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Grain growth in the inner regions of Herbig Ae/Be star disks[*]

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Abstract. We present new mid-infrared spectroscopy of the emission from warm circumstellar dust grains in
Herbig Ae/Be stars. Our survey significantly extends the sample that was studied by Bouwman et al. (2001). We find a correla-
tion between the strength of the silicate feature and its shape. We interpret this as evidence for the removal of small (0.1 μm)
grains from the disk surface while large (1–2 μm) grains persist. If the evolution of the grain size distribution is dominated by
gravitational settling, large grains are expected to disappear first, on a timescale which is much shorter than the typical age of
our programme stars. Our observations thus suggest a continuous replenishment of micron sized grains at the disk surface. If
the grain replenishment is due to the dredge-up of dust from the disk interior, the mineralogy we observe is representative of
the bulk composition of dust in these stars.

Key words. stars: circumstellar matter – stars: pre-main-sequence – infrared: ISM: lines and bands

1. Introduction

Young, low and intermediate mass stars are characterized by
the presence of an accretion disk, which is formed as a result
of angular momentum conservation in the collapsing molecular
cloud. After an initial high accretion phase, a much longer pre-
main-sequence phase ensues during which the – now passively
heated – disk slowly dissipates and possibly planets are formed.
The processes that determine the time-scale for disk dissipation
seem not well coupled to the evolutionary time-scale of the star
towards the zero-age-main-sequence. It may be linked to pa-
rameters as the environment, differences in disk properties, and
the process of planet formation.

Analysis of the IR dust emission features originating from
the disk surface can, along with other observables such as gas
content, chemistry, and shape of the spectral energy distribu-
tion (SED), be used to establish to what extend the dust composi-
tion in the disk has evolved away from that seen in the inter-
stellar medium (ISM). For instance, crystalline silicates are not
known to be present in the ISM (e.g. Demyk et al. 2000) but are
a substantial component in (some) comets and in interplanetary

dust particles (IDPs) found in the solar system (MacKinnon &
Rietmeijer 1987; Bradley et al. 1992). Clearly, the refractory
material in the proto-solar cloud went through large changes as
the solar system was formed. Similar changes in dust composi-
tion have been found in the passive disks surrounding, in par-
ticular, Herbig Ae/Be (HAEBE) stars (e.g. Malfait et al. 1998;
Bouwman et al. 2001, hereafter BO01; Meeus et al. 2001, here-
after ME01). These are intermediate mass pre-main-sequence
stars, first defined as a group by Herbig (1960).

We are studying the composition of dust in disks surround-
ing HAEBE stars, using infrared spectroscopy. In this Letter,
we present preliminary results of a large spectroscopic survey
at 10 μm of HAEBE stars whose 10 μm emission is believed to
be dominated by a disk. While BO01 analysed the composition
of the silicates using the 10 μm spectral region, their small sam-
ple did not allow a quantitative search for a correlation between
band strength (i.e. the flux ratio of the feature and continuum
emission) and band shape. We *do* find a correlation between
the strength of the silicate emission with respect to the local
continuum and the shape of the band. Strong bands are dom-
inated by small amorphous silicate grains. Weak bands have
a shape consistent with the presence of large grains and show
more pronounced emission from crystalline silicates. This sug-
gests that small grains are removed from the inner disk region
on timescales comparable to the appearance of large grains and
crystalline material at the disk surface. The observed correla-
tion implies that the 10 μm continuum radiation in HAEBE

stars is of similar level between different stars. Randomly varying continuum levels would not result in a correlation between band strength and shape. A detailed compositional analysis of the full sample will be presented elsewhere.

2. Observations and data reduction

Infrared spectra in the 10 μm atmospheric window were taken during two nights in December 2001 with the *Thermal Infrared Multi Mode Instrument 2* (TIMMI2, Riemann et al. 1998), mounted at the 3.60 m telescope at the ESO La Silla observatory. Conditions were clear, though the water content of the atmosphere was high, reducing somewhat the sensitivity and calibration accuracy of the observations. The low resolution ($R \approx 160$) N band grism was used in combination with a 1.2 arcsec slit, the pixel scale in the spectroscopic mode of TIMMI2 is 0.45 arcsec. We employed chopping and nodding, using a +10 arcsec chop throw north-south, and a −10 arcsec nod throw north-south. Spectroscopic standard stars at various air masses were observed regularly and were used to correct for the atmospheric transmission.

We flux-calibrated the spectra using the IRAS 12 μm data, correcting for the difference in spectral coverage of the TIMMI2 and IRAS band. We used near-IR and IRAS photometry to construct a spectral energy distribution, and applied two black body components (with a range in temperatures) to estimate the continuum. A full description of our data reduction will be presented elsewhere (van Boekel et al., in preparation).

In Fig. 1a we show the ISO-SWS and TIMMI2 spectrum of HD 104237, as well as the photometry based continuum estimate (solid line). The dashed lines indicate the continuum components. Figure 1b shows the ISO-SWS and TIMMI2 spectra and the continuum estimate on a linear scale. A comparisom between the ISO and TIMMI2 spectra of 6 sources shows that the two data sets agree well, beit that our new TIMMI2 spectra have on average a slightly lower (at most 0.1) 11.3 over 9.8 μm flux ratio, a possible artifact of our data reduction. This has no qualitative and marginal quantitative influence on the correlation discussed in Sect. 3.2 and shown in Fig. 3.

3. Analysis and discussion

3.1. Classification of the sources

ME01 empirically decomposed the infrared spectra of HAEBE stars into three components: a power law component, a cold black-body component, and solid state emission bands (mainly at 10 and 20 μm). They divided their sample into two groups, where the group I sources show both the power law and the cold BB component, and the group II sources only display the power law component. The group I sources are interpreted as having a large (several hundred AU) flared outer disk, whereas the group II sources have a smaller, non-flaring outer disk.

We classify the sources for which we have newly measured N-band spectra following ME01. Whereas ME01 had ISO spectra of their sources at their disposal, our classification is based solely on broad-band photometry. We find that the group I and group II sources are well separated in an
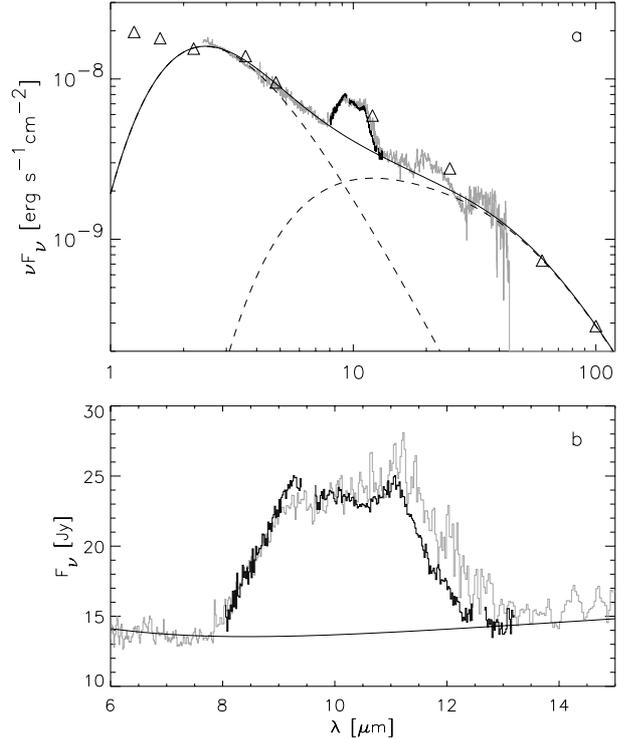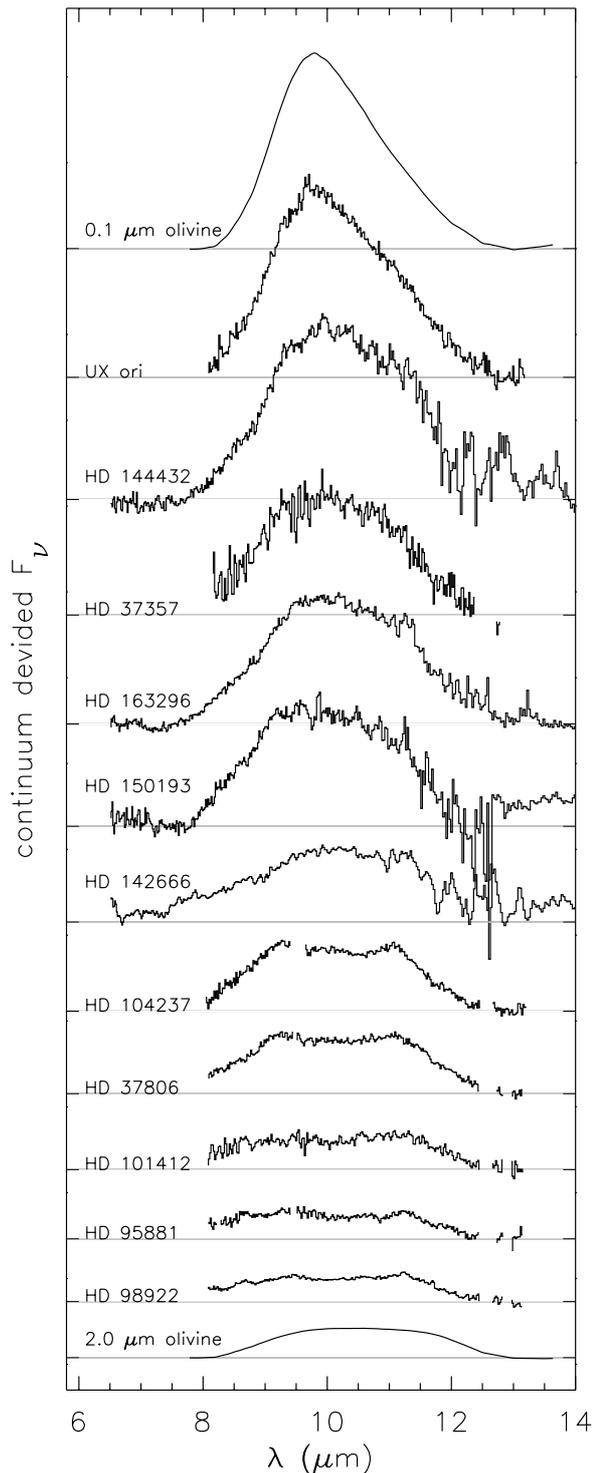

Fig. 1. The sed of HD 104237, compiled using literature photometry (triangles), ISO (grey scale) and TIMMI2 (black) data. The smooth line is the continuum estimate.

IRAS $m_{12}-m_{60}$ color versus L_{NIR}/L_{IR} diagram, where L_{NIR} is the integrated luminosity as derived from the J, H, K, L and M band photometry, and L_{IR} is the corresponding quantity derived from the IRAS 12, 25 and 60 μm points. For group I sources, $L_{NIR}/L_{IR} \leq (m_{12}-m_{60}) + 1.5$, group II sources have $L_{NIR}/L_{IR} > (m_{12}-m_{60}) + 1.5$. For the classification of the sources we applied no color correction to the IRAS data.
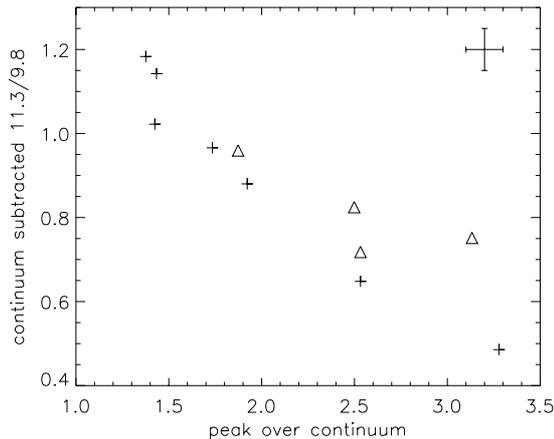
3.2. Discussion of observed trends

In Fig. 2 we plot the continuum devided N-band spectra of our group II sources, ordered by peak value. We plot $1 + F_{\nu,cs}/ < F_{\nu,c} >$, where $F_{\nu,cs}$ is the continuum subtracted spectrum ($F_\nu - F_{\nu,c}$) and $< F_{\nu,c} >$ is the mean of the continuum. Contrary to a $F_\nu/F_{\nu,c}$ plot, this representation preserves the shape of the emission band even if the continuum is not constant. For a constant continuum level it is identical to $F_\nu/F_{\nu,c}$. At the top and the bottom of the figure we plot the absorption coefficients of 0.1 and 2.0 μm olivine grains (taken from BO01), where a continuum contribution is added in order to match the levels of UX ori and HD 98922, respectively.

We clearly observe a correlation between the band over continuum ratio (which we call "strength") and the shape of the silicate feature. Sources that display a strong emission feature show a blue, *unprocessed* silicate band (i.e. similar to that seen in the ISM), dominated by small (0.1 μm) grains, with little or no evidence for crystalline silicates. The sources with weak emission bands show a broader and flatter silicate feature (which we will refer to as "processed"), which BO01 show to be dominated by large (1–2 μm) grains. We see substructure

Fig. 2. Continuum devided spectra of the group II sources. Tick marks indicate the 1.0 level.

Fig. 3. Degree of processing against feature strength for the group II sources. Triangles represent ISO-SWS spectra, crosses indicate the newly measured TIMMI2 spectra. In the upper right of the figure we indicate the typical uncertainties in the displayed quantities.

processed material could be present, swamped by the much stronger emission from the small amorphous grains. We observe a similar trend between band strength and shape in the group I sources (although the sample is small), however at on average larger band strength (van Boekel et al., in preparation). This suggests that the geometry of the disk also affects the strength of the silicate band.

In Fig. 3 we plot for our group II sources (a homogeneous group with similar SEDs) the ratio of the feature flux at 11.3 and 9.8 μm, which is a measure of the amount of processing the material has undergone, against the silicate feature strength. High 11.3/9.8 ratios indicate evolved dust and the increase of the degree of processing with decreasing feature strength is evident.

4. Discussion and conclusions

Our observations for the first time show that the silicate band shape and strength in HAEBE stars are correlated. The detailed spectral fits carried out in BO01 support our conclusion: HD 142666 and HD 104237 have mass ratios of 2.0 over 0.1 μm size grains of 1.54 and 8, respectively, whereas for HD 144432, HD 163296 and HD 150193 this quantity is less than 1.

It is interesting to compare the observed correlation to that expected for a passive, non-turbulent disk in which grains settle gravitationally. The settling timescale for dust grains in such a disk is approximately $t \approx 10^7 \times (0.1 \ \mu m/a)$ years (Miyake & Nakagawa 1995), where spherical grains with radius a, a surface density of 10^3 g cm^{-2} and a Kepler frequency of 10^{-7} s^{-1} are assumed. The typical age of the stars in our sample is several times 10^6 years, with large uncertainties. Since this age is similar to the characteristic removal time scale of 0.1 μm grains, we would expect to observe a large range in small amorphous silicate grain abundances in our sample. Indeed, Fig. 2 demonstrates that this is actually observed.

The settling time for large grains is much shorter than the typical age of our sample stars. *All micron sized and*

at 9.2, 10.6 or in the 11.2 to 11.4 μm region in the silicate bands of HD 150193, HD 104237, HD 37806, HD 95881 and HD 98922. These bands can be identified with olivines (11.2 to 11.4 μm) and pyroxenes (9.2 and 10.6 μm, Jäger et al. 1998). Note that our data do *not* exclude the presence of a certain amount of crystalline and/or large amorphous grains in sources with strong silicate bands, some emission from

larger grains should have disappeared within 10^6 years and we should not see any signature of large grains in our spectra. However, the observed change in shape of the silicate band from a peak near 9.7 μm to a broader and flatter feature can be explained by a combination of an increase of the average grain size from 0.1 to 1–2 μm and the presence of crystalline silicates (BO01; van Boekel et al., in prep.). Thus, it appears that these 1–2 μm size grains must be replenished at the surface layer.

Two mechanisms may be responsible for this replenishment: turbulent mixing from the midplane, or a supply of large grains from the inner disk by means of an X-wind. If the large grains we observe are brought up by a turbulent disk, *the silicate feature we see may be representative of composition of the bulk of the dust*. Note that in this scenario, any small grains present in the disk interior would be brought up also, and the absence of their signature in the spectra of the sources in the lower half of Fig. 2 implies that the small grains have disappeared *throughout* the disk[1]. The X-wind mechanism (Shu et al. 2001) may also be capable of adding some (processed) material on the surface of the disk. In that case, the composition of the surface layer as traced by the silicate feature is not representative of that of the bulk of the silicates.

The detection of spectral structure near 9.2, 10.6 and 11.3 μm shows that crystalline silicates are present at the surface of the disk. The most natural explanation of this phenomenon is thermal annealing of amorphous grains in the inner parts of the disk, where temperatures above the crystallisation temperature of silicates (about 1000–1100 K, Hallenbeck et al. 1998) can be reached. BO01 have analysed the 10 μm band composition and conclude that the presence of SiO_2 and forsterite indicate that thermal annealing produced the crystalline silicates.

It is interesting to compare the shape of the silicate feature to that of solar system comets, which should trace the dust composition in the proto-solar cloud at large heliocentric distance. The 10 μm feature in comets resembles that of the stars in Fig. 2 with weak silicate bands. Hanner et al. (1996) and Crovisier et al. (2000) show that comets contain some crystalline silicates. Therefore, the mid-plane of the proto-solar cloud contained processed silicates at the time of formation of the comets.

References

Bouwman, J., Meeus, G., de Koter, A., et al. 2001, A&A, 375, 950

Bradley, J. P., Humecki, H. J., & Germani, M. S. 1992, ApJ, 394, 643

Crovisier, J., Brooke, T. Y., Leech, K., et al. 2000, Thermal Emission Spectroscopy and Analysis of Dust, Disks, and Regoliths, ASP Conf. Ser., 196, 109

Demyk, K., Dartois, E., Wiesemeyer, H., et al. 2000, ISO beyond the peaks: The 2nd ISO workshop on analytical spectroscopy, ed. A. Salama, M. F. Kessler, K. Leech, & B. Schulz, ESA-SP 456, 456, 183

Hallenbeck, S. L., Nuth, J. A., & Daukantas, P. L. 1998, Icarus, 131, 198

Hanner, M. S., Hayward, T. L., Lynch, D. K., & Russell, R. W. 1996, AAS/Division for Planetary Sciences Meeting, 28, 1092

Herbig, G. H. 1960, ApJS, 4, 337

Jäger, C., Molster, F. J., Dorschner, J., et al. 1998, A&A, 339, 904

MacKinnon, I. D. R., & Rietmeijer, F. J. M. 1987, Rev. Geophys., 25, 1527

Malfait, K., Waelkens, C., Waters, L. B. F. M., et al. 1998, A&A, 332, L25

Meeus, G., Waters, L. B. F. M., Bouwman, J., et al. 2001, A&A, 365, 476

Miyake, K., & Nakagawa, Y. 1995, ApJ, 441, 361

Reimann, H., Weinert, U., & Wagner, S. 1998, in Infrared Astronomical Instrumentation, ed. A. M. Fowler, Proc. SPIE, 3354, 865

Shu, F. H., Shang, H., Gounelle, M., Glassgold, A. E., & Lee, T. 2001, ApJ, 548, 1029

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[1] We cannot exclude the presence of small grains at large distances from the central star, where the temperature is too low for a 10 μm emission feature to be formed.