

# What can we learn about protoplanetary disks from analysis of mid-infrared carbonaceous dust emission?\*

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## ABSTRACT

**Context.** The disks of gas and dust that form around young stars and can lead to planet formation contain polycyclic aromatic hydrocarbons (PAHs) and very small grains (VSGs).

**Aims.** In this paper we analyze the mid-infrared (mid-IR) emission of these very small dust particles in a sample of 12 protoplanetary disks. Our goal is twofold: first we want to characterize the properties of these particles in disks and see how they are connected to interstellar matter, and second we investigate the possibility that their emission can be used as a probe of the physical conditions and evolution of the disk.

**Methods.** We define a basis made of three mid-IR template spectra: PAH<sup>0</sup>, PAH<sup>+</sup>, and VSGs that were derived from the analysis of reflection nebulae, and an additional PAH<sup>x</sup> spectrum that was introduced recently for analysis of the spectra of planetary nebulae.

**Results.** From the optimization of the fit of 12 star+disk spectra, using a linear combination of the 4 template spectra, we found that an additional small grain component with a broad feature at 8.3  $\mu\text{m}$  is needed. We find that the fraction of VSG emission in disks decreases with increasing stellar temperature. VSGs appear to be destroyed by UV photons at the surface of disks, thus releasing free PAH molecules, which are eventually ionized as observed in photodissociation regions. In contrast, we observe that the fraction of PAH<sup>x</sup> increases with increasing star temperature except in the case of B stars where they are absent. We argue that this is compatible with the identification of PAH<sup>x</sup> as large ionized PAHs, most likely emitting in regions of the disk that are close to the star. Finally, we provide a UV-dependent scheme to explain the evolution of PAHs and VSGs in protoplanetary disks. These results allow us to put new constraints on the properties of two sources: IRS 48 and “Gomez’s Hamburger” which are poorly characterized.

**Conclusions.** Very small dust particles incorporated into protoplanetary disks are processed while exposed to the intense radiation field of the central star. The resulting shape of the mid-IR spectrum can reveal this processing and be used as an efficient probe of the radiation field i.e. luminosity of central star.

**Key words.** astrochemistry – ISM: dust, extinction – ISM: lines and bands – stars: planetary systems: protoplanetary disks – infrared: stars – methods: observational

## 1. Introduction

It is widely accepted that low-to-intermediate mass ( $<8 M_{\odot}$ ) young stellar objects (YSOs) are surrounded by a disk of gas and dust (see e.g. van Boekel et al. 2004, and references therein). There is growing evidence (see Setiawan et al. 2008, and references therein) that these disks are the cradles of planetary formation, which is why they are called “protoplanetary disks”. From a spectroscopic point of view, these YSOs are characterized by a large infrared excess due to the emission of dust present in the disk. The near-to-mid-IR region of their spectrum is dominated by the emission of hot dust at thermal equilibrium and present in the inner regions of the disk, together with the emission of stochastically heated macromolecules and nanograins emitting from the surface layers of the disk (Acke & van den Ancker 2004; Habart et al. 2004). This emission is characterized by

“aromatic infrared bands”, generally attributed to polycyclic aromatic hydrocarbons (PAHs, Léger & Puget 1984; Allamandola et al. 1985).

Several studies have investigated the properties of PAHs in disks. Nearly half of the Herbig Ae/Be (2–8  $M_{\odot}$ ) stars observed by Meeus et al. (2001) and Acke & van den Ancker (2004) show PAH emission. Concerning their less massive counterparts, T-Tauri stars ( $<2 M_{\odot}$ ), Geers et al. (2006) tend to show that PAH emission is more marginally detected, while Bouwman et al. (2008) report several sources with a strong emission feature at  $\sim 8.2 \mu\text{m}$ . These authors, as well as Sloan et al. (2005), show that the mid-IR PAH features undergo significant variations from one source to the next. However, linking these variations to the modification of local physical conditions (in particular the UV field hardness) or PAH properties (e.g. ionization state, size) remains challenging (see Peeters et al. 2002; van Dienenhoven et al. 2004; Sloan et al. 2007 on this subject). Recently, Boersma et al. (2008) have indeed argued that such modifications were linked to the chemical evolution of PAHs in the vicinity of HAe/Be stars. Making this connection is essential for two reasons. First, it will cast a new light on the properties of carbonaceous particles in the interstellar dust cycle, and second,

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**Table 1.** Characteristics of the source in the considered sample

Object	$\log(T_{\text{stellar}})$	Sp. type	Disk evolution	Age (Myr)	Ref.
HD 135 344	3.810	F4Ve	Transition	$8 \pm 4$	1, 3, 11
HD 169 142	3.914	A5Ve	Transition	$6^{+6}_{-3}$	1, 4, 12
HD 34 282	3.941	A3Vne	Thin	5	1, 5, 13
HD 97 048	4.000	A0/B9Ve+sh	Thick	$4 \pm 1$	1, 6
HD 34 700	3.774	G0IVe	Thick	$3^{+6}_{-3}$	1, 7
RR Tau	3.927	A4e	Transition	$3^{+1}_{-2.6}$	1, 8, 9
HD 141 569	3.979	A0Ve	Thin	5	1, 5
BD +40° 4124	4.291	B2Ve	Thick+Env.	$1^{+2}_{-0.9}$	1, 8, 14
CD -42° 11 721	4.470	B0IVep	Thick+Env.	$0.5^{+2}_{-0.4}$	1, 10
LkH $\alpha$ 215	4.114	B7	Thick+Env.	1	14
IRS 48	?	?	Thin	$4 \pm 1$	2
Gomez Hamburger	?	?	Thick	?	15, 16

1: [Acke & van den Ancker \(2004\)](#), 2: [Geers et al. \(2007\)](#), 3: [Doucet et al. \(2006\)](#), 4: [Raman et al. \(2006\)](#), 5: [Merín et al. \(2004\)](#), 6: [Lagage et al. \(2006\)](#), 7: [Torres \(2004\)](#), 8: [Natta et al. \(1997\)](#), 9: [Rostopchina \(1999\)](#), 10: [Wang & Looney \(2007\)](#), 11: [Brown et al. \(2007\)](#), 12: [Grady et al. \(2007\)](#), 13: [Piétu et al. \(2003\)](#), 14: [Hillenbrand et al. \(1995\)](#), 15: [Ruiz et al. \(1987\)](#), 16: [Bujarrabal et al. \(2008\)](#).

this might help in the understanding of disks evolution leading to planet formation such as coagulation and evaporation processes.

Unfortunately such a detailed analysis is difficult given the small spatial scales at which these processes occur. One way to overcome this issue is by increasing the performance of mid-IR telescopes and instruments. In this field, impressive observational *tours de force* have been performed recently revealing the mid-IR anatomy of disks ([Lagage et al. 2006](#); [Geers et al. 2007](#); [Doucet et al. 2007](#)). Another way of proceeding is by taking as much advantage as possible of the spectral information. Recently, we have studied the link between the shape of the observed mid-IR spectrum and the nature of emitting particles in various photodissociation regions (PDRs) where the spatial scale is much larger ([Rapacioli et al. 2005](#); [Berné et al. 2007](#)). We found that their emission spectra could generally be decomposed into 3 fundamental spectra attributed to a population of very small grains (VSGs), neutral PAHs (PAH<sup>0</sup>), and ionized PAHs (PAH<sup>+</sup>). We were able to link the presence of each one of the emitting populations to the local physical conditions: VSGs are present in the densest regions of the clouds and dissociated into PAH<sup>0</sup> in the more UV irradiated regions to be eventually ionized into PAH<sup>+</sup> in the cavity around the illuminating stars. Following these studies, we propose to analyze the mid-IR emission spectra of 12 YSOs showing strong aromatic emission, using the set of template spectra of VSG, PAH<sup>0</sup>, and PAH<sup>+</sup> derived from our results obtained on PDRs.

We first describe the observations and the selected sample of objects in Sect. 2. In Sect. 3, we justify the choice of template spectra and proceed to the fitting of observed spectra. In Sect. 4 we discuss on the nature of the different emitting populations and their link with local physical conditions in disks. In particular we explore the general trends in the variations of the molecular (PAH) versus very small grains emission in disks as a function of the luminosity of the central star. Conversely, we illustrate how these trends can be used to constrain the luminosity of sources that are ambiguous in spectral type and nature, such as IRS 48 and Gomez’s Hamburger.

## 2. Observations and data reduction

The selected sources (Table 1) for this study were taken from the large number of Herbig Ae/Be and T-Tauri stars that show PAH emission. The objects in this sample are very different from one another: some are evolved and probably forming planets (e.g. HD 141 569, see [Augereau et al. 1999](#); [Mouillet et al. 2001](#);

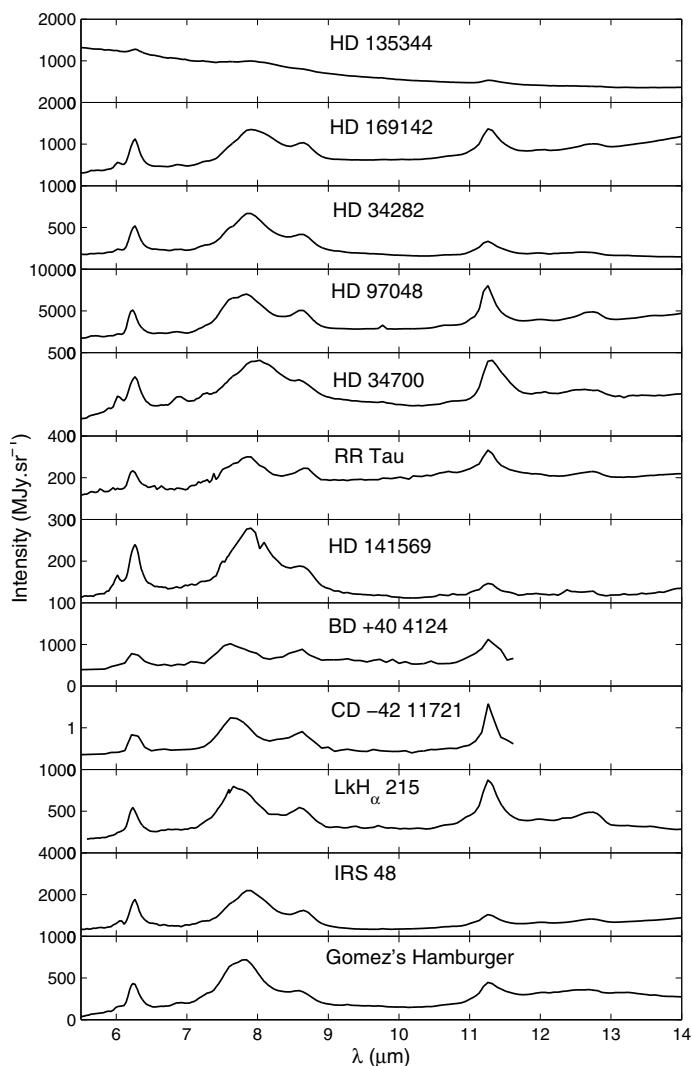
[Brittain & Rettig 2002](#)), while others are young and still probably enshrouded in the remnants of their parent cloud (e.g. CD -42° 11 721 see [Henning et al. 1998](#)). The spectral type of IRS 48 is not determined well, as discussed in [Geers et al. \(2007\)](#) and in Sect. 5.1. Furthermore, the nature of Gomez Hamburger (IRAS 1805–3211) is debatable. It was originally classified as a post-AGB star ([Ruiz et al. 1987](#)), but recent observations would instead classify it as a young star surrounded by its protoplanetary disk seen edge-on (see [Bujarrabal et al. 2008](#), and Hubble Space Telescope press release 2002/19). We have only considered objects with prominent features detected at 6.2, 7.7, and 11.3  $\mu\text{m}$ . All the sources are free of the 9.7  $\mu\text{m}$  silicate emission feature, in order to limit the contamination of this band to the 7.7, and 11.3  $\mu\text{m}$  aromatic bands. It is important to note that selecting disks that lack silicate emission constitutes a bias in our sample. The absence of silicate emission in the observed spectra can be due to several mechanisms: either the silicate grains are too far from the central source and thus not heated to temperatures that are high enough to allow emission in the mid-IR, or these grains are too large to be heated efficiently. However such effects are (at least at the first order) not related to the nature and evolution of carbonaceous grains in disks, so we argue that this bias is minor.

### 2.1. Spitzer observations

HD 135 344, HD 169 142, HD 34 282, HD 97 048, HD 34 700, RR Tau, HD 141 569, LkH $\alpha$  215, Gomez’s Hamburger, and IRS 48 were observed with the infrared spectrograph IRS ([Houck et al. 2004](#)) onboard *Spitzer*, in the low resolution ( $\frac{\lambda}{\Delta\lambda} = 60\text{--}127$ ) mode. We have only considered the data from the short-low (SL) module covering wavelengths from 5 to 14.5  $\mu\text{m}$ . We retrieved the basic calibrated (.bcd) files processed with the S15 pipeline from the *Spitzer* Science Center database. The spectra were built using the CUBISM software ([Smith et al. 2007](#)) and an aperture of  $4 \times 2$  pixels of 1.8'' to extract the spectra.

### 2.2. ISO observations

BD +40° 4124 and CD -42° 11 721 were observed between 5.8 and 11.6  $\mu\text{m}$  with the ISO-PHOT instrument onboard ISO, in spectroscopic mode ( $\frac{\lambda}{\Delta\lambda} \sim 90$ ). We retrieved the highly processed data from the ISO archive and used it directly.



**Fig. 1.** Mid-IR spectra of the 10 disks in our sample. All are from *Spitzer*-IRS observations except BD +40° 4124 and CD -42° 11 721, which are ISO-PHOT spectra and only cover the mid-IR range up to 11.5  $\mu\text{m}$ . Intensities of the spectrum of BD +40° 4124 were divided by  $10^3$  for clarity in the figure.

### 2.3. Characteristics of aromatic emission from disks

The spectrum of each one of the sources from the sample is presented in Fig. 1. Each spectrum clearly shows the presence of aromatic emission at 6.2, 7.7, and 11.3  $\mu\text{m}$ . As described by Sloan et al. (2005), the spectra resemble those defined as Class “B” by Peeters et al. (2002), having their “7.7”  $\mu\text{m}$  feature shifted towards 7.9  $\mu\text{m}$ . The coolest objects, HD 135 344, HD 162 149, and HD 34 700, have the broadest “7.7”  $\mu\text{m}$  feature, and it is shifted towards 8.3  $\mu\text{m}$ .

## 3. Analysis of the 6–14 $\mu\text{m}$ spectrum of disks

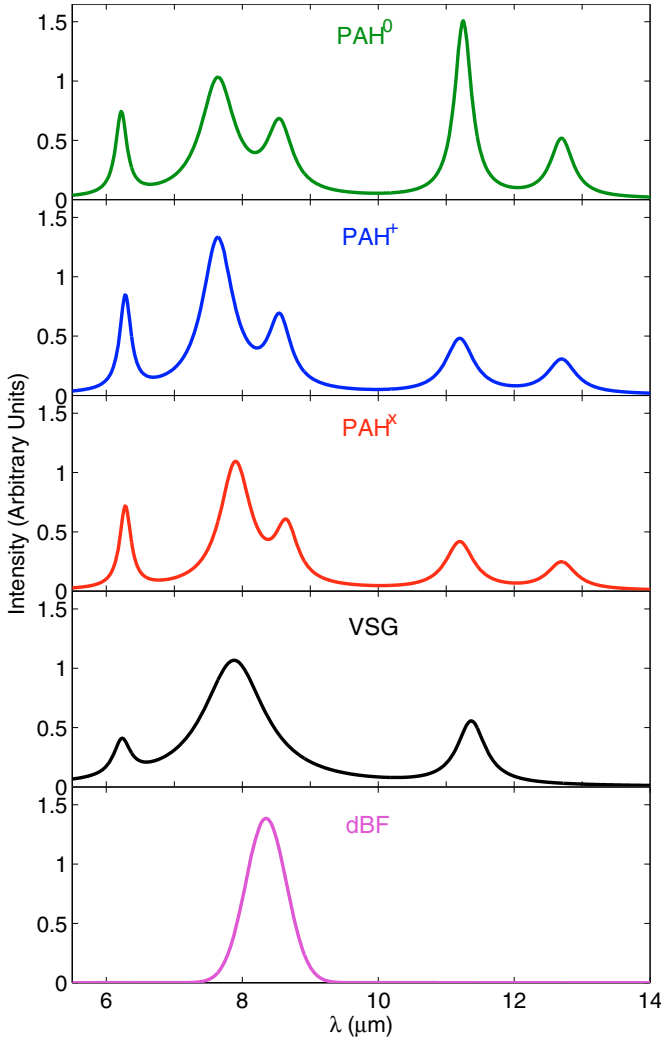
### 3.1. Fitting the mid-IR spectra

Recently, Joblin et al. (2008) have applied a fitting procedure to a sample of mid-IR spectra of planetary nebulae (PNe). The analysis employs a basis of 6 mid-IR (6–14  $\mu\text{m}$ ) template spectra to fit the continuum subtracted spectra of evolved stars: 3 PDR components (VSG, PAH<sup>0</sup>, and PAH<sup>+</sup>), very large ionized PAHs (PAH<sup>x</sup>) and two broad features centered at 8.2 and 12.3  $\mu\text{m}$ . The PDR components were extracted using blind signal separation

methods as described in Berné et al. (2007) and Rapacioli et al. (2005). The templates were then generated by fitting these components with Lorentzians after subtraction of the rising continuum for VSGs. They include all major features except a plateau at  $\lambda \geq 12 \mu\text{m}$  for VSGs, which was difficult to reproduce due to contamination by the H<sub>2</sub> line at 12.3  $\mu\text{m}$  and underlying continuum. The PAH<sup>x</sup> spectrum was built empirically to account for the mid-IR emission observed in PNe and HII regions but was inspired by quantum chemistry calculations (Joblin et al. 2008). As discussed in this paper, there is some uncertainty about the intensity of the 11.3  $\mu\text{m}$  band associated with the PAH<sup>x</sup> template spectrum. The set of template spectra used in Joblin et al. (2008) enables the mid-IR emission arising from PNe and HII regions to be successfully interpreted both in the Galaxy and Small and Large Magellanic Clouds. We therefore apply it here to the star+disk systems.

In our first attempt to fit the observations, we figured out a recurrent problem with the fits obtained for the coolest stars: the 7.7  $\mu\text{m}$  massif could not be reproduced efficiently as shown in Fig. 3 for HD 135 344. It is clear from this figure that a broad feature at  $\sim 8.3 \mu\text{m}$  is needed to account for the observed emission. What type of grains can be responsible for this emission? Sloan et al. (2007) suggest that this shifted band corresponds to the class C population defined by Peeters et al. (2002) and is due to aliphatic bonds in emitting mixtures. The fitting strategy we have used includes a template spectrum defined by a broad feature at 8.2  $\mu\text{m}$  (called “BF” in Joblin et al. 2008), based on a class C spectrum and prominent in post-AGB object. The carriers of this feature are observed to be easily destroyed by UV photons, therefore their detection in protoplanetary disks would imply that they are reformed in the parental molecular cloud or in the densest environments of the disk itself. Since the chemical conditions differ from those prevailing in evolved stars there is no reason why these species should be identical in both environments, and this explains why the 8.2  $\mu\text{m}$  BF is not able to reproduce the emission of HD 135 344. We therefore define a new BF template spectrum and refer to it as dBF (for disk broad feature) to avoid confusion with the band seen in evolved stars. The dBF template spectrum is based on the observed spectra of T-Tauri (Fig. 14 in Bouwman et al. 2008). The new fit of HD 135 344 is presented in Fig. 4. Following Joblin et al. (2008) we also used 2 versions of the PAH<sup>x</sup> spectrum. Results do not vary significantly whether the 11.3 and 12.7  $\mu\text{m}$  features are present in the template spectrum or not. This implies that the shape of the PAH<sup>x</sup> spectrum is not well-constrained in the 11.3/12.7  $\mu\text{m}$  range. It is not excluded that the carriers of the dBF also have some features in the 10–14  $\mu\text{m}$  range, but these are expected to be weak. In the following, we concentrate on the results including the 11.3 and 12.7  $\mu\text{m}$  feature in the PAH<sup>x</sup> spectrum, and no additional feature in the 8.3  $\mu\text{m}$  dBF spectrum. As discussed in Joblin et al. (2008), the main effect of using a PAH<sup>x</sup> spectrum without 11.3 and 12.7  $\mu\text{m}$  feature will be to slightly decrease the fraction of PAH<sup>0</sup> in the results of the fits. Finally, we note that the 12.3  $\mu\text{m}$  BF used in Joblin et al. (2008) is useless in the fits of protoplanetary disks, so we do not use it here. The final basis of 5 template spectra we have used for the fitting procedure is presented in Fig. 2.

Considering the geometry and density of disks, IR radiative transfer might be a concern. We have therefore re-run our fit using simple extinction parameter based on the extinction curve of Weingartner & Draine (2001), for a total-to-selective extinction ratio  $R_V = 5.5$ . Though in some cases the fit is slightly better, the estimated fraction of each population is nearly unchanged.

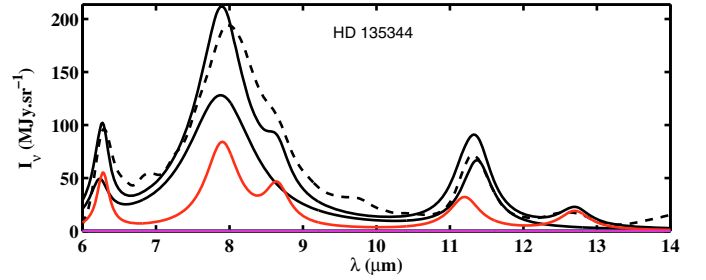


**Fig. 2.** The five mid-IR template spectra used to fit the observed emission of protoplanetary disks. The PAH<sup>0</sup>, PAH<sup>+</sup>, and VSG spectra are PDR components. The PAH<sup>x</sup> component (very large ionized PAHs) is from Joblin et al. (2008) and the 8.3  $\mu$ m dBF was introduced in this paper.

Thus, for the sake of simplicity, we present here results that do not include extinction.

### 3.2. Results

The results of the fits are presented in Fig. 4. For each object we are able to reproduce the observed spectrum quite efficiently. Table 2 gives the fractions of mid-IR integrated fluxes for each component present in the studied source. Because mid-IR emitters are heated and processed by the UV-visible photons emerging from the central star, we propose to compare the fractions of each emitting population to the theoretical total and UV luminosities of the central source given its spectral type (see Table 1). We used the spectra from the 1993 Kurucz stellar atmosphere atlas (<http://www.stsci.edu/hst/observatory/cdbs/k93models.html>) based on Kurucz (1979). We used a gravity of 4 for all sources and a stellar radius from Aller et al. (1982). The total luminosity is defined as  $4\pi R_* \int F_\lambda d\lambda$  and the UV luminosity as  $4\pi R_* \int_{91.2 \text{ nm}}^{240 \text{ nm}} F_\lambda d\lambda$  (according to Habing 1968), where  $R_*$  is the stellar radius and  $F_\lambda$  the flux from the Kurucz catalog. In Fig. 5 we plot the fraction of



**Fig. 3.** Preliminary fit of HD 135344, using only PDR components together with PAH<sup>x</sup>. Observed spectrum is the upper dashed line and fit the continuous line. The contribution of VSG, PAH<sup>x</sup>, and PAH<sup>0</sup> is represented below in black, red, and green, respectively. It appears clearly that the use of these components cannot reproduce the observed emission and that a new component with a feature at 8.3  $\mu$ m is needed (see dBF in Fig. 2). The new fit is presented in Fig. 4.

**Table 2.** Fractions of each population of the carbonaceous dust emission in the spectrum of the 12 sources of the selected sample.

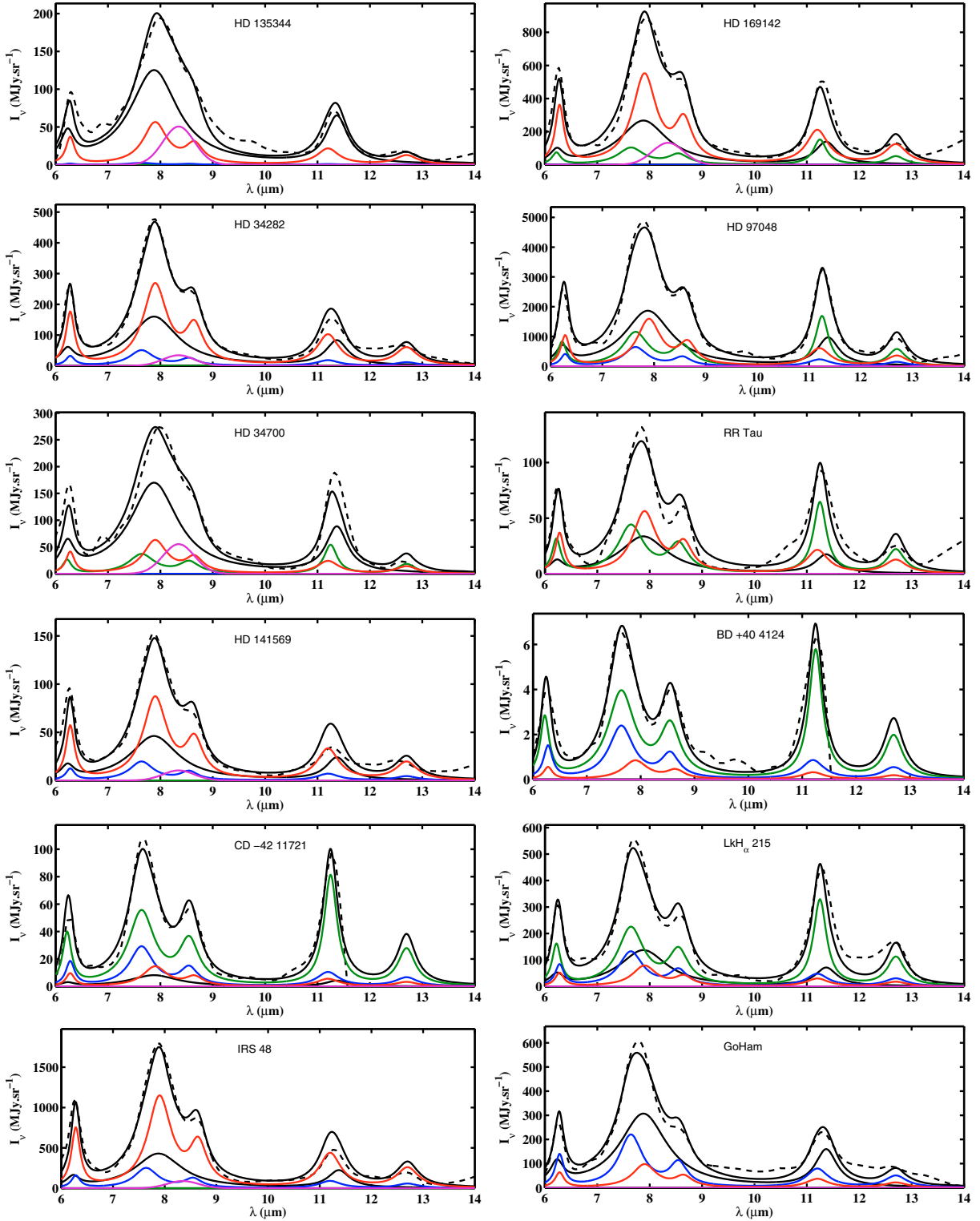
Object	Fraction of the emission (%)				
	VSG	PAH <sup>0</sup>	PAH <sup>+</sup>	PAH <sup>x</sup>	dBF
HD 135 344	66	0	1	24	9
HD 169 142	38	25	11	26	0
HD 342 82	30	13	0	51	6
HD 97 048	37	0	10	50	3
HD 34 700	61	14	0	18	7
RR Tau	27	37	0	36	0
HD 141 569	34	0	12	51	3
BD+404 124	0	61	29	10	0
CD-42 11 721	8	57	23	12	0
IRS 48	27	0	13	58	2
GoHam	54	0	32	14	0
LkH $\alpha$ 215	25	43	20	12	0

VSG emission as a function of UV luminosity, showing a clear decrease of this emission while the mass of the star increases. In contrast, the fraction of PAH emission increases with the luminosity (Figs. 6, 7). This is due to the increasing PAH<sup>x</sup> emission, whereas the PDR-type PAH emission is found to increase up to spectral type A4 and then to decrease when going towards stars of earlier spectral types (Fig. 8). The same trends are observed either using total or UV luminosity. We also observe that there are no dBF in the spectra of disk around stars of spectral type earlier than A0 (i.e. UV luminosity  $> \sim 10^{28}$  W).

## 4. Probing disks with mid-IR emission?

### 4.1. The origin of the 8.3 $\mu$ m broad feature

The 8.3  $\mu$ m dBF component is found primarily in the sources with the coolest stars, which suggests a fragile material as in post-AGB stars, possibly of aliphatic nature. Sloan et al. (2007) suggest that the grains responsible for the 8.3  $\mu$ m feature in cool protoplanetary disks are similar to the grains responsible for the “class C” spectrum of Peeters et al. (2002) and observed in post-AGB stars. However, we find that the dBF position and width are not compatible with the class C spectrum, the dBF being broader and peaking at 8.3 rather than 8.2  $\mu$ m, as also noticed by Bouwman et al. (2008).

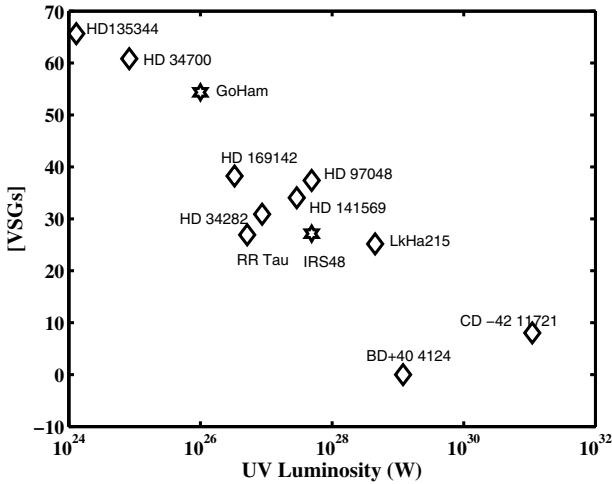


**Fig. 4.** Fits of the 12 spectra of the star+disk systems observed with *Spitzer*-IRS and ISO using our set of 5 template spectra. The observed spectrum is the dashed black line, the fit is the continuous black line. The contribution of each component is shown below in colors (using the same color code as in Fig. 2).

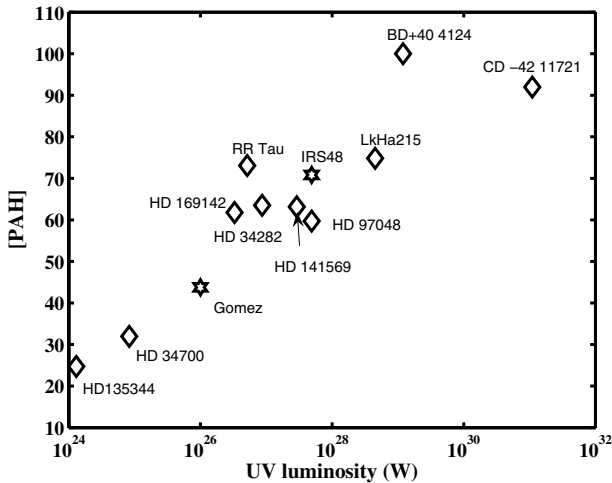
#### 4.2. Processing of VSGs

The fraction of VSG emission clearly decreases with increasing UV luminosity (see Fig. 5), while emission from free PAH molecules becomes more and more prominent. This is in line with observations of PDRs (Cesarsky et al. 2000; Rapacioli et al. 2005) where it appears that VSGs are dissociated into free PAH

molecules. It is expected that such a process is also taking place on the surface of the disk. Still, one has to consider the competition between evaporation and coagulation (Rapacioli et al. 2006), but evaporation is likely to dominate when the central star becomes hotter and therefore produces more and more UV photons. Dullemond et al. (2007) show that in more evolved disks the ratio of PAH-emission over far-infrared emission should be



**Fig. 5.** Fraction of VSG emission in the selected sources, as a function of the UV luminosity of the central star. Diamonds are for sources that have a well-defined spectral type. The spectral types of GoHam and IRS 48 (shown with star symbols in this plot) are inferred in order to agree with the found correlation. The correlation shows that VSGs are less abundant around hot stars, likely due to their rapid destruction in these harsh environments.



**Fig. 6.** Fraction of PAH ( $\text{PAH}^0 + \text{PAH}^+ + \text{PAH}^x$ ) emission in the selected sources, as a function of UV luminosity. Diamonds are for sources that have a well-defined spectral type. The spectral types of GoHam and IRS 48 (shown with star symbols on this plot) are inferred to agree with the found correlation.

much higher than what is observed, because of the lower optical thickness of the disk in the wavelength range at which PAHs absorb. Thus they propose that coagulation of PAHs could be the reason for this lack of emission. Rapacioli et al. (2005, 2006) suggest that VSGs are indeed coagulated PAHs. In this scenario, an increase in the abundance of coagulated PAHs would imply an increase in VSG emission in more evolved disks which is not observed. Instead, one could claim that this lack of PAH emission is due to the geometrical evolution of the disks. Indeed, an older and flatter disk will receive less UV photons per unit of surface, and thus the heating of PAHs (if still present) might become less efficient leading to a less intense mid-IR signal.

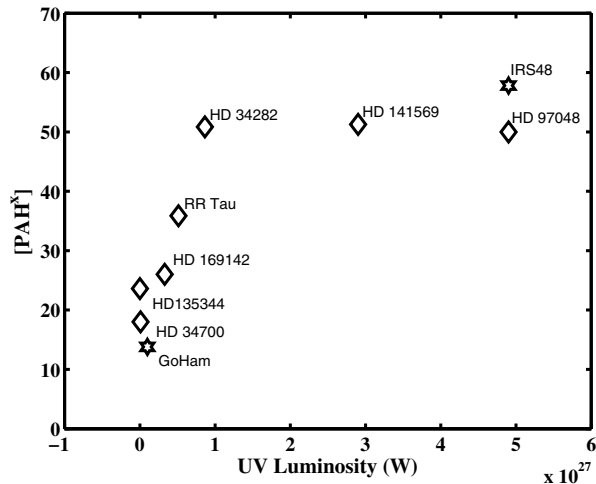
### 4.3. Evolution of PAH populations

Figure 8 presents the fraction of PDR-type PAHs as a function of the stellar UV luminosity. There is a clear rise in the fraction of emission from sources of spectral type G0 to A4, and then this fraction decreases again with increasing luminosity. The rise can be interpreted as due to the high production rate of PAHs from VSGs (see previous section) in the disks around stars of G0 to A4 spectral types. For sources that are hotter, these molecules start being destroyed by the strong UV-visible radiation field, which explains the decrease in the observed PDR-type PAH emission fraction. In contrast, the fraction of  $\text{PAH}^x$  emission increases (Fig. 6). Joblin et al. (2008) conclude that this is the likely result of the destruction of the smallest PAHs combined with efficient heating of the  $\text{PAH}^x$  population. This is consistent with  $\text{PAH}^x$  being very large ionized PAHs that can better survive in extreme irradiation conditions.

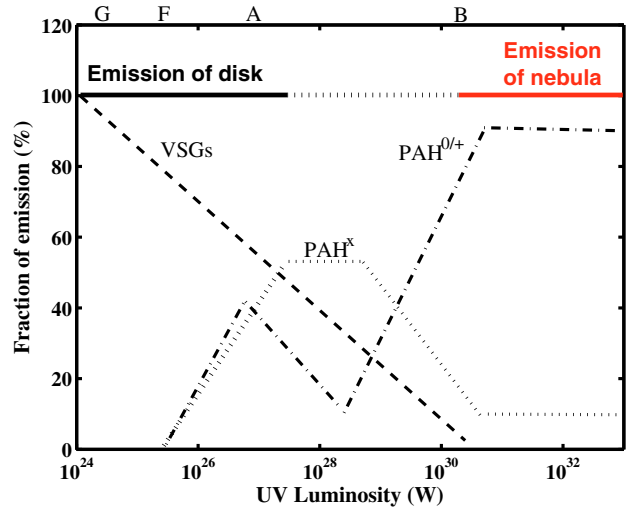
The charge state of PAHs in disks is determined by the competition between ionization rate versus electron recombination for cations/neutrals and photodetachment versus attachment rate for anions/neutrals. In disks, the gas density can be as high as  $10^{7-8} \text{ cm}^{-3}$ , and the electron attachment to PAHs can be more efficient than re-ionization by UV radiation as shown by Li & Lunine (2003). This would imply that PAHs can be found as anions ( $\text{PAH}^-$ ) that could contribute strongly to the mid-IR emission spectrum of disks. In this case it is tempting to identify  $\text{PAH}^x$  as very large  $\text{PAH}^-$ . However Visser et al. (2007) show that in flared optically thick disk (e.g. HD 97048), and even though anionic PAHs could be abundant, they are likely to be situated in deep regions of the disk where they receive too little UV light from the star to be excited so they dominate the mid-IR emission. On the other hand, they suggest that the emission at the surface of H Ae/Be disks will arise from a mixture of very large ( $>100$  C atoms), positively ionized PAHs.

Figure 7 shows that the fraction of  $\text{PAH}^x$  emission increases with UV luminosity for the studied T-Tauri and Herbig Ae stars. For the Be star nearly no  $\text{PAH}^x$  emission is detected, which we interpret as due to the absence of disk emission in the observed spectra (see Sect. 4.5), so it is not plotted on Fig. 7. Furthermore, these objects do not exhibit the dBF and their spectrum can be reproduced using the PDR spectra almost exclusively. *Spitzer*-IRAC images as well as millimeter observations (Henning et al. 1998) suggest that these sources are not isolated, and their mid-IR spectrum was indeed previously classified as “A” by van Dienenhoven et al. (2004), which is consistent with typical PDRs. This suggests that we are in fact not observing the emission from the disk but from the PDR created in the nebula around the central source. Boersma et al. (2008) come to the same conclusions concerning the B9 stars HD 37411 and HD 36917 observed with *Spitzer*, for which they suggest that the observed emission is arising from the surroundings of the star but not a disk. There can be three reason for this: (1) no PAH can resist in the disk because they are all photodissociated; (2) there is no disk because it has been already photoevaporated; (3) the geometry of the disk is such that the PAH emission is not sufficiently activated by UV-visible photons. We discuss these scenarios in Sect. 4.4.

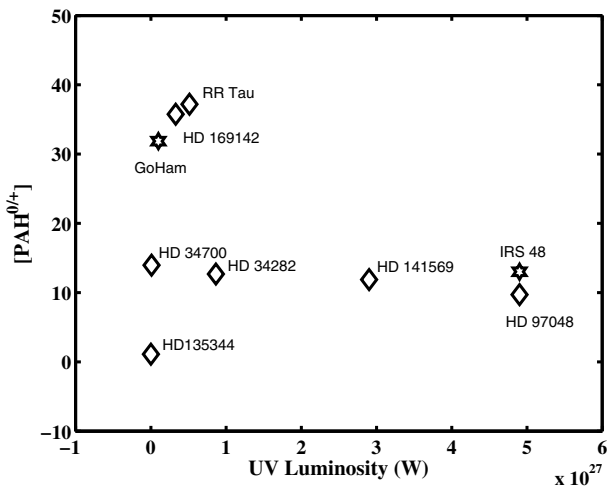
That some  $\text{PAH}^x$  emission is present in cool stars, as in the F4 star HD 135344, implies that the near-UV radiation field is sufficient to destroy some of the smallest PAHs and induce  $\text{PAH}^x$  emission. This means that  $\text{PAH}^x$  are close to the star despite HD 135344 having a rather large inner radius (see e.g. Pontoppidan et al. 2008). In this case, one could consider that PAHs are in fact coupled with a gas disk that extends closer to



**Fig. 7.** Fraction of  $\text{PAH}^x$  in the disk of T Tauri and HAe sources of the sample. Diamonds are for sources that have a well-defined spectral type. The spectral types of GoHam and IRS 48 (shown with star symbols on this plot) are estimated to agree with the found correlation.



**Fig. 9.** Schematic representation of the contributions of the very small dust particle populations to the mid-IR spectra of T Tauri and Herbig Ae/Be stars. While the spectrum of G, F, and A stars is dominated by disk emission, B star spectra are likely due to emission arising from the remnants of the parental cloud. The total emission is due to the contribution of VSGs (dashed line), PDR-type PAHs (dash-dotted line), and  $\text{PAH}^x$  (dotted line).



**Fig. 8.** Fraction of PDR-type PAHs ( $\text{PAH}^+ + \text{PAH}^0$ ) in the disk of T Tauri and HAe sources of the sample. Diamonds are for sources that have a well-defined spectral type. The spectral types of GoHam and IRS 48 (shown with star symbols on this plot) are estimated to agree with the found correlation.

the star than the thick disk (Pontoppidan et al. 2008). The presence of  $\text{PAH}^x$  in HD 135 344 argues against the possibility that these species are positively ionized as the F4 star is unlikely to produce enough UV to ionize the PAHs. On the other hand,  $\text{PAH}$  cations appear to be good candidates considering that they are very abundant in emission in the disk around A stars that produce a large amount of UV (Fig. 7). As in Joblin et al. (2008) we conclude that  $\text{PAH}^x$  are very large ionized PAHs tracing harsh irradiation conditions. Unfortunately, the observational constraints provided here are not sufficient to determine if  $\text{PAH}^x$  correspond to a population of cations or anions or even a mixture of both. We emphasize nevertheless that the detection of  $\text{PAH}^x$  around a young star provides a way to assess the presence of a disk.

#### 4.4. The mid-IR spectrum: a probe of the irradiation conditions of the disk

Finally, can we trace the morphology/content of the disks using the spatially non-resolved mid-IR *Spitzer* spectra? The answer is probably no, because the evolution of very small dust particles in disks is clearly connected to the irradiation conditions and thus to the spectral type of the central star. This connection between the composition of the mid-IR spectrum and spectral type is presented in a schematic way in Fig. 9 and corresponds to the following scenario: the dense disk is a reservoir of VSGs (such as molecular clouds in PDRs), which are constantly dissociated into free PAH molecules. The more intense the UV field (i.e. the more massive the star is), the shortest the lifetime of a VSG at the surface of the disk, where the emission is occurring. This is why the fraction of VSG emission decreases with increasing star temperature (Fig. 9). Similarly, once they are released from VSGs, the lifetime of the smallest PAHs around hot stars is too short to allow their emission to be dominant. This is why the fraction of large PAHs ( $\text{PAH}^x$ ) that resist destruction more is greater in disks around hotter stars (Fig. 9). More massive B stars only show emission of PDR-type PAHs. This might be because this emission does not arise predominantly from a disk, either because VSGs and PAHs (even very large  $\text{PAH}^x$ ) do not survive in disks around Be stars or because the disk is small or absent (see next section).

#### 4.5. Photoevaporation of disks around Be stars

We have shown that Be stars have a PDR-type emission and that the  $\text{PAH}^x$  emission is not observed in these objects. This supports the idea that there are no disks around these stars or that the disk emission in the mid-IR is too weak to be disentangled from the surrounding PDR. Visser et al. (2007) have shown (see their Fig. 3) that a radiation field of more than  $\sim 5 \times 10^7$  in units of the Habing field will destroy even large PAHs of 100 carbon atoms in less than 3 Myr. An estimate of the radiation field at a distance of 300 AU from a B2-0 star, taking only dilution effects

into account and no UV radiative transfer, gives values as high as  $10^{8-9}$ . This is high above the limit value of  $5 \times 10^7$ , so it is likely that in such a harsh environment most, if not all, PAHs will be destroyed efficiently at a radius of 300 AU and even more efficiently at smaller radii. A second possibility is that the disk itself is absent because it was photoevaporated. It is indeed believed that UV can provoke the dispersion of the gas and smallest dust particles (therefore probably including PAHs and VSGs) within a few  $10^5$  Myr (see e.g. the recent review by Alexander 2007). Recently, Alonso-Albi et al. (2008) have found that the dusty disks around Herbig Be stars tend to be lighter and smaller than those towards cooler stars, probably due to the photoevaporation effect. The PAH emission in such a small disk is thus expected to be very weak in any case (whether or not PAHs are destroyed). Note that the effect of PAH destruction in the disks around Be stars will also directly affect photoevaporation of the disk. PAHs and VSGs are responsible for most of the UV-optical thickness of the disk (Draine 2003) so their destruction would imply a decrease in the UV optical thickness. This effect combined with the higher proportion of UV photons, will tend to accelerate the photoevaporation process of the disk and implies that the lifetime of disks around massive stars could be shorter than the time needed to disperse the surrounding material as suggested by Alonso-Albi et al. (2008). The probably flatter shape of the disk around Herbig Be stars (because of the photoevaporation of the outer layers) could also contribute to the absence of PAH emission because of the self-shadowing effect.

## 5. Putting new constraints on the nature of IRS 48 and Gomez's Hamburger

### 5.1. The luminosity of IRS 48

The spectral type of IRS 48 is controversial (see discussion in Geers et al. 2007). Here we propose to classify it using the results of our analysis. With the observed abundance of PAH<sup>x</sup>, VSGs, and the presence of the dBF, we can estimate in which range of temperature IRS 48 falls. The PAH<sup>x</sup> fraction in the emission of IRS 48 is 58%, which is compatible with a luminosity of  $\sim 5 \times 10^{27}$  W based on Fig. 4. The VSG fraction is 29%, which also compatible with a UV luminosity of  $\sim 5 \times 10^{27}$  W (Fig. 5). Finally, the fraction of dBF in the spectrum of IRS 48 is 2%, which puts it near the limit for the presence of the dBF, consistent with a UV luminosity of  $\sim 10^{27-28}$  W. Furthermore, we observe a  $7.7 \mu\text{m}$  to  $11.3 \mu\text{m}$  band ratio above 2. Using Flagey et al. (2006), this implies a  $\frac{G_0 T^{1/2}}{n_e}$  above  $10^5$ . Using a temperature  $T$  of 500 K and an electron density of  $n_e = 10^4 \text{ cm}^{-3}$  at the surface of the disk (Jonkheid et al. 2007; Visser et al. 2007), this leads to a UV field of  $G_0 \sim 60\,000$  in units of the Habing field, which is similar to what is found in the emitting regions of disks around an A0 star. This value, as well as the derived luminosities, are compatible with the powering source being an early A star. If the spectral type of the source is really around F3 or even M0 (Geers et al. 2007), an excess of UV is needed and might indicate accretion processes.

### 5.2. The nature of Gomez Hamburger

Gomez Hamburger (GoHam hereafter) is subject of debate in terms of classification. It was originally classified as a post-AGB star (Ruiz et al. 1987), and recent observations would instead classify it as a pre-main-sequence (PMS) A star surrounded by its disk (Bujarrabal et al. 2008). We propose to investigate here

if the observed mid-IR spectrum of GoHam is compatible with the PMS-star + disk hypothesis. As described above, we can use the results of the fitted spectra to investigate the properties of the illuminating star. The found fractions of VSGs and PAH<sup>x</sup> and dBF carriers are compatible with a total luminosity of  $\sim 8 L_\odot$  and a UV luminosity of  $\sim 0.3 L_\odot$ . This indicates that the central star should have an effective temperature of  $\sim 7000\text{--}9000$  K. This is slightly cooler than the stellar temperature of  $\sim 10\,000$  K derived by Ruiz et al. (1987) from near-IR photometry. However, one should note that measuring the temperature of the star using photometric bands is extremely difficult and unreliable given that the disk is seen edge on, and thus that the observed light is completely scattered by the disk. Based on our analysis, the central star in GoHam would be an A5-8 star near main sequence (no emission lines are present in the visible spectrum observed by Ruiz et al. 1987). This implies a stellar mass of about  $1.7\text{--}2 M_\odot$  from evolutionary tracks (van den Ancker et al. 1998) that is compatible with the mass derived from CO observations. Our derived luminosity of  $\sim 8 L_\odot$  implies a distance of  $\sim 200\text{--}300$  pc to reproduce the SED. The Hubble Space Telescope images, as well as CO observations (Bujarrabal et al. 2008), suggest a disk radius of  $4''$ . Using the distance we derive of 200 pc this gives a physical radius of 800 AU, consistent with current estimates of the outer radius for a disk around HAeBe objects (see compilation in Habart et al. (2004) and references therein). Furthermore, the A5-8 scenario does not necessitate the presence of a binary as suggested by Bujarrabal et al. (2008).

Finally we note that the fit does not require the  $8.2 \mu\text{m}$  BF commonly seen in post-AGB stars (Joblin et al. 2008) and shows some PAH<sup>x</sup> emission. Thus, if not a PMS-star, GoHam would instead be a planetary nebula that can lack the  $8.2 \mu\text{m}$  feature and show the  $7.9 \mu\text{m}$  PAH<sup>x</sup> feature in their mid-IR spectrum.

## 6. Summary and conclusion

We have studied the mid-IR emission spectrum of 12 disks around young stars, showing clear signatures of stochastically heated grains and no silicate emission. The observed spectra, emanating from very different objects, can be reproduced using a mixture of only 5 template spectra, 3 of which are representative of interstellar (PDR) populations. In addition, a PAH<sup>x</sup> population characteristic of highly UV-irradiated environments is present as is a peculiar feature (dBF) possibly due to aliphatic material in analogy with the  $8.3 \mu\text{m}$  broad feature present in post-AGB stars. We can recapitulate the main results of this work in three points:

- (1) the mid-IR spectrum of disks traces the PDR created at the surface of the disk. As in PDRs, we find that VSGs are destroyed to become free PAHs. VSGs and small PAHs survive long enough to be observed only in the disks around cool stars. Around A stars only large PAHs have a lifetime that is long enough to allow their detection. The coagulation of PAHs at the surface of disks, i.e. mid-IR emitting region, is likely hindered by the action of the UV field and therefore not correlated with the coagulation of larger grains;
- (2) PAH<sup>x</sup> emission indicates the presence of a disk. This emission is found to be more prominent in HAe stars with high UV fields. This is compatible with PAH<sup>x</sup> being very large PAHs that can resist photodestruction better. Spectroscopy indicates that they are charged and models favor cations rather than anions. The PAH<sup>x</sup> and dBF carriers are absent around Be stars, which we interpret as the absence of emission coming from a disk. This is likely because the disk is small or even absent as it was photoevaporated;



- (3) the shape of the mid-IR PAH spectrum of Herbig Ae/Be and T-Tauri stars is not related to disk morphology but to UV-irradiation conditions. This connection can be used to infer the spectral type / mass of the central source. Using this result, we show that IRS 48 is of early A spectral type or produces a large amount of UV photons in excess due to accretion. Similarly, we constrain the nature of the central source of GoHam and show that the mid-IR emission spectrum of this source is compatible with a protoplanetary disk with a central star of spectral type around A5-8.

Finally, we emphasize that detailed studies of a large sample of disks with PAH emission are needed to provide deeper insights into the evolution of these very small dust particles along with the evolution of the disk. Furthermore, spatially resolved spectro-imagery, in the aromatic emission range, of such objects will be crucial for the understanding of local evolution of the disk, leading to planet formation.

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