Abstract. We have investigated the spatial distribution, and the properties and chemical composition of the dust orbiting HD 100546. This system is remarkably different from other isolated Herbig Ae/Be stars in both the strength of the mid-IR excess and the composition of the circumstellar dust. To explain spectral features and the amount of mid-IR dust emission the presence of a component of small ($< 10 \mu m$) grains radiating at $\sim 200$ K is required, which is not seen in other well investigated Herbig Ae/Be systems. This additional component is inconsistent with a uniform flaring disk model. The fraction of intercepted stellar light that is absorbed and re-emitted in the mid-IR is so large ($\sim 70 \%$) that it requires the disk to be more ‘puffed up’ at about 10 AU, where the grains have $T \sim 200$ K. This may occur if a proto-Jupiter clears out a gap at this distance allowing direct stellar light to produce an extended rim at the far side of the gap. The other remarkable difference with other isolated Herbig Ae/Be systems is the presence of a much larger mass fraction of the crystalline silicate forsterite in the circumstellar dust. We find that the mass fraction of crystalline silicates in HD 100546 increases with decreasing temperature, i.e. with larger radial distances from the central star. This distribution of crystalline dust is inconsistent with radial mixing models where the crystalline silicates are formed by thermal annealing above the glass temperature in the very inner parts of the disk, and are subsequently transported outwards and mixed with amorphous material. We speculate that the formation and spatial distribution of the crystalline dust may be linked to the formation of a proto-Jupiter in the disk around HD 100546. Such a proto-Jupiter could gravitationally stir the disk leading to a collisional cascade of asteroidal sized objects producing small crystalline grains, or it could cause shocks by tidal interaction with the disk which might produce crystalline dust grains through flash heating. As shown by $?), the infrared spectrum of HD 100546 is very similar to that of C/1995 O1 Hale-Bopp ($?). Using an identical methodology, we have therefore also studied this solar system comet. Both objects have an almost identical grain composition, but with the important difference that the individual dust species in Hale-Bopp are in thermal contact with each other, while this is not the case in HD 100546. This suggests that if similar processes leading to the dust composition as seen in HD 100546 also occurred in our own solar system, that Hale-Bopp formed after the formation of one or more proto-gas giants.

Key words: Circumstellar matter – Stars: formation – Stars: pre-main-sequence
The origin of crystalline silicates in the Herbig Be star HD100546 and in comet Hale-Bopp

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1. Introduction

Herbig Ae/Be stars (hereafter referred to as HAEBE stars) were first described as a group by ), in a study which was aimed at finding intermediate mass young stars. Many studies have since confirmed the young pre-main-sequence (PMS) nature of HAEBE stars. Hipparcos parallax (e.g. van den Ancker et al. 1998) allowed accurate positions in the HR diagram to be obtained, and from comparison to PMS evolutionary tracks masses of the order of 2 to 8 M⊙ and stellar ages measured relative to the birthline of typically 106 to 107 yrs were found. Direct imaging at millimeter wavelengths of several Herbig Ae stars revealed the presence of rotating flattened structures (??), believed to be the remnant of the accretion disk and the site of on-going planet formation. It is not clear whether disks are also common around more massive Herbig Be stars.

At infra-red (IR) wavelengths, the Infrared Space Observatory (?, ISO)kessler1996 has obtained full 2-200 µm spectra of the brightest HAEBE stars. These spectra show a wealth of detail concerning the thermal emission of dust in the circumstellar environment. In a series of papers, we have studied the dust emission from HAEBE stars (?????????????), focusing on the mineralogical composition of the dust. These studies indicate that a substantial modification of the dust composition from that in the interstellar medium (ISM) occurs on time scales that are still poorly constrained, but are generally less than 107 years. We mention grain growth, the formation of crystalline silicates and of crystalline H2O ice, and of hydro silicates. These modifications are important clues to the processes that eventually lead to planet formation, and which can be compared to the records of planet formation as found in solar system objects (meteorites, comets, interplanetary dust particles).

In this study we re-examine the ISO spectrum of HD100546, first presented by ?). This object has an exceptionally high fraction of crystalline silicates, and its ISO spectrum shows a remarkable resemblance to that of the solar system comet Hale-Bopp (?). ?) already suggested the exciting possibility that we are witnessing the birth of an Oort cloud with a multitude of cometary bodies being scattered by a (hypothesized) giant planet. ?) analyzed the 10 µm silicate band of 14 HAEBE stars including HD 100546, and found that its mineralogical composition deviates substantially from that of other HAEBE systems: in addition to a large fraction of forsterite, the average grain size of the particles causing the 10 µm emission is larger. Also, a lack of silica compared to forsterite was found. The latter can be interpreted as a difference in the crystallization process leading to the formation of forsterite. We decided that a closer look at the distribution of the different mineralogical components in terms of mass and temperature is needed to better understand the nature of HD 100546. We also analyze the ISO spectrum of Hale-Bopp, using the same analysis method as for HD 100546. Previously, we have carried out a similar detailed analysis for AB Aurigae and HD163296 (?) and we will compare these results with those obtained here for HD 100546. The observations of HD 100546 used in this paper are taken from ?) and ?). The observations of Hale-Bopp were secured when the comet had a heliocentric distance of 2.8 AU and are from ?).

This paper is organized as follows: in Sect. 2 we discuss the difference in dust composition and spectral energy distribution of HD 100546 compared to other HAEBE systems. In Sect. 3 we explain the method to fit the spectrum. Sect. 4 describes our results for HD 100546 and for Hale-Bopp. In Sect. ?? we compare our results to those obtained for AB Aur and HD 163296, and discuss the implications for the formation process of the crystalline silicates in HD 100546. Sect. ?? summarizes the results of our study.

2. The deviating dust composition and spectral energy distribution of HD 100546

The spectral appearance and dust properties of HD 100546 differ from that of other HAEBE stars. We will start out with a summary of these differences:
in both objects. This suggests that a different formation process – and in this respect also that of comet Hale-Bopp – is responsible for the large mass fraction of forsterite seen forsterite. However, the dust properties in HD 100546 evidence that the crystalline silicates are formed by thermal annealing. 

Fig. 1. Comparison between the energy distribution of AB Aur (light line) and HD 100546 (dark line). The spectra have been normalized to the respective stellar luminosities. Plotted are the combined ISO-SWS and LWS spectra. Note the large difference in the near- and mid-IR luminosity of both systems.

First, the ISO-spectra of HD 100546 show strong and pronounced emission, identified with the crystalline silicate forsterite, which in abundance must be far in excess of that seen in other HAEBE systems (??).

Second, ?) identified an emission component at 8.6 \( \mu \)m in the spectra of a large sample of HAEBE stars which they attribute to silica (SiO\(_2\)), and which seems to be correlated with forsterite. This correlation is interpreted as evidence that the crystalline silicates are formed by thermal annealing. However, the dust properties in HD 100546 – and in this respect also that of comet Hale-Bopp – does not comply with this correlation between silica and forsterite. This suggests that a different formation process is responsible for the large mass fraction of forsterite seen in both objects.

Third, from a detailed analysis of the 10 \( \mu \)m spectral region (??), it was shown that the typical grain size of the silicate particles emitting at these wavelengths is larger compared to the sizes found in other HAEBE systems. This suggests the disk in HD 100546 is more evolved.

Fourth, the spectral energy distribution of HD 100546 shows remarkable differences when compared to other HAEBE stars. To illustrate the difference, we have plotted in Fig. 1 the SEDs of AB Aurigae (light line) and HD 100546 (dark line) normalized to the stellar luminosity. Both dust disks intercept about 50\% of the stellar light (see Table 1). It is easily seen that AB Aur re-emits a larger fraction of this intercepted light in the near-IR, while HD 100546 shows a larger emission at mid-IR wavelengths. The far-IR and sub-millimetre luminosities are comparable. The difference in the way radiation is redistributed by the dust essentially implies that the stellar flux is absorbed at different locations in the circumstellar disk. Dust grains dominating the near-IR emission have temperatures of at least \( \sim \) 1000 K. For a grain to reach such a temperature it has to be within \( \sim 1 \) AU of the central star. In the case of AB Aur it is within this region that about half of the intercepted light is reprocessed (see Table 1). HD 100546 emits a relatively modest amount of radiation in the near-IR, however, 70\% of the total dust luminosity comes out in the mid-IR. Grains emitting at these wavelengths have typical temperatures of \( \sim 200 \) K. Assuming these grains receive direct stellar light this implies that the re-emitted mid-IR flux originates from about 10 AU from the central star.

In estimating the above emitting regions, we have assumed that the dust medium is optically thin. Let us, for the moment, hold on to this assumption. For \( \tau \ll 1 \) the emission scales with dust mass, implying that the disk of HD 100546 is less massive in the inner parts compared to AB Aur. Given that the system is older (?), it suggests that a larger fraction of the circumstellar matter has been removed from the disk (evaporated or accreted) and/or incorporated into larger bodies, substantially reducing the near-IR emission. In an optically thick view, the emission scales not with the dust mass but with emitting surface. ?) show that the near-IR excess may be due to a puffed-up inner rim surface. The height of this inner rim is a function of the stellar luminosity and of the surface density in the disk near the evaporation temperature of the dust. The low near-IR excess of HD100546 compared to AB Aur is then the combined effect of the smaller stellar luminosity, and a severe depletion of the inner disk.

Concerning the mid-IR fluxes, similar considerations apply. ?) show that the SED of AB Aur can be reproduced with a passive reprocessing flaring disk in hydrostatic equilibrium. As the mid-IR spectrum of this star is similar to that of many other HAEBE stars (?), most likely this model has generic value. However, the model can not explain the SED of HD100546. For a uniform flaring disk model to reproduce the strong mid-IR emission, the opening angle of the disk has to increase faster with radius in order to intercept more stellar light rela-
tively close to the star. Given the comparable sizes of the systems, such a solution would lead to a much larger total covering fraction. However, these are about 50% in both systems.

A possible solution for this problem is to induce a sizable gap in the circumstellar disk. Such a gap would produce a large rim at the far side of the gap (when viewed from the direction of the central star), of which the largest part would be irradiated directly by the star (see Fig. 3.1). As a result, a larger absorbing surface is created and consequently the larger emitting surface that is required. This show that in such a geometry indeed the disk scale height is increased substantially, increasing the emission from the region where the dust is \( \sim 200 \) K. In Sect. 3.1 we will speculate that a massive planet, which has formed in the disk at \( \sim 10 \) AU, may have created such a gap.

We conclude that HD 100546 differs considerably from other HAEBE systems in both dust composition and disk geometry. This implies that processes different from those observed in other HAEBE systems currently dominate the HD 100546 system. In this paper we will try to trace these processes.

3. Modelling

The diagnostic method adopted is identical for the Herbig Be star HD 100546 and comet Hale-Bopp. We use the radiative transfer program MODUST to model the circumstellar dust using the mode in which the material is assumed to be optically thin. This is correct for comet Hale-Bopp, but for the circumstellar disk of HD 100546 this may not be valid. However, in discussing dust properties we will focus on the mass over temperature distribution of the material responsible for the infrared emission. This diagnostic does not depend on the optical depth properties of the medium and therefore the simple approximation used here is still meaningful. For both objects the material is distributed in a spherical shell, which for Hale-Bopp is positioned at the distance from the sun corresponding to that of the location of the coma and tail at the time of observation. For recent applications and for descriptions of techniques used in MODUST, see e.g. \( ? \) and \( ? \).

The grains are irradiated by the central star, for which we use \( ? \) energy distributions. The Hipparcos distance to the B9Vn e star HD 100546 is \( 103 \pm 7 \) pc, yielding a luminosity \( L = 32 \) L\( \odot \) \( ? \). Comparison with evolutionary tracks, using \( T_{\text{eff}} = 10.500 \) K, places the star on the main sequence having an age of \( > 10 \) Myr and mass of \( 2.4 \) M\( \odot \). In modelling Hale-Bopp, we use Kurucz’s solar model with \( T_{\text{eff}} = 5.777 \) K.

The absorption of stellar radiation at mostly ultraviolet and optical wavelengths and re-emission in the infrared is consistently taken into account assuming the particles are in radiative equilibrium, yielding the spectral energy distribution. A key difference of this method compared to other often employed approaches in modelling circumstellar and cometary spectra is that both the spectral characteristics responsible for the distinct features as well as those responsible for the featureless continuum are modelled simultaneously. Other methods usually introduce an artificial separation between continuum and features, fitting the spectrum combining empirical temperatures with laboratory extinction efficiencies \( ? \), e.g. woode1999,mason2001 or with template extinctions based on measurements of interplanetary dust particles (IDP’s) \( ? \), e.g. woode2000, complicating a reliable interpretation.

In the near- and mid-IR, typically carbon and large \( (\gtrsim 10 \) \( \mu \)m) amorphous silicate grains are responsible for the overall continuum, while water ice is a dominant contributor in de far-IR and sub-millimetre range. At 10 \( \mu \)m the molecular vibrational modes of Si-O bonds in small amorphous silicate grains \( (\lesssim 10 \) \( \mu \)m) produce a distinct feature, as do silicate crystals in the mid-IR part of the spectrum. These latter particles, however, also produce significant flux outside of their resonances, which one can not \( a \) \( p \) \( r \) \( i \) \( o \) \( r \) \( i \) \( v \) \( i \) \( o \) \( r \) \( i \) \( r \) \( i \) \( o \) \( r \) \( i \) \( o \) distinguish from continuum only contributors. Continuum subtraction methods therefore are susceptible to (systematic) errors. This may significantly affect temperatures, abundances, and sizes derived for especially the crystalline material. Our method does not suffer from this problem. In fairness, we should mention that in other respects studies using ground based data have advantages over the interpretation of ISO data. For instance, the mid-IR observations analysed by Wooden al. (2000) which have been obtained close in time to the ISO data have much smaller beams, allowing one to study gradients in the particle properties as a function of distance to the cometary nucleus.

3.1. Size and shape properties of grains

Composition, size and shape properties of grains in protoplanetary disks may provide important constraints on the formation history of circumstellar dust. We first focus on shape properties. Very little is known about the structure of grains in circumstellar disks. Particles may be compact or “fluffy” and may be chemically homogeneous or consist of a mix of different materials. Information may be obtained from measurements of grains sublimating from solar system comets nearing perihelion. From a comparison of measurements of the angle dependence of the scattering albedo of several bright comets with theoretical predictions \( ? \) found the coma grains to be consistent with “fluffy” aggregates of smaller compact particles. Properties of the aggregate, such as temperature and spectroscopic signature, will be affected by the actual degree of fluffiness of the grain, often expressed in terms of the porosity factor of the particle \( ? \). Large porous grains may heat to much higher temperatures than compact grains of the same mass and may show spectroscopic characteristics similar to the smaller compact particles.
constituting the fluffy aggregate. Theoretical considerations suggest cometary grains to be extremely fluffy with porosity factors $0.93 \lesssim P \lesssim 0.975$ (?), effectively implying that some spectroscopically deduced properties relate to the smaller compact units making up the porous aggregate (?, e.g.) and references therein (Brucato1999). In our modelling we will therefore concentrate on (small) compact particles, leaving open the possibility that they may be part of larger fluffy aggregates.

Regarding the chemical homogeneity of the small particles, (?) pointed out that in situ mass spectra of comet P/Halley 1986 III dust showed that carbonaceous and silicate materials were mixed on fine scales, suggesting these two species are not physically separated. If this is the case, the components are likely in thermal contact. The question of thermal contact is especially relevant with respect to the magnesium over iron content of the silicate material, a major constituent of circumstellar dust, as the absorption properties of olivine ($\text{Mg}_x\text{Fe}_2-2x\text{SiO}_4$, with $x$ between 0 and 1) and pyroxene ($\text{Mg}_x\text{Fe}_{1-x}\text{SiO}_3$) sensitively depend on this ratio. The pure magnesium silicates forsterite ($\text{Mg}_2\text{SiO}_4$) and enstatite ($\text{MgSiO}_3$) are optically much more transparent than iron rich silicates, implying that if Fe-rich and Fe-poor materials coexist as separate particles – with comparable shape and size – the Fe-rich dust will reach significantly higher temperatures.

We have opted to treat the different chemical species as physically separated. In the case of Hale-Bopp this allows to investigate whether the forsterite crystals, of which the spectroscopic signatures are prominently visible in the mid-IR spectrum, are in thermal contact with the bulk amorphous silicate material, which is likely to contain a significant fraction of iron, by determining the mass-averaged temperatures of both species. If significantly different, one may assume the components to be physically separated; if similar temperatures are found, it is likely they are in thermal contact.

For each particle, we calculate the extinction properties from optical constants determined in laboratory experiments, as listed in Table 2. We assume spherical grains, for which we use Mie calculations, or a continuous distribution of ellipsoidal grains, for which we use CDE calculations, to determine the absorption and scattering coefficients (see ?) for a full review on these methods)

As we treat the CDE particles in the Rayleigh limit, we can not study grain size effects. For spherical particles this assumption is not required. The spherical particles of our multi-component mixture of grains range between minimum size $a_{\text{min}}$ and maximum size $a_{\text{max}}$ and are distributed following a power-law, i.e.

$$n(a) \propto \left( \frac{a}{a_{\text{min}}} \right)^{-m}.$$  

(1)

Theoretical calculations predict this type of size distribution whenever there is scattering and coagulation of grains through grain-grain collisions (Biermann & Hartwit 1980). To get some feeling for the value of the power-law index, extinction observations imply a size distribution with $m = 3.5$ for interstellar grains (?).

3.2. Chemical composition of grains

The grain species used to model the spectra of both objects are listed in Table 2. The dust composition is similar to that used by ?) to model the isolated Herbig Ae stars AB Aurigae and HD 163296, though more appropriate sources for the optical constants of crystalline silicates and water ice are used. Of the two isolated Herbig stars mentioned only in HD 163296 a small amount of forsterite could be identified, modeling of which did not sensitively depend on the adopted optical constants. However, for the two objects investigated here – which show prominent features of olivine – differences in laboratory measurements are important. To model the crystalline silicate features we tried three sets of data: ?) measured the optical properties of forsterite ($\text{Mg}_2\text{SiO}_4$; Fo100), ?) used a natural olivine sample, which was estimated to contain a small amount of iron, i.e. $x = 0.91$ (Fo91). The sample used by ?) contains an almost equal amount of iron ($x = 0.90$; Fo90). These measurements only cover the IR wavelengths. To estimate the optical properties of the grains at visual and UV wavelengths, where most of the stellar light is absorbed, we used measurements of comparable materials from several other sources, referenced in Table 2.

Neither in AB Aur nor in HD 163296 the $44 \mu$m feature characteristic for crystalline H$_2$O ice was found, prompting the use of amorphous water ice in modeling their circumstellar environment. In both HD 100546 and Hale Bopp, however, the $44 \mu$m feature appears to be visible, making it more appropriate to assume the water ice in these sources to be crystalline.

4. Results

4.1. HD 100546

Plotted in Fig. ?? is our best model fit to the SED of HD 100546. The resulting model parameters are listed in Table 3. The top panel shows the entire SED. A dashed line represents the Kurucz model for the central star. The lower panel shows the ISO-SWS and LWS wavelength region. Indicated are the contributions to the spectrum of the individual dust components as listed in Table 3. To fit the SED a bi-modal grain size distribution is required, similar as to that found in previous analysis of HAEBE stars (??). The small (< $10 \mu$m) grains dominate the SED shortward of $\sim 40 \mu$m, while the large (up to 200 $\mu$m) grains dominate at the longest wavelengths.

4.1.1. The small grain component

Though the small grain component contains only a minor fraction of the total dust mass (\sim 1%) it dominates the
and zone 2, respectively. The contributions to the SED of
between 9.8–43 AU, from here on referred to as zone 1
the small grains are distributed between 0.3–9.8 AU, and
observed fluxes in this wavelength range, a bi-model den-
SED at near- and mid-IR wavelengths. To reproduce the
SED at near- and mid-IR wavelengths. To reproduce the
zone 1 and 2 are plotted in Fig. ?? The inner boundary
of zone 1 at 0.3 AU is determined by the grain destruction
temperatures of the individual dust species as listed
in Table 2. A similar dust component as that in zone 1 is
also present in AB Aur, HD 163296 and HD 104247 (??). The
sudden increase in density at 9.8 AU, marking the onset
of zone 2, is found only in HD100546. It is this ad-
ditional component that produces the much larger mid-IR
luminosity compared to the other HAEBE systems as dis-
cussed in Sect. 2. As can be seen from Fig. ??, the emission
from zone 2 completely dominates the SED between ∼20
to 50 µm. The resulting total mass of $6 \times 10^{-7} M_\odot$
in small grains is two to three orders of magnitude larger
than found in the studies mentioned above.
A major fraction of the dust emission seen in HAEBE
systems is due to amorphous silicates. Though it is difficult

to determine the exact nature of the amorphous material,
an excellent fit can be made if we use the optical properties
of a silicate glass with an olivine stoichiometry (see also
Table 2). The grain size of the amorphous silicate is well
constrained by the shape and strength of the 10 µm sili-
cate feature, and the flux ratio between the 10 and 18
µm. The resulting total mass of $6 \times 10^{-7} M_\odot$
in small grains is two to three orders of magnitude larger
than found in the studies mentioned above.

<table>
<thead>
<tr>
<th>Species</th>
<th>Lattice Structure</th>
<th>Wavelength [µm]</th>
<th>$T_{\text{destr}}$ [K]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\text{Mg,Fe}]\text{SiO}_4$</td>
<td>A</td>
<td>0.2–500</td>
<td>1100</td>
<td>(1)</td>
</tr>
<tr>
<td>FeO</td>
<td>C</td>
<td>0.2–500</td>
<td>1000</td>
<td>(2)</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
<td>0.1–800</td>
<td>1000</td>
<td>(3)</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>C (ice)</td>
<td>0.05–10$^4$</td>
<td>150</td>
<td>(4)</td>
</tr>
<tr>
<td>Forsterite</td>
<td>C</td>
<td>0.04–3</td>
<td>1400</td>
<td>(5)</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>3–250</td>
<td> </td>
<td>(6)</td>
</tr>
<tr>
<td>Olivine (Fo91)</td>
<td>C</td>
<td>0.04–3</td>
<td>1400</td>
<td>(5)</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>3–250</td>
<td> </td>
<td>(7)</td>
</tr>
<tr>
<td>Olivine (Fo90)</td>
<td>C</td>
<td>0.01–0.3</td>
<td>1400</td>
<td>(8)</td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>0.3–2</td>
<td>(9,10)</td>
<td></td>
</tr>
<tr>
<td> </td>
<td> </td>
<td>7–200</td>
<td>(11)</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>M</td>
<td>0.1–10$^7$</td>
<td>1500</td>
<td>(12)</td>
</tr>
</tbody>
</table>

Abbreviations used to designate the lattice structure: A = Amorphous; C = Crystalline; M = Metallic.

References: (1) ?; (2) ?; (3) ?; (4) ?; (5) ?; (6) ?; (7) ?; (8) ?; (9) ?; (10) ?; (11) ?; (12) ?.

Table 2. Overview of dust species used. For each component
we specify its lattice structure, the wavelength interval over
which optical constants are measured, and the destruction
temperature.

Table 3. Best fit model parameters of HD 100546. Listed are the parameters defining the density and grain size distribution,
the chemical composition and the mass fraction $M_{\text{frac}}$ of the individual dust species. Both the small grain and large grain
component have a power law density distribution $\rho(r) \propto r^{-1}$ and grain size distribution $n(a) \propto a^{-2}$. The radial extent of the
small grain component is given in the table, large grains are present between 28–380 AU with a density at the inner boundary
of $\rho_0 = 1.5 \times 10^{-18}$. Note that the densities given at the inner radius $\rho_0 = \rho(r_{in})$ of zone 1 assume all dust species to be present.
However for temperatures greater than the destruction temperature $T_{\text{destr}}$ (see Table 2) the actual densities are slightly lower.

<table>
<thead>
<tr>
<th>Component:</th>
<th>Small grains</th>
<th>Large grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{frac}}/M_\odot$</td>
<td>zone 1</td>
<td>zone 2</td>
</tr>
<tr>
<td>Dust species</td>
<td>$R$ [AU]</td>
<td>$\rho_0$ [gr cm$^{-3}$]</td>
</tr>
<tr>
<td>Amorph. silicate</td>
<td>0.3–9.8</td>
<td>1.6 $\times 10^{-17}$</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.3–9.8</td>
<td>1.7 $\times 10^{-18}$</td>
</tr>
<tr>
<td>Metallic iron</td>
<td>0.3–4.9</td>
<td>4.2 $\times 10^{-19}$</td>
</tr>
<tr>
<td>Forsterite</td>
<td>0.3–24</td>
<td>6.0 $\times 10^{-21}$</td>
</tr>
<tr>
<td>Water ice</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The contributions to the SED of
the chemical composition and the mass fraction $M_{\text{frac}}$ of the individual dust species. Both the small grain and large grain