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Letter to the Editor

The spectrum of the young star HD 100546 observed with the Infrared Space Observatory*

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Abstract. It is generally assumed that planets form in the dusty disks that surround young stars (Beckwith & Sargent 1996). The Infrared Space Observatory (Kessler et al. 1996) now enables us to determine the characteristics of these disks with unprecedented spectral resolution and signal-to-noise. We present here ISO spectra of the disk that surrounds the young star HD 100546. A remarkable variety of emission features of carbon- and oxygen-rich dust occurs. Most prominent are a series of emission features that can be attributed to silicates in crystalline form, mostly forsterite. In the interstellar medium and HII regions the silicate dust is mostly amorphous, but crystalline silicates are found in comets, meteorites and interplanetary dust particles. The forsterite features of HD 100546 are astonishingly similar to those observed in the ISO spectrum of Comet Hale-Bopp (Crovisier et al. 1997), strengthening the hypothesis that the disk around HD 100546 contains a huge swarm of comets (Grady et al. 1997). We argue that the crystallisation process occurs during the early evolution of the circumstellar disks of young stars and speculate about the formation of an Oort cloud around HD 100546.

Key words: circumstellar matter – stars: individual: HD 100546 – comets: individual: Hale-Bopp – infrared: ISM: lines and bands – solar system: formation

1. Introduction

The circumstellar disks that accompany the star formation process disappear on a timescale of several million years. During this evolution, the infrared radiation which characterizes the disk, diminishes. Nevertheless, faint disks appear to survive in several main-sequence stars, such as Beta Pictoris and Vega, suggesting a reservoir of bodies the collisions of which may replenish the disk. The star HD 100546 is a so-called 'isolated Herbig Ae/Be star': its strong infrared excess and circumstellar HI emission argue for a young age, but it no longer occurs inside a star-forming region, so that it can be considered a transition object between the youngest, embedded, stars and main-sequence objects such as Beta Pic. This picture is confirmed by Hipparcos measurements of this star, which, confronted to stellar-evolution models, suggest a main-sequence age slightly in excess of 10 Myr (van den Ancker et al. 1997). Moreover, HD 100546 is an ideal target for infrared spectroscopy of a circumstellar disk, since it is bright and since its isolated nature avoids confusion with the loose surroundings that occur for embedded sources.

2. Observations

We have obtained a full scan of the spectrum of HD 100546 (Waelkens et al. 1996) in the 2.4-45 μm range with the Short Wavelength Spectrometer (SWS) (de Graauw et al. 1996) on board of ISO on August 18, 1996 (speed 4). A full scan in the 45-180 μm range was obtained with the Long Wavelength Spectrometer (LWS) (Clegg et al. 1996) on February 29, 1996. The final spectrum was produced using the standard pipeline. By scaling the flux densities of the different detectors to the median, sigma-clipping the spectrum with $\sigma = 2$, and rebinning to the expected resolution, we obtained the final result. The full SWS-LWS spectrum of HD 100546 is shown on Fig. 1.

3. Identification and modelling

The spectrum is characterized by a large variety of narrow and broad emission features superposed on a continuum. From earlier photometric observations (e.g. Hu et al. 1989; Malfait et al. in press), it is known that the circumstellar continuum consists of a warm and a cool component which intersect at 6 μm. Immediately apparent circumstellar emission features are the 3.29, 6.24, 7.9, 8.6 and 11.3 μm PAH bands, a series of mid-IR bands

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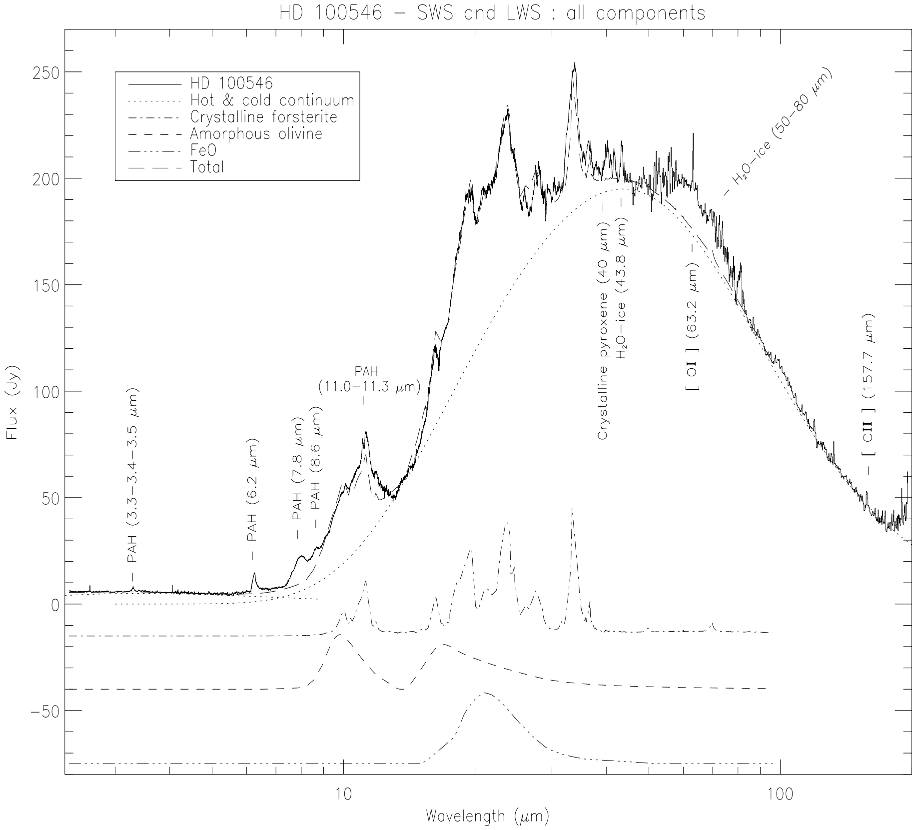

Fig. 1. The full SWS-LWS spectrum of HD 100546 shows a large variety of (optically thin) emission features. Direct fitting of the underlying continuum is only possible in the far-IR, which determines the density law of the dust. A good match to the whole spectrum (see below) requires components of crystalline and amorphous silicates, FeO, H_2O-ice as well as PAHs.

that are discussed below, and a broad shoulder around 60 μm due to crystalline water ice, besides atomic lines from HI, [OI] at 63 μm, and the [CII] 158 μm line. The latter may indicate the presence of a photon dominated region around the star, but may also be due to background contamination. A detailed analysis of the PAH features will be carried out when the data for a broader sample are available. An interesting remark that can already been made is that since a band at 3.45 and one at 3.52 μm is present, some hydrogenation has occured (Schutte et al. 1990).

The wealth of solid-state emission features precludes a clear definition of the circumstellar continuum. Therefore, in interpreting the spectrum, we have adopted a strategy in which the emission lines are iteratively subtracted, as is illustrated on Fig. 1 and Fig. 2. The strong emission bands at 10.2, 11.4, 16.5, 19.8, 23.8, 27.9, and 33.7 μm, and weaker ones at 10.5, 12.0, 21.7, 31.3, 36.3, and 69 μm closely match in position and strength those of crystalline forsterite ($\mathrm{Mg_2SiO_4}$) as determined from laboratory spectra (Koike et al. 1993). These labspectra are obtained for forsterite particles with a radius of 0.5 μm. Such small grains should, however, already have been removed from the HD 100546 disk due to radiation pressure and also to Poynting-Robertson drag. It is, however, also likely that collisional replenishment with small particles has occured.

Other crystalline olivines with a different Mg/Fe ratio produce similar spectra as forsterite, but agree less well with the observations. The dust of HD 100546 clearly contains much more olivines than pyroxenes, though the 40.5 μm emission feature points to the presence of some crystalline clino-pyroxene. The best discriminant for the Mg/Fe ratio probably is the longest-wavelength emission feature, which occurs near 69 μm for pure forsterite and at 73 μm or more for mixtures with more than 10% iron (Koike et al. 1993); in the LWS spectrum of HD 100546 a weak but distinct emission feature is observed at 69 μm (Fig. 3). The strengths of the features between 11 and 30 μm are correctly described with a unique temperature of 210 $\pm$ 5 K, but cooler particles ($\sim$ 40-55 K) have to be invoked in order to account for the longer-wavelength features (Fig. 4). These temperatures have been derived by interpreting the different strengths of the forsterite features in the spectrum compared to lab-measurements (Koike et al. 1993) as due to temperature effects, using the model by Waters et al. (1988) (method similar to Bouwman et al., 1997).

After subtraction of the crystalline forsterite features from the SWS spectrum, a broad 10 μm band persists, that is partly affected by PAH emission, but mostly due to amorphous silicate. As was anticipated from a study of the IRAS LRS spectrum (Grady et al. 1997), this feature is best matched with olivines rather than pyroxenes, with a large Mg/Fe ratio. After accounting for this amorphous silicate component and the accompanying 18 μm feature, broad emission bands persist around 23 and 60 μm. The former can be reproduced successfully with the optical constants of FeO (Henning et al. 1995), the latter by those of crystalline water ice. The water ice band at 43 μm is much weaker than the one at 60 μm, from which it follows that the water ice is located in the outer parts of the disk, with a temper-

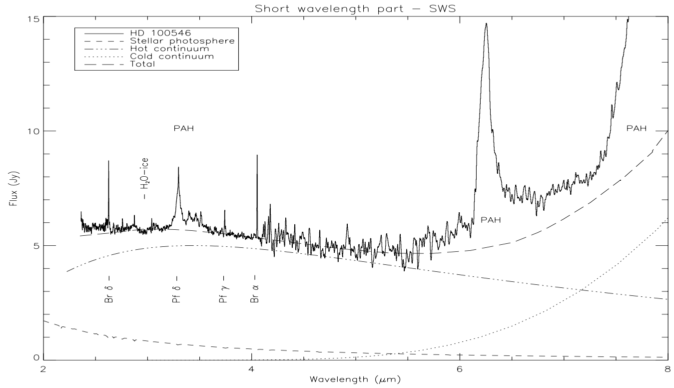

Fig. 2. Short wavelength part of the spectrum

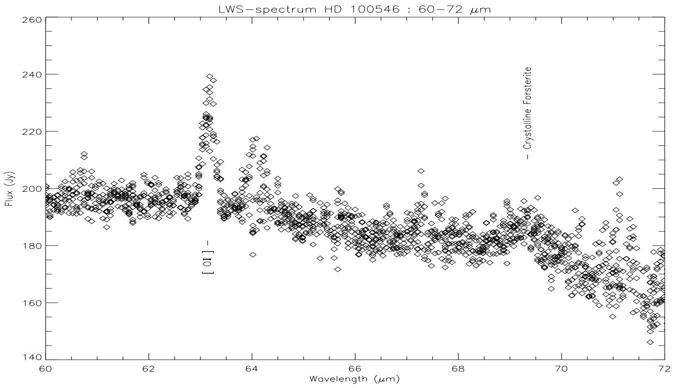

Fig. 3. Part of the LWS spectrum displaying the 69 μm forsterite emission. The location in wavelength of this feature is critically dependent on the Mg/Fe ratio of the crystalline olivine dust. Moreover, the presence of this weak feature in the spectrum indicates that the crystalline forsterite is not only confined to the inner part of the dust disk. In addition to this emission peak, we also see the [OI]-line at 63 μm.

ature below 50 K, arguably as a coating on a crystalline silicate core (Omont et al. 1990). Barlow (1997) noted that the 60 μm H_2O-ice feature in NGC 6302 is accompanied by another broad feature between 87 and 98 μm; as can be seen on Fig. 1, this feature is also apparent in the LWS spectrum of HD 100546.

Once all these solid-state features are removed (but not before) it is possible to represent the underlying hot and cold continua with a model. Applying the optically-thin model developed by Waters et al. (1988), while adopting the usual emissivity law $Q_\lambda \propto \lambda^{-1}$, a best fit for the cold continuum is found for a dust surface density law dropping as $r^{-1.4}$ and for inner and outer disk temperatures of 210 $\pm$ 10 and 43 $\pm$ 2 K, respectively. Fitting the hot continuum requires an emissivity law $Q_\lambda \propto \lambda^{-1.2}$ and a steeper density drop, proportional to r^{-2}, yielding inner and outer temperatures of 1550 $\pm$ 50 and 350 $\pm$ 20 K, respectively.

More radiative modelling will be needed in order to place firm constraints on the amount of different dust components, though we can already say that the fraction of crystalline over amorphous silicates will at most be 0.1, since a small degree of crystallisation changes the optical properties drastically (see eg. laboratory measurements by Hallenbeck et al. (1997))

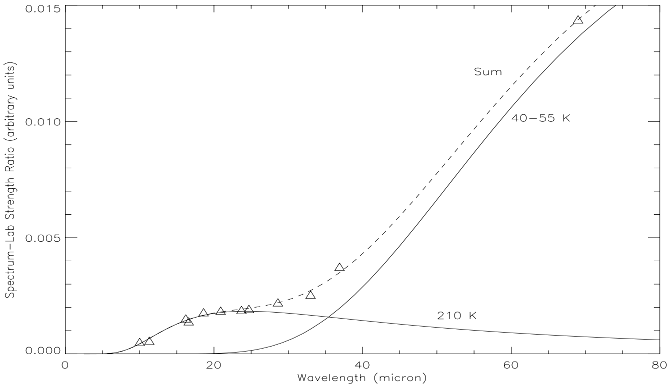

Fig. 4. Ratio between the strengths of the forsterite features in the spectrum and in the laboratory measurement (Koike et al. 1993) (expressed in arbitrary units), modelled with two components with temperatures of 210 K and 40-55 K.

4. Discussion and conclusions

Of the crystalline olivine features, only the 11.36 μm feature has been reported for stars before ISO. It has been observed in the IRAS-LRS spectrum of HD 100546, but suffers from blending with the 11.3 μm PAH-feature. The 11.36 μm emission peak has also been observed in the spectra of Beta Pic and a few similar stars (e.g. Telesco & Knacke 1991; Knacke et al. 1993; Sylvester et al. 1996). It is remarkable that the silicate dust in the interstellar medium (ISM) and in the HII regions where young stars form, appears to be essentially amorphous. The main features of the so-called ‘astronomical silicates’ (Draine & Lee 1984) are the broad 9.7 μm band due to the $\mathrm{Si-O}$ stretch and the somewhat weaker 18.6 μm band due to the $\mathrm{Si-O-Si}$ bending mode. Laboratory experiments on silicate glasses with realistic cosmic compositions are able to reproduce these bands fairly reliably, and do not predict important features beyond 20 μm (Dorschner et al. 1995).

On the other hand, there are several pieces of evidence for the presence of crystalline silicates in solar-system material. Meteoritic silicates are much more crystalline than the interstellar varieties (Brownlee 1985), as are interplanetary dust particles (IDPs) collected from high-flying aircraft (Sandford & Walker 1985). In several solar-system comets the 10 μm silicate feature has a shape which significantly deviates from that of typical astronomical silicate (Hanner et al. 1994): the peak of the feature at 11 rather than at 9.7 μm can be explained by an additional crystalline-olivine component. In addition, the presence of crystalline features at 23.8 and 28.4 μm has been reported for comet P/Halley from airborne spectrophotometry in the region from 16 to 30 μm (Herter et al. 1987).

More spectacular even is the nearly perfect match of the crystalline forsterite features of HD 100546 with those observed with SWS for comet Hale-Bopp (Fig. 5) (Crovisier et al. 1997). Our observations of HD 100546 therefore are a strong confirmation of the presence of a massive cloud of comets surrounding this star. Evidence for comets orbiting Beta Pictoris was first proposed (Ferlet et al. 1987) as an explanation for the intermittent absorption features in terms of infall of small bodies onto

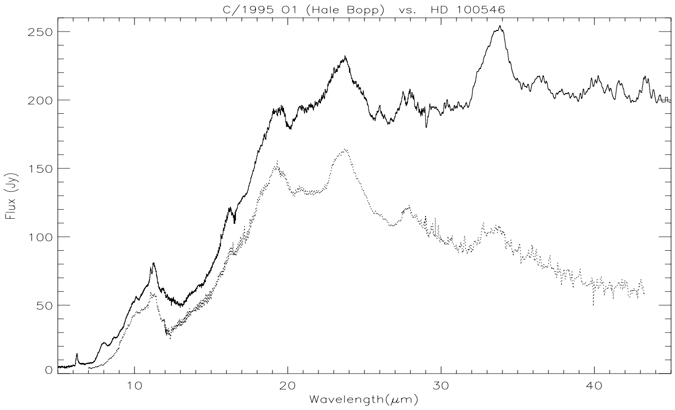

Fig. 5. Comparison between the ISO-SWS spectrum from the comet C/1995 O1 (Hale-Bopp) (courtesy Crovisier et al. 1996) with the spectrum of HD 100546. HD 100546 is represented by a full line, while the dotted line corresponds to Hale-Bopp.

the star. Recent IUE observations show that also HD 100546 is exposed to an intense bombardment by small bodies (Grady et al. 1996), from which can be seen that the silicates are probably magnesium-rich (Grady et al., 1997). Comparing the strength of the features in the objects, adopting a distance of 103 ± 7 pc for HD 100546 (van den Ancker et al., 1997), and taking advantage of the fact that the temperatures of the emitting bodies are about the same, we find that the forsterite emission of HD 100546 is equivalent to that of 10^{13} comets such as Hale-Bopp!

What are the conditions which favor the formation of crystalline silicates? The growth of such silicates requires both higher temperatures and larger densities than those which prevail in the Oort cloud where most comets reside. It has been proposed (Fernandez 1978) that the Oort cloud owes its origin to the ejection towards the outer solar system of residual solid matter by the giant planets. An exciting prospect is that this process is actually happening in the disk of HD 100546. In this scenario, the crystalline silicates are formed close to the central star. It is unlikely, however, that crystallisation has occured at temperatures as low as 210 K (Hallenbeck et al. 1997), which is the temperature of the inner edge of the cool disk, where most forsterite emission originates.

The presence of crystalline material farther out, as attested by the 69 μm feature, could then be due to the destruction through collisions of comets that have migrated farther outwards. A sizeable fraction of the comets is also expected to migrate inwards, and such objects have been claimed to be responsible for the intermittent absorption features that are observed; since the maximum dust temperatures of the warm inner disk corresponds to the sublimation temperature of silicates, it certainly is a possibility that the inner dust is mainly composed of comet debris. Thus, besides explaining how comets such as Hale-Bopp can contain appreciable amounts of crystalline material, the scenario provides indirect evidence that giant planets have already been formed in the HD 100546 system, supporting the hypothesis that the dip around 6 μm in the energy distribution of this and similar stars is the result of the formation of larger bodies (Waelkens et al. 1994).

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