Protoplanetary disks around Herbig Ae/Be stars: Indications from ISO spectroscopy

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Abstract

An analysis of solid-state features in infrared spectra of 46 Herbig Ae/Be is presented. The presence and strength of solid-state emission bands was compared to other indicators of circumstellar material, such as Hα emission, optical variability and sub-mm continuum fluxes. The correlation between these different indicators is weak, if present at all, in our sample. However, a strong dependence on spectral type of the central star seems to be present: stars with spectral type earlier than B9 show either amorphous silicate in absorption or infrared spectra dominated by PAH emission, whereas more than 70% of the stars of later spectral type show silicate emission. We conclude that the infrared spectrum of Herbig Be stars is in general dominated by emission from the circumstellar envelope, whereas the lower-mass Herbig Ae stars show a spectrum that is dominated by a disk that is passively heated by the central star.

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 emission and absorption in spectral lines, of which Hα is most prominent. 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 both the type of Hα line profile and the amount of optical variability may be taken as an indicator for the presence and orientation of circumstellar disks in HAeBes. Although the optical-sub-mm energy distribution of Herbig Ae/Be stars has been well explored by previous authors (e.g. Hillenbrand et al. 1992), the chemical and mineralogical composition of the dust remained poorly studied until the 1995 launch of the *Infrared Space Observatory* (ISO; Kessler et al. 1996). 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, 1999; van den Ancker et al. 1999; poster Meeus et al.). Here we present the first inventory of solid-state features in all Herbig Ae/Be stars observed by the *Infrared Space Observatory* and investigate their correlation with the traditional tracers of circumstellar material outlined above.

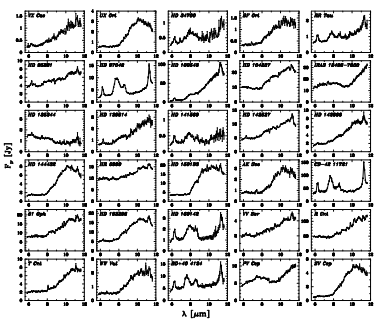

Fig. 1. ISO-PHOT spectra of the program stars.

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) and the spectroscopic mode of the photometer (ISOPHOT; Lemke et al. 1996). 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 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).

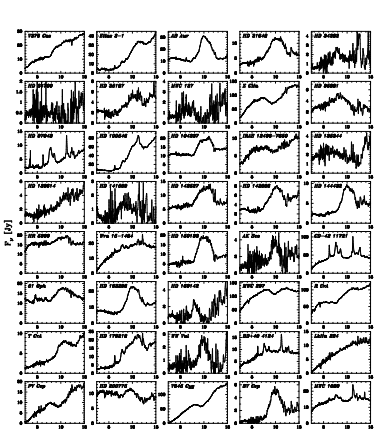

Fig. 2. ISO-SWS spectra of the program stars.

3. Results

We investigated the correlation of infrared spectral features with parameters of the systems from literature (Γ_V, level of optical variability, Hα profile, sub-mm flux) using different diagnostic diagrams (Figs. 3–8). 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.
- Stars with spectral type earlier than B9 show either amorphous silicate in *absorption* or infrared spectra dominated by PAH emission.
- In sharp contrast to the early-type Herbig stars, amorphous silicate in *emission* is found for nearly 70% of the stars in our sample with spectral type B9 or later.
- 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.
- Rapidly accreting stars, as traced by outflow activity, are more likely to have silicate features in absorption.
- No strong correlation of the presence or strength of infrared solid-state features with dust masses derived from sub-mm photometry was found.
- Crystalline silicates (only found in emission) are present in 15% of the sources, all of spectral type B9 or later.
- Sources which show evidence for crystalline silicates are on average closer to the zero-age main sequence than sources which only show amorphous silicates.

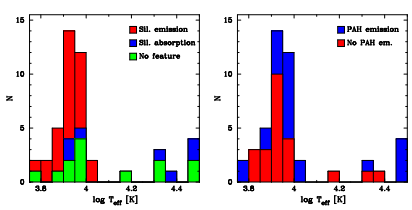

Fig. 3. Distribution of sources that show the 10 μm silicate feature in emission, absorption, or do not show this feature, as a function of effective temperature of the central star (left) and distribution of sources with or without the PAH bands in emission as a function of stellar effective temperature (right).

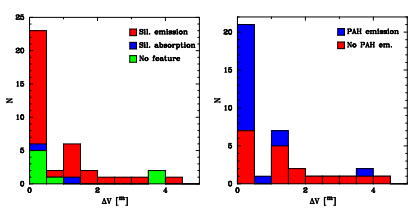

Fig. 4. Distribution of sources that show the 10 μm silicate feature in emission, absorption, or do not show this feature, as a function of variability in the V band (left) and distribution of sources with or without the PAH bands in emission as a function of optical variability (right).

Table 1. Properties of program stars. P in column 5 indicates a P Cygni Hα line profile, D stand for double-peaked and S for a single-peaked Hα profile. E in columns 8–10 stands for emission, whereas absorption features are marked A.

Name	Region	d [pc]	Sp. Type	Hα	V_{max}	ΔV	PAHs	Am. Sil.	Cryst. Sil	Rem.
V376 Cas	Cas R1	630	B5e	P	15.05	1.00	–	–	–	
VX Cas	Cas R1	630	A1Ve+sh	D	11.02	1.20	E	E	–	bin.
Elias 3-1	Tau-Aur	160	A6:e	–	15.24	0.42	E	E	–	
AB Aur	Tau-Aur	140	A0Ve+sh	P	6.98	0.20	E	E	–	
HD 31648		130	A3Ve	P	7.72	0.11	E	E	–	
UX Ori	Orion OB1a	340	A3IIIe	D	9.39	2.96	–	E	–	
HD 34282		160	A0.5Ve	–	9.64	0.77	E	–	–	
HD 34700	Taurus	160	G0Ve	S	9.19	0.05	E	–	–	
HD 35187	Taurus	150	A2Ve+A7Ve	D	8.05	0.21	E	E	–	bin.
BF Ori	Orion OB1c	510	A5-6IIIe	D	9.59	3.03	–	E	–	
RR Tau	Taurus?	160	A3–5e	D	10.70	3.64	E	–	–	
MWC 137	Mon R1	1100	Bep	S	11.78	0.17	E	–	–	
Z CMa	CMa R1	1050	F6IIIe	P	8.68	1.45	–	A	–	bin.
HD 95881	Cha OB2-4	118	A2IIIVe	D	8.18	0.16	E	–	–	
HD 97048	Cha I	180	B9.5Ve+sh	D	8.42	0.14	E	–	–	
HD 100546	Cha OB2-4	103	B9Vne	D	6.64	0.19	E	E	E	
HD 104237	Cha III	116	A4Ve+sh	D	6.57	0.11	–	E	E	
IRAS12496−7650	Cha II	180	Ae	D	18.66	–	–	A	–	
HD 135344	Sco OB2-3	140	F4Ve	S	8.54	0.18	–	E	–	
HD 139614	Sco OB2-3	140	A7Ve	S	8.22	0.12	E	E	–	
HD 141569	(L169)	99	A0Ve	D	7.10	0.03	E	–	–	bin.
HD 142527	Sco OB2-2	145	F7IIIe	S	8.38	0.09	E	E	–	
HD 142666	Sco OB2-2	145	A8Ve	D	8.58	1.12	E	E	E	
HD 144432	Sco OB2-2?	200	A9Ve	D	8.19	0.05	–	E	E	
HR 5999	Lupus 3	210	A5–7IIIIVe+sh	D	6.73	1.76	–	E	–	bin.
Wra 15-1484	DC335.1+0.2	2000	B0:[e]	D	12.61	0.03	E	–	–	
HD 150193	Sco OB2-2	150	A1–3Ve	D	8.80	0.05	E	E	–	bin.
AK Sco	DC348.0+3.7	150	F5+F5IVe	D	8.75	1.23	–	E	–	bin.
CD−42°11721	DC343.3-0.6	400	B0IVep	S	11.11	0.67	E	A	–	
51 Oph	Sco OB2-1	130	B9.5Vne	D	4.77	0.02	–	E	–	
HD 163296		122	A3Ve	D	6.83	0.07	–	E	E	
HD 169142	Sco OB2-1	145	A5Ve	S	8.16	0.11	E	–	–	
MWC 297	(L515)	250	B1.5Ve	S	11.90	0.61	–	A	–	
VV Ser	Ser R1	330	A2IIIe	D	11.58	1.37	–	E	–	
R CrA	NGC 6729	130	A1–F7ev	D	10.15	4.32	–	E	–	Sp. var.
T CrA	NGC 6729	130	F0e	D	12.86	1.89	–	E	–	
HD 179218	L693	240	B9e	S	7.39	0.03	E	E	E	
WW Vul	Vul R1	440	A4IVe+sh	D	10.25	2.05	–	E	–	
BD+40°4124	Cyg R1	980	B2Ve	C	10.37	0.58	E	–	–	
LkHa 224	Cyg R1	980	A7e	D	12.54	3.96	–	–	–	
PV Cep	Cep R2	440	A5:e	P	17.76	6.90	–	A	–	
HD 200775	Cep R2	440	B2.5IVe	D	7.42	0.04	–	–	–	bin.
V645 Cyg	Cyg OB7	740	A0–5e	P	13.17	1.00	–	A	–	
BD+46°3471	L1054	900	A4e+sh	P	10.10	0.11	–	E	–	bin.
SV Cep	Cep R2	440	A0–2Ve	S	10.25	1.46	–	E	–	
MWC 1080	L1238	2200	B0e	P	11.19	0.57	E	A	–	bin.

4. Conclusions

The strongest correlation found is between spectral type of the central star and silicate emission: Herbig stars of spectral type earlier than B9 show silicate absorption, whereas a large majority (≈70%) of the Herbig Ae stars of later type show silicate *emission*. Since strong optical variability due to variable circumstellar extinction is also only found in Herbig stars with spectral type of B9 or later (van den Ancker et al. 1998), both phenomena may be related. However, no correlation between the level of optical variability and silicate emission could be found, perhaps due to our limited sample size.

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 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.

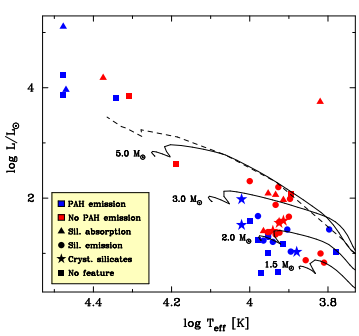

Fig. 5. Hertzsprung-Russell diagram with the position of our program stars. The plot symbol indicates the solid state components present in the ISO spectra. Sources which do show amorphous silicate in absorption are plotted as triangles, those who only show amorphous silicates in emission as dots, the 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).

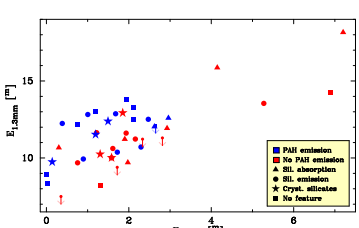

Fig. 6. Plot of excess emission above photospheric levels at K (2.2 μm) versus that at 1.3 mm for the stars in our sample. Sources which show PAH emission are plotted as blue symbols, whereas those that do not are plotted in red. Triangles indicate sources which show amorphous silicate in absorption, dots amorphous crystalline emission, stars both crystalline and amorphous silicates in emission and squares indicate sources without a strong 10 μm silicate feature.

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