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ISO Observations of Pre-Main Sequence and Vega-type Stars

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Abstract. I present an overview of the results obtained by the *Infrared Space Observatory* (ISO) on circumstellar material in pre-main sequence (PMS) stars. Results obtained for embedded YSOs, Herbig Ae/Be systems and T Tauri stars are reviewed and their connection to the disks around Vega-type systems is discussed. Although the gas contents of the PMS environment will also be discussed briefly, this review will mainly focus on the composition, mineralogy and evolution of dust in these systems, and the results will be compared to those found in other classes of objects, including solar system comets.

1. Introduction

One of the most exciting developments in the study of pre-main sequence and young main sequence stars is the advent of space-based infrared observatories. The first infrared space mission, IRAS, discovered the presence of excess infrared emission above photospheric levels in many young stellar objects (YSOs) due to the presence of circumstellar disks or envelopes containing small dust particles. More surprisingly, IRAS also discovered infrared excesses in several nearby main sequence stars. These Vega-type stars (after the prototype Vega; Aumann et al. 1984) have infrared excesses that usually start at longer wavelengths (typically > 25 μm) than in YSOs, indicative of much cooler dust temperatures. A particularly intriguing case is the A-type star β Pictoris, exhibiting both an infrared excess and a circumstellar disk seen in scattered light, which may form the evolutionary link between YSOs and Vega-type stars. Thirteen years after the IRAS mission its successor saw first light: the *Infrared Space Observatory*[1] (ISO; Kessler et al. 1996). Unlike the all-sky IRAS mission, ISO could do pointed observations and offered multiple modes of operation. It gave us our first glimpse of the sky at wavelengths longer than 100 μm and revealed the richness of the infrared spectrum.

In this review, I will discuss the results obtained by ISO on pre-main sequence and Vega-type stars, focussing on the the evolution of circumstellar dust. In section 2 I will briefly introduce the capacities of the instruments on board

[1]Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

ISO. The next section is devoted to a qualitative discussion of the infrared spectra of young stars, and outlines a possible evolutionary scenario for circumstellar dust. Section 4 deals with the originating region of the infrared radiation from pre-main sequence stars, whereas section 5 reviews the new picture of Vega-type stars that ISO had given us and their relation to young stars. In the last section I will summarize the main conclusions of this review and will look forward to the new questions that may be answered by future infrared missions.

2. The Infrared Space Observatory

ESA's *Infrared Space Observatory* consisted of a 60 cm cryogenically cooled telescope with four focal plane instruments, operating at wavelengths from 2.4 to 240 microns. Launched in November 1995, it collected more than 26,000 scientific observations before it finally ran out of liquid helium in April 1998, after a greatly successful mission that lasted eight months longer than expected.

The first of the four instruments, the infrared camera (ISOCAM; Cesarsky et al. 1996) covered the 2.5–18 μm band with two different 32 $\times$ 32 pixel detectors. Each detector had several discrete band pass filters as well as circular variable filters (CVFs) with a resolution of about 35. The second focal plane instrument, the photo-polarimeter (ISOPHOT; Lemke et al. 1996), covered the largest wavelength range of the ISO instruments: 2.5–240 μm. Its scientific capabilities included multi-filter and multi-aperture photometry, polarimetry, imaging and low-resolution ($R \approx 100$) spectrophotometry in the 2.5-4.9 and 5.8-11.6 μm wavelength ranges.

The other two instruments on board ISO were two complementary spectrometers. The short-wavelength spectrometer (SWS; de Graauw et al. 1996) consisted of a scanning spectrograph with a spectral resolution ranging from 1200 to 2400 covering the wavelength range of 2.4–45 μm. By inserting Fabry-Pérot filters, the resolution of the instrument could be enhanced by a factor 20 in the wavelength range from 11.4 to 44.5 μm. Similar to SWS, the ISO long-wavelength spectrometer (LWS; Clegg et al. 1996) consisted of a scanning spectrograph in the 43–198 μm range, with a resolution of either 150–200, or 6800–9700 in Fabry-Pérot mode.

3. Spectral evolution of pre-main sequence stars

3.1. Massive YSOs

The ISO mission allowed us for the first time to explore those parts of the infrared spectrum that are hidden from view by the earth's atmosphere. Because of this, major steps forward have been made in our understanding of the star formation process. In the standard picture of star formation (Shu et al. 1987) four distinct phases can be distinguished. First, a number of dense cores develop within a molecular cloud. At some point, the dense cores collapse to form embedded protostars which accumulate material by accretion from the surrounding cloud. As the embedded protostars accrete mass, they also lose mass due to a strong stellar wind, which eventually leads to the dispersion of the reservoir of mass from the protostellar envelope and the end of accretion. The former protostar,

now a pre-main sequence star surrounded by a circumstellar disk, begins to contract slowly, increasing its central temperature until hydrogen ignition takes place and it has become a stable star on the main sequence.

Spectra taken with all four focal plane instruments on board ISO have revealed a large variety of properties of gasses, dust and ices around YSOs that can be well interpreted in the scenario outlined above. The first stages of the spectral evolution of pre-main sequence objects are illustrated in Fig. 1, where we show ISO-SWS spectra of three massive YSOs, NGC 7538 IRS9 , AFGL 2591 and S106. The infrared spectrum of NGC 7538 IRS9 (Whittet et al. 1996) consists of a smooth continuum with broad, strong absorption bands due to silicates and ices. Frozen H_2O, CO, CO_2, CH_4, CH_3OH and a band around 6.8 μm whose carrier remains unidentified are all commonly detected in the lines of sight towards embedded YSOs and may be regarded as a strong indicator of youth.

The infrared spectrum of AFGL 2591 (van der Tak et al. 1999) already shows striking differences with that of NGC 7538 IRS9. Although the massive young star is embedded to about the same degree as NGC 7538 IRS9, as evidenced by the similarity of the depth of their 10 μm silicate profile, the relative prominence of the ice absorption of some species, such as H_2O and CO_2 is diminished, whereas the absorption bands of CO, CH_4 and CH_3OH have completely vanished. In contrast to NGC 7538 IRS9, higher resolution ISO-SWS spectra of AFGL 2591 show a large number of sharp absorption lines due to gas-phase CO, CO_2 and H_2O (Helmich et al. 1996; van Dishoeck et al. 1996). The temperatures derived from these gaseous molecules amount to a few 100 K, well above the evaporation temperature of most ices.

The difference between the infrared spectra of NGC 7538 IRS9 and AFGL 2591 can easily be understood by *assuming* that the former is in an earlier evolutionary stage than the latter. Whereas the NGC 7538 IRS9 inner envelope consists of mostly unprocessed interstellar material, AFGL 2591 has already heated the inner region of its envelope to above the evaporation temperature of most ices and has formed a so-called "hot core" region. By analyzing gas/ice abundances in a larger sample of YSOs, van Dishoeck et al. (1999) found a good correlation between gas temperature and gas/ice abundance, showing that this process of the evaporation of ice mantles and the heating of the YSO's envelope is more general than illustrated here by the two examples of NGC 7538 IRS9 and AFGL 2591, and may in fact be a good indicator of age for embedded YSOs.

A second difference between the spectra of NGC 7538 IRS9 and AFGL 2591 in Fig. 1 is the presence of emission lines due to H_2, [Si II] and [S I] in AFGL 2591, which appear absent in NGC 7538 IRS9. In particular the detection of [S I] 25.25 μm is significant, since this line can only be formed with detectable intensity in regions of shocked gas (van den Ancker et al. 2000b). This shocked gas is most likely the result of the interaction of AFGL 2591's outflow with the surrounding cloud and traces the clearing of the circumstellar envelope of a young star.

Compared to NGC 7538 IRS9 and AFGL 2591, the spectrum of S106 (van den Ancker et al. 2000a), the third massive YSO shown in Fig. 1, looks very dif-

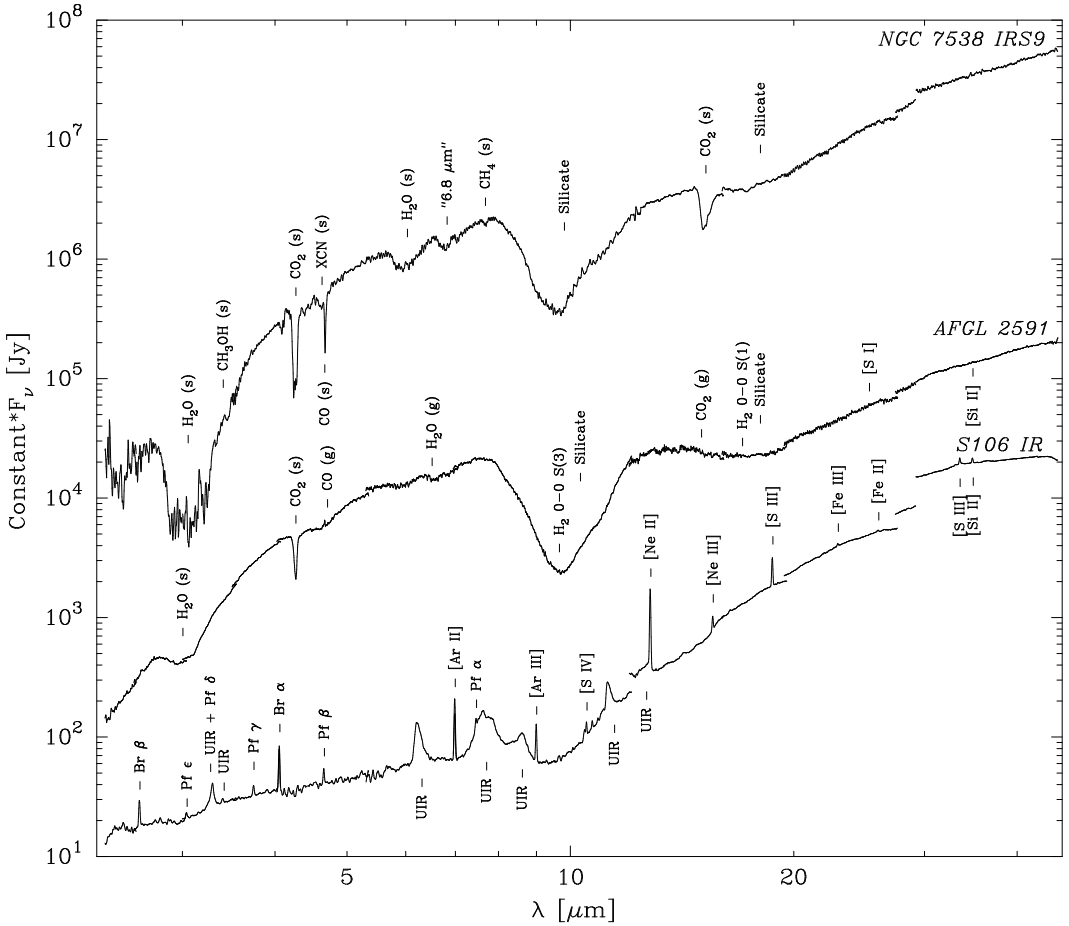

Figure 1. ISO-SWS spectra of the heavily embedded massive YSO NGC 7538 IRS9 (Whittet et al. 1996), the intermediately embedded massive YSO AFGL 2591 (van der Tak et al. 1999) and the bipolar nebula S106 (van den Ancker et al. 2000a), illustrating the spectral evolution of high-mass YSOs.

ferent. It consists of a smooth[2] continuum with a large number of sharp, strong emission lines due to recombination in the Brackett and Pfund series of H I, and due to numerous fine-structure transitions of ionic species. In addition to this, the unidentified infrared (UIR) emission bands, often attributed to polycyclic

[2]The "jumps" seen at discrete wavelengths in the spectrum are due to the fact that the SWS uses entrance apertures of different sizes for different wavelength regions, so for a source that is not point-like, such as S106, one may receive more flux where such a change in aperture occurs.

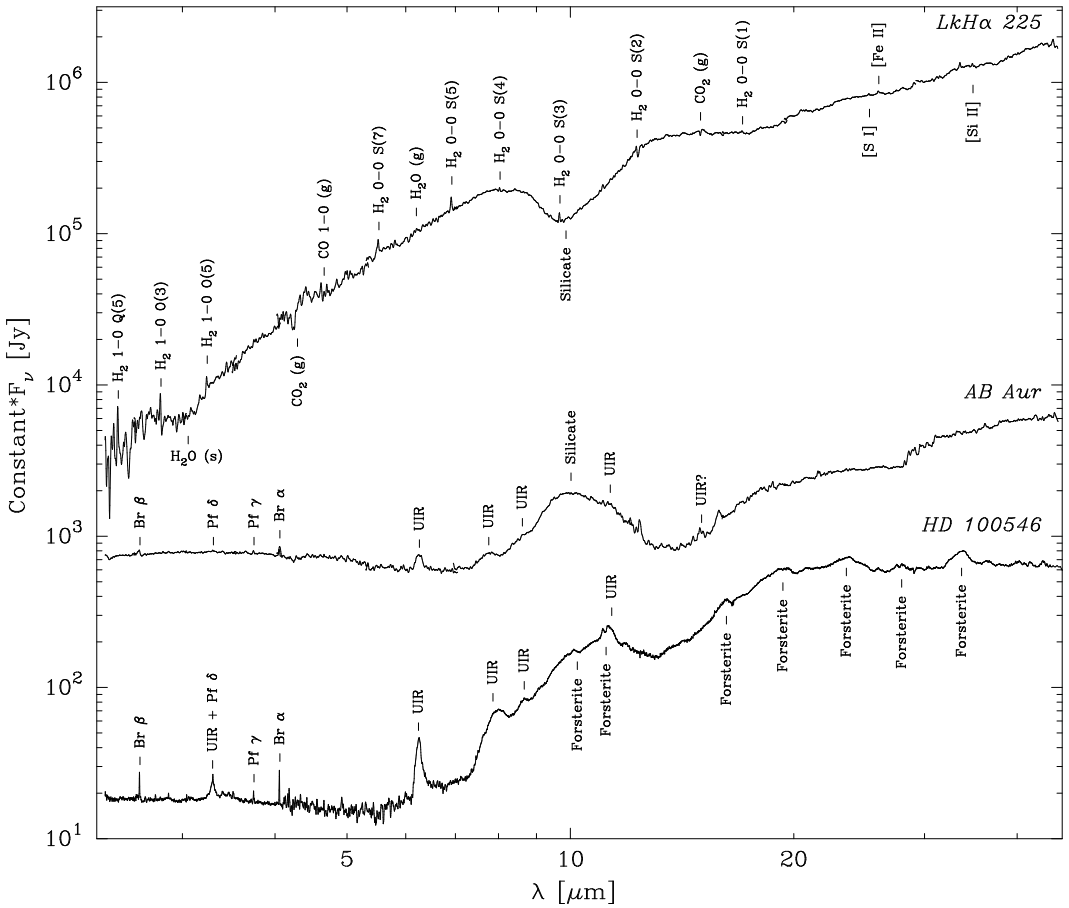

Figure 2. ISO-SWS spectra of the embedded intermediate-mass YSO LkHα 225 (van den Ancker et al. 2000b), and the Herbig Ae stars AB Aur (van den Ancker et al. 2000c) and HD 100546 (Malfait et al. 1998), illustrating the spectral evolution of intermediate-mass pre-main sequence stars.

aromatic hydrocarbons (PAHs)[3], are present at 3.3, 3.4, 6.2, 7.6, 7.8, 8.6, 11.3 and 12.7 μm. The central star in S106 has developed a strong stellar wind, as evidenced by the recombination lines, which has cleared most of the its natal cloud. The high ionization species in the spectrum show that it is now surrounded by a substantial H II region. The UIR emission as well as emission due to H_2 and other gas-phase molecules indicate that a so-called photo-dissociation region (PDR; see Hollenbach & Tielens 1999 for a comprehensive review), a mostly neutral region whose surface is photoelectrically heated under the influence of UV radiation, is present as well. The presence of this PDR emission

[3]Note however that ISOCAM CVF images did not retrieve the dependence of the relative strength of the UIR bands on UV field expected for PAHs (Uchida et al. 2000 and references therein).

shows that some regions of mostly neutral material, perhaps the remnants of the highest density clumps in the original cloud, remain.

3.2. Intermediate-mass stars

So far our discussion of YSO spectral evolution has focussed on massive objects. The infrared spectrum of these objects is typically dominated by their wide circumstellar environment and in fact evidence for the existence of protoplanetary disks around massive YSOs is weak. We now focus on intermediate-mass (2–10 $M_\odot$) pre-main sequence stars, the Herbig Ae/Be (HAeBe) stars. In Fig. 2 we again show the ISO-SWS spectra of three of these, the embedded intermediate-mass YSO LkHα 225, and the two relatively isolated Herbig Ae/Be systems AB Aur and HD 100546.

Although there are some indications that deeply embedded intermediate-mass YSOs may have a different method of thermally processing their circumstellar ices (c.f the case of Elias 29, Boogert et al. 2000), the overall spectra of embedded intermediate-mass YSOs appear similar to those of high-mass YSOs. For example, the spectrum of LkHα 225 (van den Ancker et al. 2000b) shown in Fig. 2 resembles that of many moderately embedded massive YSOs. Silicate absorption, as well as absorption due to water ice are visible and gas-phase CO, CO_2 and H_2O are present, indicative of a relatively evolved, warm core. Strong shock-excited emission lines of H_2, [S I], [Fe II] and [Si II] are present, again most likely related to the presence of an outflow from this star.

However, the next stage in the evolution of a intermediate-mass YSO, represented here by the well-studied Herbig Ae star AB Aur (van den Ancker et al. 2000c), yields a very different spectrum than that in the corresponding stage in the life of a massive star. The lines from the Pfund and Brackett series of H I, indicative of a strong wind, are still present, but the spectrum lacks the multitude of atomic fine-structure lines seen in the spectrum of S106, indicating that the central star of AB Aur does not emit sufficient UV photons to create a substantial H II region.

Several UIR bands can be seen in the spectra of AB Aur and HD 100546 shown in Fig. 2. An analysis of all spectra of Herbig Ae/Be stars found in the ISO data archive shows that the UIR bands are present in about 50%, without a strong preference for a certain spectral type. Whereas undoubtedly in some cases the observed UIR emission arises in filamentary PDR structures included in the rather large beam of the ISO spectrometers (e.g. $20'' \times 14''$ for the SWS), ground-based imaging as well as ISOCAM CVF data show that more commonly the UIR emission arises close to the star. At present it is not clear why some Herbig Ae/Be stars show this compact UIR emission, whereas others with apparently very similar properties do not. However, the absence of UIR bands in some Herbig Ae/Be stars does show that models depending on the presence of very small dust grains to explain the observed near-infrared excess in Herbig Ae/Be stars will not be successful in all cases.

The answer to the question why only some HAeBes show UIR emission may come from the observation that a few objects (e.g. AB Aur, Fig. 2) exhibit strong UIR bands due to C–C stretching modes, whereas the bands due to C–H bonds are weak or absent, suggesting that either the PAHs have been stripped of most of their hydrogen atoms, or that they are rather large (> 100 C atoms). The

presence of the rare UIR bands at 3.43 and 3.53 μm in a small number of Herbig stars (most noticeably HD 97048 and Elias 1; Van Kerckhoven et al. 1999) may reflect an even further chemical processing stage, in which nanodiamonds, not unlike those found in meteorites in our own solar system, have been formed (Guillois et al. 1999).

Although C-rich dust is certainly present, the general appearance of the infrared spectrum of most Herbig Ae/Be stars is determined by O-rich dust particles. Broad emission features in the 8–12 and 17–19 μm ranges due to silicate O–Si–O bending and stretching modes are found in a large fraction of Herbig Ae/Be stars. In some more embedded objects they are seen in absorption. At longer wavelengths, emissions due to water ice and hydrous silicates have been reported in some Herbig stars (Malfait et al. 1998, 1999). A broad spectral feature ranging from 14 to 38 μm was observed by van den Ancker et al. (2000c) in the Herbig Ae/Be stars AB Aur and HD 163296, which could due to a blend of the 28 μm resonance of iron-oxide with the 19 μm resonance of amorphous silicates. Interestingly, iron or iron-oxide at $\sim$ 1000 K can also naturally explain the near-infrared excess observed in virtually all HAeBes.

The fact that the silicate features are seen in emission suggests that the emitting material is optically thin at 10 μm in the objects where this is the case. This puts strong constraints on the distribution of dust and its temperature structure. However, millimeter continuum observations imply that the masses contained in these disks can be substantial, leading some authors to suggest that the observed silicate emission could arise in an extended optically thin region above the dense mid-plane of the disk (Natta et al. 1999; Bouwman et al. 2000.

In most stars the 9.7 μm silicate emission appears broad and smooth, such as in AB Aur. It is essentially the inverse of the very smooth silicate features seen in absorption towards all embedded YSOs (e.g. AFGL 2591 and LkHα 225 in Figs. 1 and 2). Comparison with laboratory determinations of optical constants of silicates shows that the lattice structure of these silicates must be amorphous, i.e. relatively unordered. Although most common, not all Herbig stars show the very smooth silicate emission profiles seen in AB Aur. An especially spectacular example is that of the Herbig B9 star HD 100546 (Waelkens et al. 1996; Malfait et al. 1998), shown as the bottom curve in Fig. 2. Here we see that the 8–12 μm silicate feature shows a lot of sub-structure, and many broad bands with strengths up to that of the underlying continuum appear in emission at the longer wavelengths of the SWS wavelength range. These sharper features are indicative of silicates in which the lattice structure is more crystalline. Note that detailed modelling of the dust composition shows that even though the crystalline silicates dominate the appearance of the infrared spectrum, the bulk of the silicates is still in the amorphous form (Malfait et al. 1999). Comparison with lab data shows that the peaks seen in the HD 100546 spectrum must be due to the mineral forsterite (Mg_2SiO_4). This is exactly the same material as is found in comets in our own solar system (Crovisier et al. 1997), suggesting that the processing of circumstellar dust in the primitive solar system bears similarity to that in HAeBes.

3.3. T Tauri stars

The SWS and LWS were sufficiently sensitive to allow the study of massive YSOs at distances up to several kiloparsecs, as well as the nearest intermediate-mass stars, but they lacked the sensitivity to study even the nearest T Tauri stars, low-mass pre-main sequence stars which may represent a better analog of the protosolar nebula than the Herbig Ae/Be stars. However, the spectroscopic modes of the more sensitive ISOPHOT and ISOCAM instruments, although limited to wavelengths smaller than 18 μm, also allowed valuable information on the dust composition in the nearest young stars of solar mass to be gathered. Based on ISOPHOT data, Natta et al. (2000) show that the amorphous silicate emission features exhibited by most Herbig Ae stars are also found around all nine studied T Tauri stars in the Chamaeleon I dark cloud. Possibly due to the higher requirements with respect to signal to noise and spectral resolution, crystalline silicates still await their first detection in a low-mass YSO. Although a detailed study of the dust composition of T Tauri objects awaits more sensitive mid-IR spectroscopic instruments such as the infrared spectrograph on board NASA's *Space Infrared Telescope Facility* (SIRTF), there are at the time of writing no indications that the spectral evolution sketched in the previous subsection for intermediate-mass YSOs would not equally apply to solar-mass pre-main sequence stars.

4. Disks and envelopes around young stars

The IRAS mission detected infrared radiation, believed to originate in circumstellar disks or envelopes, from many young stellar objects. However, its poor spatial resolution inhibited a comprehensive study of young clusters. Higher spatial resolution at wavelengths not hindered by interstellar extinction allowed ISO's camera to provided a new complete census of nearby star forming regions, resulting in a doubling of the known number of YSOs in each (Olofsson et al. 1999). The new cluster members are mainly at the low-luminosity end of the luminosity distribution, indicating that the initial mass function continues to rise slowly (with index -0.2) until brown dwarf masses.

Preliminary results of a ISOPHOT study of 97 T Tauri stars in five young clusters have been reported by Robberto et al. (1999). They found the fraction of stars with 60 μm excesses to decrease from around 60–70% in Taurus, ρ Oph and the R CrA region to below 20% in the older Cham I and TW Hydra associations. More than 80% of the stars in these clusters that exhibit near-infrared excess emission also show a far-infrared excesses. In contrast, only one star that has no near-infrared excess has one at 60 μm. No 60 μm excesses were detected in the eldest clusters studied by Robberto et al., suggesting that for low-mass stars the dust in disks between 0.3 and 3 AU disappears on timescales of $\sim$ 10 Myr.

A long-standing problem in studies of pre-main sequence stars has been the question whether the observed infrared excesses arise in a relatively stable circumstellar disk or in an infalling envelope. This question can be answered by studying the spatial extent of sources in the infrared. Ábrahám et al. (2000) observed seven Herbig Ae/Be stars at mid-infrared wavelengths with ISOPHOT and concluded that at $\lambda < 25$ μm the observed emission mainly arises from a compact area, whereas at longer wavelengths it is spatially extended. At

wavelengths longer than 100 μm, the emission is never dominated by the Herbig Ae/Be stars, but by dust cores of about $1'$ in size. These results show that at least in these cases the observations exclude a "disk-only" geometry and a (not necessarily spherical) envelope needs to be present as well. They do not exclude the possibility that in some cases only a disk remains. Further study of a sample that also contains Herbig stars located in relative isolation is required to provide the definitive answer to this problem.

Although the infrared continuum will be dominated by the circumstellar dust, the gas in the disk will also produce spectral signatures in the infrared. The pure rotational lines of H_2, all located in the mid-infrared, are especially interesting since they directly probe the dominant gas component in the disk and hence allow us to measure disk masses without relying on an essentially unknown CO/H_2 ratio. For most YSOs observed with ISO the observed H_2 appears too warm (typically 500 K) to be associated with the circumstellar disk: it probably arises in the loose stellar surroundings and is associated with either PDRs or with shocked gas in outflows (e.g. van den Ancker et al. 2000a, b). However, van Dishoeck et al. (1998) report the detection of the H_2 0–0 S(0) and S(1) lines toward the isolated Herbig Ae star HD 163296. The implied temperature of only 150 K, the disappearance of the H_2 emission off-source and the absence of ro-vibrational H_2 emission in ground-based imaging all argue in favor of an interpretation in which the H_2 lines observed in HD 163296 originate in the circumstellar disk. The total observed gas mass in this object is 0.007 $M_\odot$. The value of 35 for the gas to dust ratio in the HD 163296 disk that is derived by combining this gas mass with the dust mass in the HD 163296 computed by Bouwman et al. (2000) is surprisingly close to the canonical value of 100 for the gas/dust ratio in the interstellar medium.

5. Vega-type Stars

One of the most unexpected results of the IRAS mission was the discovery of an infrared excess due to the presence of circumstellar dust around several nearby main-sequence stars (Aumann et al. 1984). Spectacular images showing an edge-on disk around the relatively young main-sequence star β Pictoris (Smith & Terrile 1984) raised the question whether these disks are a remnant of the star formation process, or represent the extrasolar equivalents of the Kuiper belt in our own solar system. However, the IRAS survey and subsequent ground-based follow-up research lacked the sensitivity to determine what fraction of nearby stars show the Vega phenomenon.

Using the ISO photometer, Dominik et al. (1999) performed a deep survey on a volume-limited sample of nearby main-sequence stars of spectral types A, F, G and K. They found infrared excesses in approximately 21% of nearby stars. However, Vega-type phenomena appear much more common in A- and F-type than in stars of later spectral type. This need not necessarily reflect a different disk mass, but may be due to a mixture of disk illumination and time evolution. Based on the same data-set, Habing et al. (1999) report a distinctly bimodal distribution of the frequency of dust disks with age: more than 50% of stars younger than 300 Myr have infrared excesses at 25, 60 or 170 μm, while most stars older than 400 Myr do not. Ninety percent of the disks disappear when

the star is between 300 and 400 Myr old. These timescales are similar to those derived for the final-clean up phase of our own solar system. This result clearly shows that in most cases the Vega-type phenomenon represents remnants of the star formation process and that the vicinity of the sun hosts a considerable population of relatively young stars.

However, not *all* debris disks decay after 400 Myr. In about 10 percent of the cases circumstellar dust persists for longer than 400 Myr. At present is is unclear what causes these disks to live longer than most. A hint to the answer may come from the detection of a 60 μm excess in ρ^1 Cnc (Dominik et al. 1998). Around this 4 Gyr-old star both a planet and a disk are present and it is not inconceivable that the presence of a third body may be required to keep a circumstellar disk stable on long time scales.

Soon after their discovery it was realized that the timescale for the removal of dust particles around Vega-type stars is much smaller than their age: radiation pressure will push the small dust particles out of the system, whereas Poynting-Robertson drag will bring the larger ones in to where they are evaporated. Therefore they must be re-supplied, at least for some fraction of the stellar lifetime. Possibilities that have been speculated upon to provide the mechanism for the replenishment of small dust grains include collisions between larger bodies or the evaporation of extra-solar comets.

Indications to the origin of the dust seen in the Vega-type systems may come from infrared spectroscopy. Solar system comets show a number of distinctive spectral signatures in the infrared due to the presence of crystalline silicate dust (e.g. Crovisier et al. 1997). Ground-based spectroscopy of the β Pic system in the 10 μm atmospheric window seemed to suggest a high degree of similarity of the dust seen in this system to that in comets (Telesco & Knacke 1991; Knacke et al. 1993). However, Pantin et al. (1999) report an absence of the expected mid-infrared crystalline silicate features in the ISO-SWS spectra they obtained of β Pic. At present it is unclear whether comets need to be discarded as the source of dust in Vega-type systems, or that the in many ways unusual β Pic disk has a different composition than most Vega-type stars. Infrared spectroscopy of fainter, more typical, Vega-type stars with SIRTF will be able to clarify this issue within the coming years.

6. Concluding remarks

The *Infrared Space Observatory* has yielded great new insights in the the evolution of disks into planetesimals and planets. For the first time we are able to analyze the chemical composition and evolution of circumstellar dust and only after the ISO mission has it been realized how important solid-state resonances are for the interpretation of infrared energy distributions. In fact the flux in all four IRAS bands, centered at 12, 25, 60 and 100 μm, can be dominated by solid-state emission features, demonstrating the necessity of infrared spectroscopy to interpret the energy distributions of pre-main sequence objects.

One of the most exciting ISO results has been the discovery of crystalline silicates, such as found in our own solar system, in some Herbig Ae/Be stars. The fact that in embedded YSOs the silicates are invariably amorphous shows that for intermediate-mass stars, the transition from amorphous to crystalline

must occur in the HAeBe phase of evolution. The mechanism responsible for this transition is yet unclear. Laboratory experiments show that crystallization of silicates may be achieved by either a slow annealing of warm grains, or by heating the dust grains to temperatures above $\sim$ 1000 K. Since the crystalline dust in Herbig Ae/Be stars is observed to have much lower temperatures, substantial mixing in the disk would be required in this scenario. However, a study of ISO spectra of post-AGB stars by Molster et al. (1999) shows that in these objects crystallization occurs at much lower temperatures over long time-scales. They suggest that the same low-temperature annealing process at work in these stars may also be responsible for the crystallization of silicates in young stars. If proven, this same process will be responsible for the creation of crystalline silicates in solar-system comets, a conclusion which ultimately may alter our view of the origin of our own solar system.

ISO has also left us with a feeling for the richness and variety of the infrared spectra of young stars, resulting in the qualitative picture of spectral evolution sketched in section 3. However, a quantitative conformation of this picture awaits bigger samples and in particular its extension towards solar-mass young stars. Indeed, van den Ancker et al. (2000c) remark upon the fact that stellar ages as derived from the position in the Hertzsprung-Russell diagram do not show a one-to-one correlation with degree of crystallinity. The fact that in a typical young cluster only half of the pre-main sequence objects shows an infrared excess (e.g. Beckwith et al. 1990), suggests that this may be due to greatly differing time-scales for disk evolution from object to object. The lack of correlation between submm spectral index, an indicator for grain growth, and degree of crystallinity noted by these authors is more puzzling. Apparently these two processes are not necessarily coupled, suggesting that processes other than stellar mass and age, perhaps the environment of the star, are important.

The discovery that the Vega-type phenomenon is common in relatively young main-sequence stars, whereas it is rare in stars older than 400 Myrs has considerably strengthened the connection between pre-main sequence and Vega-type stars. However, the final proof of an evolutionary link between these two categories of objects still remains to be made and most likely will be made soon: the last of NASA's great observatories, SIRTF, is scheduled to be launched in the near future and, with its greatly enhanced sensitivity, promises to continue the path of discoveries that has been explored by ISO.

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