PROPERTIES AND EVOLUTION OF DISKS AROUND PRE-MAIN-SEQUENCE STARS OF INTERMEDIATE MASS

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This chapter discusses the properties of the immediate circumstellar environment of pre-main–sequence stars of intermediate mass (the Herbig Ae/Be stars or HAe/Be), with particular emphasis on the properties and evolution of the circumstellar disks. HAe/Be stars cover a large range of spectral types and luminosities; this has implications for their environments, which, by the time a star becomes optically visible, are very different in early B stars (HBe; $M_\star \gtrsim 5\ M_\odot$) and in stars of later spectral types (HAe; $M_\star \lesssim 5\ M_\odot$). A variety of recent infrared and millimeter observations are reviewed. They indicate that HBe stars generally lack clear evidence of disks; they are often found inside large cavities, depleted of dust and gas. We interpret these observations as evidence of a rapid evolution of the circumstellar environment, possibly caused by the strong stellar radiation fields. In contrast, circumstellar disks appear to be associated with a large number of cataloged HAe stars. We discuss the properties and evolution of these disks, within the context of possible grain growth and planet formation.

I. INTRODUCTION

Disks of gas and dust are associated with the majority of classical T Tauri systems (TTs) in nearby star-forming regions (see the chapters by Mundy et al. and by Wilner and Lay in the present volume). The TTs have spectral types M and K, and corresponding stellar masses in the range $0.25 \lesssim M_*/\mathrm{M}_\odot \lesssim 1$. Herbig (1960) was first to identify pre-main-sequence stars of earlier spectral types, and greater masses, and

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he compiled a list of 26 candidate young objects in the spectral range F0 to B0. These stars are now invariably known as "Herbig Ae/Be stars" (or HAe/Be stars), and the number of candidates has expanded to about 300 stars (Thé et al. 1994; de Winter 1996). We will adopt here an "evolutionary" definition of HAe/Be; namely, all stars of spectral type approximately in the range A–B, which lie on pre-main–sequence evolutionary tracks in the HR diagram. This criterion is applied very loosely to stars earlier than about B2, which remain on the ZAMS only for a very short time. The current sample includes stars of mass $\sim 2{-}20$ M$_\odot$, with luminosities of a few L$_\odot$ to $\sim 10^4$ L$_\odot$ and effective temperatures from 8000 to 30,000 K. The ages of catalogued HAe/Be stars range from $\lesssim 10^5$ to about 10^7 yr.

HAe/Be stars comprise an inhomogeneous class of objects not only because of their masses, luminosities and temperatures, but also because of their evolutionary histories. Like the TTs, Herbig stars of spectral types A and late B (HAe, for simplicity) become optically visible long before arriving at the main sequence, and their pre-main-sequence evolution can be studied in detail. Conversely, stars with spectral types earlier than about B5 (henceforth HBe) never emerge from enveloping circumstellar material throughout their brief pre-main-sequence phases (Palla and Stahler 1993; see also the chapter by Stahler et al. in this volume). Also, as for O stars, their high luminosities and hard radiation fields have a disruptive effect on their environments. A common property of all HAe/Be stars, and one that differentiates them from stars of lower mass, is that their entire pre-main–sequence evolution occurs along radiative tracks.

Much progress in our knowledge of HAe/Be stars has been made since the time of the Protostars and Planets III conference. Many results are summarized in the proceedings of the conference on HAe/Be stars held in Amsterdam in 1993 (Thé, Pérez and van den Heuvel 1994), and recent work has been covered in a number of reviews such as those by Pérez and Grady (1997) and by Waters and Waelkens (1998). We refer the reader to these reviews for complete summaries of the observational properties of HAe/Be stars.

In this work, we concentrate on just one aspect of intermediate-mass stars, namely the existence, properties and evolution of circumstellar disks during the pre-main-sequence phase. Understanding disks is of crucial importance in any study of star and planet formation. In recent years, disks around HAe stars have attracted increasing attention because these stars have masses similar to those of the main-sequence disk sources β Pic (A5), α PsA (A3) and α Lyr (A0). These latter stars, which presumably passed through a Herbig Ae phase en route to the main sequence, appear to be surrounded by disks of debris produced by ongoing collisions and disruptions of large solid bodies (cf. Backman and Paresce 1993). The debris disks may be visible signatures of stellar environments in which planets have already been created (see Lagrange et al. this volume, and references therein), raising the possibility that disks around their HAe progenitors could be sites of planet formation.

Strom et al. (1993) in their PPIII chapter discuss the properties and evolutionary timescales for disks around intermediate-mass as well as solar-mass stars. They concluded that the inference of disks around stars of mass >3 $M_{\odot}$ was very uncertain. In fact, in the years immediately following, hard evidence for disks around HAe/Be stars was very elusive and they were the subject of intense debate, as we will discuss in §II. The situation has been drastically changed by recent observations in different areas, among them single-dish and interferometric observations at millimeter wavelengths, *Infrared Space Observatory* (ISO) data, new forbidden line surveys, and long-term photometric and polarimetric monitoring.

II. THE DISK DEBATE

While it is clear that HAe/Be stars are accompanied by circumstellar dust and gas, there has been much uncertainty on the geometry of the circumstellar environment and, more specifically, on the association of intermediate-mass stars with disks. We will give in this section a brief summary of the "disk debate" (see also Waters and Waelkens 1998). If HAe/Be stars do not have (and never had) circumstellar disks, we are forced to conclude that the mechanism of formation of massive stars differs from that of solar mass stars, which is generally agreed to require the presence of an accretion disk (Adams, Shu & Lizano, 1987). Coalescence of lower mass stars in dense clusters, for example, has been proposed as an alternative formation mechanism by Bonnell et al. (1998) (see Stahler et al, this volume).

In the following, we identify *disks* as geometrically thin accretion and/or reprocessing structures (including the debris disks of Vega-like stars). The definition of *envelope* is much less precise. We will use it for any distribution of dust (and gas) which subtends a substantial solid angle at the star and has low optical depth at visible wavelengths. Often, *envelopes* are identified with infalling envelopes (Terebey et al. 1984). When this is the case, we will explicitly use the expression *infalling envelope*.

A. Spectral Energy Distribution

In TTs, strong evidence for circumstellar disks came from the shape of the spectral energy distribution (SED) at infrared and millimeter wavelengths (see Beckwith and Sargent 1993a). HAe/Be stars have SEDs similar to those observed for TTs. Hillenbrand et al. (1992) proposed a classification of HAe/Be stars in three groups. Group I corresponds to objects with SEDs well fitted by the emission expected from flat circumstellar accretion disks. Group II has SEDs that can be best understood in terms of a star+disk system surrounded by a roughly spherical envelope of dust and gas. Group III stars have very small infrared excesses, often consistent with free-free emission from stellar winds. These three groups might correspond to an evolutionary sequence (from Group II to I to III), in which the amount of circumstellar matter decreases with time.

The Hillenbrand et al. (1992) interpretation was challenged by a number of authors on various grounds. Hartmann et al. (1993) pointed out that the high accretion rates derived for Group I stars by Hillenbrand et al. (1992) imply an emission in the near-infrared and visual much larger than observed. The possibility that a dominant contribution to the mid-infrared emission of HAe/Be stars could come from transiently heated particles, as observed in reflection nebulae, was suggested (Hartmann et al. 1993; Prusti et al. 1993; Natta and Krügel 1995).

Several teams of authors found that all the SEDs of HAe/Be can instead be interpreted as the emission of spherical envelopes of various optical depths and density profiles (Berrilli et al. 1992; Miroshnichenko et al. 1997; Pezzuto et al. 1997). Far-infrared, high spatial resolution observations proved that the 50 and 100 μm emission of many stars belonging to Group I is in fact extended over scales ranging from $\sim$0.03 to $\sim$0.3 pc, inconsistent with the disk interpretation (Natta et al. 1993; Di Francesco et al. 1994). Most sources, especially the HBe objects, are also found to be extended in the 1.3 mm continuum (Henning et al. 1998). Detailed radiative transfer models of some of those stars (Natta et al. 1993), however, showed that the combined spatial and spectral constraints could not be satisfied by spherical envelopes alone, but that both disks and envelopes had to contribute to the observed SEDs: the disk emission in the near and mid-infrared, and the envelope emission in the far-infrared. Observations at different wavelengths may therefore be sensitive to different source components with greatly different spatial scales.

B. The Disk-Wind Connection

A strong, albeit indirect, line of evidence for disks in TTs is provided by the correlation of wind indicators, such as the intensity of forbidden lines, with disk indicators, such as near-IR excess emission (Cabrit et al. 1990). This correlation has found an explanation in the theory of accretion-driven mass loss (see, for example, Edwards et al. 1993), where disk accretion, coupled with the stellar magnetic fields, provides the energy source for the outflow. The correlation of forbidden line intensity with excess infrared luminosity observed in TTs extends to HAe/Be stars, suggesting that disk accretion is also driving the mass-loss in these stars (Corcoran and Ray 1998).

Forbidden lines in TTs tend to have blue-shifted profiles. The most widely accepted explanation is that an optically thick disk occults the redshifted emission of a stellar wind or other outflow close to the star (Appenzeller et al. 1983; 1984; Edwards et al. 1987). The situation in HAe/Be stars is much more controversial. The line profiles tend to be much more symmetric than in TTs, with strongly blueshifted profiles confined to the most embedded objects (Böhm and Catala 1994; Corcoran and Ray 1997). However, there is a slight tendency to blueshifted profiles. Corcoran and Ray (1997) claim that their results are consistent with the prediction of the two-component forbidden line emission model of TTs (Hamann 1994; Hirth et al. 1994; Hartigan et al. 1995; Kwan and Tademaru 1995), where the high-velocity (jet) component is present only in the more embedded, younger objects and disappears first, leaving only the low-velocity component, emitted by a poorly collimated disk wind. In HAe/Be stars, this low-velocity emission is broader and more symmetric than in TTs due to the faster rotation of the disk.

III. DISKS AS SEEN WITH MILLIMETER INTERFEROMETRY

A fundamental step forward in proving the presence of circumstellar disks in HAe/Be stars has come from interferometric observations at $\lambda \sim 1$ mm and $\lambda \sim 3$ mm (Di Francesco et al. 1997; Mannings and Sargent 1997; Mannings et al. 1997). The detection of compact millimeter emission on scales of 1–2 arcsec is considered reliable evidence that the emitting dust is in a disk, rather than in a spherical envelope around the star, since the optical depth of such an envelope would have to be by far larger than observed in order to account for the measured flux (see Beckwith et al. 1990; Mannings and Sargent 1997). Table 1 provides a summary of the millimeter interferometric observations of HAe/Be stars obtained up to now. For each star, we give spectral type, distance, effective temperature, luminosity, age and mass. The last two quantities were derived by comparing the position of the stars on the HR diagram with the predictions of pre-main-sequence (Palla and Stahler 1993) and main-sequence (Schaller et al. 1992) evolutionary tracks (see discussions in van den Ancker et al. 1998 and Fuente et al. 1998). The wavelength of the observations is given in Column 10, and the measured flux in Column 11.

A. Disk Masses

The simplest way to estimate disk masses from the observed millimeter continuum fluxes is to assume that the emission comes from optically thin, isothermal dust at temperature $T_{\rm D}$:

$$M_{\rm D} = d^2 \frac{F_{\rm mm}}{\kappa_{\rm mm} B_{\rm mm}(T_{\rm D})} \tag{1}$$

where d is the distance of the source, $F_{\rm mm}$ the observed flux, $B_{\rm mm}$ the Planck function at $T_{\rm D}$, and $\kappa_{\rm mm}$ the dust opacity per gram of gas at the observed wavelength. We have compared Eq.(1) to model-predicted millimeter fluxes for disks of different $M_{\rm D}$. The disk structure is described in terms of power-law temperature and surface density profiles (Beckwith et al. 1990; Natta 1993) and we have varied the model parameters (central star, disk mass, outer radius, temperature and surface density profile) over a large range of possible values. We found that Eq.(1) recovers the correct value of $M_{\rm D}$ (within a factor of 2–3) for disks with $M_{\rm D} \lesssim 0.3\,{\rm M}_\odot$, *provided* that one allows $T_{\rm D}$ to vary as a function of the spectral type of the star as indicated in Table 2. The disk masses $M_{\rm D}$ derived with this prescription are given in Table 1, Column 12. We have adopted here (and in the following) $\kappa_{1.3{\rm mm}} = 1$ cm^{-2} g^{-1} of dust (as suggested by Ossenkopf and Henning 1994), and a wavelength dependence $\kappa \propto \lambda^{-\beta}$ with $\beta = 1$, unless otherwise specified. We also assume a dust-to-gas mass ratio of 0.01. The $\kappa_{1.3{\rm mm}}$ value is consistent, within the uncertainties, with that computed by Pollack et al. (1994), who proposed a dust model for protoplanetary disks based on the composition of the primitive solar nebula. For a discussion of the uncertainty on κ at millimeter wavelengths, see for example Mannings and Emerson (1994) and Pollack et al. (1994).

Virtually all stars in our sample with spectral type *later* than B8 (12 out of 16) are detected by interferometers, in contrast with the detection of only one star (R Mon) out of 7 earlier than B8 (see Table 1). This, in itself, could simply reflect a selection effect, arising from the sensitivity of the mm continuum measurements, since on average HBe stars are further away than HAe stars. In fact, the derived disk mass of HAe stars has an average value of $M_{\rm D} \sim 0.06\,{\rm M}_\odot$, with a spread of more than one order of magnitude. The smallest values of $M_{\rm D}$ are $\sim 0.02\,{\rm M}_\odot$. The upper limits on $M_{\rm D}$ for HBe stars are $\sim$ 0.1–0.2 ${\rm M}_\odot$, with the single exception of BD+31 346, for which ${\rm M_D} \lesssim 0.01\,{\rm M}_\odot$. However, if we consider the ratio of the disk mass to stellar mass $M_{\rm D}/M_*$ (see Fig. 1), we find that Ae stars tend to have higher values than the upper limits set for HBe stars. R Mon, the only early Be star detected with the interferometers, has a ratio ${\rm M}_D/{\rm M}_\star$ ($\sim$0.007) lower than any of the HAe stars in our sample.

The highest values of $M_{\rm D}$ and of $M_{\rm D}/{\rm M}_\star$ are found in the most embedded stars (such as PV Cep, MacC H12 and V1318 Cyg). This may be a true effect (more embedded objects may have more massive disks), but it is also possible that $M_{\rm D}$ is overestimated because the temperature of the outer disk is higher than we have assumed, due to heating by surrounding dust ("backwarming"; see the discussion of this effect in Butner et al. 1994).

B. Frequency of occurrence of HAe/Be disks

There is a clear difference between the frequency of occurence of disks around HBe stars (where it may be close to zero) and HAe stars. In order to estimate the latter, we cannot rely on the ratio of detections/non-detections in interferometric observations, since the sample of observed stars included only objects known to have strong mm flux from single-dish observations. However, for most HAe stars the interferometers recover, within the uncertainties, all the flux measured by single-dish telescopes. Natta et al. (1997) collected single-dish mm observations of a sample of 30 HAe stars in the age range $10^5 - 10^7$ yr. The sample was put together to study disk masses in HAe stars with and without strong photometric variability. Their sample includes only stars for which millimetric observations (either detections or non-detections) were found in the literature. Insofar as this sample could be considered representative, it indicates that the frequency of occurrence of disks is very large, between 75% and 100%.

C. The gas disk

Observations in the emission lines of ^{13}CO(1→0), CO(1→0) and CO(2→1) with the Owens Valley interferometer show that in 5 out of 11 cases a gaseous disk, as well as a dusty disk, is associated with HAe stars (Mannings and Sargent 1997; Mannings et al. 1997; Mannings and Sargent 1999). For AB Aur, HD 163296, MWC 480 and MWC 758 the CO lines display the typical velocity pattern expected in a Keplerian rotating disk, i.e. an ordered velocity gradient directed along the major axis of the extended gas structure (cf. model predictions by Beckwith and Sargent 1993b). For the A2e system MWC 480, this interpretation is confirmed by detailed kinematic modeling (Mannings et al. 1997).

The CO emission is usually more extended than the continuum emission, and it has been possible to derive sizes and aspect ratios (Mannings and Sargent 1997, 1999 and Mannings et al. 1997) from interferometric CO observations of AB Aur, HD 163296, MWC 480 and MWC 758. The CO disks have radii ranging from < 85 AU in CQ Tau to 700 AU in MWC 480.

Masses derived from CO lines, assuming a ratio CO/H_2 as in molecular clouds, are significantly smaller than those derived from continuum emission. The discrepancy could be due to molecule depletion onto grains at low temperatures, or to optical depth effects in the CO lines (cf. Dutrey et al. 1996). It is also possible, in principle, that gas is globally depleted with respect to dust. Sensitive follow-up observations using optically thin lines of CO isotopomers and molecules less easily depleted onto grains than CO are necessary to improve estimates of gaseous disk masses. In the meantime, estimates of dust and gas masses derived using continuum fluxes appear to be more reliable.

D. Comparison with T Tauri Disks

It is interesting to compare the masses of disks found around HAe stars with those detected in TTs. We have recomputed disk masses in TTs (a total of 87 stars) from the observed millimeter fluxes (Beckwith et al. 1990; Osterloh and Beckwith 1995) using Eq.(1) with $T_{\rm D}$=15 K, as appropriate for stars of spectral type later than F0 (see Table 2), and $\kappa_{1.3{\rm mm}} = 1$ cm^{-2} g^{-1} of dust. We have also added to the HAe/Be stars reported in Table 1 15 HAe stars with single-dish mm measurements from Natta et al. (1997). In spite of the large dispersion of values for any given spectral type, there is a statistically significant trend (significant at the 4$-$5σ level according to three different statistical tests, the Cox proportional hazard model, the generalized Kendall's tau and the Spearman's rho test) of decreasing disk mass in stars of later spectral type: $M_{\rm D}$ decreases by about an order of magnitude between A0 and M7. Not surprisingly, since spectral type and mass are not independent, we find a correlation with similar statistical significance if we plot M$_{disk}$ as a function of the stellar mass M$_\star$ (Fig. 2, top panel). While M$_{disk}$ seems to decrease with M$_\star$, the ratio of disk mass to stellar mass is roughly constant for stars in the range A0–M7 (or, alternatively, in the mass range $\sim 4 - 0.3$ M$_\odot$), with an average value of $\sim$0.04 and a large dispersion (Fig. 2, bottom panel). Note again the low values of M$_D$/M$_\star$ for early-B stars, i.e., for masses $\gtrsim$5 M$_\odot$. We do not know if this constancy has implications of any relevance for the process of disk formation and evolution. We just note that this value is much smaller than the stability threshold against self-gravitational perturbations ($M_{\rm D}/M_* \sim 0.24$; Shu et al. 1990). It seems that pre-main sequence stars of all masses have relatively low-mass disks.

IV. THE MID-IR SPECTRUM OF HAe/Be

The range of wavelengths between $\sim$5 and $\sim$15 μm (the mid-IR) contains important information on the circumstellar environment of HAe/Be stars. In particular, we find in the mid-IR a prominent silicate band with peak at about 10 μm, together with the series of so-called unidentified IR bands (UIB) at 6.2, 7.8, 8.6, 11.3, and 12.5 μm often attributed to polycyclic aromatic hydrocarbons (PAHs). While this wavelength interval is only partially accessible from the ground, ISO obtained high-quality spectra which cover the whole mid-IR for a large number of HAe/Be stars. We have collected a sample of 30 HAe/Be stars with known mid-IR spectra (Wooden 1994; Prusti et al. 1999; Siebenmorgen et al. 1998, 1999; van den Ancker, personal communication). This sample is not complete, and will grow in number and statistical significance as more ISO spectra are published. However, it is sufficient to illustrate some of the HAe/Be star properties relevant to our discussion.

A. Unidentified Infrared Bands

UIBs are seen practically in all the early-type stars observed so far by ISO (personal communication by the SWS (Short Wavelength Spectrometer) team); they are weaker in stars of later spectral type, where they can be detected only in high quality, high resolution spectra. UIB emission arises in regions of low optical depth exposed to UV radiation; it is often extended and not centered on the exciting star (see Siebenmorgen et al. 1999).

In some stars, the UIBs, and, more generally, the emission of transiently heated species, dominate the emission in the mid-IR. However, this seems to be true only for a few, relatively old, early-type stars. In most HAe stars, the mid-IR flux is due to a strong continuum, probably emitted by grains in thermal equilibrium with the local radiation field.

B. The Silicate Feature

The silicate feature is present in virtually all (75%) sources of spectral type A0 or later in our sample, but only in 4 of the 14 with spectral type earlier than A0. Wooden (1994) was first to point out that silicate emission is common among later type HAe/Be stars, while it is generally absent in early type sources whose spectra are dominated by UIBs.

Silicate emission in the 10 μm region is related to the existence of hot ($T_{\rm D} \gtrsim$ 500 K) grains with size $\lesssim$few μm and optical depths at the feature peak $\tau_{\rm sil}$ $\sim$0.5–1. This corresponds to $A_V \sim$ 2.5–5 for standard interstellar grains (Cohen and Witteborn 1985). A spherical envelope of dust around the star can reproduce the HAe observed silicate emission feature if its inner radius is controlled by dust sublimation (which for silicates occurs at about 1500 K; Berrilli et al. 1992; Miroshnichenko et al. 1997; Pezzuto et al. 1997).

Optically thick disks cannot account for the silicate emission. In fact, if we consider a three-component star+disk+envelope system, the continuum mid-IR emission due to the disk dilutes the silicate emission of the envelope until it disappears (Natta 1993). More realistic disk models, which include the effects on the emitted spectrum of a disk atmosphere, have been proposed for TTs by Calvet et al. (1991) and, more recently, by Chiang and Goldreich (1997). The disk atmosphere, heated by the stellar radiation to temperatures higher than the effective temperature of the underlying disk (analogous to a stellar chromosphere), produces a strong silicate emission feature on top of the continuum emission of the thick disk itself. For TTs, these models account well for several observed properties, and they directly link the presence of silicate emission with the existence of a circumstellar disk. Similar models could presumably account also for the silicate emission observed in HAe/Be stars.

The absence of silicate emission among HBe stars indicates that these stars lack the hot and optically thin dust component that emits the feature. If HBe stars are surrounded by dusty envelopes, the envelopes must have large inner holes, unless grains have grown to sizes $\gtrsim$few μm (but see §VIID). In fact, spherical envelope models, which extend to the sublimation radius and can account for the observed SEDs of HBe stars, all predict strong silicate emission (Berrilli et al. 1992; Miroshnichenko et al. 1997; Pezzuto et al. 1997). In order to suppress the silicate emission in a B0 star (which has a typical dust sublimation radius $\sim 8 \times 10^{13}$ cm), the inner radius of the envelope must be about 0.02 pc or 700 times larger than the dust sublimation radius. Such large cavities around several HBe stars have been inferred from far-infrared (Natta et al. 1993) and millimeter (Fuente et al. 1998) observations. If HBe stars have disks, the lack of silicate emission implies that they cannot sustain extended chromospheres, which would likely give rise to strong features.

V. THE ENVIRONMENT OF UXORs

Additional detailed information on the circumstellar environment of HAe/Be stars is provided by a large subgroup of highly variable stars, named UXORs after the first such identified star, UX Ori. UXORs are defined by their especially large photometric variability, with deep irregular minima, where a star can fade by as much as 2-3 magnitudes. At present, this subclass includes a few tens of objects, mostly HAe stars. van den Ancker et al. 1998 estimate that about 1/3 of the HAe stars may be UXORs. To our knowledge, no HBe star is a UXOR. UXORs show spectroscopic evidence of sporadic, high-redshift absorption events (see Grady et al., this volume).

A. An Inhomogeneous Environment

The most striking result in studies of UXORs is that the circumstellar dust seems to be distributed in an extremely inhomogeneous fashion. The most accepted interpretation of their variability (but see also Thé 1994; Eaton and Herbst 1995) is based on the variable circumstellar extinction model suggested by Wenzel (1969) and modified by Grinin (1988). According to this model, the brightness minima are caused by optically thick dusty clumps in orbit around the star which sporadically intersect the stellar radiation along the line of sight to the star. The "bluing effect" (i.e. the fact that the radiation first becomes redder and then bluer as the star fades) and the behavior of the polarization, which is maximum when the light intensity reaches a minimum, can be explained by scattering of the stellar light by a flattened and rather optically thin torus of dust around the star, seen edge-on by the observer, within which the postulated clumps are embedded. The contribution of this scattered component to the total radiation observed at any given time increases when the direct (unpolarized) radiation of the star is absorbed by the intervening dust clump.

The dust mass of an individual clump which produces a deep brightness minimum when intersecting the line-of-sight is estimated to be $M_c \sim 10^{20}$–10^{21} gr (Voshchinnikov and Grinin 1991; Meeus et al. 1998), comparable with the masses of the largest comets in the Solar System (Festou et al. 1993). We can roughly estimate the total mass of dust in clumps from the expression $M_{\rm D} \sim \phi(Rz/r_{\rm c}^2)M_{\rm c}$, where ϕ is the probability that one clump occults the star, $r_{\rm c}$ and $M_{\rm c}$ are the radius and mass of an individual clump, and R and z are the radius and scale height of the volume occupied by the clumps, respectively. Assuming a clump radius of the order of the stellar radius, and taking ϕ to be ~ 0.1 and z to be ~ 0.5R (see below), we obtain a dust mass $\lesssim 10^{-6}$ $M_\odot$ within a distance of 100 AU from the star. The short timescales ($\lesssim$ 1 day) observed in several episodes of variability can be accounted for only if clumps exist within a few AU of the star (Grinin 1994; Hutchinson et al. 1994; Sitko et al. 1994). The relation of the UXORs phenomena to the presence of dust very near to the star may account for the lack of UXORs among HBe stars (van den Ancker et al. 1998).

The estimates of the mass of dust in the optically thin torus that scatter the stellar radiation range from $\sim 10^{-8}$ (Voshchinnikov 1998) to $\sim 10^{-6}$ $M_\odot$ (Friedemann et al. 1994).

B. The origin of UXORs

UXORs have many properties in common with non-variable HAe stars. The SEDs at infrared and millimeter wavelengths have very similar shapes, and the ratio of IR to bolometric luminosity is comparable (Hillenbrand et al. 1992). The mass of dust estimated from mm observations does not depend on the level of the UXOR activity of the star (Natta et al. 1997). Moreover, of the four highly variable stars for which mm interferometer observations exist, three (UX Ori, HD 34282 and CQ Tau) have compact emission and disk masses similar to the other HAe stars. In fact, the clumps and the optically thin tori together contain only a very small fraction of the mm-observed amount of dust ($\sim 10^{-6}$ vs. $\gtrsim 10^{-4}$ $M_\odot$; see Table 1), most of which must reside in an optically thick circumstellar disk.

This suggests that the complex and highly inhomogeneous environments of UXORs are in fact common to all HAe stars, and that only those seen through a clumpy torus are UXORs. If so, the fact that about 1/3 of HAe stars are UXORs (van den Ancker et al. 1998) is consistent with a torus opening angle of order 35°.

Recently, Grinin et al. (1998) have suggested that binarity can be an important aspect of the UXORs phenomenon. They have found a cyclic variability with periods of a few years in some UXORs and interpret it as due to the large-scale perturbations produced in a postulated circumbinary disk by the presence of a companion star (or, possibly, a giant planet) at distances of 3–10 AU from the star.

It is, on the other hand, possible that UXORs represent a later evolutionary phase rather than a purely geometrical effect. This hypothesis is based on the interpretation that sporadic, high-velocity redshifted absorption events measured in a wide array of metal lines (and in Hα) are due to the infall and evaporation of planetesimals or protocomets in star-grazing orbits (Pérez et al. 1993; Grady et al. 1996a; Grinin et al. 1994; Sorelli et al. 1995 and the chapter by Grady et al. in this volume). High-velocity infall in metal lines characterizes evolved systems such as β Pic (Lagrange et al., this volume), where it has been interpreted as evidence of evaporation of large bodies in star-grazing orbits, and in several A-shell main-sequence stars (Grady et al. 1996b). Further support for this interpretation comes from the detection of crystalline silicates, similar to those detected in comets (Waelkens et al. 1996; Malfait et al. 1998b; see also Grady et al., this volume). However, Natta et al. 1997 found that UXORs do not generally appear to be older than non-UXOR HAe stars.

VI. THE CIRCUMSTELLAR ENVIRONMENT OF HBe STARS: RAPID EVOLUTION?

As discussed in the previous sections, HBe stars seem to lack in general the compact continuum emission expected from a circumstellar disk; additionally, very few HBe stars show silicate emission, while strong UIB are always present in their spectra; no HBe star shows UXOR activity. Maps at far-infrared and millimeter wavelengths, both in the continuum and in molecular lines, show that often the stars are located in the centers of large empty cavities; the emission either comes from the matter at the edges of the cavities, or, in some cases, it is clearly not associated with the optical star (Fuente et al. 1998; Henning et al. 1998; Di Francesco et al. 1998). On the other hand, at a very early stage of their evolution, both dense envelopes and circumstellar disks exist around early-B stars (Kurtz et al., this volume; see also the interferometric mm detection of R Mon). It is therefore tempting to ascribe the different environment of optically visible HAe/Be stars of different spectral type to a much more rapid environmental evolution in the most massive and luminous stars. Fuente et al. (1998), in their millimeter study of a small group of HBe stars, find a timescale of less than 10^6 yr for complete dispersal of surrounding dense gas and dust.

Radiation fields can both halt the accretion as soon as the infall rate decreases below a critical value, and affect the circumstellar disk itself. The effect of radiation pressure on the infalling envelope during the protostellar phase has been discussed by various authors (see Stahler et al. this volume). Radiation pressure reverses the infalling motion as soon as the mass-infall rate decreases below a threshold value $\dot{M}^{\rm in}_{\rm lim}$. We follow Jijina and Adams (1996) and estimate $\dot{M}^{\rm in}_{\rm lim} \sim L_\star/(v_{\rm in}\, c)$, where $v_{\rm in}$ is the infall velocity at the dust sublimation radius, $L_\star$ is the stellar luminosity and c is the speed of light. Fig. 3 shows $\dot{M}^{\rm in}_{\rm lim}$ for stars of various masses as they evolve on the HR diagram from the birthline to the ZAMS. The survival of the infalling envelope against radiation pressure for a star of given mass depends on how quickly $\dot{M}_{\rm in}$ decreases during the pre-main–sequence evolution. For example, a star of 5 $M_\odot$ disperses the infalling envelope as soon as $\dot{M}_{\rm in}$ decreases below $\sim 3 \times 10^{-7}$ $M_\odot$ yr^{-1}. A star of 2 $M_\odot$ can preserve an infalling envelope until the infall rate decreases well below 10^{-8} $M_\odot$ yr^{-1}. Radiation pressure can easily account for the large cavities, almost devoid of matter, in which many HBe stars lie. The further evolution of these stars may involve the formation of shells of enhanced density where the pressure of the surrounding matter equals the radiation pressure; these regions will emit strong PAH features (see, for example, the HD 97300 ring of PAHs in Siebenmorgen et al. 1998).

The dispersal of the infalling envelope may trigger a rapid evolution of the circumstellar disk, which will accrete onto the star on a viscous timescale (typically, $\sim 3 \times 10^5$ yr for the outer disk of a B0 star). The direct effect of radiation pressure on the circumstellar disk morphology can also be important. Recent work by Drew et al. (1998) and Proga et al. (1998) describes how, if the star has an accretion disk in Keplerian rotation, radiation pressure will drive a low-velocity, high-density equatorial disk wind. It is not clear how this will affect an underlying disk chromosphere, nor if the wind itself will contain hot dust. UV photons from the star can also affect the disk structure (Hollenbach et al. 1994; see Hollenbach et al. this volume). Interferometric observations of the dust continuum emission do not rule out that residual "light" disks (i.e., with a ratio of disk to stellar mass much smaller than the typical value ~ 0.04 observed in lower-mass stars) may exist around HBe stars. Such disks could emit the large near- and mid-IR fluxes that characterize many HAe/Be stars (Hillenbrand et al. 1992). If so, it is likely that the disks are vertically compressed and eroded in their outer parts by the effect of radiation pressure and UV radiation.

The location of HBe stars in clusters may also explain the rapid evolution of the HBe environment and the absence of massive circumstellar disks. Hillenbrand (1995) and Testi et al. (1997, 1999) have shown that stars earlier than about B7 tend to be found in clusters, while stars of later spectral type tend to form in small groups. At the moment, however, it is not clear if the density of stars in these clusters is large enough to have significant gravitational influence on the evolution of the immediate surroundings of the HBe stars in the very short timescales we derive, and we favor the idea that the fast evolution is caused by the stellar radiation field.

VII. DISK EVOLUTION IN HAe SYSTEMS

The circumstellar environment of HAe stars differs significantly from that of HBe stars. For many stars, there is convincing evidence of circumstellar disks, whose evolution is very likely controlled not by the stellar radiation field but by physical processes occurring within the disk itself. As for HBe stars, the disk matter can accrete onto the star in a viscous timescale, or can be blown away in a stellar wind. Gravitational perturbations by companion stars may dissipate the disk, entirely or in part, depending on the separation between the stars (see Lubow and Artymowicz, this volume). Alternatively, and of more interest to us, the grain component may grow and accumulate to bodies of very large sizes (1–10 km – planetesimals). These, in turn, might coalesce to form terrestrial planets and the cores of giant planets (Lissauer 1993). The gas originally in the disk will either accrete onto and form the giant planets, or be dispersed from the system. This scenario, used to explain the formation of the Solar System, leads to the formation of a secondary or debris disk, where grains are continuously formed by fragmentation of larger bodies; secondary disks have little dust mass (most of the original disk dust is locked into planets) and no gas. This type of secondary disk is observed in Vega-like stars, the best known example being β Pic (Lagrange et al., this volume). Hence disk evolution can be studied by examining the dependence on time of the mass of small grains and gas in the disk and the growth of grains from sizes typical of ISM grains to much larger sizes. Since different parts of the disk may evolve on different timescales, we will consider separately the existing evidence for evolution of the outer disk and of the inner disk.

A. The Inner Disk

The inner regions ($\lesssim$ a few AU) of a typical circumstellar disk are optically thick at all wavelengths; their emission peaks at near- and mid-infrared wavelengths. The dissipation of the inner disk, due either to an actual decrease of the disk mass or to the coagulation of the grains into larger bodies will cause the region to become optically thin at these wavelengths, with a consequent decrease of the emitted flux.

The evolution of the inner disk is best seen if the timescale of disk dissipation differs for the conditions of the inner disk and of the outer disk. The inner regions of the disk may become optically thin (and therefore “disappear”) before the outer parts of the disk if the timescale of the agglomeration of grains into larger bodies is shorter in the relatively dense material. Pollack et al. (1996) discuss the effect of the formation of a Jupiter-size planet in the inner disk around a solar-mass star. The planet will clear a gap in the disk; material outside the gap can no longer enter the inner disk (but see also Lubow and Artymowicz, this volume), while the small grains and gas in the gap accrete onto the planet with timescales which can be quite short ($\sim 5 \times 10^5$ yr for Jupiter conditions; see Boss 1996). The signature of such processes is a spectral energy distribution characterized by a "deficit" of emission (a gap) in the mid-infrared with respect to longer wavelengths.

There are no objects with a clear mid-infrared gap among the HAe/Be stars studied by Hillenbrand et al. (1992). Waelkens et al. (1994) and Malfait et al. (1998a) find a large number of stars with IR excesses characterized by a dip at 10 μm among isolated (in general ZAMS) HAe stars. They interpret their results in terms of an evolutionary sequence similar to that just outlined. This very attractive idea needs to be pursued further.

B. The Outer Disk

The evolution of the outer disk is best studied by means of its millimeter emission. If disks evolve into planetary systems, we expect to see a significant decrease of the millimeter flux. If grains coagulate into much larger bodies (size $\gtrsim$ a few cm), the mass of dust in the disk does not change but $\kappa_{1.3\mathrm{mm}}$ decreases (Miyake and Nakagawa 1993; Pollack et al. 1994). Values of M_{D} derived from the measured millimeter flux via Eq.(1) with invariant κ_{mm} should decrease with time as the outer disk evolves.

We show in Fig. 4 disk masses (derived as in §IIa) as a function of the age of the star for many stars of spectral type about A belonging to different groups. Note that in this figure we have plotted *dust* masses only rather than dust+gas masses, since the ratio of dust to gas is likely to vary widely from group to group.

The youngest stars in Fig. 4 are the HAe stars (circles) from Table 1 and Natta et al. (1997). A second group of stars is formed by Vega-like stars of spectral type A (squares) studied by Sylvester et al. (1996). These stars lie in the same region of the diagram occupied by HAe stars; only in one case (HD 218396) do we derive an upper limit ($M_{\mathrm{dust}} \lesssim 1.2\times10^{-5}$ M$_\odot$) that is significantly lower than in HAe stars. We have added to Fig. 4 dust mass estimates for the three best-studied Vega-like stars β Pic, α PsA and α Lyr (Holland et al. 1998) and for HR 4796 (Greaves et al. 1999). The arrows at an age of a few hundred Myr show the upper limits recently derived (Natta et al. 1999) for a group of main-sequence A-shell stars, which show evidence of infalling gas in their spectra (Grady et al. 1996b). Finally, we have added upper limits from Zuckerman and Becklin (1993) for stars in the Pleiades and UMa clusters.

Fig. 4 indicates that there is no evidence that M_{dust} changes over the time interval between 10^5 and 10^7 yr, i.e., over the pre-main–sequence evolution of the stars. If we divide the stars (both HAe and Vega-like) into two groups, one with ages below 3 Myr (20 stars) and one with ages above 3 Myr (29 stars), we find that the two groups have similar distributions of $M_{\rm dust}$. The fraction of non-detections is not smaller in the first (younger) group (9/20) than in the second (older) one (7/29). Note that a similar result, i.e. the lack of a trend of disk mass versus age up to 10^7 yr, was found by Beckwith et al. (1990) for TTs in Taurus-Auriga. The transition from relatively massive disks, which characterize the pre-main–sequence evolution of HAe stars, to debris disks seems to occur at about 10^7 yr and to be very fast. A fast transition time was found for naked TTs by Wolk and Walter (1996). At later times, the debris disks show a slow decline of mass with time, as noted by Zuckerman and Becklin (1993).

C. Grain Growth, Formation of Planetesimals and Planets

Some evidence that growth to *millimeter size* grains may happen earlier in the evolution is provided by the observed shape of the SEDs at submm and mm wavelengths (cf. similar work for TTs disks by Beckwith and Sargent 1991 and Mannings and Emerson 1994). The values of the spectral index α determined from single-dish observations in the range $350-1300$ μm (see Table 3), are $\alpha \gtrsim 2.8$ in all the early B stars in which disks have not been detected. On the contrary, stars of spectral types later than A0 with detected disks have $\alpha \lesssim 2.3$. The relation between α and the dust opacity law (which is usually written as $\kappa \propto \lambda^{-\beta}$ in the sub-mm and mm range) is not uniquely defined, since for a given value of β, α depends upon the temperature and surface density profiles, as well as the disk mass and outer radius (see the discussion in Beckwith et al., this volume). Mannings (1994) showed that in the case of the A0 system HD 163296, the observed low value of $\alpha = 1.94$ could be accounted for only if $\beta \lesssim 1$, which, in turn, requires grain sizes in the range $\sim$1–3 mm (cf. Miyake and Nakagawa 1993; Pollack et al. 1994). HD 163296 has been detected with the Owens Valley interferometer and has a disk mass of ~ 0.08 M$_\odot$ (see Table 1). Low values of α occur for sources of all ages in our HAe sample (which, however, includes only one star, VY Mon, younger than 10^6 yr).

These results need to be confirmed by detailed analysis of more objects, since they provide a very interesting clue to the evolutionary status of HAe disks. Namely, theoretical calculations predict that in the disk midplane grains grow very rapidly from micron-size to kilometer-size bodies (see Beckwith et al., this volume, and references therein; also Lissauer 1993). The characteristic timescale for this process depends on the initial grain size distribution, the density of the circumstellar matter, its turbulent velocity and several other parameters (again, see Beckwith et al., this volume and references therein). For the conditions of the primitive Solar nebula, grain growth from sizes typical of grains in the interstellar medium to meter-size (and larger) occurs in less than 10^5 yr (the age of our youngest stars) at distances of 30 AU from the Sun, and it is faster at shorter distances (Weidenshilling 1997; Schmitt et al. 1997). Based on these results, it is not easy to understand how disk grains can have typical millimeter sizes over a long period of time. Some help may come from observations of UXORs. As discussed in §V, the UXOR phenomena, which may be in fact common to all HAe stars, seem to require the simultaneous presence of large dust clumps, with properties typical of planetesimals, in orbit around the star, and of a much more massive disk of grains of few millimeter size at most.

It is tempting to speculate that most visible HAe stars have disks where grain growth has already occurred, reaching a sort of "bimodal" size distribution: while most of the original disk dust mass is in grains with typical sizes of a few millimeters, a small fraction of it resides in large bodies (planetesimals). There is little dust mass in grains with size intermediate between these two limits. This situation should be very stable, lasting for the majority of the pre-main–sequence life of the star. Kenyon and Luu (1998, 1999) discuss how, at the distance of the Kuiper Belt, the growth from about 1 to 100 km size is accompanied by the formation of a very large amount of relatively small grains, whose size spectrum is, however, very uncertain. Once the largest objects grow to more than $\sim$1000 km, then the system loses the small grains very quickly. It is possible then that the transition from "normal" HAe disks to β Pic-like structures is linked to the formation of very large planetesimals. Then, the timescale for this to happen around A-type stars must be of order 10^7 yr. It is not clear if a similar scenario could apply also to the inner disk.

VIII. SUMMARY

We have discussed in this chapter several topics concerning disks around HAe/Be stars. There is today convincing evidence that many young intermediate-mass emission-line stars, like their lower-mass counterparts, the classical TTs, are surrounded by disks for most of their pre-main–sequence evolution.

The most massive and luminous stars among the HAe/Be class, however, may form an exception, since they do not show obvious evidence of disks. The environment of these systems evolves relatively quickly, compared with Ae systems, possibly under the action of the strong stellar radiation fields.

A large part of this chapter has been dedicated to HAe/Be stars of lower mass and luminosity. These stars are found very often to be surrounded by disks, which account for most of the observed millimeter fluxes. These disks are roughly similar to those of TTs, with masses

$\sim$0.06 $M_\odot$, radii in the range 100–300 AU, and ratios of the disk to stellar mass of $\sim$0.04. In a large fraction of HAe systems, there is evidence that a small fraction of the circumstellar dust is in clumps of $\sim 10^{20} - 10^{21}$ gr orbiting around the star. However, most of the dust mass is in small grains ($\lesssim$ few millimeters) distributed throughout the circumstellar disk.

There is no evidence that the circumstellar environment of HAe stars "evolves" significantly during the pre-main–sequence phase (between $\sim 10^5$ and $\sim 10^7$ yr). At 10^7 yr, we find a large number of HAe stars with "normally" massive disks of dust and gas, as well as a few Vega-like stars (including β Pic), which retain a secondary debris disk after the original gas and dust disk has disappeared. If the growth of grains from sub-micron to planetesimal size occurs very rapidly, as most calculations indicate, then the conditions to initiate such growth in stars of intermediate mass may be present only after a period of about 10^7 yr. Two different kinds of observations, however, indicate that this might not be the case. Disk emission in HAe stars is characterized by a shallow spectral index in the sub-mm and mm, which is interpreted as an indication of growth of grains to millimeter sizes early in the pre-main–sequence phase. The large-amplitude optical variability and sporadic infalling phenomena characteristic of UXORs are observed among HAe stars of any age. We are tempted to speculate that some kind of evolution has already occurred in all HAe stars, by the time they become optically visible. A "bimodal" grain size distribution may have been reached: while most of the original disk dust mass is in grains with typical sizes of a few millimeters, a small fraction of it resides in very large bodies (planetesimals). This situation is very stable, lasting for most of the pre-main–sequence life of the star.

Clearly, much work is needed to understand the evolution of the environments of both HBe and HAe stars. The body of observational data is growing and is beginning to supply crucial information. In contrast, theoretical models of a number of the processes involved are still very preliminary. Greater effort in this direction is certainly required.

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FIGURE CAPTIONS

Figure 1. Disk mass (dust + gas) as a function of the spectral type of the star for HAe/Be stars with millimeter interferometric measurements. Detections are shown by circles, 3σ upper limits by triangles.

Figure 2. Panel a): M_{disk}, the disk mass (dust + gas) is shown as a function of the mass of the star for HAe/Be and T Tauri stars in Taurus. The stellar masses of HAe/Be stars have been computed as described in the text; TTs masses are from Beckwith et al. (1990). Panel b): ratio of the disk mass over the stellar mass as function of $M_\star$. In both panels detections are shown by circles, 3σ upper limits by triangles. Filled symbols refer to stars with single-dish observations, open symbols to interferometric measurements. The dashed line in Panel a) is the best-fitting curve which has slope 0.64±0.14. Note that the two samples (TTs and HAe/Be stars) do not provide a complete coverage of the mass spectrum, since there is a lack of stars in the interval ~0.8–1.3 $M_\odot$.

Figure 3. Limit on the infall mass rate as function of the spectral type of the star for stars of different mass. Each solid line corresponds to the evolutionary track on the HR diagram of a star of given mass, as labelled. The birthline for an infall rate of 10^{-5} $M_\odot$ $yr^{-1}$is shown as a dashed line, the ZAMS by the thick solid line. Infalling envelopes with mass-infall rates smaller than $\dot{M}_{lim}^{in}$ are dispersed by radiation pressure.

Figure 4. Dust mass as function of the age of the star for stars of spectral type about A. HAe stars are shown by circles, Vega-like stars from Sylvester et al. (1996) by squares. The arrows at age$\sim 3\times10^8$ yr plot upper limits to M_{dust} for a small group of MS A-shell stars. Diamonds show the dust content of the best-known Vega-like stars β Pic (age from Crifo et al. 1997), α Psa (age from Barrado y Navascués et al. 1997), α Lyrae (age from Backman and Paresce 1993) and HR4796 (age from Stauffer et al. 1995). The upper limits derived by Zuckerman and Becklin (1993) for the Pleiades and Ursa Major are also shown. Limits are shown by arrows. Ages for pre-main–sequence stars (both HAe and Vega-like) have been determined by comparing their position on the HR diagram to theoretical evolutionary tracks of Palla and Stahler (1993). The observed HR location has been determined uniformly by us from available visual photometry, using Hipparcos distances whenever available.