ISO Spectroscopy of Protoplanetary Disks around Herbig Ae/Be Stars

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Abstract

I present an analysis of infrared solid-state features present in the sample of 46 Herbig Ae/Be stars observed spectroscopically by the *Infrared Space Observatory* (ISO). The presence, strength and shape of solid-state bands was compared to other indicators of circumstellar material, such as gaseous emission lines, optical variability and sub-mm continuum fluxes. The appearance of the 10 μm silicate feature in emission or absorption is clearly related to the strength of gaseous emission lines that are believed to be powered by accretion. The presence or absence of PAH features appears to be unrelated to any of the other indicators of circumstellar material studied. I conclude that the infrared spectra of most stars in our sample are dominated by a circumstellar disk that is passively heated by the central star. Some evidence for grain growth and mineralogical processing of material in these disks is presented.

1. Introduction

Herbig Ae/Be stars are young intermediate-mass (2–10 $M_\odot$) stars which are still surrounded by gas and dust from their natal cloud. Many are surrounded by circumstellar disks which are believed to be the site of on-going planet formation. The dust in these circumstellar disks, heated by the central star and possibly by viscous heating of material that is being accreted, shows up as excess emission above photospheric levels at infrared to sub-mm wavelengths. The circumstellar gas shows up in free-free emission at radio wavelengths and through gaseous emission lines. Large-amplitude ($> 1^m$) variations in optical brightness are seen in some Herbig Ae stars, and are commonly ascribed to variable amounts of extinction of the starlight due to dust circumstellar clouds moving in and out of our line of sight towards the central star. Therefore the amount of optical variability may be taken as an indicator for the presence and orientation of circumstellar disks in HAeBes. The chemical and mineralogical composition of the dust remained poorly studied until the 1995 launch of the *Infrared Space Observatory* (ISO). This first possibility to study the complete infrared spectrum of these objects in detail revealed a large variety in dust properties, from small aromatic hydrocarbons to silicate dust. Moreover, some sources were shown to contain partially crystalline dust grains, similar to those found in comets in our own solar system (Malfait et al. 1998, 1998, A&A 332, L25; van den Ancker et al. 1999, A&A 357, 325). Here we present the first complete inventory of solid-state features in all Herbig Ae/Be stars observed spectroscopically by ISO and investigate their correlation with the traditional tracers of circumstellar material outlined above.

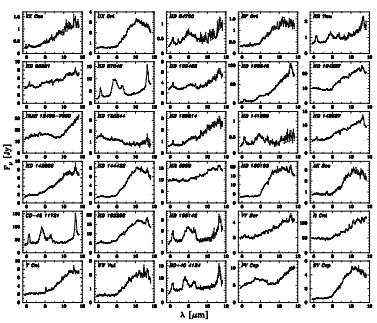

Fig. 1. ISO-PHOT spectra of the program stars.

2. Data Analysis

A careful inspection of the ISO data archive revealed the presence of spectroscopic data on 46 Herbig Ae/Be stars, obtained with the short-wavelength spectrometer (SWS; de Graauw et al. 1996, A&A 315, L49) and the spectroscopic mode of the photometer (ISOPHOT; Lemke et al. 1996, A&A 315, L64). Data were retrieved and reduced in a standard fashion, after which they were corrected for remaining fringing and glitches, averaged, and rebinned to a lower spectral resolution. The resulting spectra are shown in Figs. 1 (ISOPHOT) and 2 (SWS).

Spectra were inspected for the following features:

- The emission bands at 3.3, 3.4, 6.2, 7.6, 7.8, 8.6, 11.3 and 12.7 μm, often attributed to polycyclic aromatic hydrocarbons (PAHs) (e.g. BD+40° 4124).
- The emission band at 3.43 microns due to small diamond crystals (e.g. HD 97048).
- The broad band around 10 μm due to amorphous silicates (e.g. AB Aur, PV Cep).
- Sharper bands at 10.2, 11.4, 16.5, 19.8, 23.8, 27.9 and 33.7 μm due to crystalline silicates (e.g. HD 100546).

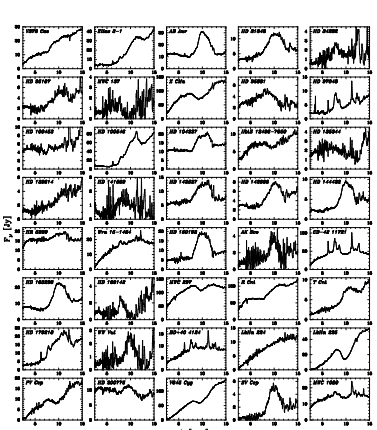

Fig. 2. ISO-SWS spectra of the program stars.

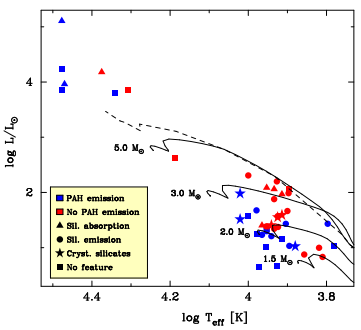

Fig. 3. Hertzsprung-Russell diagram with the position of our program stars. The plot symbol indicates the solid state components present in the ISO spectra. Sources which do show amorphous silicate in absorption are plotted as triangles, those who only show amorphous silicates in emission as dots, the ones which show both crystalline and amorphous silicates in emission are plotted as stars, whereas sources without in which no silicate feature could be discerned are plotted as squares. Plot symbols are blue for the sources which show PAH emission, whereas they are red for sources which do not show the PAH emission bands. Also shown in the figure are the pre-main sequence evolutionary tracks (solid lines) and the birthline (dashed line) by Bernasconi (1996, A&AS 120, 57).

3. Results

We investigated the correlation of infrared spectral features with parameters of the systems from literature (T_*, level of optical variability, accretion rates, sub-mm flux) using different diagnostic diagrams (Figs. 3–9). We notice the following effects:

- PAH features are present in about half the stars in our sample, with no strong preference for spectral type.
- However, sources which show PAH emission appear to be located closer to the zero-age main sequence in the HRD than sources which do not show PAH emission.
- Only three sources in our sample (HD 97048, Elias 3–1 and MWC 297) show the 3.53 μm emission feature attributed to nano-diamonds.
- Amorphous silicate emission is found in both optically variable and optically constant Herbig Ae stars, with about equal frequency and strength. Crystalline silicates were only found in optically constant stars.
- There is no strong dependence of the frequency and strength of solid-state emission features with the type of Hα emission-line profile shown by our program stars.
- There appears to be a fairly good correlation between accretion rates (as derived from infrared H I emission lines) and the appearance of the amorphous silicate feature in absorption in emission.
- Crystalline silicates (only found in emission) are present in 15% of the sources, all of spectral type B9 or later.
- No strong correlation of the presence or strength of infrared solid-state features with dust masses derived from sub-mm photometry was found.
- However, there may be some correlation between the slope of the energy distribution in the sub-mm (indicative of grain growth), and the presence of crystalline silicates.
- Sources which show evidence for crystalline silicates are on average closer to the zero-age main sequence than sources which only show amorphous silicates.

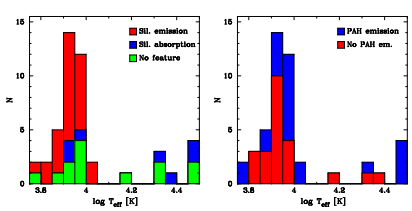

Fig. 4. Distribution of sources that show the 10 μm silicate feature in emission, absorption, or do not show this feature, as a function of effective temperature of the central star (left) and distribution of sources with or without the PAH bands in emission as a function of stellar effective temperature (right).

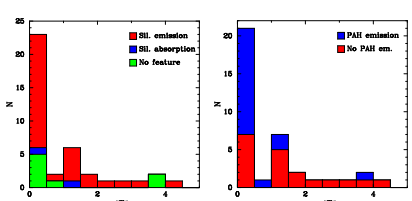

Fig. 5. Distribution of sources that show the 10 μm silicate feature in emission, absorption, or do not show this feature, as a function of variability in the V band (left) and distribution of sources with or without the PAH bands in emission as a function of optical variability (right).

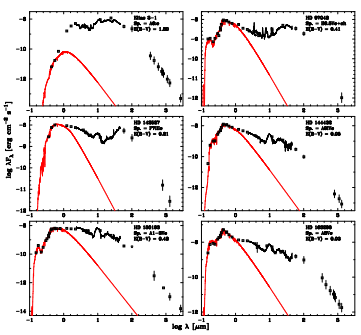

Fig. 6. Examples of Spectral Energy Distributions (SEDs) of Herbig Ae/Be stars. Also shown in each plot (red lines) is the model for the emission from the stellar photosphere used to derive the excess emission as a function of wavelength.

4. Conclusions

The strongest correlation found is between the strength of infrared H I emission lines (directly related to the accretion luminosity), and the 10 μm silicate feature: stars with accretion rates higher than a few times 10^{-7} $M_\odot$ yr^{-1} typically show silicate in absorption, whereas the more slowly accreting systems show silicate emission (Fig. 7). This can be simply explained by assuming that we are looking at a disk that is optically thick at 10 μm and is heated both by viscous dissipation of energy from accretion, and by direct radiation from the central star. When the heating due to accretion dominates, the mid-plane of the disk will be cooler than the surface layers, and we see the silicate feature in absorption. In contrast to this, the surface layers will be hotter than the mid-plane in systems in which the accretion has largely ceased, and we will see the 10 μm silicate feature in emission.

In most sources with absorption due to amorphous silicates, we also observe the absorption bands due to H_2O and CO_2 ice, with a relative strength comparable to that in the interstellar medium. However, two sources (Z CMa and V645 Cyg) show strong silicate absorption, but no evidence for water or CO_2 ice bands, demonstrating the chemical evolution that has taken place in the wide circumstellar environment of these objects.

No strong correlation between spectral type and PAH emission could be found. This is surprising, since the excitation of PAH molecules is thought to require intense ultraviolet radiation fields. This means that on average the particles responsible for the PAH emission must be closer to the central star, and hence suffer less geometric dilution of the stellar radiation field, in Herbig Ae stars than in Herbig Be stars.

Both the differences in silicate and in PAH behaviour can be explained by assuming that the infrared spectrum of Herbig Be stars is in general dominated by their circumstellar envelope rather than a disk. In contrast, the more slowly evolving Herbig Ae stars have time to disrupt their envelope and their spectrum may be dominated by thermal emission from the protoplanetary disk.

Crystalline silicates, as are also found in comets in our own solar system, are visible in 15% of the late-type Herbig stars, all of systems that have low accretion rates, are relatively isolated and appear to be relatively old (a few million years). Therefore also in young stars longevity appears to be a prerequisite for the annealing process. These systems form a close analogue to the young solar system and may provide the strongest clue to date that the same processes that have led to rocky planets in our own solar system are also taking place around other stars.

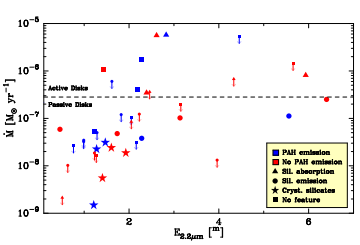

Fig. 7. Plot of the accretion rates of Herbig Ae/Be stars (as derived from infrared H I recombination lines) versus the excess emission above photospheric levels at K (2.2 μm). Sources which show PAH emission are plotted as blue symbols, whereas those that do not are plotted in red. Triangles indicate sources which show amorphous silicate in absorption, dots amorphous crystalline emission, stars both crystalline and amorphous silicates in emission and squares indicate sources without a strong 10 μm silicate feature. Note the clean separation between sources with 10 μm silicate absorption and silicate emission features in this diagram.

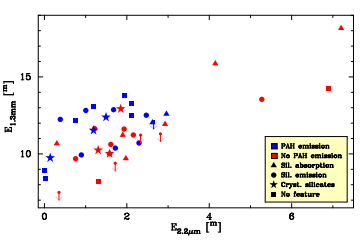

Fig. 8. Plot of excess emission above photospheric levels at K (2.2 μm) versus that at 1.3 mm for the stars in our sample. Plot symbols have the same meaning as in Fig. 6. The excess at K (i.e. the amount of small dust particles) correlates well the excess at 1.3 mm (i.e. the total mass of the disk).