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Mid-IR observations of circumstellar disks*

II. Vega-type stars and a post-main sequence object

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Abstract. We present spectral energy distributions and new *N*-band photometry and spectroscopy for a sample of six main sequence stars and one post-MS object using the ESO TIMMI2 camera at La Silla observatory (Chile). All objects are thought to possess circumstellar material and for the majority of the targets this is their first *N*-band spectroscopic observation. The emission spectra (observed in three cases), modelled with a mixture of silicates consisting of different grain sizes and composition, confirm the suspected presence of disks around these targets. The most important discovery is that HD 113766, a young Vega-type star, is host to highly processed dust which is probably second generation. It is the first time a Vega-type star with such highly evolved dust has been observed. Silicate emission of basically unevolved dust is seen in case of the post-MS object HD 41511 and the Vega-type star HD 172555. In addition, to study the cold dust, we observed a subsample at 1200 μm with the bolometer array SIMBA at the SEST in La Silla but we only got upper limits for those five objects. This shows that these Vega-type stars have a smaller amount of dust than their precursors, the T Tauri and Herbig Ae/Be stars.

Key words. stars: circumstellar matter – stars: planetary systems: protoplanetary disks – infrared: stars – techniques: spectroscopic – submillimeter

1. Introduction

Circumstellar (CS) disks are a by-product of the star-formation process and are expected and observed to gradually disappear. The disk evolution is witnessed in the spectral energy distribution by a transition from a dust-dominated to a star-dominated appearance. In the pre-main sequence phase, when the stars are optically visible, the presence of these disks causes an excess that stretches from the near-IR to the millimeter (mm) regime. In a following stage, the near-IR excess disappears first, which is often attributed to clearing of the inner disk, thus creating a gap around the central star (e.g. Malfait et al. 1998a).

As these disks further evolve, their gas content diminishes and the dust is also gradually removed. Observations have shown that by an age of roughly 15 Myr most of the disk mass has disappeared, as searches for molecular gas around older objects result in non-detections (e.g. Greaves et al. 2000; Zuckerman et al. 1995). From the theoretical point of view, numerical simulations for the formation of giant planets by Pollack et al. (1996) predict that these are formed during the first 10 to 16 million years. Thus, formation of gas giants – if taking place – must be completed by that time, as after the gas dispersal not enough material will be left to still form them. It is thus important to study those transition systems where the disk is evolving but which still have enough material to form planets. These objects have an age of roughly 10 to 20 Myr.

It was a surprising discovery of IRAS (Aumann et al. 1984) that several much older main sequence stars, such as Vega (350 Myr), still possess a far-IR excess. These objects are now classified as Vega-type and their infrared excess is attributed to the thermal re-emission of dust particles at a temperature between 50 and 125 K (Backman & Paresce 1993; Laureijs et al. 2002).

Once the gas is cleared out in a protoplanetary disk, which may occur at timescales as short as 10 Myr, the dust is not coupled anymore and smaller particles will be removed through various processes (e.g. Poynting-Robertson drag, particle collision, radiation pressure; see Backman & Paresce 1993, for an overview). The grain removal timescales are shortest in the inner regions of the disk and may be as short as a few 10^5 yr for an A0 type star. If dust is still observed to be present, it must be replenished, as otherwise the inner boundaries would rapidly move outwards. An important source of dust replenishment is thought to be the collision of planetesimal-sized bodies within the CS disk (Backman & Paresce 1993). As these reservoirs become smaller and the age of the sources increases, it is

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Table 1. Stellar parameters and known fluxes of our target sample. V-band magnitudes and the IRAS 12 μm fluxes are taken from the SIMBAD database. $T_{\rm adopted}$ and $(\log g)_{\rm adopted}$ list the temperature and surface acceleration which we used for the Kurucz atmosphere models. The mm-flux of HD 41511 was measured in Jura et al. (2001). Stellar ages: (1) Zuckerman & Song (2004) quote 300 Myr with a caveat (methods used: X-ray emission and lithium age); Decin et al. (2000) give 3500 Myr as an upper range (isochrones); (2) Song et al. (2001, evolutionary tracks); (3) Song et al. (2001, evolutionary tracks); (4) Meyer et al. (2001, estimation from evolutionary tracks); (5) Zuckerman & Song (2004); (6) Lachaume et al. (1999, isochrones and Ca lines). The distances are taken from (7) Decin et al. (2000); (8) Chen & Jura (2001); (9) Fekel et al. (2002); (10) Jura et al. (2001); (11) Meyer et al. (2001); (12) Zuckerman et al. (2001); (13) Jourdain de Muizon et al. (1999).

Object	Class	Spectral type	$T_{\rm adopted}$ [K]	$(\log g)_{\rm adopted}$	V [mag]	$F_{12\,\mu{\rm m}}$ [Jy]	$F_{1350\,\mu{\rm m}}$ [mJy]	Age [Myr]	Ref.	d [pc]	Ref.
HD 10647	Vega-type	F8 V	6000	4.5	5.52	0.82	–	300–3500	(1)	17.4	(7)
HD 38678	Vega-type	A2 Vann	9000	4.5	3.55	2.18	–	231	(2)	21.5	(8)
HD 40932	MS	A5 / F5 V	7500	4.5	4.13	–	–	693	(3)	47.5	(9)
HD 41511	post-MS	Apsh	9000	4.5	4.97	143.5	25.4 ± 2.4	–	–	330	(10)
HD 113766	Vega-type	F3 / F5 V	6750	4.5	7.56	1.59	–	10–20	(4)	130	(11)
HD 172555	Vega-type	A5 IV-V	7500	4.5	4.78	1.47	–	12	(5)	29.2	(12)
HD 207129	Vega-type	G0 V	6000	4.5	5.58	0.81	–	6000	(6)	15.6	(13)

expected that the inner boundary of the disk moves outwards, resulting observationally in a gradual disappearance of first the mid-IR and later also the far-IR excess until the excess becomes undetectable. Habing et al. (2001) have investigated the incidence and survival of remnant disks around main-sequence (MS) stars from observations with ISOPHOT and found that at least 15% of the nearby field stars of spectral type A to K have CS dust. Greaves & Wyatt (2003) find a much higher detection rate of debris towards MS A-type than to G-type stars, even within a similar age-bin. The time dependency of Vega-like excesses was further studied by Decin et al. (2003) who reviewed previous results from other authors and cannot confirm a global power law for the amount of dust seen in debris disks as a function of time. About the properties – composition and size distribution – of the warm dust encircling Vega-type objects, little is known so far. Some N-band spectra of Vega-like stars were shown by Sylvester et al. (1996) and Sylvester & Mannings (2000), however, most of the objects in their sample were Herbig Ae/Be stars which are close to the zero-age main sequence.

In Schütz et al. (2005, hereafter referred to as Paper I) we have analysed the mid-IR emission of eight pre-main sequence stars (two T Tauri, two Herbig Ae/Be stars and four FU Ori type objects). Here we present a search and analysis of CS matter for a sample of Vega-type stars and disk candidate objects. Our final goal is to prove the existence of CS matter and to get insight into the dust composition from modelling the N-band silicate emission features – where present. In Sect. 2 we introduce our targets and describe in Sect. 3 the observations and data reduction. The spectral energy distributions (SED) are discussed in Sect. 4, while the spectra are analysed in Sect. 5. We derive upper limits for dust masses in Sect. 6.

2. Observed sources

Most objects in our sample are classified as disk candidates in the literature and show excess emission towards longer wavelengths. With one exception, HD 41511 – a post-main sequence star with dust outflow, all sources are main sequence stars. A summary of our targets and their stellar parameters together with known IRAS and mm fluxes is given in Table 1. We note that for many of our sources this is their first observation in the mid-IR, apart from IRAS, and give references in those cases where further mid-IR data have been published.

- **HD 10647** (alias q_1 Eri) is a Vega-type source with 60 μm excess detected from ISOPHOT data (Decin et al. 2000). A planet (2.10 AU semi-major half axis, $M = 0.91\ M_{\rm Jup}$) was recently discovered (Mayor 2003).
- **HD 38678** (alias ζ Lep) shows excess emission around 25 μm (Laureijs et al. 2002) and 60 μm (Habing et al. 2001) measured with ISOPHOT. Based on photometry and a marginally resolved emission at 17.9 μm, obtained with the Keck I telescope, Chen & Jura (2001) conclude that the dust may reside within 6 AU distance to the star and is likely being replenished by collisions of larger bodies.
- **HD 40932** (alias μ Ori) is a spectroscopic quadruple system whose members might still possess a remnant debris disk. The amount of IR-excess is controversial. Since the object was mentioned in a list of IR excess stars by Oudmaijer et al. (1992), its Vega-type status is a matter of speculation, although Oudmaijer et al. (1992) had clarified that the IRAS fluxes given for this source were upper limits. No IRAS measurements are displayed in SIMBAD.
- The binary system **HD 41511** (alias SS Lep) consists of an A-type star with an M-type companion. For many years the primary was considered a Herbig Ae/Be (HAeBe) candidate, while now both components appear to lie beyond the main sequence (e.g. Jura et al. 2001). Based on an analysis of the sub-mm to mm SED, Jura et al. (2001) suggest that the stellar outflow forms a circumbinary disk in which larger grains are formed by coagulation. Indications of a possible 10 μm emission feature seen in IRAS low-resolution spectra is discussed by Fajardo-Acosta & Knacke (1995).
- Mannings & Barlow (1998) confirmed **HD 113766** as a Vega-like source. The unresolved excess flux was found to originate from the primary star of this binary system (Meyer et al. 2001) with a separation of $1\farcs335$ (Fabricius & Makarov 2000). Hints of spectral features can be seen in

Table 2. Results from TIMMI2 photometry and spectroscopy as well as SIMBA observations are merged in this table. The airmass and TIMMI2 integration time refer to *N*-band spectroscopy. Mid-IR photometry was obtained in the N11.9 passband (λ_0 = 11.6 μm). Errors represent the accuracy of this aperture photometry and do not necessarily include the uncertainty which measurements on different nights may introduce due to atmospheric fluctuations (errors caused by the latter one might amount up to 10% for the *fainter* sources).

Object	Airmass (*N*-spec)	t_{int} (*N*-spec) [min]	$F_{N11.9}$ [Jy]	t_{int} (1200 μm) [min]	$F_{1200\,\mu m}$ [mJy]	*N*-spec features
HD 10647	1.1	31	0.55 ± 0.03	248	<17	stellar (excess > 25 μm)
HD 38678	1.4	37	1.62 ± 0.04	–	–	stellar (excess > 18 μm)
HD 40932	1.3	31	1.05 ± 0.02	45	<24	stellar
HD 41511	1.1	4	117.0 ± 0.1	–	–	Silicate emission
HD 113766	1.6	25	2.12 ± 0.02	83	<18	Silicate emission
HD 172555	1.3–1.4	40	1.20 ± 0.04	83	<26	Silicate emission
HD 207129	1.1	37	0.70 ± 0.05	178	<15	stellar (excess > 20 μm)

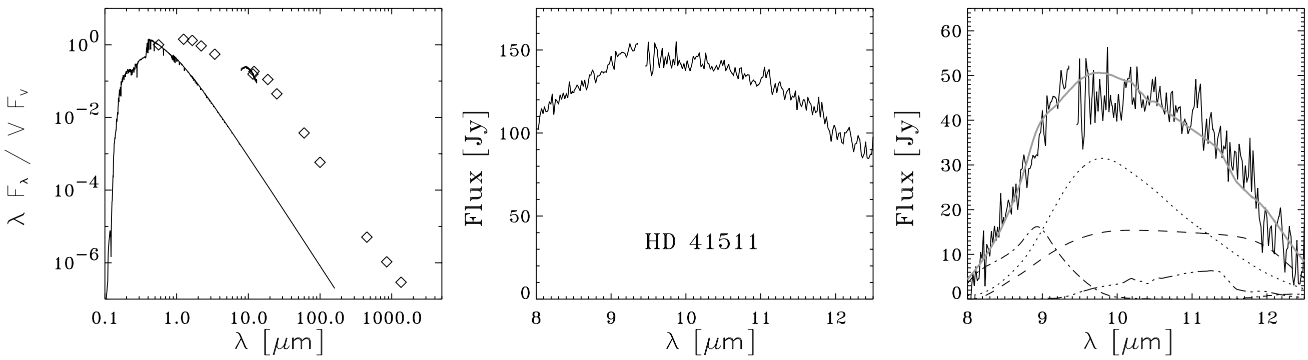

Fig. 1. *Left panel*: spectral energy distribution for the post-MS star HD 41511. *Mid panel*: the corresponding TIMMI2 *N*-band spectrum. *Right panel*: decomposition of the dust emission. The different linestyles represent small amorphous olivine (*dotted*), large amorphous olivine (*dashed*), silica (SiO_2, *dash-dotted*) and crystalline forsterite (*dash-three dots*).

(unpublished) ISOPHOT data, obtained from the ISO Data Archive[1].

- **HD 172555** was identified as Vega-type by Mannings & Barlow (1998) by cross-correlating the Michigan Catalog of Two-dimensional Spectral Types for the HD Stars with the IRAS Faint Source Survey Catalog.
- **HD 207129** is surrounded by a cold, ring-like debris disk, as concluded from ISO photometry by Jourdain de Muizon et al. (1999). In contrast to the independent methods by which Lachaume et al. (1999) derived a solar-like age, Zuckerman & Webb (2000) estimate an age of only 40 Myrs, relying on space motion and location in space. This object demonstrates that for some sources the age determination done with different methods is not always consistent.

3. Observation and data reduction

The mid-IR observations were carried out during runs in December 2002 and September 2003 with the ESO TIMMI2 camera[2] at La Silla observatory. In Paper I we describe the observations and data reduction in detail.

For those targets in our sample which have never been studied longward of the infrared, additional observations were obtained in November 2002 and July 2003 with the 37-channel bolometer array SIMBA at the SEST in La Silla. We used the fast scanning mode at 250 GHz (λ = 1200 μm). Corresponding integration times are listed in Table 2. The data reduction with MOPSI[3] includes despiking, baseline fitting, suppression of the correlated sky noise, opacity and gain-elevation correction as well as co-adding the single maps to a final one (cf. the Appendix in Chini et al. 2003 for a short introduction to MOPSI). Uranus was used as flux calibrator.

4. Spectral energy distributions

We used the TIMMI2 and SIMBA photometry in Table 2 to construct a spectral energy distribution (SED) for the targets, together with additional fluxes from the literature in the passbands UBVRI, JHK (2MASS), 12, 25, 60 and 100 μm (IRAS) as well as ISOPHOT data – when available. For HD 41511 (sub-)mm data already existed. In Figs. 1 and 2 the resulting optical to mm spectral energy distributions are displayed, with an indication of the TIMMI2 *N*-band spectra to show their agreement with the photometry. To emphasise the non-stellar contribution to the SED, we plotted a Kurucz atmosphere model

[1] `http://www.iso.vilspa.esa.es/ida/`

[2] `http://www.ls.eso.org/lasilla/sciops/3p6/timmi/`

[3] MOPSI has been developed and is maintained by R. Zylka, IRAM, Grenoble, France.

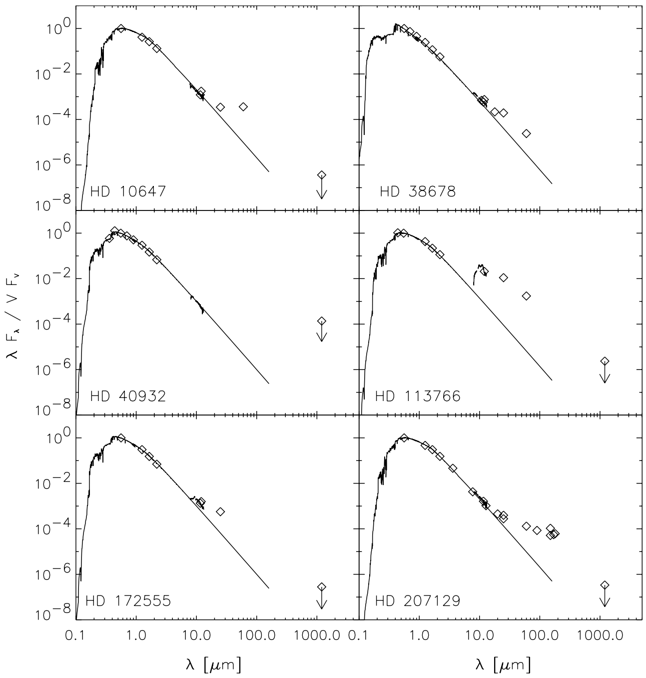

Fig. 2. Spectral energy distributions for our Vega-type sources. A Kurucz model is overplotted to represent the stellar contribution to the SED. The mm-fluxes are upper limits, as indicated by the arrow.

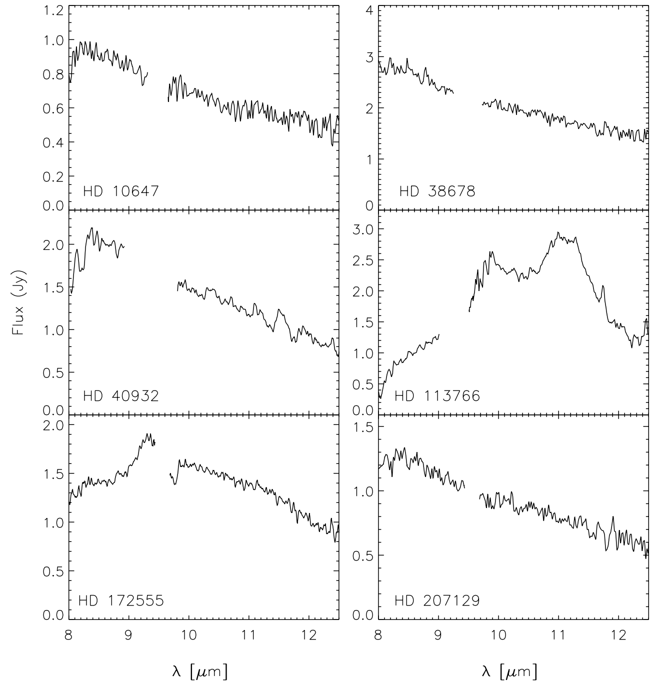

Fig. 3. TIMMI2 spectra of the Vega-type stars. For some objects the data between approximately 9.0 and 9.7 μm is taken out, as there was a detector problem in the 2002 run. Smaller gaps between about 9.4 and 9.7 μm occur where we cut out uncorrectable atmospheric ozone features.

(Kurucz 1994) with the stellar parameters in Table 1. We applied no reddening correction for the Vega-type sources as their relatively cold CS material is unlikely to cause a significant extinction – also reflected in their observed $[B-V]$. For HD 41511, however, we reddened the Kurucz model with an $A_{\rm V}$ = 0.8 mag (Malfait et al. 1998a).

The SED of the quadruple system HD 40932 can be entirely explained by stellar emission (its given photometry includes all four components). For HD 10647, HD 38678, HD 172555 and HD 207129 a moderate excess emission begins longward of 8 μm or even further. HD 113766 shows substantial excess starting around 8 μm, but none in the near-IR. This can be explained by the absence of hot CS material located close to the star, suggesting that an inner hole in the disk was created.

The post-main sequence object HD 41511 has the largest excess in the sample, ranging from the J-band to the mm region, that has been attributed to a circumbinary disk (Jura et al. 2001). Its SED shows resemblance to that of the binary post-AGB star HR 4049. Dominik & Dullemond (2003) proposed a model for HR 4049, in which a massive circumbinary disk is highly optically thick and possesses a very hot inner disk rim that causes the near-IR excess. Since – unlike HR 4049 – we also see 10 μm emission, an optically thin layer surrounding the optically thick disk is further required, in which warm silicate grains reside and re-radiate the absorbed UV and optical photons.

5. Mid-IR features

In Figs. 1 and 3 we show the N-band spectra for all targets. To quantify the differences between these sources and to determine the composition of CS dust, we adopt the same procedure as described in Sect. 4 of Paper I which is briefly summarised in the following. For further details we refer to Paper I.

When stars are formed out of their parental cloud, the material in their disks is assumed to have a similar composition as in the interstellar medium, in which amorphous silicates are the main component observed at 10 μm (Kemper et al. 2004). Changes in the composition and size are expected to occur during the subsequent evolution of the star+disk system, eventually leading to a planetary system. Laboratory experiments have shown that, due to thermal annealing, amorphous silicates gradually turn into crystalline forsterite and silica (e.g. Rietmeijer 1989; Hallenbeck & Nuth 1997). Bouwman et al. (2001) found a correlation between the amount of forsterite and silica in the disks of Herbig Ae/Be (HAeBe) stars, showing that thermal annealing indeed takes place in these objects. A similar correlation was also found for the lower-mass T Tauri stars (Meeus et al. 2003). These authors also concluded that dust around HAeBe stars and T Tauri stars has very similar characteristics. Therefore, we modelled our current sample of Vega-type stars with the same dust species as those found in young stellar objects, as their evolutionary predecessors are most probably Herbig and T Tauri stars. All the above-mentioned dust species emit in the N band, making this an excellent window to study dust evolution in the inner parts of the circumstellar (CS) disk.

To determine the composition of the CS dust, we first determine and subtract a local continuum to our TIMMI2 spectra by fitting a blackbody to the 8–13 μm region. Subsequently, we model the continuum-subtracted spectra with a linear combination of emission features from the following dust species,

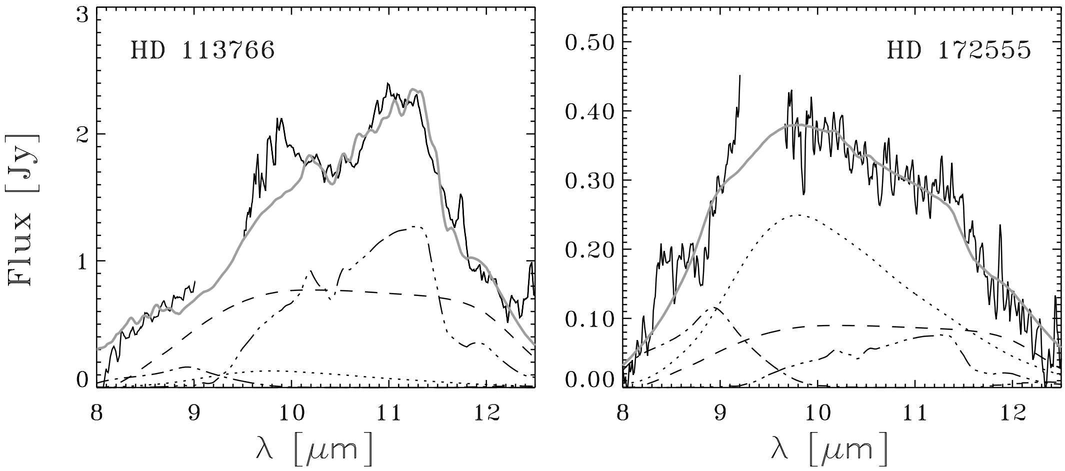

Fig. 4. *Left panel*: decomposition into dust components for HD 113766. *Right panel*: similar analysis for HD 172555. The different linestyles represent small amorphous olivine (*dotted*), large amorphous olivine (*dashed*), silica (SiO_2, *dash-dotted*) and crystalline forsterite (*dash-three dots*).

which are commonly found in disks of pre-main sequence stars:

- Amorphous olivine ($[Mg,Fe]_2SiO_4$) with grain sizes of 0.1 and 2.0 μm, to which we will refer to as "small" and "large" silicate grains.
- Crystalline silicates: magnesium forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$). The latter one, however, was not found in this target sample as it is a rare find even in young sources (cf. Paper I).
- Silica (SiO_2).

We applied the absorption coefficients from Bouwman et al. (2001). PAHs were not included in the fit, as we did not detect any PAH features in our spectra. Modelling results for the emission spectra, together with the separate contribution of each dust component are shown in Figs. 1 and 4. When deriving in what amounts the different dust species are present, the linear coefficients of the fit – which are proportional to the radiating surface of the grains – need to be converted to mass. However, it is not possible to determine the absolute amount of mass for each species present, as we have no spatially resolved data to derive the particles' size, density or temperature distribution as a function of radius within the disk. Therefore, we derived mass ratios of the different species under the assumption that (1) the particles are spherical and (2) the particles have the same density. The mass ratios are meaningful to compare the objects in our sample and to establish the amount of processed dust we observe at 10 μm. In Table 3 we list the derived mass ratios. Apart from $m_{2.0}/m_{0.1}$, which gives the mass ratio between large and small amorphous grains, the mass ratios always compare the mass of a particular species (forsterite or SiO_2) with the total mass in amorphous silicates (both small and large). Please note that for a given mass, small particles have a larger total emitting surface than large ones. Inversely, a similar amount of observed radiation will result in a much smaller mass when caused by small grains than if it was caused by larger grains. It is also important to point out that our results are only valid for the warm dust, which is located in the inner part of the disk ($r < 10$ AU) and radiates in the 10 μm region.

Table 3. Mass ratios derived from the model fits to the *N*-band spectra: large to small amorphous olivine ($m_{2.0}/m_{0.1}$), crystalline to amorphous silicates ($m_{\rm forst}/m_{\rm sil}$) and SiO_2 to silicates ($m_{SiO_2}/m_{\rm sil}$).

Object	$m_{2.0}/m_{0.1}$	$m_{\rm forst}/m_{\rm sil}$	$m_{SiO_2}/m_{\rm sil}$
HD 113766	12.0	0.39	0.03
HD 41511	1.0	0.05	0.09
HD 172555	0.7	0.09	0.09

5.1. Vega-type stars

- **HD 10647** and **HD 38678**: the spectra we observe are stellar, excess emission is only found longward of 25 μm resp. 18 μm. The far-IR excess of these objects can be explained by a remnant, low-mass debris disk around these rather old ($\leq$3500 and 231 Myr) main-sequence stars. Absence of an IR excess at shorter wavelengths could be a result of the clearing of large inner disk parts, possibly due to planets orbiting these stars. Indeed, a planet around HD 10647 has been reported (cf. Sect. 2).
- **HD 40932**: no indication of CS material is seen in the SED, so we conclude that this source is not a Vega-type candidate.
- The spectrum of **HD 113766** is dominated by crystalline silicate (forsterite) and large, amorphous silicates. Small grains and SiO_2 are quasi absent. In Fig. 5, upper panel, we show the similarity of HD 113766 with the solar-system comet Hale-Bopp, while in the mid panel it is compared to the Herbig Be star HD 100546. Both comparison objects have very similar spectral features (Malfait et al. 1998b), just like those observed in HD 113766. Bouwman et al. (2001) analysed their spectra and concluded that both reference objects were sources of highly processed dust, given their high mass-ratios of forsterite. However, contrary to the

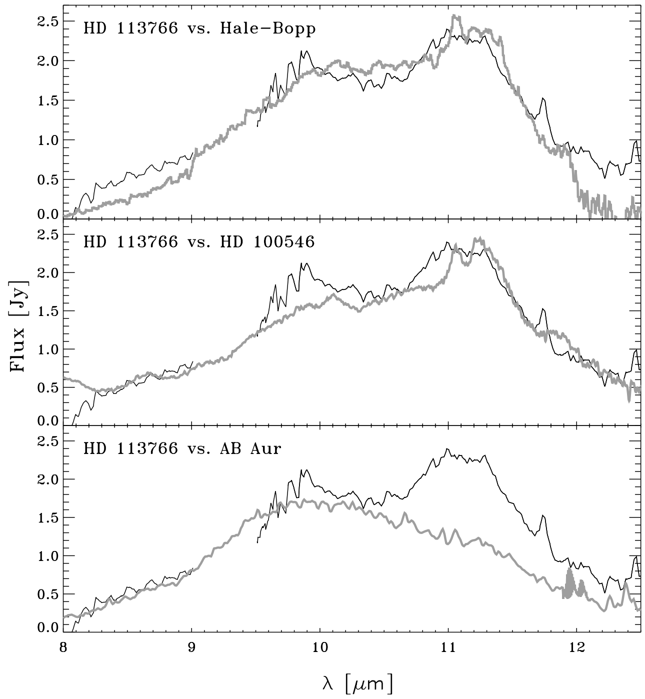

Fig. 5. Comparison of HD 113766 with comet Hale-Bopp and the Herbig Be star HD 100546 (both scaled in y-direction). The resemblance is remarkable and demonstrates that HD 113766 has similar dust characteristics as those objects. In contrast, AB Aur, a young HAe star with very little processed dust is shown in the bottom panel.

forsterite-SiO_2 correlation they generally found for HAeBe stars (an increasing amount of forsterite is accompanied by an increasing amount of SiO_2, which follows naturally from the thermal annealing process), these two objects seem to lack SiO_2, that we also observe in HD 113766. It is thus unlikely that thermal annealing caused the observed crystalline silicates in these objects. As an explanation, Bouwman et al. (2001) suggested that the crystalline silicates were rather "second generation" dust from the destruction of highly differentiated large parent bodies. Probably, HD 113766 is also host to such "second generation" material, which might point to the presence of a planet orbiting this star, causing planetesimal-sized bodies to collide. HD 113766 may thus be a promising target for exoplanet searches.
In Fig. 5, lower panel, we also compare HD 113766 with the HAe star AB Aur, which has a very small amount of processed silicates. The peak around 10 μm is caused by *amorphous* silicates, while the emission from *evolved* silicate grains (upper and mid panel) is most prominent around 11.3 μm (cf. Paper I; Bouwman et al. 2001). The spectral behaviour of other HAeBe stars lies between these two extremes.

- The SED of **HD 172555** appears stellar until 8 μm, where the excess emission starts. A decomposition of the spectrum shows that small amorphous olivine grains are dominant, but larger sized olivine together with a smaller amount of SiO_2 and crystalline forsterite are present as well. The dust around this object appears quite young, i.e. unprocessed, when compared to HD 113766 which has a similar age. Although the unknown emission around 9.3 μm was seen in data from different runs and obtained under good observing conditions, we do not claim it as a new dust feature here due to its proximity to atmospheric bands. Observations with space-based instruments should be able to clarify this issue.
- **HD 207129** shows a stellar spectrum between 8–13 μm. Excess emission starts around 20 μm.

5.2. Post-main sequence objects

- In the CS dust of **HD 41511** both small and large amorphous silicates dominate, while there is a smaller amount of SiO_2 and crystalline silicates. The CS dust composition is actually quite similar to that of the much younger object HD 172555. However, as HD 41511 is in its post-MS stage, the dust was probably condensed from outflows of the central star and subsequently processed.

6. SIMBA measurements

At millimeter wavelengths, the emission from our Vega-type candidates can safely be assumed as optically thin and therefore proportional to the total disk mass. The mm measurements are therefore an excellent tool to derive the disk masses. For optically thin dust emission, the following expression can be used:

$$M = \frac{F_\nu\, d^2}{\kappa_\lambda\, B_\nu(T)}, \quad (1)$$

with F_ν and d as the mm flux and the target's distance, respectively. $B_\nu(T)$ represents the blackbody intensity which in the Rayleigh-Jeans limit equals $\frac{2kT}{\lambda^2}$. The assumed opacity κ_λ is the main uncertainty when deriving the disk mass. For consistency with previous works we use a mass absorption coefficient of $\kappa_0 = 1.7$ cm^{2}g^{-1} at 850 μm (e.g. Sylvester et al. 2001). This scales into $\kappa_\lambda = 1.2$ cm^{2}g^{-1} at 1200 μm using

$$\kappa_\lambda = \kappa_0 \left(\frac{\lambda_0}{\lambda}\right)^\beta \quad (2)$$

and an opacity index $\beta = 1$ following Mannings (1994) and Sylvester et al. (2001). This mass estimate is only a measure of the mass contained in grains radiating at mm wavelengths, while larger particles and large-sized bodies are invisible.

Another uncertainty in Eq. (1) is the mm dust temperature of Vega-type disks. Sylvester et al. (2001) applied a value of 30 K, while the four prototype Vega-like disks (β Pic, Fomalhaut, Vega and ϵ Eri) appear to have dust temperatures between 70 and 100 K (e.g. Sheret et al. 2004). If our objects were detected at various sub-mm and mm wavelengths, the dust temperature profile as a function of the distance to the star could be obtained from numerical modelling. Zuckerman & Song (2004) derived temperatures from IRAS data for some of our targets, but these may not correspond to the grains emitting at mm wavelengths. Therefore we will assume a mm dust temperature of 50 K and, for comparison, re-calculate the disk

Table 4. (1) Upper limits for circumstellar dust masses obtained from our measurements at 1200 μm and assuming a $T_{\rm dust}$ = 50 K. HD 40932 was not considered, since the TIMMI2 spectra together with the SED had shown the non-existence of CS matter. (2) Reference dust masses re-calculated with $T_{\rm dust}$ = 50 K. See Sheret et al. (2004) for their actual masses.

Object	$M_{\rm moon}$ (50 K)	Ref.
HD 10647	<6	(1)
HD 113766	<345	(1)
HD 172555	<25	(1)
HD 207129	<4.5	(1)
β Pic	15.5	(2)
Fomalhaut	2.5	(2)
Vega	1.1	(2)
ϵ Eri	0.15	(2)

mass of the four prototype Vega-disks with this value. For their actual temperatures and dust masses see Sheret et al. (2004).

Since the mm-fluxes in Table 2 are all upper limits, we can only derive an upper limit for the disk masses of our sources. The disks in this subsample are still spatially unresolved, so the parameters grain size, disk radius and mass cannot be obtained simultaneously from modelling the far-IR to mm SED. Even our grain size estimation from fitting the mid-IR spectra is not helpful in this respect, since grains of different size may dominate the emission at those wavelengths.

The derived dust mass limits are shown in Table 4 together with re-calculated masses of the four prototype Vega-disks. All values are given in moon masses with $M_{\rm moon} = 3.7 \times 10^{-8}\ M_{\odot} = 7.3 \times 10^{22}$ kg. Sylvester et al. (2001) note that mm dust masses for T Tauri stars lie in the range of 1–40 $\times 10^{-5}\ M_{\odot}$ ($\approx$0.3–11 $\times 10^3\ M_{\rm moon}$) and Herbig Ae stars between 5–30 $\times 10^{-5}\ M_{\odot}$ ($\approx$1.4–8 $\times 10^3\ M_{\rm moon}$, although some lower-mass HAe disks are also known). From the derived upper limits we infer dust masses for our targets below 350 $M_{\rm moon}$, while for most of these objects the mass lies substantially below this value. The observed dust mass limits are thus in agreement with their Vega-type status.

7. Summary and conclusions

We studied N-band spectra of seven stars, known or suspected to have a circumstellar disk, and analysed their dust composition by fitting the observed spectra with known emission features from different dust species which are commonly found in CS disks. The Vega-type nature of HD 10647, HD 38678, HD 113766, HD 172555 and HD 207129 was confirmed, but we did not find any CS material around HD 40932 and reject it as a Vega-type candidate.

In our sample of five Vega-type stars only the youngest ones show an excess at 10 μm. For the other sources, the excess starts at longer wavelengths, which can be best explained by clearing of the inner disk as is expected by theory (cf. Introduction). HD 113766 and HD 172555 are thus the only two stars in our sample which are transitional objects between the young (age < 10 Myr) stars – where planet formation could still be on-going and which still possess a lot of warm dust – and the older (age > 50 Myr) Vega-type stars that only show cold dust and thus a far-IR excess.

The biggest surprise in our sample is HD 113766, since such a feature-rich spectrum was never observed before for a Vega-type object. The analysis of its dust composition reveals highly processed dust similar to that in comet Hale-Bopp and the Herbig Be star HD 100546. It is – to our knowledge – the first time that such highly processed dust was found around a main-sequence object. The lack of SiO_2 suggests that the dust may be second generation, which might further hint at the presence of a planet disturbing the orbits of smaller bodies, causing them to collide with each other. The large resemblance of the dust around HD 113766 to that found in comets and interplanetary dust particles in our own solar system (IDP; Bradley 2003) suggests that we might see the early stages of our solar system by observing this object.

In contrast, small amorphous grains dominate the disk of HD 172555 (which is of comparable age to HD 113766), suggesting that the dust around HD 172555 is probably still first generation. This is further supported by the presence of a small amount of silica *and* forsterite, pointing to thermal annealing in the disk of this object. Around the post-MS star HD 41511 only a small amount of processed dust is found, which is expected if the dust is being condensed in the outflow of this evolved object.

We wonder why for HD 113766 and HD 172555, despite their prominent mid-IR features (revealing a substantial amount of warm dust), no significant excess at longer wavelengths was detected (including IRAS far-IR photometry). This means that these objects may have only a very small amount of cold dust or a truncated disk. According to their age (between 10 and 20 Myr), these targets constitute a class of stars where the formation of planet(esimal)s – if they would take place – should just be finished. Is it possible that, besides the inner clearing, the cold dust in the outer regions is also removed? In case of HD 113766, one option is that the disk was truncated by its companion. In both objects, it might eventually also be a giant planet, located in the outer regions of the disk, which plays a role in causing the cold dust to disappear. A larger sample of stars with ages around 10–50 Myr should be examined with more sensitive telescopes and higher spatial resolving power to answer these questions.

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