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SWS observations of young main-sequence stars with dusty circumstellar disks *

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Abstract. We present SWS full-scan observations of three objects that are thought to be in a stage of evolution between the youngest, embedded, Herbig Ae/Be stars and Beta Pictoris, a young main-sequence star with a circumstellar disk. The 8-12 μm spectra of all three stars cannot be understood in terms of purely amorphous silicates, but require the presence of crystalline silicates in different amounts. Around two objects both oxygen-rich and carbon-rich dust particles are present: the spectrum of HD 100546 displays the full set of UIR features; in the spectrum of HD 142527 both the 3.29 and 3.42 μm emission features are observed, as well as a strong 3.51 μm feature. The spectrum of HD 100546 is extremely rich in silicate features in the spectral range from 20 to 45 μm; some of these features strongly suggest the presence of appreciable amounts of crystalline silicates.

Key words: Circumstellar matter – Stars: Individual: HD100546 – Stars: Individual: HD142527 – Stars: Individual: 51 Oph – ISM: abundances – Infrared: ISM: lines and bands

1. Introduction

The discovery by IRAS of cool dusty disks around main-sequence stars such as Vega, Fomalhaut and Beta Pictoris has opened new prospects of studying observationally the processes that accompany the formation of planetary systems around stars. The evolved nature of Vega and Fomalhaut (Backman and Paresce 1993) suggest that the debris disks of these stars are not planetary systems that are presently being formed, but rather that collisions of small bodies continuously replenish the disks. In the case of Beta Pictoris, however, the photospheric parameters are those of a ZAMS object (Holweger and Rentsch-Holm 1995); even for this star continuous replenishment of the dust disk is required in order to explain the still high infrared excess, and arguably this replenishment is linked with the existence of large numbers of infalling bodies whose impacts on the star are frequently observed (e.g. Lagrange et al. 1996).

The IRAS mission has also revealed much larger infrared excesses in many other objects with masses similar to Vega, Fomalhaut and Beta Pictoris, i.e. a few solar masses (e.g. Walker and Wolstencroft 1988, Oudmaijer et al. 1992). Some of these objects, the Herbig Ae/Be, hereafter Haebe, stars occur in star-forming regions, others are isolated objects. In this paper, we present ISO-SWS observations of three such isolated large-excess stars, 51 Ophiuchi, HD 142527 and HD 100546. Our working hypothesis is that these objects, which present several characteristics typical for Haebe stars (Hα emission, high excesses) are intermediate in age between the youngest, still partially embedded, Haebe stars and young Vegatype stars such as Beta Pictoris and also HR 4796 (Jura 1990; Stauffer et al. 1995).

The goal of our ISO programme on isolated Haebe stars and Vegatype stars is to characterize the circumstellar dust grains in these objects and eventually to un-

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ravel the evolution of their circumstellar disks. The spectroscopic capability of ISO offers an unprecedented opportunity of describing all the solid-state emission features of these disks. An important fraction of these features fall within the spectral range covered by SWS; therefore full AOT-01 scans were obtained. For a description of the instrument and its main features, we refer to de Graauw et al. (1996) and to Kessler et al. (1996), both appearing in this issue of A&A. Since the energy distributions typically peak near 60 μm, it is expected that similar observations with LWS will yield important additional information. By focussing on isolated objects, we are not faced with interpretation problems due to the presence in the slit of remnants of the loose circumstellar envelope which characterizes the still embedded Haebe stars. However, the study of the spectra of these youngest Beta Pictoris progenitors will be important to describe the earliest evolution of dust debris disks as well. Thanks to the extended lifetime of the ISO mission, it may also be possible to study Beta Pictoris itself; unfortunately, most other Beta Pictoris-like stars are rather faint to be observed at high spectral resolution with ISO.

2. Targets and observations

The object 51 Ophiuchi (B9.5Ve) is often considered as a close analog to Beta Pictoris. Its infrared excess is larger than that of Beta Pictoris (Waters et al. 1988), but smaller than that of the two other objects considered here; it is rather flat up to 12 μm and rapidly decreases at longer wavelengths. The optical spectrum reveals ionised circumstellar gas (Waters et al. 1988), and the Ca K lines suggest the presence of infalling bodies (Lagrange et al. 1990).

The star HD 100546 (B9Vne) is one of the few Haebe-like stars that is close enough so that an IRAS LRS spectrum could be obtained. Hu et al. (1989) pointed out the peculiarity of this spectrum, which peaks near 11 μm and suggested the presence of SiC grains. Sitko et al. (1996) pointed out that a more likely interpretation is that the 11 μm emission is due to the presence of olivine in a crystalline form. From a study of IUE spectra of this star, Grady et al. (1996) report the spectacular presence of accretion events on the star, which they attribute to infalling planetesimals. This object has the largest infrared flux in our sample, peaking at 242 Jy at 25 μm.

The star HD 142527 (F6IIIe) was considered by Pottasch and Parthasarathy (1988) as a possible post-AGB star, on the ground of its infrared excess and luminosity class. However, our unpublished spectra and photometry show that this object is not of the high luminosity typical for post-AGB stars, and presents the typical characteristics of a Haebe star. It is the coolest and presumably lowest-mass star in our sample. As for HD 100546, the infrared excess of this star is huge; the energy distribution derived from the IRAS observations peaks at 105 Jy at 60 μm.

As mentioned before, only AOT-01 scans were obtained for the three stars considered, 51 Ophiuchi, HD 100546 and HD 142527. They were taken with speeds 3, 1, and 2 respectively. Each spectrum was processed using the SWS Interactive Analysis and the standard SWS pipeline software and calibration files. Details of the processing chain and the calibrations may be found in de Graauw et al. (1996), Schaeidt et al. (1996), and Valentijn et al. (1996).

The final spectra were produced by scaling the flux densities of the different detectors to the median, sigma-clipping the spectra with $\sigma = 1.5$, and rebinning to the expected resolution.

3. The 8-12 μm silicate feature

A distinctive spectral feature of the Beta Pictoris disk is the silicate emission in the 10 μm region. This feature has been observed from the ground by Telesco and Knacke (1991) and by Knacke et al. (1993). These authors observed that the silicate feature observed in Beta Pictoris differs significantly from that of typical 'astronomical silicate' as observed in the dust shells of AGB stars and in the ISM, in the sense that it peaks at 11 μm rather than at 9.7 μm. This difference is attributed to the presence of an additional crystalline silicate component in addition to the usual amorphous component. The similarity of the Beta Pictoris silicate feature with that observed for comet P/Halley (Campins and Ryan 1989) and other comets (Hanner et al. 1994) is striking.

Ground-based 10 μm spectra of these rather faint objects are severely hampered by the important atmospheric emission at these wavelengths, and in particular also by the strong ozone absorption near 9.5 μm. It therefore seems sound to base an accurate and unambiguous confrontation of observed spectra with theoretical models on space-borne data.

In Figure 1 we present the 10 μm spectra for the three programme stars. With the current status of data reduction it is premature to discuss the reality of narrow features in the spectra. However, the overal trends are reliable. For 51 Oph we observe a fairly steep rise between 8 and 10 μm and a flat spectrum between 10 and 11.5 μm, in good agreement with the ground-based findings by Knacke et al. (1993). In the cases of HD 142527 and HD 100546 the rise extends from 8 to 11 μm and is followed by a fairly rapid decrease towards the underlying dust continuum.

It is clear that amorphous silicates cannot fully account for the silicate emission of these stars, but that an additional crystalline component is present in a fraction that is relatively small in 51 Oph and larger in the two other objects. In the case of HD 100546 a strong band peaking at 11.25 μm is observed, which may be partially due to the emission of partially crystalline olivine at 11.2 μm. However, at least a fraction of the feature in this object

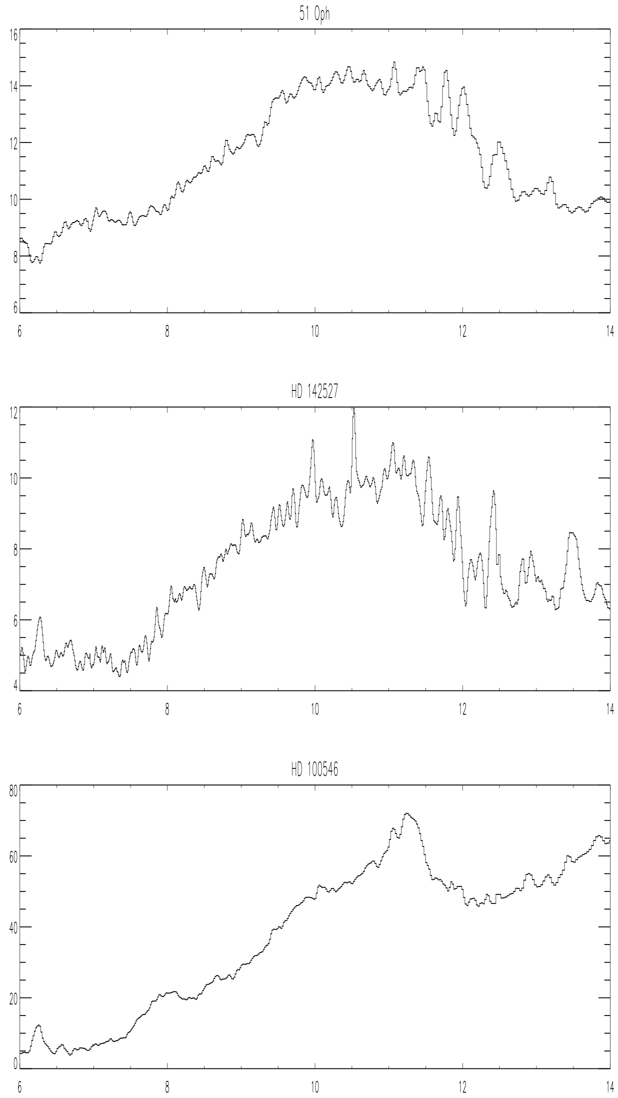

Fig. 1. The observations of the 8-12 μm silicate features in 51 Oph, HD 142527 and HD 100546. Wavelengths on the abscissa are in μm, fluxes on the ordinate are in Jy.

must be attributed to the 11.3 μm feature of carbon-rich particles as well (see following section).

4. Emission by carbon-rich particles

It is apparent from Figure 1 that the 11.3 μm feature of HD 100546 is accompanied by the other members of the family of the so-called 'unidentified infrared features' (UIRs) which are attributed to small carbon-rich particles, the most popular explanation being in terms of PAHs (Leger and Puget 1984). The 3.3 (not on the figure), 6.2, 7.7, and 8.8 μm all clearly occur for HD 100546. In the case of 51 Oph the PAH features are weak or not present.

In Figure 2 we show the spectrum of HD 142527 in the region of the 3.29 μm PAH feature. This feature is accompanied by the satellite feature at 3.42 μm and also by a prominent emission peaking at 3.51 μm. The 3 μm spectrum of HD 142527 is then rather similar to that of the Haebe star HD 97048 (Blades and Whittet 1980). The 3.51 μm feature was first seen in HD 97048, and subsequently also in the young object Elias 1 (Whittet et al. 1984) and in the post-AGB stars HR 4049 (Geballe et al. 1989) and HD 52961 (Oudmaijer et al. 1995). This feature has been attributed to C-C overtone and combination bands in highly excited PAHs or amorphous carbon particles by Schutte et al. (1990). We have also recovered this feature in the spectrum of HD 100546.

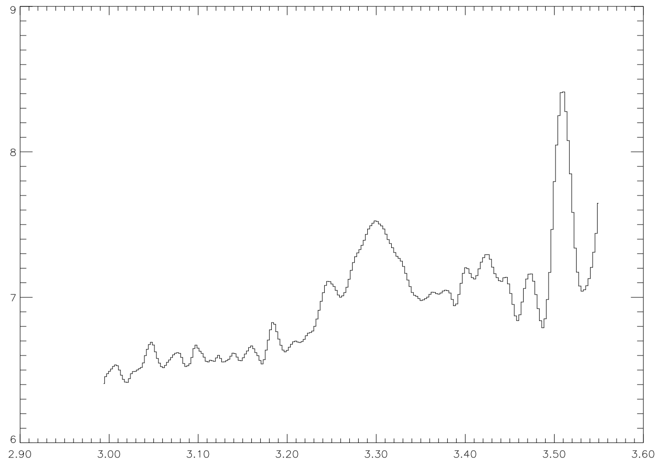

Fig. 2. The 3 μm spectrum of HD 142527. Wavelengths on the abscissa are in μm, fluxes on the ordinate are in Jy.

Inspection of the SWS spectra of other programme stars suggests that the occurrence of PAH features in the oxygen-rich dust surrounding young stars is rather common, confirming the results of the ground-based survey by Sylvester et al. (1996).

5. Silicate features in the 20-45 μm region

The infrared spectral region that is accessible from the ground is known to be richer for carbon-rich environments than for oxygen-rich ones. In contrast, laboratory studies (Koike et al. 1989, Jäger et al. 1995) predict a large variety of oxygen-rich features in the spectral region beyond 20 μm. As is shown by Waters et al. (1996), the ISO data fully confirm this expectation.

In our sample so far, the object HD 100546 seems to present the most promising case for a detailed study of the characteristics of oxygen-rich dust. On Figure 3 we show the full SWS spectrum of this object. Very prominent emission features are observed to peak at 23.7 and 33.5 μm. So far, the expected 18 μm silicate feature is not prominent, being blurred in the steep rise of the spectrum between 13 and 20 μm. Some uncertainty remains about the reality of the feature that is observed at 19.6 μm, which occurs at the edge of two bands of the spectrometer.

Distinct features are observed at 27.7 and 36 μm. Finally, the 43 μm feature which is observed for some oxygen-rich evolved objects (Waters et al. 1996), is not prominent in HD100546.

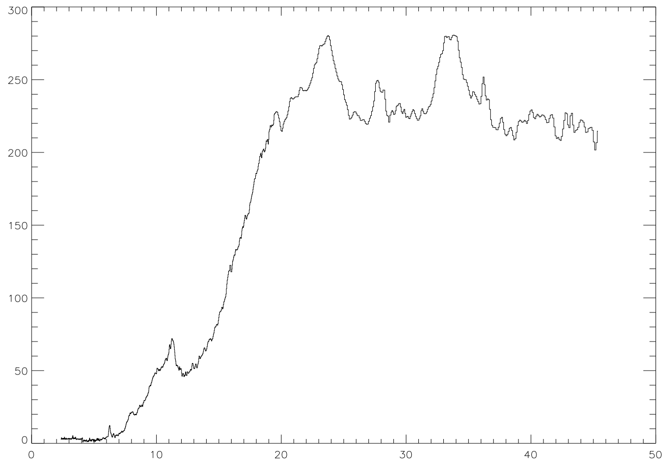

Fig. 3. The full SWS spectrum of HD 100546. Wavelengths on the abscissa are in μm, fluxes on the ordinate are in Jy.

Herter et al. (1987) obtained airborne spectrophotometry of comet P/Halley from 16 to 30 μm. They observed a narrow emission feature at 28.4 μm and weaker features at approximately 23.8 and 26.7 μm; in their spectrum some indication can be found for an additional weak feature near 19.6 μm. The coincidence of these features with those observed for HD 100546 is striking. It should be noted, however, that the airborne observations by Glaccum et al. (1987), obtained at other dates, could not confirm the results by Herter et al. (1987).

According to Koike et al. (1989) spectral features at 23, 33 and 36 μm could be indicative of the presence of silicates in crystalline form. Koike et al. (1993) pointed out that forsterite produces peaks at 20, 24, and 34 μm, which weaken as the Mg/Fe ratio in the grains decreases. Since the 23.7 and 33.5 μm peaks are so strong in HD100546, and also the 19.6 μm peak is well observed, our data suggest that the circumstellar dust of HD100546 is rich in forsterite, with a relatively large Mg content. According to Koike et al. (1993) a 28 μm peak, which is also observed in HD100546, is present for all olivines. On the other hand, the 43 μm peak, more typical for pyroxenes, is not prominent in HD100546. In Section 3, we have indicated evidence that also the shape of the 10 μm emission of HD 100546 points to a component of crystalline silicates.

6. Discussion

The results presented in this paper confirm, if it were necessary, that these large-infrared-excess isolated main-sequence stars are linked to both the Haebe stars and Beta Pictoris-like objects. The crystalline silicate feature of the latter is also a distinct characteristic of 51 Ophiuchi, HD 100546 and HD 142527. The link with the Haebe stars, suggested by the spectral types, Hα emission and infrared energy distributions, is now confirmed by the 3.52 μm features (HD 100546 and HD 142527) that were previously observed for the Haebe stars HD 97048 and Elias 1.

The ISO data confirm the extraordinary richness in terms of solid-state features of the infrared spectra of the circumstellar disks of young stars. This richness certainly owes much to the relatively large densities of these disks and the occurrence of substantial UV radiation of the central star. The presence of small carbon-rich particles in these oxygen-rich environments is probably due to a chemistry that follows the dissociation of CO molecules by the UV radiation field.

The major new result of this paper is the detection of crystalline silicates in the circumstellar media of these stars. While the silicates in the interstellar medium essentially appear to be amorphous (Mathis 1990 and references therein), crystalline silicates do occur in appreciable amounts in meteorites (Brownlee 1985), interplanetary dust particles (Sandford and Walker 1985) and comets (Hanner et al. 1984). It is tempting to conclude that the processing from amorphous to crystalline grains takes place during the early evolution of the debris disks that surround young stars. When SWS spectra of more objects become available, a quantitative analysis of objects in different evolutionary stages should reveal how composition and size distribution of the dust particles change with time.

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