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Letter to the Editor

Mid-IR spectroscopy of T Tauri stars in Chamealeon I: Evidence for processed dust at the earliest stages

G. Meeus[1], M. Sterzik[2], J. Bouwman[3], and A. Natta[4,⋆]

[1] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
e-mail: gwendolyn@aip.de
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile
e-mail: msterzik@eso.org
[3] CEA, DSM, DAPNIA, Service d'Astrophysique, CE Saclay, 91191 Gif-sur-Yvette Cedex, France
e-mail: bjeroen@discovery.saclay.cea.fr
[4] Osservatorio Astrofisico di Arcetri, INAF, Largo E. Fermi 5, 50125 Firenze, Italy
e-mail: natta@arcetri.astro.it

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Abstract. We present mid-IR spectroscopy of three T Tauri stars in the young Chamealeon I dark cloud obtained with TIMMI2 on the ESO 3.6 m telescope. In these three stars, the silicate emission band at 9.7 μm is prominent. We model it with a mixture of amorphous olivine grains of different size, crystalline silicates and silica. The fractional mass of these various components change widely from star to star. While the spectrum of CR Cha is dominated by small amorphous silicates, in VW Cha (and in a lesser degree in Glass I), there is clear evidence of a large amount of processed dust in the form of crystalline silicates and large amorphous grains. This is the first time that processed dust has been detetected in very young T Tauri stars (~1 Myr).

Key words. circumstellar matter – stars: pre-main sequence – stars: planetary systems: protoplanetary discs – stars: individual: CR Cha, Glass I, VW Cha – infrared: stars

1. Introduction

Most studies of the dust composition in young stellar objects have concentrated on Herbig Ae/Be stars (HAEBEs), as they are brighter than solar-mass T Tauri stars (TTS). Silicate emission at 10 μm has been detected in several TTS (Cohen & Witteborn 1985; Hanner et al. 1998), but the signal-to-noise of those observations was too low for an investigation of the properties of the emitting silicates. More recently, Natta et al. (2000) have obtained low-resolution mid-infrared spectra of 9 TTS in Chamealeon, using PHOT-S on board of ISO. All 9 stars showed silicate emission at 10 μm, interpreted as due to a mixture of amorphous silicates of radius $\lesssim$1 μm on the surface of circumstellar discs. In some cases, there was a hint that a crystalline silicate component could be present, but the poor quality of most spectra and their limited coverage of the red side of the feature ($\lambda < 11.7$ μm) prevented any detailed analysis.

Claims of the possible presence of a crystalline silicate component at 11.3 μm have been made for some old TTS (see, for example, Weinberger et al. 2002). However, the first clear evidence of crystalline materials in a low-mass object has been obtained only this year for the 10 Myr-old TTS Hen3-600A by Honda et al. (2003) using the 8.2 m SUBARU telescope.

We are interested in extending the analysis of the silicate content of discs to a large sample of TTS, possibly younger than Hen3-600A. In this letter, we present mid-IR spectra of three TTS in the young Chamealeon I cloud, already observed by Natta et al. (2000). We show that the profiles are different in the three objects with a varying ratio of amorphous versus crystalline materials. In one star (VW Cha) the ratio of crystalline to amorphous silicates is about 20%, comparable to the values in the most evolved HAEBE stars and in solar system comets.

2. Observations and data reduction

We used TIMMI2 at the ESO 3.6 m telescope to obtain *N*-band spectra of Glass I, CR Cha (also known as LkHα 332-20) and VW Cha during the nights 16–18/5/2003. These are three well-studied TTS with similar spectral types, all lying in the Chamealeon I dark cloud. In Table 1, we list the parameters of our sample stars (from Natta et al. 2000). The mid-infrared spectra were obtained with standard chopping/nodding techniques along the slit with a respective throw of 10 arcsec. On source integration times were 1920 s for Glass I, 2640 s for CR Cha, and a total of 7200 s for

Send offprint requests to: G. Meeus, e-mail: gwendolyn@aip.de

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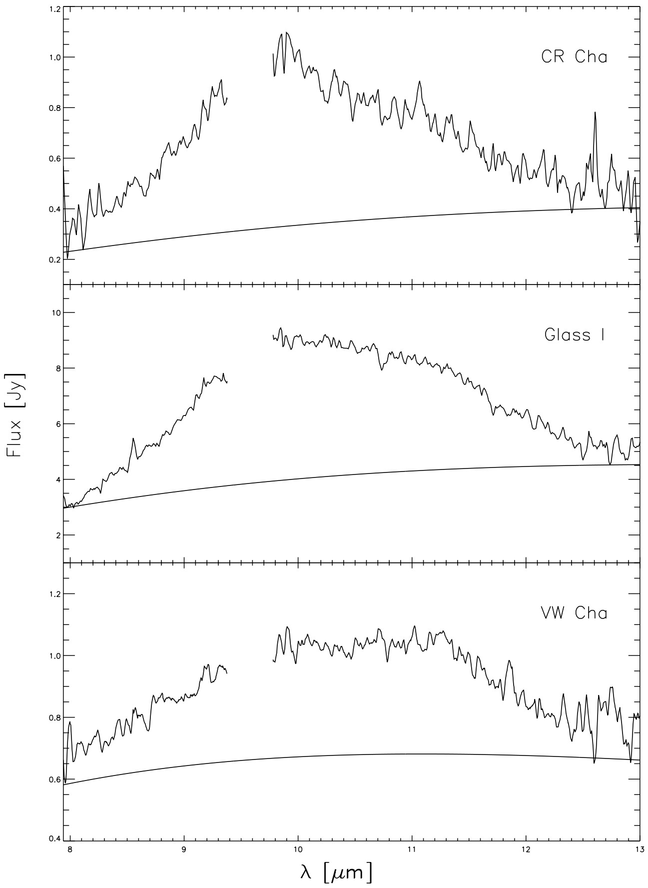

Fig. 1. Observed TIMMI2 spectra of the three TTS, with a black body fit, representing the continuum.

VW Cha. All observations were performed at airmasses below 2, typically around 1.6. In both nights, HD 133774 (K5III, N1 = 14.11), HD 169916 (K1IIIb, N1 = 38.71), and HD 175775 (G8/K0II-III, N1 = 24.04) served as both telluric and flux standard stars and were observed at similar airmasses as the science targets. These standards are primary ISO calibration standard stars, and are described in detail at `http://www.ls.eso.org/lasilla/Telescopes/360cat/timmi/html/stand.html`. The SED models used are according to Cohen (1998). The atmospheric ozone feature at 9.54 μm was used for wavelength calibration. The cross-calibration of the telluric standards among each other shows a smooth and reliable removal of the atmospheric bands, without introducing additional artifacts in the useful wavelength regime of 8–13 μm. Spectrophotometric calibration was achieved by observing each target in the N1 filter (central wavelength $\approx 8.6\,\mu$m), and normalising the integrated flux in the corresponding spectral passband to the observed value. We measured fluxes of 4.6 ± 0.4 Jy for Glass I, 0.5 ± 0.2 Jy for CR Cha and 0.8 ± 0.15 Jy for VW Cha.

The spectra are shown in Fig. 1. The profile of Glass I, the only star for which the ISO data have high quality, is very similar to that of Natta et al. (2000).

Table 1. Stellar parameters from Natta et al. (2000), apart from the age of VW Cha, which is discussed in the text.

Object	Spectral type	$T_{\rm eff}$ (K)	L_* ($L_\odot$)	M_* ($M_\odot$)	Age (Myr)
CR Cha	K2	4900	3.3	1.2	1.0
Glass I	K4	4600	1.6	0.9	1.0
VW Cha	K5/K7	4350	2.9	0.6	$1.0^{+1}_{-0.6}$

3. Observed sources

A summary of the properties of the three observed stars is given in Table 1. Unless otherwise stated, they are taken from Natta et al. (2000).

CR Cha is a CTTS, for which no companions have been discovered (Takami et al. 2003).

Glass I is a binary (separation 2.″8); the primary is a K4 WTTS (Chelli et al. 1988), the secondary an IR G-type object (Covino et al. 1997). Stanke & Zinnecker (2000) attribute the 10 μm emission to the secondary. Since the secondary is not visible in the optical, the age is estimated from the optical properties of the primary, assuming that they are coeval.

VW Cha is a 0.″7 binary, with both members being CTTS; the IR emission is attributed to the primary. Using adaptive optics, Brandeker et al. (2001) discovered a companion to the secondary at a separation of 0.″1. The age uncertainty for this object derives primarily in the uncertainty of the extinction towards VW Cha: Brandner & Zinnecker (1997) give $A_V \sim 1.3$ while Brandeker et al. (2001) state 3.0; the larger the adopted extinction, the younger the derived age of the object. Most likely, the age of the system lies between 2 and 0.4 Myr, values derived by these authors.

4. Modelling and results

To determine the composition of the circumstellar (CS) dust in our TTS, we have adopted the procedure successfully used in interpreting the ISO spectra of HAeBe stars by Bouwman et al. (2001). We first fitted a black body to the continuum, as shown in Fig. 1. The determination of the continuum is difficult due to a lack of reliable measurements outside of the feature, and we estimate that it could be higher by 10% for VW Cha, the most difficult case. This continuum uncertainty, however, has only a negligible effect on the results discussed in the following. We fitted the continuum-subtracted spectra with a linear combination of several dust species, namely:

1. amorphous olivine ($[Mg,Fe]_2SiO_4$) with a size of 0.1 and 2.0 μm, representing small and large grains,
2. crystalline silicates: magnesium forsterite (Mg_2SiO_4) and pure magnesium enstatite ($MgSiO_3$),
3. silica (SiO_2).

These species are commonly found in the dust discs of Herbig Ae/Be systems. Details of the procedure and references to the adopted cross sections can be found in Bouwman et al. (2001).

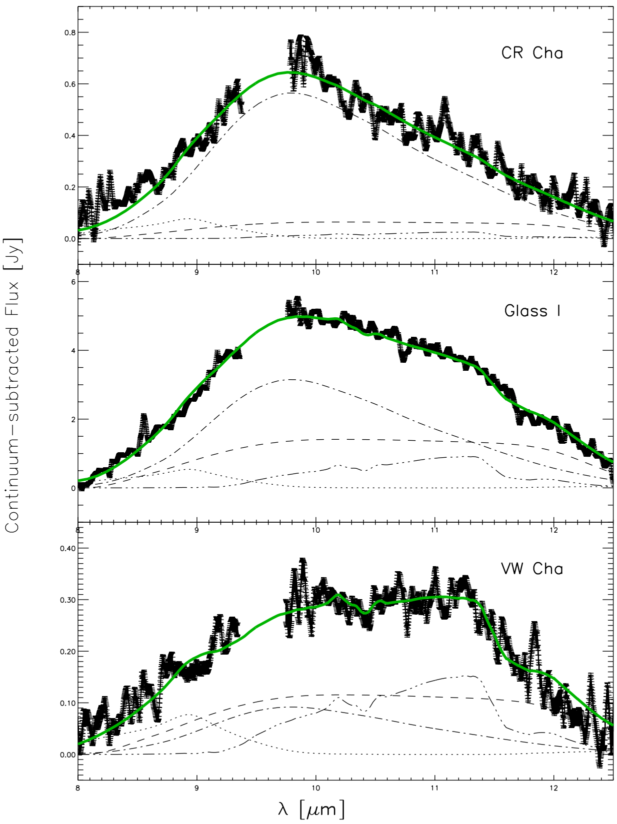

Fig. 2. Fit to the continuum-subtracted spectra, with each separate component shown. We also show the formal error on the data, which has been determined from the background. The true errors are likely to be larger as the division by the standard star might produce artefacts from telluric features. Light grey: sum of all components, dash dot: small ($a = 0.1\,\mu$m) amorphous silicate, dashed: large ($a = 2.0\,\mu$m) amorphous silicate, dotted: silica; and dash triple dot: forsterite.

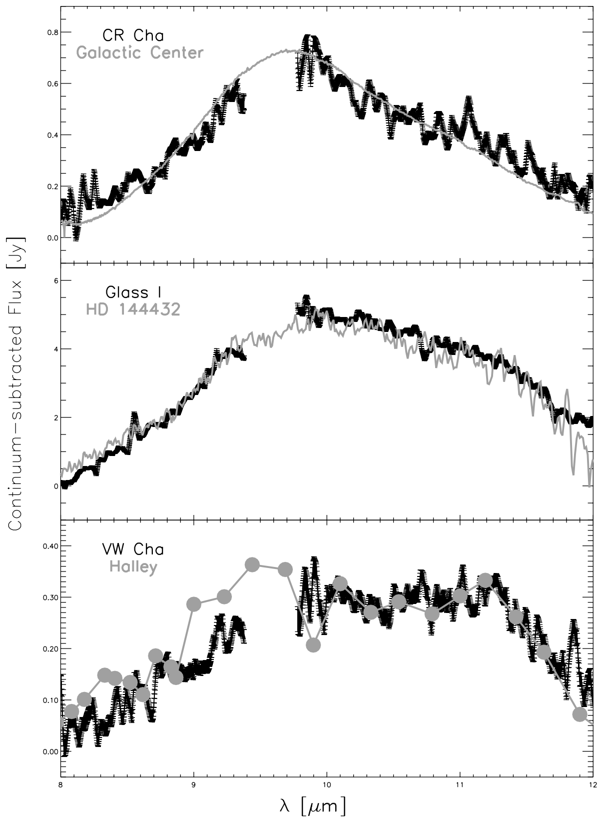

Fig. 3. Comparison of the Cha TTS spectra with that of different objects. *Top*: CR Cha with ISM silicate bands (inverted absorption band profile towards Sgr A*), which are dominated by amorphous silicates (at least 99%, Kemper et al., in prep.), *Middle*: Glass I with the HAe star HD 144432, *Bottom*: VW Cha with comet Halley (data from Bregman et al. 1987), which is a source of highly processed dust (Bouwman et al. 2001). Halley's data point at 9.9 μm has a problematic ozone subtraction, according to the authors. The sequence shows an increasing amount of processed dust.

Table 2. Temperature of the black body (BB) representing the continuum and mass ratios: large to small amorphous silicates ($m_{2.0}/m_{0.1}$), crystalline to amorphous silicates ($m_{\rm forst}/m_{\rm sil}$) and silica to silicates ($m_{\rm SiO_2}/m_{\rm sil}$).

Object	BB	$m_{2.0}/m_{0.1}$	$m_{\rm forst}/m_{\rm sil}$	$m_{\rm SiO_2}/m_{\rm sil}$
CR Cha	350 K	0.23	0.02	0.04
Glass I	380 K	0.92	0.08	0.03
VW Cha	460 K	2.57	0.19	0.07

We did not include Polycyclic Aromatic Hydrocarbons (PAHs), since the PHOT-S spectra did not detect any feature between 6 and 8 μm, where the signal-to-noise was quite good (Natta et al. 2000).

Figure 2 shows the fits to the 10 μm spectra together with the separate contributions of each dust component; the derived mass ratios of the different species are listed in Table 2. In our final fit, we did not include enstatite, as it did not improve the fitting result. It is immediately clear that different species contribute in different amounts to the overall shapes. The values of these ratios vary significantly from one star to the other. In particular, VW Cha has the largest fraction of large to small amorphous silicate grains – 11 times that of CR Cha and 3 times that of Glass I, and the largest amount of crystalline silicates and silica – a factor 10 and 2 more for crystalline silicates and a factor 4 and 2 more for silica than CR Cha and Glass I, respectively. In contrast, the spectrum of CR Cha is dominated by small amorphous silicate grains. Glass I is intermediate between the two. Natta et al. (2000) already noticed excess emission in their Phot-S spectrum of Glass I at 8.5 and 11.3 μm and attributed this tentatively to silica and crystalline silicates. Our higher-quality spectrum of Glass I confirms this suggestion.

5. Discussion

We compared our TTS spectra with objects of different evolutionary status: the ISM, a sample of 14 HAEBEs studied by Meeus et al. (2001) and a few solar system comets. We found a good similarity between some objects and our TTS, as is shown in Fig. 3. These comparison objects were modelled by Bouwman et al. (2001) who showed that they cover a broad range in the amount of processed dust, going from practically amorphous (the ISM) to highly processed (comet Halley).

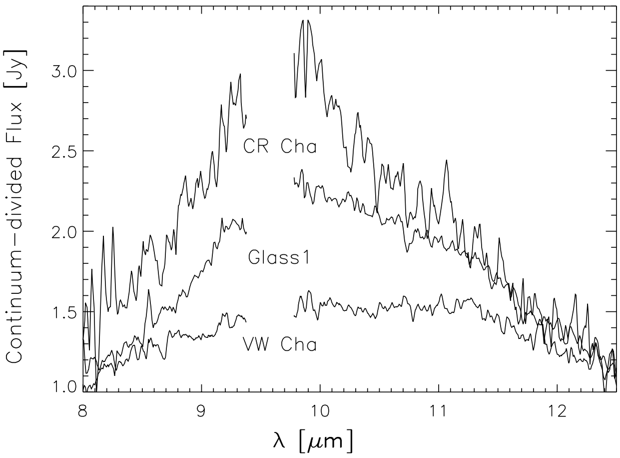

Fig. 4. Continuum-divided spectra of the 3 objects. VW Cha clearly has the weakest feature, CR Cha the strongest.

Even more interestingly, we find trends in our small sample of TTS similar to those that have already been identified in HAEBEs. The first of such trends is an *anti-correlation between silicate grain size and strength of the band*, interpreted as a dust evolutionary process (van Boekel et al. 2003). Figure 4 shows that this is also the case for the three TTS. VW Cha has the weakest feature and the smallest mass fraction of small silicate grains. CR Cha, on the other hand, has the strongest feature and the largest mass fraction of small grains.

In a study of the 10 μm feature, Bouwman et al. (2001) derived a *correlation between the amount of silica and that of forsterite*, and suggested a common origin in the process of thermal annealing. This process is responsible for the conversion of amorphous silicates into crystalline silicates, with silica as a by-product. We find a similar correlation in our data, as VW Cha has both the largest amount of silica and of crystalline forsterite. The ubiquity of the correlation is interesting, also in view of the well-known difficulty with the thermal annealing hypothesis, since the observed crystalline dust appears to be colder than the minimum temperature required for such a process to be efficient. Laboratory experiments suggest a temperature of 1000 K to anneal amorphous silicates into crystalline on a time-scale of a month, while a slightly lower temperature (875 K) would require more than 30 Myr (Hallenbeck et al. 2000). This means that the dust, once crystallised, should be somehow transported to colder, more outward disc regions. Radial mixing by diffuse transport in CS discs has been proposed as a way to do it (Wehrstedt & Gail 2002).

We find no conclusive evidence for the presence of enstatite in our TTS spectra, apparently contradictory to the results of Honda et al. (2003) who found evidence for a substantial mass fraction of enstatite dust in the Hen3-600A system. However, among HAEBEs the presence of enstatite seems to be rare as well, as only one out of 14 studied objects (HD 179218) showed evidence for this dust species (Bouwman et al. 2001). This is probably due to its formation process: annealing experiments of silicate smokes (e.g. Rietmeijer 1988; Hallenbeck et al. 2000) show that the initially formed forsterite and silica can produce enstatite only on a considerably longer time scale. Only around objects which are much more luminous, such as evolved stars or HD 179218, or considerably older, such as Hen3-600A, the time-temperature conditions would be right to readily form large amounts of enstatite.

Our results indicate clearly that dust evolves in TTS in ways very similar to those observed in HAEBE stars. The evolution does not seem to depend on the luminosity, temperature or mass of the central star. It is also difficult to reconcile our data with the idea that "age" is the only dominant factor. Our observations clearly show that the dusty disc of VW Cha is host of a lot of warm processed dust. CR Cha, in contrast, has a similar age and spectral type but a lot of unprocessed dust. All our three stars are about ten times younger than Hen3-600A, the only other TTS where crystalline dust was firmly detected.

Interestingly, we note that VW Cha is a close binary system, in which the secondary is also a binary. The disc is circumprimary and is probably tidally truncated by the secondary binary, as it is not detected at longer ($\lambda \sim 60$ μm) wavelengths (Brandeker et al. 2001). Glass I, which has intermediate properties, is also a binary, but with a larger separation than VW Cha. *It is possible that interaction with close companions may speed up dust evolution* as it induces vertical mixing, stirring up the dust from the midplane. This causes a (continuous) replenishment of unprocessed dust into the disc atmosphere where dust processing in the form of thermal annealing is expected to take place. Also, we would observe IR emission from larger grains as grain growth occurs faster in denser regions, such as the midplane. That dust processing in close binaries would occur faster is for the moment just speculation, since a much larger sample of stars is obviously required in order to investigate its viability.

6. Conclusions

The 10 μm emission feature is clearly detected in three young TTS in Chamealeon I. The dust composition, obtained by fitting the shape of the feature with a mixture of materials, derived from detailed studies of HAEBE stars, differs significantly in the three stars. In particular, the spectrum of CR Cha is dominated by small, amorphous silicates. The spectrum of VW Cha shows evidence of highly processed dust, as shown by the high mass fraction of large amorphous silicates and of crystalline ones. Glass I seems to be intermediate between the two other stars.

This trend, as well as the correlation between the relative amount of small grains and the intensity of the feature and that between the amount of silica and forsterite, are also found in HAEBE stars. Also, as in HAEBE stars, dust evolution does not seem to be uniquely controlled by the stellar age. Our Chamaeleon sample consists of three stars of practically the same spectral type and age and widely different dust. Looking for possible clues to this unknown "trigger" of dust evolution, we noticed a correlation in our stars between dust processing and the presence of close companions. Although a sample of three stars is by far too small to provide any evidence, we suggest that this possibility should be explored further.

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