Proto-Planetary Disks Around Herbig Ae/Be Stars: Constraints from ISO Spectroscopy

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Abstract
We have investigated the infrared spectra of all 46 Herbig Ae/Be stars for which spectroscopic data is available in the ISO data archive. We have classified the sample sources according to the strength of their mid-IR energy distribution. The systems with stronger mid-IR (20—100 micron) excesses relative to their near-infrared (1—5 micron) fluxes are called group I sources. This is confirmed by the significantly higher 11 micron full-width-at-half-maximum (FWHM) in these sources (Fig. 6). Sample stars that do not display PAH features at other wavelengths, are not expected to have PAH 11.2 micron feature. Hence the detected 11 micron feature is probably due to crystalline silicates only. We conclude that 1/3 of the sample stars display crystalline silicate emission in their spectra. The true fraction of systems that possess crystalline silicates in their disks will likely be higher, as the 11.3 micron feature is only sensitive to grains with temperatures above 100 K. No correlation is seen between the strength [F/C] of the amorphous 10 micron silicate feature (Si 9.7) and the 11 micron feature (Fig. 7). In addition, the PAH features are uncorrelated to the strength of the amorphous silicate features.

1. Sample
We have investigated the infrared spectra of all 46 Herbig Ae/Be stars observed with the Short Wavelength Spectrometer (SWS) and the Photometer (PHT) on board of the Infrared Space Observatory (ISO). Some examples are shown in Fig. 1. Our sample includes the solid-state bands at 3.3, 6.2, 7.7, 8.6 and 11.2 micron linked to Polyatomic Aromatic Hydrocarbons (PAHs), the reemission features at 3.4 and 3.5 micron (C—H stretch) and the crystalline silicate feature at 11.3 micron. We have detected PAH emission in 87%. Amorphous silicate emission was detected in the spectra of 52% of the sample stars, amorphous silicate absorption in 13%. We have detected crystalline silicate emission in 11 stars (24% of our sample), of which four (9%) also display strong PAH emission.

2. Correlations of the PAH Features
The line-over-continuum flux ratios (L/CF) of the PAH features correlate well over several orders of magnitude (Fig. 2). The PAH 6.2 and 7.7 micron. Nevertheless, when looking more closely, differences occur from source to source. In Fig. 3, the ratio of the line fluxes of the PAH feature at 8.6 and 6.2 micron is plotted versus the ratio of the line fluxes of the features at 3.3 and 6.2 microns. The full line in the plot represents the line flux ratio of MWC 1080 under variable extinction. From the figure it is clear that the observed scatter cannot only be due to extinction effects. Hence at least in some Herbig stars, the PAH molecules themselves are different. Possible reasons for these differences are PAH grain size, irradiation, chemical composition of the interstellar medium.

3. Crystalline silicates
The feature at 11 micron is a blend of the PAH 11.2 and the crystalline silicate 11.3 micron feature, when both are present. Fig. 5 shows that the four stars display this blend, since their 1 micron line flux is larger than the 3 micron line flux. The degree of crystallinity of the PAH molecules is directly exposed to radiation from the central star. In this model, self-shadowed disks should display weaker PAH emission than flared disks, consistent with our observations.

4. Solid-state bands and disk geometry
The spectral energy distribution (SED) of Herbig stars can be roughly classified in two groups: group I and Be stars with a strong mid-IR (60—100 micron), if it has Show modest mid-IR SEDs (Mees et al. 2001, A&A 365, 476). Dullemond (2002, A&A 395, 863) interprets this classification in terms of disk geometry: group I sources have flared disks, group II self-shadowed disks (Fig. 6). The classification of the sources can be expressed in a diagram like in Figs. 9 and 10. The strong mid-IR group II sources are cooler than the group I sources and appear in the lower right part of this diagram.

The plotting symbols in Fig. 9 are proportional to the strength of the PAH luminosity. Group II sources are clearly more moderate PAH emitters. PAH emission is believed to originate from the interstellar medium. The classification of the disk is group I sources makes that the PAH molecules in the surface layers of the disk directly to the stellar UV radiation field. In group II sources, the outer parts of the disk lie in the shade of the puffed-up inner rim and hence receive almost no direct stellar photons. This interpretation is consistent with the observations.

Fig. 10 shows that the 11 micron feature is similar in group I and II. The geometry of the disk does not seem to influence the small warm amorphous silicates that cause the feature. We conclude that the infrared solid-state bands of the disk exist with the interpretation of the infrared SED by the disk geometry. Preliminary results from our analysis of gas-phase optical emission lines support this hypothesis as well.

References

Fig. 2. Correlation of the PAH 6.2 and 7.7 micron feature. The line flux ratio of MWC 1080 under variable extinction is plotted versus the line flux ratio of ISO1080 under variable extinction. PAH molecules are thought to be excited by UV photons. An absorbed photon induces an electronic transition, which is followed by rapid transitions to lower levels, leaving most of the energy in the bending/stretching modes of the C-C and C-H bonds of the molecule.

Fig. 3. The line flux ratios of the PAH features at 3.4 and 3.5 micron times the PAH 6.2 and 7.7 micron feature. The PAH 6.2 and 7.7 micron feature are related to Polyatomic Aromatic Hydrocarbons (PAHs).

Fig. 4. The ratio of the near-to-mid-IR luminosity LNIR/LIR is plotted versus the IRAS [12]-[60] color (after van Boekele et al. 2001, A&A 365, 476). Dullemond (2002, A&A 395, 863) interprets this classification in terms of disk geometry: group I sources have flared disks, group II self-shadowed disks (Fig. 6). The classification of the sources can be expressed in a diagram like in Figs. 9 and 10. The strong mid-IR group II sources are cooler than the group I sources and appear in the lower right part of this diagram.

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Fig. 12. (right) The feature at 11 micron is a blend of the PAH 11.2 and the crystalline silicate 11.3 micron feature, when both are present. Fig. 5 shows that the four stars display this blend, since their 1 micron line flux is larger than the 3 micron line flux. The degree of crystallinity of the PAH molecules is directly exposed to radiation from the central star. In this model, self-shadowed disks should display weaker PAH emission than flared disks, consistent with our observations.

Fig. 13. The ratio of the 11 micron feature to the 6.2 and 7.7 micron feature. The line represents the average FWHM in our sample, when excluding the four outliers.

Fig. 14. Ablow-up of the two different types of disk models: flared (left) and self-shadowed (right). Both with these disks have group I SEDs, self-shadowed disk systems are group II objects. The thick black line shows the disk in the lower right part of this diagram.

Fig. 15. (left) The ratio of the 11 micron feature to the 6.2 and 7.7 micron feature. The line again represents the line fluxes of MWC 1080 under variable extinction. The spectral energy distribution (SED) of Herbig stars can be roughly classified in two groups: group I and flare stars with a strong mid-IR (60—100 micron), if it has Show modest mid-IR SEDs (Mees et al. 2001, A&A 365, 476). Dullemond (2002, A&A 395, 863) interprets this classification in terms of disk geometry: group I sources have flared disks, group II self-shadowed disks (Fig. 6). The classification of the sources can be expressed in a diagram like in Figs. 9 and 10. The strong mid-IR group II sources are cooler than the group I sources and appear in the lower right part of this diagram.

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Fig. 12. (right) The ratio of the 11 micron feature to the 6.2 and 7.7 micron feature. The line represents the average FWHM in our sample, when excluding the four outliers.