler-Silacci et al. (2007) calculated the radially integrated cumulative flux of the 10 μm emission image. The 10 μm emission zone is then defined as the radial zone where the cumulative flux reaches 20-80% of the total 10 μm emission. The results are presented in the Fig. 1 (*right panel*), showing the location of the 10 μm emission zone as a function of the luminosity of the central object. The relation between the distance and the luminosity is given by $R_{10} = 0.35\ \mathrm{AU}(L_{*}/L_{\odot})^{0.56}$. According to this relation, and since grain size probed by mid-IR spectroscopy is correlated to L_{*}, the IRS observations would provide an observational evidence for a statistical dependence of the grain size on the distance from the star, with the larger grains closer to the star. These results were obtained using the CGPlus two-layer disk model, so only geometrical considerations were studied. Future modelling including more details of grain coagulation, thermal processing and accretion events will be needed to strengthen this study. But the complexity of such modelling is beyond the scope of this poster.

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