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HERBIG AE/BE STARS

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ABSTRACT

We review the wide range of observed properties of Herbig Ae/Be stars and try to combine this rich data set into a consistent picture of their circumstellar environment and evolutionary status. We discuss in some detail the geometry of the circumstellar environment. The presence of disks in Herbig Ae/Be stars is inferred from direct and indirect observational evidence. Envelopes can dominate the spectral energy distributions on large angular scales. In some stars, a fairly massive disk persists until the star has reached the main sequence. The evidence for an evolutionary link between isolated Herbig Ae/Be stars and β Pictoris is summarized.

1. INTRODUCTION

One of the most fascinating problems in modern astrophysics is how stars and planets form out of the interstellar medium. Star formation involves a large range of complex physical processes, and each of these processes depends on many different parameters, such as time, the stellar and circumstellar mass, angular momentum, metallicity, and the environment in which the star formation takes place. A remarkable amount of progress has been made in the past two decades toward a better understanding of low-mass ($\sim$1 $M_\odot$) star formation (T Tauri stars; see e.g. Levy & Lunine 1993), both as a result of greatly improved observational techniques and through theoretical modeling.

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The past 10 years or so have witnessed an increased interest in the formation of intermediate mass stars, with mass range between about 2 and 10 $M_\odot$ (e.g. Catala 1989, Grady & Pérez 1998). These more massive counterparts of the T Tau stars are known as the Herbig Ae/Be stars (hereafter referred to as HAEBE stars) because Herbig (1960) first studied them in a systematic way. The HAEBE stars are the subject of this review.

The distinction between T Tau stars and HAEBE stars is not merely a matter of semantics. Pre–main-sequence (PMS) stars with masses in excess of 2 $M_\odot$ are expected to follow fully radiative tracks once the quasistatic contraction has ended. Stars more massive than about 10 $M_\odot$ spend their whole PMS time as obscured objects. Therefore, the evolution of intermediate-mass PMS stars is qualitatively different from that of lower- and higher-mass stars owing to the differences in stellar and circumstellar physics, as well as in time scales.

Star formation is well known to occur in two very distinct regimes (e.g. Lada et al 1993b). Massive stars are only formed in giant molecular clouds, while low-mass star formation can occur in these giant molecular clouds, as well as in less massive dark clouds. Thus, HAEBE stars are interesting also as the interface between low-mass and high-mass star formation (Appenzeller 1994).

HAEBE stars have gained considerable interest also as the possible progenitors of β Pictoris and Vega-type stars, which are intermediate-mass main-sequence objects surrounded by circumstellar debris disks. Various arguments that the existence of these disks points to the presence of planetary bodies open the possibility that the environment of HAEBE stars is the site of current planet formation.

In this review, we discuss the observed properties of HAEBE stars, with emphasis on the composition and geometry of the circumstellar environment and the evolution of the star and its surroundings. We have organized this paper as follows: Section 2 discusses the definition of the class of HAEBE stars, and Section 3 presents an overview of the observed properties of these stars. In Section 4, we deal with the issue of the geometry of the circumstellar matter; in Section 5, we discuss evolution; and in Section 6, we summarize the review and discuss future work.

2. DEFINITION OF HERBIG AE/BE STARS

The HAEBE stars were first discussed as a group in a paper by Herbig (1960) that started this field. He studied Ae and Be stars associated with a nebulosity and selected a sample of 26 stars based on three criteria: (*a*) The star has spectral type A or B with emission lines, (*b*) it is located in an obscured region, and (*c*) the star illuminates a bright nebulosity in its immediate vicinity. As Herbig (1960) pointed out in the abstract of his paper, “the peculiarities did not appear unique to this group: they may be found as well in stars that are not associated with nebulosity." Additions to the original list were made by Finkenzeller & Mundt (1984) and Herbig & Bell (1988). Recently a new catalogue of HAEBE stars was published by Thé et al (1994a).

While Herbig's empirical definition has been very useful in past years, the recent discovery of objects that share many but not all of the properties in Herbig's list justifies a slight adjustment of the definition. In particular, the IRAS all-sky far-infrared (FIR) survey has revealed several new HAEBE stars (Hu et al 1991, Walker & Wolstencroft 1988, Oudmaijer et al 1992, Bogaert 1994) that appear isolated; i.e. they are not associated with nebulosity and are not clearly located in an area of active star formation (see also Hillenbrand 1994). The following set of properties may serve as a useful working definition of HAEBE stars: (*a*) spectral type A or B with emission lines, (*b*) infrared (IR) excess due to hot or cool circumstellar dust or both, and (*c*) luminosity class III to V.

Criterion *b* excludes "classical" Be and Ae stars, since their IR excess is due to free-free emission from ionized gas in a circumstellar disk (e.g. Gehrz et al 1974, Dachs & Wamsteker 1982, Dougherty & Taylor 1992, Waters & Marlborough 1994). Criterion *c* excludes the B[e] supergiants, massive post–main-sequence stars with flattened equatorial outflows (Zickgraf et al 1986). Confusion between genuine members of the HAEBE group and other types of stars with circumstellar matter (CSM) may still be possible however, in particular for symbiotic stars and B-type central stars of planetary nebulae. The suggestion to include a criterion on IR excess in the definition of HAEBE stars was made by Davies et al (1990) and by van den Ancker et al (1997a), whose definition is almost identical to the one given above.

3. OBSERVED PROPERTIES OF HAEBE STARS

Observations of HAEBE stars now exist covering the wavelength range from X rays to radio, and they show a wide range of phenomena. Evidence for stellar winds, bipolar outflows, accretion, circumstellar disks, and envelopes has been found. Below we give an overview of these properties with some key references, without attempting to be complete.

3.1 *Fundamental Parameters*

A direct determination of the fundamental parameters characterizing HAEBE stars has only been possible for a few objects, either because they are members of a spectroscopic binary or multiple system or because of a measurement of the distance using HIPPARCOS. Of particular interest is TY CrA, which was discovered as an eclipsing binary by Kardopolov et al (1981), as a single-lined spectroscopic binary by Casey et al (1993) and Lagrange et al (1993), and finally as a double-lined spectroscopic binary by Corporon et al (1994).

The latter authors derived masses of 2.8 ± 0.2 and 1.5 ± 0.1 $M_\odot$ for both components. While the primary rotates subsynchronously, the secondary does so supersynchronously. The somewhat less massive, F5-type, binary AK Sco was found to be a double-lined system (Andersen et al 1989); despite the variable-star name, no eclipses are observed for this object, so that only accurate lower limits for the masses are known. The binary nature of NX Pup was studied by Schöller et al (1996), who derived spectral types and masses of components A and B of F0-F2 and 2 $M_\odot$ and F7-G4 and 1.6–1.9 $M_\odot$, respectively, and an age of 3–5 Myr for the system.

Van den Ancker et al (1997a, 1998a) derived astrophysical parameters (T_{eff}, luminosity, mass) for a sample of HAEBE stars for which the Hipparcos mission resulted in 3σ detections of the parallax (Figure 1). The brightness limit set by Hipparcos induces a selection effect toward the least embedded, putatively

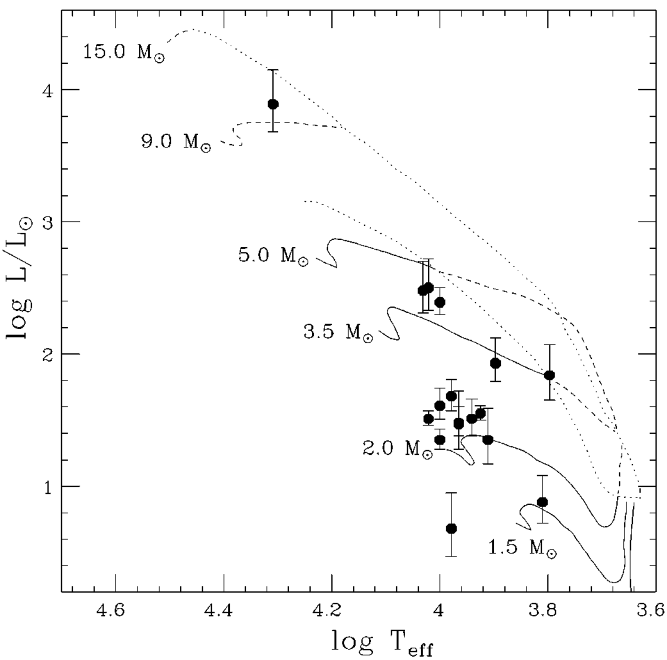

Figure 1 Hertzsprung-Russell (HR) diagram of HAEBE stars based on Hipparcos distances (taken from van den Ancker et al 1998a). *Solid lines* indicate evolutionary tracks from Palla & Stahler (1993). The *dotted lines* mark the position of the "birthline" for accretion rates of 10^{-4} and 10^{-5} $M_\odot$/year, where stars first become visible and begin their quasistatic contraction phase (see Section 5).

most evolved sources, which indeed cluster near the zero-age main sequence (ZAMS). The Hipparcos luminosities of the active objects HR 5999 and HD 200775 point to a PMS evolutionary stage (however, see the discussion on HD 200775 by van den Ancker et al 1997a). The Hipparcos distance of only 110 pc for BD+40°4124 is incompatible with the one derived from its appartenance to a young cluster (Hillenbrand et al 1995).

3.2 *Spectral Energy Distribution*

The spectral energy distribution (SED) of HAEBE stars is characterized by the presence of (large) amounts of CSM, which can dominate the SED at IR wavelengths; there is also some evidence for a contribution from the circumstellar gas to the ultraviolet (UV) continuum. This indicates that the CSM has a wide range in temperature and density, significantly above and below the stellar effective temperature. The effects of the CSM on the SED are sometimes hard to separate from the intrinsic SED of the stellar photosphere, owing to uncertainties in spectral type and the effects of anomalous extinction by circumstellar dust. In addition, variability of the SED is observed on many time scales, ranging from hours to decades, which hampers the construction of SEDs from nonsimultaneous observations.

The UV continuum of HAEBE stars is sometimes characterized by an excess, which can be attributed to warm gas near the star with temperatures exceeding T_{eff} (e.g. Blondel & Tjin A Djie 1994, Meeus et al 1998). Note that the magnitude of the excess strongly depends on the extinction correction. Since HAEBE stars can have substantial circumstellar extinction and are often found in star-forming regions, the extinction law may deviate significantly from that of the average extinction curve derived for the interstellar medium. This introduces an additional uncertainty concerning the magnitude or even the existence of a UV excess. Warm gas is found in accreting T Tauri stars (Bertout et al 1988), but in HAEBE stars, the effect on the SED is much less dramatic. This could be caused by smaller accretion rates in combination with the higher stellar temperatures of HAEBE stars. If the UV excess in HAEBE stars is interpreted in terms of accretion, rates on the order of 10^{-7} $M_{\odot}$/year are derived (Blondel & Tjin A Djie 1994). The lack of veiling in the optical spectra of most HAEBE stars (Böhm & Catala 1993, Ghandour et al 1994) indicates that the contribution of warm gas at these wavelengths is small. This property can be used to put constraints on mass accretion rates. In FU Ori stars however, the contribution from CSM dominates the entire SED (e.g. Z CMa; Hartmann & Kenyon 1996 and references therein). The accretion rates derived for these stars are several orders of magnitude larger than in "typical" HAEBE stars with little veiling.

X-ray observations indicate that very hot gas is present near HAEBE stars (Damiani et al 1994, Zinnecker & Preibisch 1994, Skinner & Yamauchi 1997), but its location and origin are not clear. Zinnecker & Preibisch (1994) suggested that the X rays are related to a stellar wind, but they left open the possibility of a low-mass T Tau companion. Skinner & Yamauchi (1997) proposed that the X rays detected in HD 104237 originate from a corona of the HAEBE star or from a lower-mass T Tau companion, or from both. Because HAEBE stars are not known to have convective outer layers, the physical mechanism responsible for a corona around the primary is unclear. A possible mechanism based on differential rotation has been discussed by Vigneron et al (1990) and Tout & Pringle (1995). The detection of X-ray emission in other, non-HAEBE stars with similar spectral type (Berghöfer et al 1997) suggests that the X-ray properties may not be related to the HAEBE nature of the star but may be due to a low-mass companion with an active chromosphere.

At long wavelengths ($\lambda > 1\ \mu$m), HAEBE stars show strong excess radiation, which is interpreted in terms of circumstellar dust with a wide range in temperatures. One of the first HAEBE stars detected at mid-IR ($\sim$10 μm) wavelengths was R Mon (Mendoza 1966, Low & Smith 1966). Many papers have since discussed IR and (sub-)millimeter photometry of HAEBE stars (e.g. Low et al 1970, Geisel 1970, Gillett & Stein 1971, Strom et al 1972, Allen 1973, Cohen 1973, 1980, Sitko 1981, Lorenzetti et al 1983, Berrilli et al 1987, Mannings & Sargent 1997, Pezzuto et al 1997, Abraham et al 1998, Malfait et al 1998a). The SEDs of many HAEBE stars show a sharp onset of IR excess at $\lambda \approx 1$–$2\ \mu$m, which corresponds to dust temperatures up to 1500 K (Figure 2). In a much quoted paper, Hillenbrand et al (1992) studied the IR properties of 47 HAEBE stars and classified them in three groups based on the slope of the IR continuum. Group I sources have IR slopes approximately given by $\lambda F_\lambda \sim \lambda^{-4/3}$; group II stars have rising spectra toward longer wavelength; and group III stars have small excesses similar to classical Be stars, in which the excess is probably due to free-free emission from a circumstellar disk. Hillenbrand et al (1992) used this classification to distinguish between different geometries of the CSM, i.e. disks (group I) versus disks plus envelopes (group II). We return to this controversial issue when we discuss the geometry of the CSM of HAEBE stars in Section 4.

Submillimeter and millimeter photometry can be used to derive dust masses, provided that assumptions are made concerning the characteristic temperature and opacity of the dust (Hillenbrand et al 1992, Henning et al 1994, Mannings 1994, Sandell & Weintraub 1994, Mannings et al 1997, Mannings & Sargent 1997, Di Francesco et al 1997, Natta et al 1998). These dust masses are relatively insensitive to geometry assumptions because the dust is optically thin at these wavelengths, and free-free emission is not believed to contribute significantly to the flux (e.g. Mannings & Sargent 1997; however, see also di Francesco et al 1997). The dust masses derived this way depend on the assumed opacity of

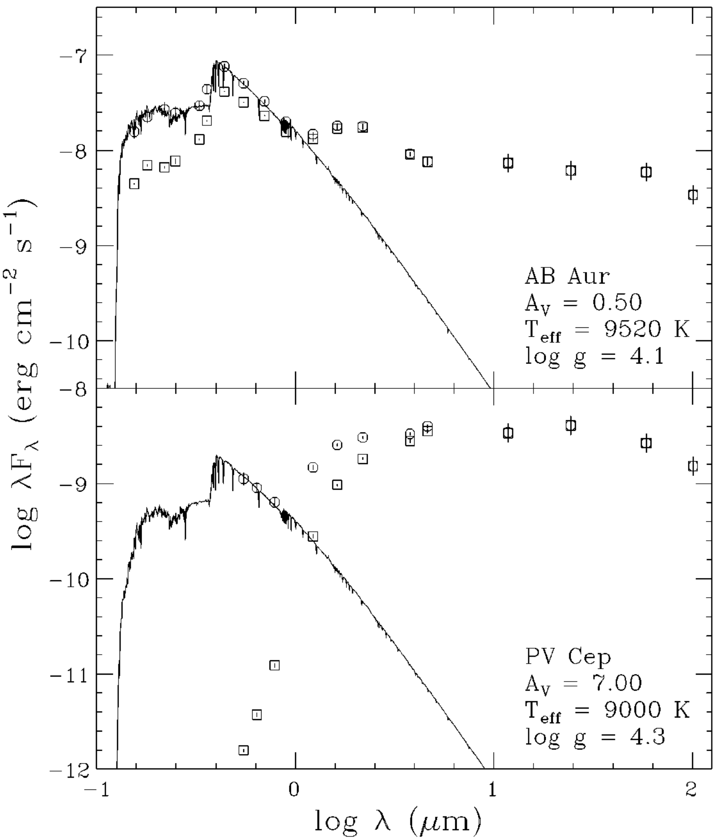

Figure 2 Spectral energy distribution (SED) of AB Aur [Hillenbrand et al's (1992) group I] and PV Cep (group II). *Squares* indicate observed fluxes, *circles* extinction corrected data. Note the onset of an IR excess already at $\lambda \sim 1$–2 μm.

the dust and on the gas/dust ratio; both quantities are not well known. The derived total masses (usually obtained assuming a gas-dust ratio of 100) range between $\sim 10^{-3}$ and ~ 10 $M_\odot$. The majority of these measurements were obtained with single dish telescopes, resulting in rather poor spatial resolution. Therefore the dust masses derived for embedded objects in the cores of active star-forming regions may suffer from confusion with the surrounding cloud. In some cases [e.g. LkHα 198 (Lagage et al 1993); LkHα 234 (Cabrit et al 1997); see also Testi et al 1997], embedded IR companions are found close to the optical star, which complicates the interpretation of low spatial resolution data.

3.3 *Photometric Variability; UX Ori Variables*

The optical continuum of HAEBE stars can be variable on several time scales, suggesting that different physical mechanisms may be responsible. Several types of variability can be distinguished. The best-documented type of variability is characterized by sudden drops in brightness of up to 3 mag in V, accompanied by an increased reddening and degree of polarization, and followed by a slow recovery lasting weeks (UX Ori variables, after the prototype UX Ori; see Figure 3). These variations are called Algol-like minima and are

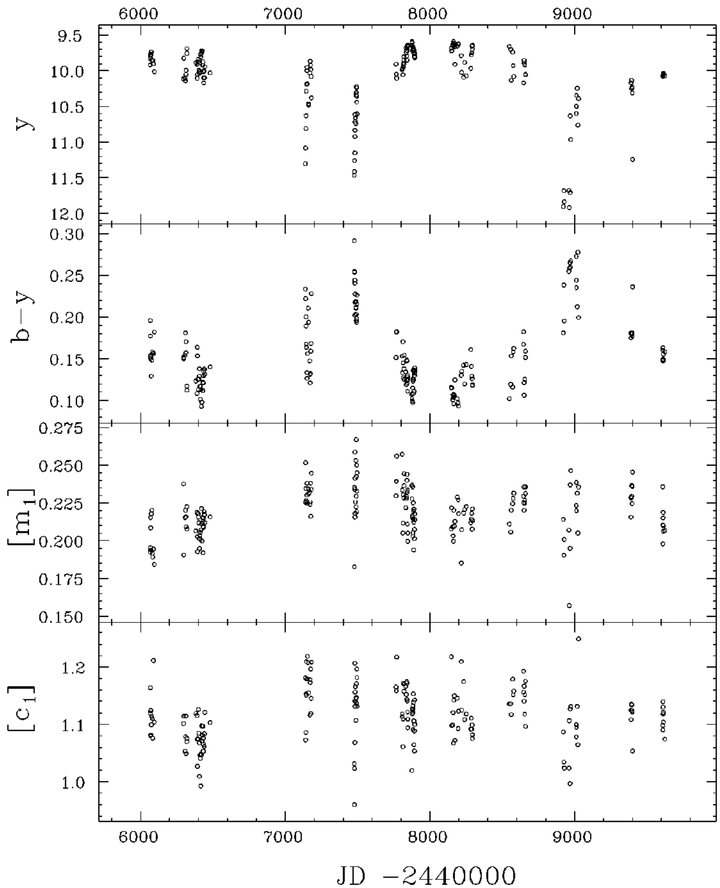

Figure 3 Optical light curve of the UX Ori type variable BF Ori in the Strömgren system. Note the deep, irregular minima caused by variable circumstellar extinction.

due to variations in the column density of circumstellar dust in the direct line of sight toward the star (first proposed by Wenzel 1968, Wenzel et al 1971; see also Herbst et al 1983a,b, Finkenzeller & Mundt 1984, Zatsjeva & Chugainov 1984, Davies et al 1990, Bibo & Thé 1991, Friedemann et al 1992, Grinin et al 1994, Voshchinnikov et al 1996, Shevchenko et al 1997, van den Ancker et al 1998a). Several HAEBE stars experience a color reversal when fading (Figure 4); i.e. after reaching a certain magnitude, the star becomes bluer while continuing to fade (Wenzel 1968, Zatsjeva 1973, Evans et al 1989, Bibo & Thé 1990, Voshchinnikov & Grinin 1992). The blueing effect is probably due to an increased contribution from scattered light to the total flux. These variations demonstrate that the dust shells surrounding HAEBE stars are not smooth but clumpy. In two stars, BN Ori and V351 Ori, the deep extinction minima abruptly stopped occurring (van den Ancker et al 1996, Shevchenko et al 1997). Therefore, the fraction of stars showing this type of variability may be underestimated. Interestingly, the large drops in brightness are observed only in stars with spectral type A0 or later (Finkenzeller & Mundt 1984, Bibo & Thé 1991). A recent study of Hipparcos photometry of HAEBE stars by van den Ancker et al (1998a) confirms this conclusion. They suggest that the lack of strongly variable Herbig Be stars is due to the fact that these stars are optically invisible for most of their PMS accretion phase. No evidence for a relation between variability and projected rotational velocity $v \sin i$ has been found.

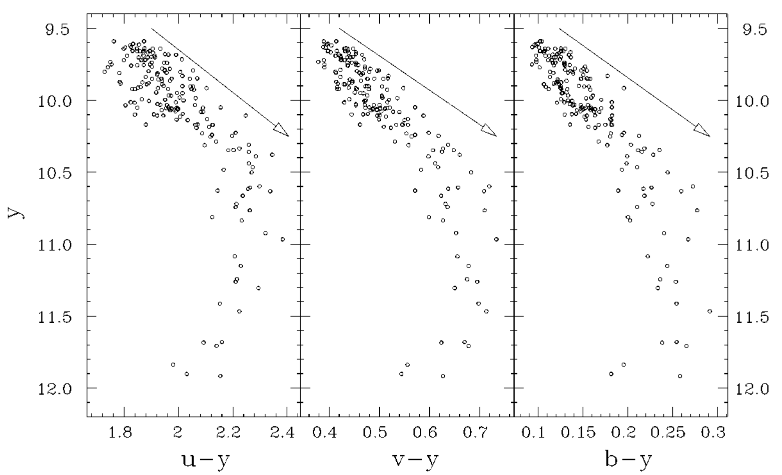

Figure 4 Color magnitude diagram of BF Ori in the Strömgren system, showing the blueing effect, where the colors become bluer as the star fades to magnitudes fainter than $y \simeq 11.5$. The *arrow* indicates the slope of the interstellar reddening vector.

A second type of variability shows long-term fading or brightening, often covering decades [e.g. PV Cep (Friedemann et al 1992); BN Ori (Shevchenko et al 1997)], which may be related to FU Ori outbursts (Hartmann & Kenyon 1996) or to gradual changes in the degree of circumstellar extinction. Finally, variations at low amplitude ($<0.5^m$ in V) are observed, possibly owing to photospheric or chromospheric activity (e.g. Davies et al 1990, Catala et al 1993, Herbst 1994) or to stellar pulsations (Kurtz & Marang 1995).

3.4 *Polarimetry*

The optical continuum of HAEBE often shows intrinsic and variable polarization (e.g. Zellner 1970, Vbra 1975, Garrison & Anderson 1978, Vbra et al 1979, Grinin et al 1988, 1991, Scarrot et al 1989, Jain et al 1990, Krikova et al 1997), which can be used to derive information on the distribution of CSM (for a review, see Grinin 1994). Polarization can be due to electron scattering (seen in e.g. classical Be stars) or to dust scattering, either from aligned grains or from grains in a nonspherical distribution around the star. Electron scattering is unimportant in HAEBE stars, given the large degree of polarization observed (several percent). Variations in polarization are often correlated with the deep photometric minima, and they can be explained in terms of dense dust clouds obscuring the light from the star and allowing only light scattered by dust particles to escape. In the case of UX Ori, such a model can also explain the changes in Hα (Grinin et al 1994). In some stars, the position angle of the polarization also shows strong variations, which indicates that significant changes in the spatial distribution of the scattering particles must occur (e.g. Grinin et al 1988). These observations are suggestive of large, comet-like bodies falling toward the star.

3.5 *Line Spectra*

Except for peculiar objects such as Z CMa, in which the accretion luminosity dominates the optical spectrum, the spectral classification of HAEBE stars in terms of the MK scheme does not raise particular problems; i.e. the photospheric absorption lines are well correlated in strength with those of normal A- and B-type main-sequence stars (Finkenzeller 1985). Only in the most embedded sources is there a clear hint for peculiar line weaknesses due to veiling by an additional thermal continuum (Corcoran & Ray 1994), but veiling is weak or not present at all in objects such as AB Aurigae (Böhm & Catala 1993). No evidence has been found so far for metal depletion by selective accretion (Dunkin et al 1997).

Projected rotational velocities for HAEBE stars have been determined by Finkenzeller (1985) and Böhm & Catala (1995). The results of both studies show that the HAEBE stars rotate at intermediate values for $v \sin i$, typically in the range between 60 and 200 km/s; i.e. they are depleted of slow rotators and on average rotate faster than T Tauri stars but more slowly than classical Be stars.

What distinguishes the line spectra of HAEBE stars from those of normal main-sequence stars is, by definition, the presence of emission lines (Herbig 1960, Cohen & Kuhi 1979, Hamann & Persson 1992) and also the complex variability of both the emission and absorption features. The Hα emission shows a wide variety in different stars, with single- and double-peaked emission as well as P Cygni profiles (Garrison & Anderson 1977). Variability of the Hα emission is documented for several stars, e.g. HD 163296 (Pogodin 1994) and AB Aurigae (Catala 1997). Other atoms and ions frequently observed in emission are O I, Ca II, Si II, Mg II, and Fe II. The interpretation of the emission lines is controversial, however. While Hamann & Persson (1992) concluded from the similarity of the behavior of emission lines in HAEBE and T Tauri stars that the outflows are disk-wind–driven, Catala (1997) reproduced the Hα emission of AB Aurigae in terms of a chromospheric-wind model.

Forbidden lines in HAEBE stars (Herbig 1960, Cohen & Kuhi 1979, Finkenzeller 1985, Hamann 1994, Böhm & Catala 1994, Corcoran & Ray 1997, Böhm & Hirth 1997) are an important diagnostic for the circumstellar environment of HAEBE stars, and they appear in these stars in general as more symmetric than in their lower-mass analogs (Appenzeller et al 1984, Edwards et al 1987). Blueshifted [O I] profiles have only been observed for a few rather deeply embedded objects. There is agreement that this blueshifted high-velocity (200 km/s) gas originates in an outflow whose redshifted part is obscured by a disk, but an outflow may exist without extended high-velocity [O I] emission (Hirth et al 1994). Controversy remains on the interpretation of the symmetric [O I] profiles, which have typical widths of a few tens of kilometers per second, in other HAEBE stars.

Intensive monitoring of absorption lines of HAEBE stars, both in the optical and in the UV, has revealed a complex variability pattern. Praderie et al (1986) undertook an intensive monitoring of the UV spectrum of AB Aurigae with the International Ultraviolet Explorer (IUE) and detected variations in the Mg II and Fe II lines. For the Mg II lines, they detected an apparent periodicity of 45 ± 6 h in the blue wings of the line profiles, whereas for the Fe II lines, no clear periodic behavior could be evidenced. An optical campaign on the Ca II K line of the same star yielded a periodicity of 32 ± 4 h (Catala et al 1986). Monitoring of other optical lines of AB Aurigae (Catala et al 1997) in turn revealed variability on time scales ranging from 20 min up to 8–10 h. A similar study was undertaken for HD 162396 (Catala et al 1989), for which indications were found for a period of 50 ± 8 h for the Mg II lines and a period of 35 ± 5 h for the Ca II K line. For both objects, the observed variability and periodicity were interpreted in terms of a model in which the Ca II K period is the rotation period of the star and the UV lines are formed in a differentially rotating and chromospherically driven wind.

Baade & Stahl (1989b) studied the profile variations of optical lines of HD 162396 and detected rapid and complex variations not unlike those observed for AB Aurigae by Catala et al (1997). Although it was not possible to determine periodicities from these data, the authors pointed out that the absorption line profile variability of HD 162396 is not unlike that observed in stars that are thought to be nonradial pulsators.

Another interpretation of line-profile variability of some HAEBE stars was put forward by Graham (1992), who argued that the variable absorption and inverse P Cygni profiles he detected in He I, Na I, O I, and Si II lines of these stars were due to clumpy accretion of CSM onto these stars. Blondel et al (1993) advanced a similar interpretation for the redshifted Lyα emission they detected in IUE spectra of several HAEBE stars. In a long series of papers, Thé and coworkers studied the properties, and in particular the photometric and spectroscopic variability, of the bright HAEBE star HR 5999 (Thé & Tjin A Djie 1978, Thé et al 1978, 1981, Tjin A Djie et al 1982, Pérez et al 1993; see also Baade & Stahl 1989a). From their study of the UV variability of HR 5999, Pérez et al (1993) concluded that the star is surrounded by an optically thick accretion disk. Grinin et al (1994) suggested that the photometric and spectroscopic variability of UX Ori is due to the infall of comet-like bodies onto the star. The variability pattern of redshifted absorption lines is similar to that observed in β Pictoris (e.g. Ferlet et al 1993). Grady et al (1996) labeled this phenomenon the β Pictoris phenomenon among HAEBE stars and confirmed that several HAEBE stars show variable red absorption features in their UV and optical spectra (Figure 5). Sorelli et al (1996) showed that the redshifted Na I absorption seen in several HAEBE stars can be explained by a model in which small, dense clumps of matter fall toward the star and that the absorption components must be formed very close to the star ($<$10 R_*). Grady et al (1996) suggested that the presence of C IV lines points to collisionally excited gas, while Catala (1988) explained the formation of C IV lines in HAEBE stars in terms of a moderate-temperature expanding chromosphere.

3.6 *Infrared Spectroscopy*

Infrared spectroscopy of HAEBE stars is widely used to determine the composition and geometry of the circumstellar gas and dust (e.g. Cohen 1975, Blades & Whittet 1980, Aitken & Roche 1981, Allen et al 1982, Whittet et al 1983, Brooke et al 1993, Chen & Graham 1993, Wooden 1994, Waelkens et al 1996). These studies show evidence for the presence of both C-rich and O-rich dust components. In about 20% of HAEBE stars, the well-known IR emission

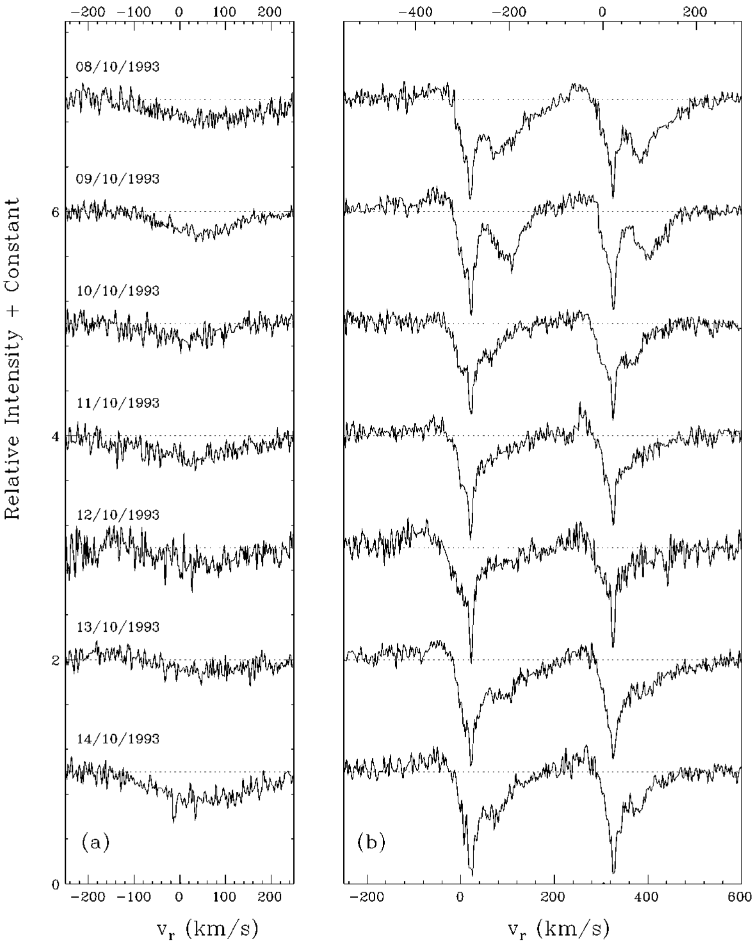

Figure 5 Short time scale variability in the He I (*left*) and Na I lines of BF Ori (De Winter 1996). The variable redshifted absorption is interpreted in terms of clumpy accretion.

bands at 3.29, 6.2, 7.7, 8.6, and 11.3 μm are seen (Brooke et al 1993), indicating the presence of polycyclic aromatic hydrocarbons (PAHs). The location of the PAHs is not clear; evidence for extended emission has been found (e.g. Prusti et al 1994), but the emission in the 3.52-μm feature of HD 97048 is much more compact than that of the 3.29-μm feature, suggesting that different components have very different spatial distributions (Roche et al 1986). The 10-μm region of HAEBE stars is usually dominated by the presence of (sometimes strong) emission from O-rich silicates (e.g. Grady et al 1997, Sylvester et al 1996, Waelkens et al 1996, Hanner et al 1995, Berrilli et al 1987, 1992, Reimann et al 1997). The emission character of the silicates suggests that the material emitting at 10 μm is predominantly optically thin. Hanner et al (1995) suggested that in HD 150193 the 11.2-μm crystalline olivine feature is present. This feature is commonly observed in comets in our Solar System (e.g. Hanner et al 1994) and in β Pictoris (Telesco & Knacke 1991).

Infrared recombination lines of hydrogen in HAEBE stars were studied by, for example, Bunn & Drew (1992), Nisini et al (1995), and Drew et al (1997). Recombination line radiation can be used as a probe of the high-density gas near the star, which may either be in an outflow or in a disk. Nisini et al (1995) derived mass loss rates in the range of 10^{-8}–10^{-6} $M_\odot$/year from the strength of the IR HI lines; these mass loss rates are uncertain because the line shapes sometimes are not compatible with an outflow.

The Infrared Space Observatory (ISO) (Kessler et al 1996), launched successfully by the European Space Agency in November 1995, has opened the IR window from 2.4 to 180 μm to high signal-to-noise spectroscopy at intermediate ($\lambda/\Delta\lambda \sim 1000$) and high ($\lambda/\Delta\lambda \sim$ 1–3 10^4) resolution. The first results obtained for HAEBE stars reveal rich dust spectra, with a variety of emission features of carbon- and oxygen-rich dust.

We display in Figure 6 the combined ISO Short Wavelength Spectrometer (SWS) (de Graauw et al 1996) and Long Wavelength Spectrometer (LWS) (Clegg et al 1996) spectra of the field HAEBE star HD 100546 (Malfait et al 1998b) and the young Fe star HD 142527, for which the circumstellar extinction is low. It is remarkable that in these two objects and in other HAEBE stars, all dust features are observed in emission and thus are optically thin. In HD 100546, the strength of some emission features is on the order of that of the underlying continuum. On the other hand, the substantial optical extinction that is observed for some HAEBE stars with IR excesses that are similar to that of HD 100546 argues for the presence of an optically thick dust component as well. A natural explanation is that a dense thin disk occurs, which hides the star if it is observed nearly edge-on, and that low-density dust clouds occur up to substantial vertical distances (see also Section 4).

The ISO observations have confirmed the presence of PAH emission in a substantial fraction of, though not in all, HAEBE stars. A spectacular result is the presence of various silicate emission features that were not reported in any astronomical object before the ISO mission. The high amount of structure encountered in the silicate emission features of HD 100546 points to the presence of crystalline silicates, in this particular case forsterite (Mg_2SiO_4) (Waelkens et al 1996). A more detailed modeling of the combined SWS-LWS spectrum of HD 100546 (Malfait et al 1998b; Figure 6) reveals the presence of

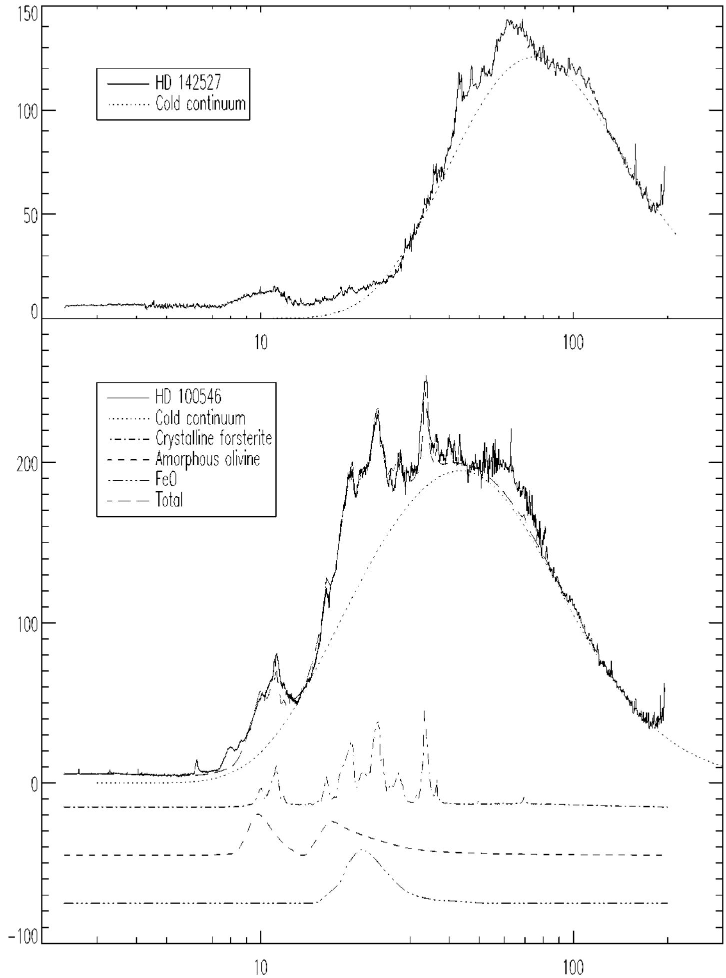

Figure 6 Full ISO Short Wavelength Spectrometer (SWS) and Long Wavelength Spectrometer (LWS) spectra of HD 100546 and HD 142527, showing a very rich variety of solid state bands, due to silicates (amorphous and crystalline), FeO, polycyclic aromatic hydrocarbons (PAHs), crystalline H_2O ice, and a broad emission feature at 100 μm.

additional emission features, such as amorphous silicates and FeO grains. Both HD 142527 and HD 100546 show strong emission from crystalline H_2O ice at 43 and 60 μm. In addition, a broad feature is apparent at about 100 μm in HD 142527 and (weakly) in HD 100546. The presence of this feature may be correlated with those of crystalline H_2O ice. Figure 6 clearly demonstrates that care should be taken when interpreting SEDs based on IRAS broadband photometry, since prominent solid-state features can occur at the central wavelengths of all IRAS bands.

ISO has detected pure rotational H_2 lines in the direction of embedded HAEBE stars such as BD+40°4124, LkHα224, and LkHα225 (Wesselius et al 1996) and S106 IR and Cep A East (van den Ancker et al 1998b). It appears likely that the H_2 emission originates in the loose surroundings of these objects and provides diagnostics for the presence of photon-dominated regions versus shocks in the radiation fields of these rather hot HAEBE stars (van den Ancker et al 1998b). van Dishoeck et al (1998) report the detection of the H_2 S(1) and S(0) lines toward the less massive, isolated HAEBE star HD 163296, and they argue that for this object, it is more plausible that the emission originates from the warm gas in a circumstellar disk rather than from shocked or photon-heated gas in a surrounding envelope.

4. GEOMETRY OF THE CIRCUMSTELLAR ENVIRONMENT

A great deal of attention has been given in the recent literature to the geometry of the circumstellar material of HAEBE stars. Evidence for the presence of disks as well as envelopes has been found. The picture is somewhat confusing because studies using different diagnostics seem to be contradictory in their conclusions concerning the presence of disks. Because HAEBE stars are believed to be the more massive counterparts of T Tau stars, it seems natural to assume that HAEBE stars have similar geometries of their surroundings, i.e. an (optically) thick disk and a bipolar outflow. However, detailed studies have shown that the picture is not so simple. We discuss the geometry of the CSM of HAEBE stars based on (*a*) direct imaging, (*b*) the interpretation of SEDs and (*c*) spectroscopy.

4.1 *Direct Imaging*

The evidence for outflows from HAEBE stars has been extensively reviewed by Ray & Mundt (1993) and Mundt & Ray (1994). Taking into account various selection effects, they estimated that about 10 or 20% of optically selected HAEBE stars are associated with observable bipolar outflows and/or Herbig Haro (HH) objects. In general, the outflows are found for the most embedded sources. It appears that the outflows of HAEBE stars are rather similar to those observed for the less massive T Tauri stars as far as morphology and collimation are concerned. Not surprisingly, the outflow velocities of HAEBE stars tend to be somewhat higher, typically in the range between 600 and 900 km/s, than found in T Tauri stars. For the FU Ori variable Z CMa (Hartmann et al 1989), Poetzel et al (1989) observed a jet extending over 3.6 pc and identified 15 HH objects, with outflow velocities up to 620 km/s. The similarity between T Tau and HAEBE outflows is suggestive of a common origin. The evidence that the winds in T Tauri stars are driven from accretion disks (Edwards et al 1993) can then be interpreted as strong evidence for the presence of disks around HAEBE stars as well.

Near-IR imaging, both in the continuum and in solid-state bands, has been used to search for extended emission from envelopes surrounding HAEBE stars. Brooke et al (1993) found that in several objects, the 3.29-μm C-H stretch band is spatially extended, suggesting that the small grains responsible for the emission are not always confined to a compact region. The 3.52-μm feature seen in HD97048 is not extended (Roche et al 1986), which suggests that its carrier is confined to a compact region near the star. This demonstrates that hot dust must be present close to the star. Leinert et al (1994) showed from speckle interferometry that the angular size of AB Aur is $<$30 milliarcsec in the K band, suggesting that the hot dust is indeed very close to the star and not in a halo. Prusti et al (1994) showed that the mid-IR continuum emission of HD 97048, HD 97300, and HD 176386 is extended. [Recent 10-μ imaging of HD 97300 has cast some doubt on the reality of the association of the IRAS source with HD 97300 (ME van den Ancker, private communication)]. We conclude that small grains can be present both near the star and in the more extended envelope.

Evidence for a disk in the Herbig Ae star AB Aur was found by Marsh et al (1995) from high-resolution 10- and 20-μm imaging. The size of the AB Aur disk was found to be $\sim$80 AU at 17.9 μm. Direct evidence for disks has now been convincingly found by millimeter interferometry (Mannings & Sargent 1997, Mannings et al 1997; Figure 7). Observations of the the CO velocity fields of AB Aur, HD 163296, and HD 31648 (MWC 480) show clear signatures of rotation that are consistent with a Keplerian disk. In HD 163296 and HD 31648, the dust continuum sources also are resolved and elongated. Typical disk radii found are on the order of 200–600 AU, and disk masses are in the range of 0.005–0.05 $M_\odot$ (based on the dust continuum). The small angular size of the dust envelopes found from the interferometric maps in combination with the dust mass result in very high optical extinction if spherical symmetry is assumed, and the conclusion seems inevitable that the dust is in a highly flattened geometry. Di Francesco et al (1997) detected only one out of 6 HAEBE stars (Elias 3-1, A6) using millimeter interferometry. For Elias 3-1 a disk with a mass of 0.1 $M_\odot$

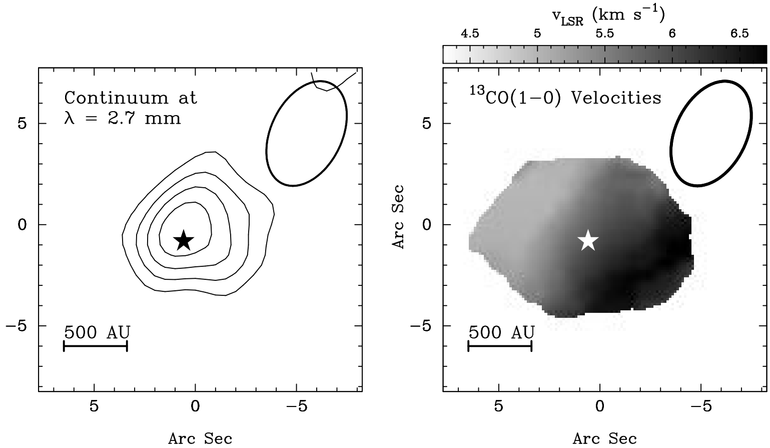

Figure 7 Owens Valley millimeter-wave measurements of AB Aur. *Left*: contour plot of continuum emission at $\lambda = 2.7$ mm. The 1σ noise is 0.7 mJy beam^{-1}. Contours begin at 3σ and are separated by 2σ. The *black asterisk* represents the position of the star, corrected for proper motion to the epoch of the observations. The orientation and size ($5''.5 \times 3''.5$ full width at half maximum or FWHM) of the synthesized beam are represented by the *ellipse* at the *top right of the panel*. The continuum source is not spatially resolved, and has a flux density of 10.6 ± 0.4 mJy. The upper limit to the radius is 280 AU for a distance of 160 pc. *Right*: *grayscale-coded* intensity-weighted mean velocities of ^{13}CO(1-0) gas. Blueshifted emission, indicative of approaching gas, is confined entirely to the northeast (*upper left*) of the star, while redshifted emission (receding gas) is found only to the southwest. Deconvolution from the beam, assuming an elliptical Gaussian brightness profile, suggests source dimensions of 450×110 AU. The aspect ratio implies an inclination angle of 76°. Diagram adapted from Mannings & Sargent (1997).

was found, while the FIR emission is extended, which suggests an envelope. Di Francesco et al (1997) concluded that free-free emission may contribute significantly to the millimeter continuum and that most of the submillimeter and millimeter emission arises from an envelope. Di Francesco et al's (1997) sample contains mostly luminous sources, whereas Mannings and coworkers focused on lower-luminosity Ae stars (Mannings et al 1997, Mannings & Sargent 1997). It is possible that for luminous sources, the time scale for dissipation of a disk is shorter than for lower-mass stars and that an envelope dominates the FIR emission for most of the PMS evolution.

Observations of the 50- and 100-μm dust emission of HAEBE stars with the Kuiper Airborne Observatory (KAO), and of the millimeter dust emission using single-dish telescopes, have shown that in a substantial fraction of stars the emission is extended (Harvey et al 1979, Natta et al 1992, 1993a, Di Francesco et al 1994, Henning et al 1994, Mannings 1994). The extended emission component cannot be explained by a "disk-only" geometry, and suggests the presence of a (not necessarily spherical) envelope. Natta et al (1993a) found that in order to explain the size and shape of the FIR energy distribution of several Hillenbrand et al (1992) group II sources, the central object must have colors much redder than that of the central star, and suggest this may be the star-disk system. Di Francesco et al (1994) showed that some group I sources, with energy distributions that can be explained by disks only, also exhibit extended emission at 100 μm, which suggests that the distinction between groups I and II may not necessarily separate different geometries of the circumstellar environment. Out of six stars studied by Di Francesco et al (1994), only AB Aur was found to be a point source at 100 μm, which is consistent with the interferometric maps of AB Aur (Mannings & Sargent 1997). In a case study of LkHα 198, Butner & Natta (1995) argued that the presence of embedded companions, such as those found for LkHα 198 by Lagage et al (1993), cannot explain the extended 100-μm emission and that the optical star must be responsible for this diffuse component.

Recent submillimeter imaging of the intermediate-mass FU Ori star Z CMa, using the SCUBA camera at the James Clerk Maxwell Telescope, revealed the presence of a highly flattened, extended emission region (Figure 8). While the

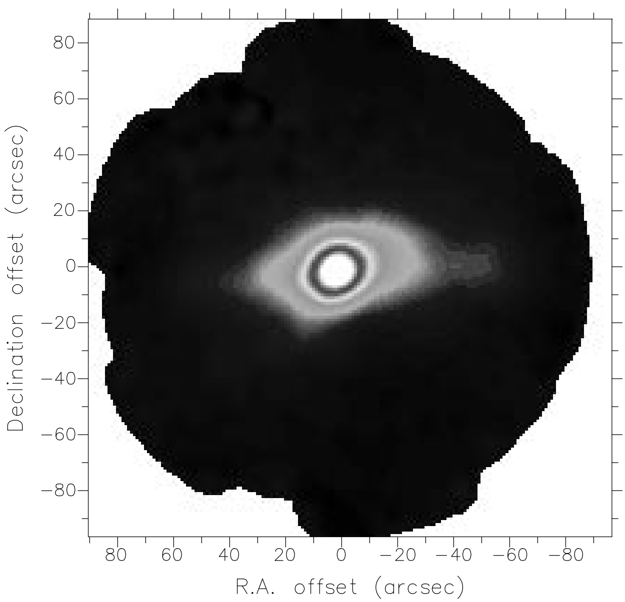

Figure 8 Submillimeter map of Z CMa taken with the SCUBA camera at the James Clerk Maxwell Telescope, showing the highly flattened envelope structure (ME van den Ancker & G Sandell, in preparation).

emission has an angular size typical for an envelope, the geometry is disk-like. Highly flattened envelopes may have a different SED from spherical ones because a large fraction of the envelope does not receive stellar radiation directly.

4.2 *Spectral Energy Distribution*

The IR spectral energy distribution (SED) is widely used to derive constraints on the geometry of HAEBE shells. Many models for the IR and millimeter emission from dusty circumstellar disks have been developed (e.g. Kenyon & Hartmann 1987, Adams et al 1988, Bertout et al 1988, Beckwith et al 1990, Hillenbrand et al 1992, Natta 1993, Efstathiou & Siebenmorgen 1996, Steinacker & Henning 1996, Men'shchikov & Henning 1997). Hillenbrand et al (1992) modeled the SEDs of their group I sources in terms of optically thick circumstellar disks with accretion rates on the order of 10^{-6} $M_{\odot}$/year. This interpretation meets with some serious difficulties, however, which were pointed out by Hartmann et al (1993). The basic argument is that the accretion rates derived by Hillenbrand et al (1992) would inevitably lead to substantial disk emission at near-IR wavelengths, which is not observed. This accretion energy does not appear at other wavelengths (optical, UV). Instead, the sharp onset of IR excess at 1–2 μm in many HAEBE stars suggests the presence of an inner hole.

Several observations point to accretion rates that are significantly lower than those derived by Hillenbrand et al (1992). Radio continuum observations of HAEBE stars by Bertout & Thum (1982), Güdel et al (1989), and Skinner et al (1990, 1993) show that several stars have weak radio emission associated with them, mostly thermal. The radio emission is interpreted in terms of a weak stellar wind (10^{-8} $M_{\odot}$/year) and is not consistent with high accretion rates through an optically thick disk. The lack of substantial veiling at optical wavelengths (e.g. Böhm & Catala 1993) suggests that accretion rates are low.

Hartmann et al (1993) proposed that the SEDs of HAEBE stars are consistent with envelopes rather than optically thick disks, and they suggested that the near-IR emission seen in HAEBE stars is in fact caused by very small grains heated to nonequilibrium temperatures, such as PAHs. Emission by PAH is not unusual in HAEBE stars. In a survey of 24 HAEBE stars, Brooke et al (1993) found emission in 20% of the sample, preferentially in B-type stars. Natta et al (1993b) investigated the effect of PAHs and very small grains on the near-IR continuum of HAEBE stars, and they concluded that these particles cannot account for all the 2- to 10-μm emission unless very high abundances of small grains are used. The absence of PAHs in several HAEBE stars with substantial near-IR excess (e.g. AB Aur) shows that the hot dust emission cannot in all cases be accounted for by PAH-like grains and that PAHs cannot solve the inferred presence of an inner hole.

It is clear from the above discussion that it is difficult to derive reliable information about the geometry of HAEBE star shells from SED fitting. This may not be surprising, given the still large uncertainties in dust opacity, dust composition, grain-size distribution, and lack of angular resolution. For several stars now found to possess flattened disks (Mannings et al 1997, Mannings & Sargent 1997), fits to the SED can be found in the literature that used spherical models (e.g. Pezzuto et al 1997, Miroshnichenko et al 1997), and sometimes disk models are even ruled out. Claims concerning the absence of disks based on SEDs therefore must be used with caution. On the other hand, disk models with high accretion rates are also ruled out. The large IR luminosities of the circumstellar material, interpreted by Hillenbrand et al (1992) in terms of active disks in which the IR luminosity is partly due to accretion, may be to a large degree the result of passive disks that reradiate at IR wavelengths the stellar flux absorbed at optical and UV wavelengths.

In a comparative study of three isolated HAEBE stars, Meeus et al (1998) argue that the lack of balance between the energy absorbed in the UV along the line of sight, and that emitted in the IR, results from a disk-like geometry. They also point out that the UX Ori variable HD 142666 and the nonvariable HAEBE star HD 144432 have nearly identical SEDs and spectral types but very different amounts of circumstellar extinction and variability, which again is consistent with a disk-like geometry viewed at a different inclination angle. Natta et al (1998) come to a similar conclusion based on their comparison of dust mass and variability of a sample of UX Ori stars.

4.3 *Spectroscopy*

Forbidden line emission in HAEBE stars, in particular the [O I] and [S II] lines, has been used to derive constraints on geometry. Based on an analogy with the lower-mass T Tau stars (Appenzeller et al 1984), strongly blueshifted emission in these lines is taken as evidence for the presence of a bipolar outflow of which the receding part is obscured by an optically thick accretion disk. Indeed, surveys of [O I] emission in HAEBE stars have found evidence for blueshift but in only $\sim$15%, which are often stars with strong bipolar outflows (Corcoran & Ray 1997, Böhm & Catala 1993, 1994, Böhm & Hirth 1997), and even fewer have extended forbidden line emission. Most stars have [O I] centered at the stellar velocity and have modest line widths (50–100 km/s), with a range in line shape (single peaked, double peaked), and only a few heavily embedded stars show evidence for a strong outflow. Spatially resolved [O I] emission shows that, analogous to T Tau stars, high-velocity components are extended, while the low-velocity emission is not (e.g. in Z CMa; Poetzel et al 1989). Such observations are in qualitative agreement with the model proposed for T Tau stars by Kwan & Tademaru (1988), in which the high-velocity emission arises in a bipolar outflow, while the low-velocity component is formed in a disk corona (Hirth et al 1994). Conclusions are less obvious when no strong outflow activity is observed, and in these cases the geometry of the gas responsible for the [O I] emission is still debated (see e.g. the discussion in Böhm & Hirth 1997). However, the [O I] may originate in an extended surface layer of an optically thick disk, which would not result in blueshifted emission. For instance, in AB Aur, the [O I] is weak and symmetric at the stellar velocity (e.g. Corcoran & Ray 1997), but the millimeter interferometric map of this star by Mannings & Sargent (1997) points to a disk.

Spectroscopy of the circumstellar dust has shown that the 9.7-μm silicate feature in HAEBE stars is in emission, suggesting that the dust in the circumstellar shell is optically thin at that wavelength. This puts strong constraints on the distribution of dust and its temperature structure and has been used as an argument against the presence of optically thick disks. The cases of AB Aur and HD 163296 demonstrate that rotating disks with substantial dust mass can have silicate 9.7-μm emission. Such emission could arise in an extended region above the densest part of the disk (perhaps similar to the [O I]). The strong photometric variations observed in many HAEBE stars show that the dust shell is very clumpy, which may also help in combining a large dust mass with (partially) optically thin silicates.

4.4 *Conclusion*

While the issue of geometry will likely remain controversial for some time to come, the recent millimeter interferometric maps show that rotating disks are present in HAEBE stars, for which spectroscopic evidence has been claimed to argue against optically thick disks. Therefore these spectroscopic diagnostics must be reexamined critically in view of the new observational evidence. Direct imaging shows that envelopes are present as well, which may dominate the SEDs in many cases, but which do not necessarily rule out the presence of disks. Finally, it is likely that the (evolution of the) geometry of the circumstellar environment depends on stellar mass and/or luminosity, as do the time scales for the PMS evolution and disk dissipation processes.

5. EVOLUTION OF HAEBE STARS

HAEBE stars are interesting as the interface between low-mass and high-mass star formation (Appenzeller 1994), and their study should be revealing about the differences between the environments where low-mass and high-mass stars form and about the relative importance of various physical processes that determine PMS evolution. PMS evolutionary models for HAEBE stars have been recently computed by Palla & Stahler (1993 and references therein), D'Antona & Mazzitelli (1994), Swenson et al (1994), and Bernasconi (1996).

From a theoretical point of view (e.g. Palla & Stahler 1993), it is customary to ascribe the mass range between 2 and 8–10 solar masses to the HAEBE stars in our Galaxy. The lower limit corresponds to the mass above which stars are radiatively stable when they begin their quasistatic contraction. The upper limit corresponds to the mass above which stars start burning hydrogen before they emerge from their contracting envelope; i.e. it occurs where the "stellar birthline" (Stahler 1983) intersects with the ZAMS. Higher-mass PMS stars are therefore not expected to be optically visible before they reach the ZAMS, though the limit may depend on the environment as well as on metallicity, to which the latter is attested by the detection of higher-mass HAEBE analogs in the Large Magellanic Cloud (Beaulieu et al 1996).

With respect to both lower- and higher-mass stars, intermediate-mass stars spend a relatively long time in the protostar contraction phase, i.e. before the stellar birthline. This effect receives observational support from the study of the Orion Nebula cluster by Hillenbrand (1997), who derived systematically lower post-birthline ages for PMS stars in the relevant mass range.

Rather good agreement between the location of observed HAEBE stars in the Hertzprung-Russell (HR) diagram and model computations is found, but to the extent that accretion contributes only a minor fraction of the observed bolometric luminosity. In turn, the high accretion rates, and accordingly high accretion luminosities claimed by Hillenbrand et al (1992) from fitting the SEDs with a disk model, would result in significantly lower stellar luminosities. This would, however, locate most objects rather far from the birthline and leads to the somewhat paradoxal result that the stars with highest IR excesses would be the most evolved (Palla & Stahler 1994).

5.1 *HAEBE Stars in Clusters*

Censuses of PMS stars in the mass range of HAEBE stars in young open clusters and associations have been made by several authors, e.g. in Orion (Hillenbrand 1997), NGC1333 (Lada et al 1996), NGC6611 (Hillenbrand et al 1993, De Winter et al 1997), NGC2244 (Pérez 1991), NGC2264 (Lada et al 1993a), NGC6383 (Thé et al 1985), and NGC6530 (van den Ancker et al 1997b).

A striking result from these studies is the relative rarity of HAEBE stars among the PMS stars in some of these clusters. In their study of the SEDs and spectral types of PMS stars in NGC2244, Pérez et al (1987) found that only on the order of 10% present large IR excesses, whereas in at least 60% of the objects, no excess is apparent. The fraction of excesses appears to be larger in younger associations, such as the Orion Nebula cluster (Hillenbrand 1997) and NGC1333 (61%, Lada et al 1996), but also in the 5-Myr cluster NGC2264 (Lada et al 1993a). These data suggest a decay time for the HAEBE phenomenon in clusters on the order of a few million years, with cluster-to-cluster differences.

On the other hand, the occurrence of field HAEBE stars with post-ZAMS ages up to 10 Myr (van den Ancker et al 1997a) suggests that in some environments the disks may survive significantly longer than is observed in rich clusters. Imaging of the environment of the bright HAEBE star BD$+40^{\circ}$4124 (Hillenbrand et al 1995) reveals a small cluster containing a fraction of possibly more than 80% of sources with IR excesses.

These surveys may suggest that disks in intermediate-mass–star-forming regions survive more easily than those in massive–star-forming regions, the latter being ablated by the radiation field of hot cluster members. Some support for this conjecture may be found in the sharp truncation at the outer radii that has been observed for the Orion proplyds (McCaughrean & O'Dell 1996).

Testi et al (1997) have carried out a search for clustering around 19 HAEBE stars and detected embedded sources in most cases. They found a clear dependence between the spectral types of the HAEBE star and the richness of the embedded cluster around it, in the sense that hotter stars tend to be surrounded by richer clusters. However, because the near-IR imaging technique they used favors the detection of embedded sources, no conclusions can be drawn about the fraction of naked young stellar objects (YSOs) in these clusters.

By all means, it would be hazardous to state that age and cluster environment are the only parameters that determine the HAEBE versus naked status of a young star, and a distinct place seems to be reserved for a concept such as stellar individuality. In a very long baseline interferometry (VLBI) survey of the ρ Ophiuchi molecular cloud, André et al (1992) detected radio emission from several naked A-type YSOs and suggested that fossil magnetic fields have been instrumental in rapidly clearing the environment of these stars. It is indeed well known that a fair fraction of main-sequence A- and B-type stars display chemical peculiarities that are associated with such fossil fields, and it is most likely that these fields affect the PMS evolution.

5.2 *Activity, Accretion, and Outflows*

With respect to T Tauri stars, HAEBE stars may be expected to be distinct not only because of a different environment in which they are formed, but also because of the absence of deep convection zones. The activity of HAEBE stars observed in the UV has been interpreted as chromospheric (e.g. Praderie et al 1986, Catala 1988). Proposed explanations for the presence of surface convection zones are differential rotation (Vigneron et al 1990) and deuterium burning (Palla & Stahler 1990). However, Palla & Stahler (1993) retracted the latter as an explanation for HAEBE stellar activity because the limited convection zones vanish by the time the star joins the classical radiative portion of its evolutionary track. Because HAEBE stars that are already on the main sequence also display activity (e.g. HD 104237), deuterium burning cannot be its source.

In the recent literature, the accretion from a circumstellar disk is most often invoked as the source of the activity, in HAEBE as well as in T Tauri stars (Bertout et al 1988, Blondel et al 1993, Edwards et al 1993, Ray & Mundt 1993). This hypothesis is consistent with the similarity of the outflows observed for both kind of objects (Mundt & Ray 1994) and with the correlations between the strengths of the winds and the various indicators of the importance of the circumstellar disks (Bertout 1989, Cabrit et al 1990, Blondel et al 1993).

Both the strengths of accretion and of outflows decline with evolution, but at least during the early stages, this does not appear to happen at a steady rate. The very young star Z CMa behaves as a typical FU Orionis star (Hartmann et al 1989), and its jet, which extends over 3.6 pc, illuminates at least 15 HH objects (Poetzel et al 1989). Hartmann et al (1989) derived from the SED of Z CMa a present accretion rate of 10^{-3} solar masses per year, which corresponds with an accretion luminosity that is higher than the stellar luminosity (Poetzel et al 1989). Typical accretion and outflow rates for HAEBE stars close to or on the main sequence are of the order of 10^{-8} and 10^{-9} solar masses per year, respectively (Blondel et al 1993, Grady et al 1996).

5.3 *The β Pictoris Connection*

The detection by the IRAS satellite that some main-sequence stars are surrounded by dust debris disks (Aumann et al 1984, Gillet 1986) has widened the scope of the study of HAEBE stars. From an observational point, it is not obvious, however, that these Vega-type stars are close cousins to the HAEBE stars because at least prototypes such as Vega itself and Fomalhaut are well evolved from the ZAMS (Backman & Paresce 1993). Also, the large fraction of Vega-type objects among main-sequence stars and even giants (Zuckerman et al 1995, Plets et al 1997) argues against a young age for the objects with dust debris disks. Because of the faintness of the excesses, estimating this fraction from IRAS-based studies is a delicate matter, but a recent analysis involving the statistical analysis of data with strong observational selection effects leads to a fraction of about 13% of excess stars both among main-sequence stars and their giant descendants (Plets 1997).

Although the high ages of some Vega-type stars do argue for a stable disk or for a regular disk replenishment, it is very likely that the material orbiting Vega-type stars is a remnant of the disk these stars had as YSOs. This is particularly likely for β Pictoris, which is the most active Vega-type star and for which a Hipparcos age greater than 8 Myr has recently been derived (Crifo et al 1997; for a recent review of β Pictoris, see Artymowicz 1997). Variable absorption features in the UV (e.g. Lagrange et al 1989) and the optical (e.g. Ferlet et al 1993) spectral lines of β Pictoris are currently interpreted in terms of the impact of small, cometary-like bodies onto the star; this accretion process apparently is too weak to lead to detectable outflow characteristics.

In IRAS-based searches for Vega-like stars (e.g. Walker & Wolstencroft 1988), several candidates have been identified that are rather isolated HAEBE stars. Optical and UV studies of these objects (Grinin et al 1994, Grady et al 1996 and references therein) have shown that intermittent absorption features similar to those occurring for β Pictoris are also present for these HAEBE stars, and blueshifted emission is also present in several of them. Brown et al (1997) confirmed this picture with observations of the isolated HAEBE star HD 104237 with the Goddard High Resolution Spectrograph onboard the Hubble Space Telescope.

5.4 *Spectral Evolution in the Infrared*

Inevitably, the evolution (of the CSM) of HAEBE stars must go from heavily embedded to naked, much in the manner proposed by Lada (1987) for T Tau stars. The SED will evolve from CSM-dominated to stellar-dominated, possibly with an IR excess due to emission from cool dust grains throughout the main-sequence lifetime (Vega stars), at a rate determined by the time scales of stellar and circumstellar evolution.

Observationally, the IR continuum of very young HAEBE stars (close to the birthline) is dominated by thermal radiation from dust (in an envelope and disk), whereas the fine-structure lines are due to shocks that occur at the interface between the bipolar outflow and the ambient cloud. During this early phase, accretion rates are still high, $\sim 10^{-6}$ to 10^{-5} $M_\odot$/year, and the star is not yet optically visible. In a later phase, more of the stellar light can escape into the ambient medium, and the IR spectrum will develop the character of a photon dominated region (PDR). Still later, accretion drops to below 10^{-7} $M_\odot$/year, and the star is clearly visible. The IR SED is still dominated by the disk/envelope complex; which component dominates depends on wavelength, angular scale, mass of the star, and environment. This phase is what one may call a typical HAEBE star. Finally, as accretion drops even further, a β Pictoris phase follows, and possibly a Vega-type star.

Grain removal processes such as radiation pressure and Poynting-Robertson drag are expected to destroy the debris disks on time scales much shorter than typical main-sequence lifetimes. The persistence of debris disks over the main sequence then shows that processing of the circumstellar grains must occur, in the sense that larger gravitationally bound bodies are formed that, through incidental collisions, replenish the disk. From the covering factors in the range 15–30% that they observed for the cometary impacts on HAEBE stars, Grady et al (1996) deduced that the impactors are appreciably larger than typical Sun-grazing comets. In β Pictoris, the presence of a planet has been invoked to explain the stable existence of an inner cleared region in the disk (Roques et al 1994, Lazzaro et al 1994, Lagage & Pantin 1994) and the disk asymmetries (Lagage & Pantin 1994, Burrows et al 1995).

The link to comets is also apparent in β Pictoris from the cometary-like appearance of the 10-μm silicate feature (Telesco & Knacke 1991, Knacke et al 1993). This silicate feature differs from the more widespread feature observed in astronomical sources, in the sense that a crystalline component peaking at 11.2 μm is superposed on the typical amorphous component. The detection by ISO of crystalline material around near–main-sequence HAEBE stars confirms the link with β Pictoris and with the presence of cometary bodies in particular. As can be seen in Figure 9, the ISO SWS silicate spectrum of the HAEBE

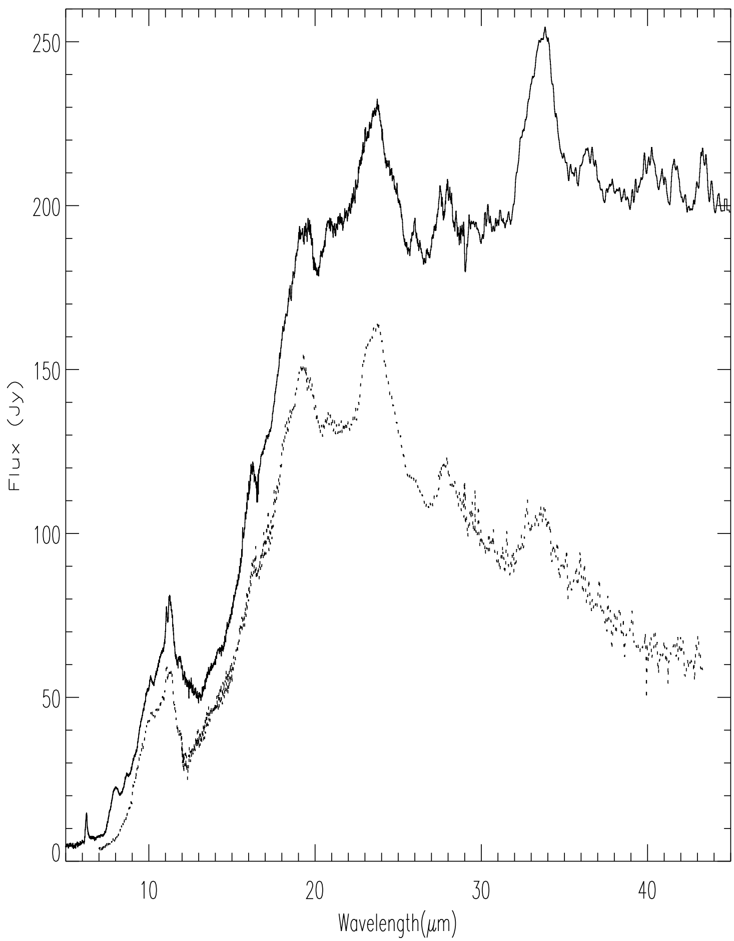

Figure 9 The ISO SWS spectra of HD 100546 (Malfait et al 1998b) and comet Hale-Bopp (Crovisier et al 1997, *lower spectrum*). Note the remarkable similarity in solid-state structure observed at 11.3, 16.5, 23.5, 27.5, and 33.8 μm. These features are attributed to crystalline silicates, specifically forsterite. In HD100546, there is also evidence for pyroxenes at 40.5 μm.

star HD 100546 displays a striking resemblance to that of comet Hale-Bopp (Crovisier et al 1997). The presence of crystalline silicates in both objects demonstrates that significant grain processing must have occurred. Crystallization may either be the result of slow annealing of warm grains or of heating of these grains to temperatures on the order of 1000 K. Laboratory experiments suggest that the former possibility is very difficult to achieve (Hallenbeck & Nuth 1998). Perhaps the protoplanetary disk in HD 100546 underwent substantial mixing. Such mixing is incorporated in recent models for protoplanetary disk evolution (Shu et al 1997).

The ISO spectra of the youngest HAEBE stars are consistently characterized by nearly amorphous silicate features, whereas the shoulder in the 10-μm silicate feature, attributed to crystalline olivine, is observed in several HAEBE stars that are already main-sequence objects, such as HD 100546, but also HD 104237 and HD 179218. On the other hand, the observations so far do not imply that a well-defined correlation exists between the processing of the dust and the stellar age.

Waelkens et al (1994) and Malfait et al (1998a) pointed out that the significant amount of isolated HAEBE stars with an IR excess, characterized by a dip around 10 μm, may be interpreted in terms of an evolutionary scenario in which the formation of larger bodies occurs in the disk region near the ice sublimation temperature. However, the validation of this scenario depends on the interpretation of the near-IR excesses.

6. CONCLUSIONS AND FUTURE WORK

HAEBE stars show a very rich variety of physical processes, involving the simultaneous infall and outflow of matter in a complex circumstellar environment. The PMS nature of the majority of HAEBE stars is now well established, and as more detailed studies of individual objects are carried out, the phenomenological classification of HAEBE stars may be replaced by criteria more connected to their evolutionary status.

The picture that emerges justifies a characterization of HAEBE stars as the more massive analogues to T Tau stars. The lower-luminosity Herbig Ae stars seem to fit this description particularly well, but the situation for the more embedded, more luminous Herbig Be stars is less clear. Nevertheless, for Herbig Ae stars, significant differences with T Tau stars are obvious, such as the spectral signatures of accretion. Active accretion disks and bipolar outflows are found in more embedded stars, while the accretion rates are significantly lower for the less embedded objects. Accretion in optically bright HAEBE stars is modest and irregular; photometric, spectroscopic, and polarimetric data strongly point to a clumpy circumstellar environment. These observations are consistent with the presence of comet-like bodies that are accreted onto the star, and they support an evolutionary link between HAEBE stars and β Pictoris.

The new millimeter interferometric maps of HAEBE stars have demonstrated that both disks and envelopes are present, and these observations underpin the need for high angular resolution data to resolve the issue of the geometry of the circumstellar material. While the interpretation of SEDs in terms of geometry remains ambiguous without high angular resolution images, the ISO spectra show a remarkable richness of solid-state structure, which clearly has an impact on the analysis of broadband SEDs. The ISO data also give support to the exciting hypothesis that the environment of HAEBE stars can be the site of planet formation.

Several intriguing problems concerning the nature and evolution of HAEBE stars remain. The observations of young open clusters demonstrate that only a small fraction of all intermediate-mass young stars are HAEBE stars. This is related to the apparent lack of correlation between the time scale of evolution of the central star and of the CSM, also seen in lower-mass T Tau stars. What physical processes determine the evolutionary time scale of the CSM? Do the envelopes and disks in HAEBE stars dissipate on similar time scales, and how does this depend on spectral type? In particular, the evolution of the CSM in the more massive Herbig Be stars is less well understood, partly because of the smaller sample and of the extreme embeddedness of these objects.

A matter that is still open is whether or not *all* HAEBE stars evolve into Vega-type stars, i.e. keep a substantial FIR excess throughout their main-sequence life. Vice versa, it is not obvious that all Vega-type stars were HAEBE stars in their infancy. Vega-type stars have little or no gas and only cool dust grains, but HAEBE stars still have large amounts of (molecular) gas. This suggests that the gaseous component of the CSM evolves on a different time scale than the dust component. Is the gas near the star in HAEBE stars replenished by infalling, evaporating cometary bodies?

The exciting opportunities that will arise as large new interferometers become available at near-IR and millimeter wavelengths will resolve the detailed geometry of the environment of HAEBE stars on a scale comparable to that of the solar system (10–100 AU). The study of the high excitation gas, and thus of the physical mechanism that drives the activity, will have to rely on other diagnostics, however. Obviously, the combination of observational techniques in a wide wavelength region is most likely to ensure significant progress. Along these lines, the interpretations of the forbidden line emission in the optical spectra of HAEBE stars and of silicate emission at 9.7 μm need to be investigated in the light of new evidence for (optically thick) circumstellar disks.

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