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ASTRONOMY AND ASTROPHYSICS

An improved classification of B[e]-type stars

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Abstract. We review the classification criteria for the B[e]-type stars (B type stars with forbidden emission lines in their optical spectrum) and we express these in terms of physical characteristics of the stars and the circumstellar (CS) matter. We show on the basis of observations that these criteria can be met in different kinds of stars of different mass and different evolutionary stages. We propose that the name "B[e] phenomenon" is more appropriate than the name "B[e] stars". We propose the definition of five classes of stars which show the B[e] phenomenon:

(a) B[e] supergiants or "sgB[e] stars"
(b) pre-main sequence B[e]-type stars or "HAeB[e] stars"
(c) compact planetary nebulae B[e]-type stars or "cPNB[e] stars"
(d) symbiotic B[e]-type stars or "SymB[e] stars"
(e) unclassified B[e]-type stars or "unclB[e] stars"

The primary and secondary classification criteria for each of these groups are defined. We also present lists of objects for each group, except for the SymB[e] stars.

It is possible that some stars satisfy the criteria for more than one of the classes sgB[e], HAeB[e], cPNB[e] and SymB[e]. In that case the evolutionary phase of the star is unclear and the star should be assigned to class unclB[e].

Key words: stars: emission-line, Be – stars: fundamental parameters – stars: pre-main sequence – stars: supergiants

1. Introduction

The term "B[e] stars" was introduced by Conti (1976), based on discussions with J.-P. Swings who had made a detailed investigation of the defining B[e] star HD45677 (Swings, 1973). For historical details, see Swings (1976) and Conti (1997). The B[e] classification designates those stars of spectral type B which show forbidden emission lines in their optical spectrum, where the notation "[e]" follows that for forbidden lines.

Groups of B-stars that show forbidden lines of mainly [Fe II] and other low ionization species as well as strong Balmer emission lines had already been described earlier by several authors: Geisel (1970), Wackerling (1970), Allen & Swings (1972, 1976) and Ciatti et al. (1974). The stars were sometimes indicated as "BQ[ ] stars", were the "Q" indicates abnormal spectra with forbidden lines. Most authors noticed that the stars also show strong permitted lines, such as the Balmer lines, and a strong infrared excess in the near and mid-IR at $\lambda > 5$ μm due to dust emission.

Subsequent studies of B[e] stars by various authors have shown that the group is very heterogeneous and contains for example massive supergiants, pre-main sequence stars, symbiotic stars, compact protoplanetary nebulae and other stars of yet unknown mass or evolutionary stage. A review of the definition and the different kinds of B[e] stars has been given by Zickgraf (1998). Reviews of the other characteristics of B[e] stars can be found in Hubert & Jaschek (1998).

The grouping of stars with different evolutionary stages into one and the same class of "B[e] stars" is confusing. This is especially true if the spectroscopic, photometric or polarimetric observations are discussed, without indications to which evolutionary types of B[e] stars these characteristics refer. Therefore it is better to refer to the "B[e]-phenomenon", rather than to a very heterogeneous group of "B[e] stars". Consequently we propose to abondon the generic classification of "B[e] stars" and replace it with five classes, whose names and designations indicate the evolutionary phase, if known. The stars in all five classes show the B[e] phenomenon in their spectra.

In Sect. 2 we describe the "old" criteria of the B[e] stars and we express these in terms of physical conditions. In Sects. 3, 4, 5, 6 and 7 we introduce the new proposed classification together with the primary and secondary classification criteria. In each of these sections we give a list of stars that show the B[e] phenomenon and belong to that class. The results are discussed in Sect. 8.

2. The B[e] phenomenon

2.1. The criteria

The criteria for the presence of the B[e] phenomenon is the same as that previously used for B[e] stars. They are largely based on the studies by Allen and Swings (1972, 1976). The criteria were introduced for the first time in a systematic way by Allen & Swings (1976). They have recently been reviewed by Zickgraf (1998).

1. Strong Balmer emission lines.
2. Low excitation permitted emission lines of predominantly low ionization metals in the optical spectrum, e.g. Fe II.
3. Forbidden emission lines of [Fe II] and [O I] in the optical spectrum.
4. A strong near or mid-infrared excess due to hot circumstellar dust.

If a star satisfies these criteria, the star shows the ”B[e] phenomenon”.

In addition to these primary criteria, the optical spectrum may also show permitted and forbidden emission lines of higher ionization species, e.g. He II λ4686, [O III] λ5007, but this is not a defining characteristic.

These spectroscopic criteria were defined for the optical spectrum and should not automatically be extended to other wavelength regions. For instance, the $ISO - SWS$ spectrum of many luminous supergiants show the emission line of [Fe II] at λ25.99 μm. If this were taken as an indication of the B[e] phenomenon, the class of stars that show the B[e] phenomenon would be even more heterogeneous than it is already.

2.2. The physical conditions

The four criteria for the B[e] phenomenon can be expressed in terms of physical conditions for the circumstellar material around the stars.

(a). The presence of strong Balmer emission lines and possibly other permitted low ionization lines implies that the atmosphere above the stellar continuum forming region has a very large emission measure of singly ionized gas. For an Hα luminosity of about 10^{37} to 10^{38} erg s^{-1}, which is a typical value for a B supergiant that shows the B[e] phenomenon, the emission measure (EM = volume integral of $n_{\rm e}^2$) should be about 10^{62} to 10^{63} cm^{-3} if $T_{\rm e} = 1.5 \times 10^4$ K (Osterbrock, 1989, case B). This value of the EM scales with the line luminosity and with $T_{\rm e}^{+1}$. The typical Hα luminosity of a pre-main sequence B star that shows the B[e] phenomenon is 10^{-2} to 10^{-1} $L_\odot$ and the emission measure is between 1.5×10^{56} and 1.5×10^{57} cm^{-3}.

(b). The presence of the emission lines of low ionization metals, such as Fe II, indicates that the temperature of the emitting region is about 10^4 K and that the ionization is most likely due to the radiation from the B star itself.

(c). The presence of forbidden lines of low excitation metals such as [Fe II] and [O I] indicates that the CS material is geometrically extended so that there is a large amount of low density gas. The typical luminosity of the [Fe II] λ4244 line in the spectrum of B[e] supergiants is 10^{35} erg s^{-1}. Viotti (1976) has shown that a medium emitting permitted and forbidden Fe II lines with a line ratio [Fe II]$_{\lambda 4424}$/ Fe II$_{\lambda 4233} \simeq 1$ has a density of $n_{\rm e} < 10^{11}$ cm^{-3} and a dilution factor of about 10^{-4}. The critical density for the the line emitting region of the [O I] 6300 Å line is 1.1×10^6 atoms cm^{-3}.

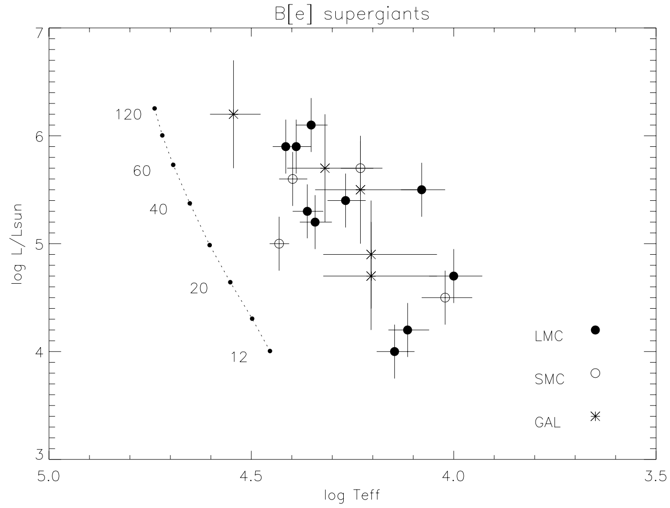

Fig. 1. The location of the Galactic, LMC and SMC B[e] supergiants in the HRD. The line indicates the main sequence. (Data from Table 1)

(d). The infrared excess due to dust with a temperature of about 500 to 1000 K, which is typical for stars showing the B[e] phenomenon, indicates that the density in the CS material is higher than the critical density of $\rho \simeq 10^{-18}$ g cm^{-3} (Bjorkman 1998) at the distance where the equilibrium temperature of the dust is about 500 to 1000 K. The equilibrium temperature of the dust varies with distance from the stars as $T_{\rm dust} \simeq T_{\rm eff} (2r/R_*)^{-2/5}$ (Lamers & Cassinelli 1998). So the dust must be at a distance of about $r \geq 5 \times 10^2$ to $r \geq 10^3$ R_* if $T_{\rm eff}$=20 000 K. This minimum distance scales with ${T_{\rm eff}}^{5/2}$.

In this discussion we have not taken into account the geometrical distribution of the CS material. There is ample evidence that the CS material of stars showing the B[e] phenomenon is concentrated in a circumstellar disk (see e.g. Hubert & Jaschek 1998). In that case the emission measure of the permitted lines is high because the emitting ions are concentrated in a disk of relatively high density on the order of 10^{10} atoms cm^{-3}. The formation of dust is facilitated because of the high density in the disk, and because the disk can shield the stellar radiation. Moreover, the temperature in a disk will decrease outward more rapidly than in a spherical circumstellar envelope, because the photons can easily escape in the direction perpendicular to the plane of the disk.

3. B[e] supergiants or ”sgB[e] stars”

The most homogeneous group of stars that show the B[e] phenomenon is formed by the B type supergiants in the LMC and SMC. They were studied by Zickgraf et al. (1985, 1986, 1989, 1992, 1996a, b) and by Gummersbach et al. (1995). Stars with similar characteristics have also been identified in the Galaxy (e.g. Wolf & Stahl 1985, McGregor et al. 1988a, Winkler

& Wolf 1989). For a review see Zickgraf (1998). We propose a spectral type designation of "sgB[e]" for these stars.

The location of the LMC, SMC, and Galactic B[e] supergiants in the HR-diagram is shown in Fig. 1. The uncertainty of the LMC and SMC supergiants in $T_{\rm eff}$ is about 1500 K for the cooler supergiants and 2000 K for the hotter ones (e.g. Gummersbach et al. 1995). The uncertainty is about $\Delta L \simeq 0.2$ to 0.3 dex. The distance and hence the luminosity of the Galactic B[e] supergiants is much more uncertain than of the Magellanic Cloud stars. Mc Gregor et al. (1988a) estimate an uncertainty of about 0.3 dex in L_*. The temperatures have an uncertainty of about 5000 K, due to the severe extinction. All stars are supergiants with a luminosity of log $(L_*/L_\odot) > 4.0$. There is a vague indication that the sample of LMC and SMC stars consists of two groups: one with log $(L_*/L_\odot) > 5.0$ and one with log $(L_*/L_\odot) < 4.6$. However this might also be due to the small number statistics.

Part of the spectrum of the typical B[e] supergiants Hen S134 is shown in Fig. 2. The figure shows the strong Hα emission, the many emission lines of Fe II and He I, and the forbidden emission of [O I]. The bluer part of the spectrum (not shown here) contains many [Fe II] lines.

3.1. *The criteria for sgB[e] stars*

Based on the observed characteristics described above, we propose the following criteria for the B[e] supergiants.

Primary criteria

A1: The stars show the B[e] phenomenon.
A2: The stars should be supergiants with log $(L_*/L_\odot) \gtrsim 4.0$.

Secondary criteria

B1: Indications of mass loss in the optical spectrum, e.g. P Cygni profiles of the Balmer lines, or double peaked Balmer emission lines with violet shifted central absorption.
B2: Hybrid spectra, i.e. simultaneous presence of narrow low-excitation emission lines and of broad absorption features of higher-excitation lines.
B3: An enhanced N-abundance with an abundance ratio of $N/C > 1$ or an enhanced He/H ratio. This shows that the star is in an evolved evolution stage where the products of the CN-cycle have appeared at the surface.
B4: B[e] supergiants in the Galaxy usually have a very high extinction with $A_V \gtrsim 3^m$ and strong interstellar bands because they are massive stars located at large distances in the galactic plane.
B5: The photometric variations of B[e] supergiants are usually small and on the order of $0.1^{\rm m}$ to $0.2^{\rm m}$.

An exception to criterion B5 is the star R4 in the SMC, which showed an LBV type outburts of $\approx 0.5^{\rm m}$ (Zickgraf et al. 1996a). The stars that satisfy the criteria for the B[e] supergiants are listed in Table 1. Some of the Galactic B[e] supergiants also satisfy the criteria of other B[e] classifications (see below). This is largely due to the uncertainty in their distance. These stars are indicated separately in Table 1.

4. Pre-main sequence B[e] or "HAeB[e] stars"

A fraction of the stars that show the B[e] phenomenon are clearly very young stars because they appear in star forming regions. These stars may appear as pre-main sequence stars and show, therefore, many characteristics of and are related to the Herbig Ae/Be stars, also called "HAeBe-stars" (Thé et al. 1994). In particular, the stars often show spectroscopic evidence of infall rather than outflow in the optical spectrum. HAeBe stars are strongly variable, probably due to irregularities in the CS dust (Grinin et al. 1994 and references therein). We propose a spectral type designation of "HAeB[e]" for these stars.

The HAeB[e] stars can easily be distinguished from other stars showing the B[e] phenomenon if they are still embedded in post-natale material. This distinction does not always apply in crowded star forming regions, e.g. in clusters where, due to different clearing mechanisms, young stars appear naked on the ZAMS compared to their isolated counterparts. De Winter et al. (1998) have shown that no stars showing the B[e] phenomenon are found in young clusters. This sets an upper limit to the lifetime of the HAeB[e] stars of about 6×10^6 years.

The comparison between the location of stars of spectral type B, or log $T_{\rm eff} > 4.0$, that are in their gravitational contraction phase, and the theoretical evolutionary tracks of Palla & Stahler (1993) shows that the stars have masses $M_\star > 2.5\ M_\odot$ and that they are younger than 3 Myr. Due to their short pre-main sequence lifetime the fraction of B stars in this phase is small and the detection of these objects is difficult. Indeed, only a few genuine Herbig Be stars are known (Thé et al. 1994).

The location of the confirmed HAeB[e] stars in the HR diagram is shown in Fig. 3. The stars have luminosities of log $(L_*/L_\odot) \lesssim 4.5$. The Balmer lines of HAeB[e] stars are often double peaked with a peak separation of 60 to 300 km s^{-1}(Fernández et al. 1995; Reipurth et al. 1996). Fig. 4 shows the visual spectrum of a typical HAeB[e] star V380 Ori.

4.1. *The criteria for HAeB[e] stars*

Based on the characteristics described above, we propose the following criteria

Primary criteria

A1: The stars show the B[e] phenomenon.
A2: They are associated with star forming regions.
A3: They show spectroscopic evidence of accretion or infall, e.g. inverse P Cygni profiles.

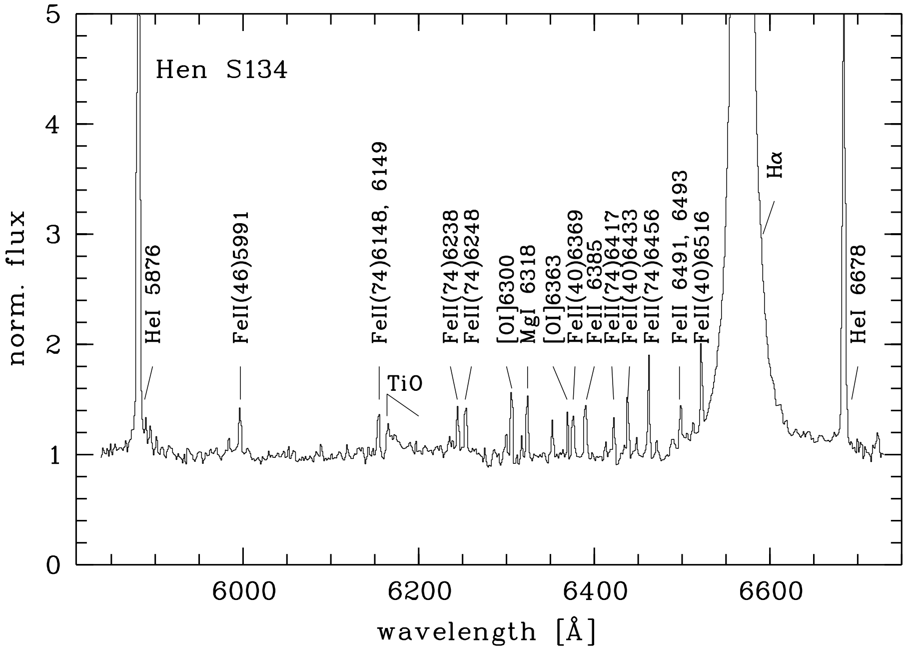

Fig. 2. The spectrum of the typical B[e] supergiants HD 38489 = Hen S134 in the wavelength range of 5800 to 6750 Å, showing the permitted emission lines of Hα, He I and Fe II and the forbidden emission lines of [O I]. The spectrum (resolution $\sim$ 2Å) was obtained in April 1984 with the Boller & Chivens spectrograph at the ESO 2.2 m telescope (see also the high resolution spectrum displayed in Zickgraf et al. 1989).

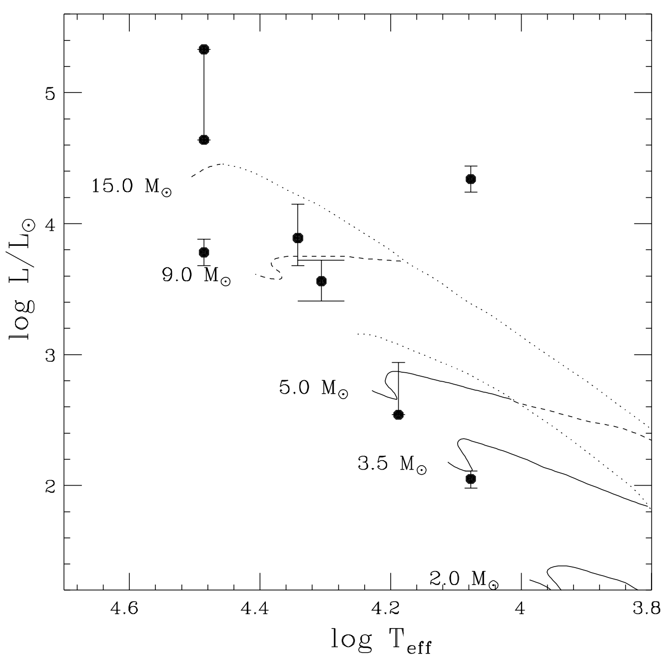

Fig. 3. Hertzsprung-Russell diagram of HAeB[e] stars of which spectral type and luminosities could be estimated, see Table 2. Also shown are the theoretical pre-main sequence evolutionary tracks (solid lines and dashed lines) and the birthlines for accretion rates of 10^{-4} (upper dotted line) and 10^{-5} $M_{\odot}$ yr^{-1} (lower dotted line) from Palla & Stahler (1993).

Secondary criteria

B1: log $(L_*/L_{\odot}) \lesssim$ 4.5, because HAeBe stars are the progenitors of stars in the mass range of 2 to about 15 $M_{\odot}$ (Palla & Stahler, 1993).

B2: The stars show large irregular photometric variations on time scales from days to 10^3 days. The photometric variations are ususally characterised by variable extinction (Bibo & Thé, 1991), but the variability range decreases to earlier spectral types (van den Ancker et al. 1998). During very deep minima the scattered light can become a significant contribution causing the observed colours to get bluer (e.g. Grinin et al. 1994).

B3: The energy distribution shows the presence of warm and cool dust.

Criterium A2 is not always met because there are also isolated HAeB[e] stars just as there are isolated HAeBe stars (Thé et al., 1994). Accretion, criterium A3, around HAeBe stars are mostly seen as events and not continuously. Normally HAeBe stars show variable asymmetric double peaked Hα profiles. Occasionally the stars show inverse P Cygni profiles, which indicate infall. This occurs when the amount of infalling matter is much larger than normal (e.g. Grinin et al. 1994). The presence of warm and cold dust, criterium B3, is explained by some models as being due to a circumstellar disk with an outward decreasing temperature (Hillenbrand et al. 1992) or by an accreting more spherical envelope (Berilli et al. 1992), while in other models it is explained in terms of warm dust in the accretion disk and cold dust in the remnant of the star formation cloud (Natta et al. 1993).

The HAeB[e] stars are listed in Table 2.

5. Compact planetary nebulae B[e] stars or ”cPNB[e]-stars”

A group of stars that show the B[e] phenomenon are in an evolutionary phase of low mass stars that will become planetary nebulae. This was first noticed by Ciatti et al. (1974) who suggested

Table 1. The B[e] supergiants or sgB[e] stars

Name	Spectral type	$T_{\rm eff}$ [10^3 K]	log L_* [$L_\odot$]	reference
LMC:				
Hen S12	B0.5	23	5.3	Zickgraf et al. (1986)
Hen S22 = HD 34664	B0-B0.5	23-26	5.8-6.0	Zickgraf et al. (1986)
Hen S35	B1Iab	22	5.2	Gummersbach et al. (1995)
Hen S59	B5II	14	4.0	Gummersbach et al. (1995)
Hen S93	B9Ib	10	4.7	Gummersbach et al. (1995)
Hen S111 = HDE 269599s	B:	–	–	McGregor et al. (1988b), Stahl et al. (1989)
Hen S134 = HD 38489	B0	26	5.9	Zickgraf et al. (1986)
Hen S137	B6Ib/II	13	4.2	Gummersbach et al (1995)
R66 = HDE 268835	B8	12	5.5	Zickgraf et al. (1986)
R82 = HDE 269217	B2-3	18.5	5.4	Zickgraf et al. (1986)
R126 = HD 37974	B0.5	22.5	6.1	Zickgraf et al. (1985)
SMC:				
Hen S18		25	5.5-5.7	Zickgraf et al. (1986)
Hen S23 = AV 172	B8	10-11	4.5	Zickgraf et al. (1992)
Hen S65 = R50	B2-3	17	5.7	Zickgraf et al. (1986)
R4	B0	27	5.0	Zickgraf et al. (1996a)
Milky Way:				
CPD-52°9243	∼B3Ia	17	5.5	Winkler & Wolf (1989)
GG Car	B0-B	16	4.7	McGregor et al. (1988a), Lópes et al. (1992)
Unclear classification:				
HD 87643[1]		15	4.2-4.9	McGregor et al. (1988a), §7.2: HAeB[e]?
MWC 300[2]	B1Ia$^+$	20.8	5.7	Wolf & Stahl (1985), de Winter (1996)
MWC 349A[1]		29	4.5-5.2	Cohen et al. (1985), §7.2: HAeB[e]?

(1): B[e] supergiants that also have a different B[e] classification.
(2): Faint emission lines.

that some BQ[ ] stars are evolving into some kind of planetary nebula. Swings & Andrillat (1979) noticed striking similarities between the spectra of stars with the B[e] phenomenon and spectra of objects in the Catalogue of Galactic Planetary Nebulae (Perek & Kohoutek 1967). The optical spectrum of many *compact* planetary nebulae shows strong Balmer emission lines and emission lines of Fe II and forbidden lines of [Fe II] and [Ca II]. In addition there can be forbidden lines of higher ionization stages such as [O III], [S III], [Ne III] (e.g. Allen & Swings 1976). Examples are the Butterfly Nebulae M2-9 (Swings & Andrillat 1979), and the protoplanetary IR source Hen 3-1475 (Riera et al. 1995). Many of these objects show a strong IR excess, which is a characteristic of the B[e] phenomenon. We propose to designate these stars as "cPNB[e] stars".

The spectrum of the cPNB[e] star HD 51585 (OY Gem), which is a planetary nebula but which clearly shows the B[e] phenomenon is shown in Fig. 5. The spectrum was described in detail by Jaschek et al. (1996).

5.1. The criteria for cPNB[e] stars

Based on the characteristics described above we propose the definition of the class of compact planetary nebulae B[e] stars or the cPNB[e] stars.

Primary criteria

A1: The stars show the B[e] phenomenon.
A2: The spectra indicate that the stars are possibly nebulae.
A3: The luminosity is log $(L_*/L_\odot) \lesssim 4.0$

Secondary criteria

B1: In addition to the forbidden low ionization lines, the spectrum can also show forbidden emission lines from a range of higher excitations, such as [O III], [S III], [Ne III], [Ar III] and [Ar V].
B2: The spectrum can show evidence for N enhancement, which is indicative of an evolved evolutionary phase.
B3: The energy distribution can show the presence of cold dust, $T_{\rm d} < 100$ K, which is a remnant of the AGB wind.

The cPNB[e] stars that satisfy these criteria are listed in Table 3.

6. Symbiotic B[e] stars or "SymB[e] stars"

A fraction of the stars that show the B[e] phenomenon are symbiotic stars which are interacting binaries with a cool giant and

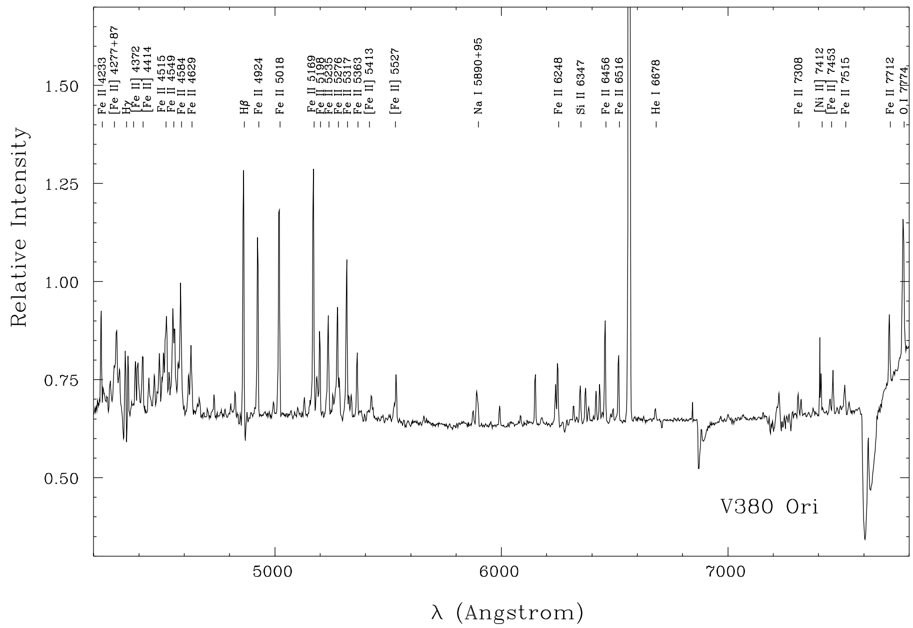

Fig. 4. The 4200 - 7800 Å low resolution spectrum (1.80 Å pixel^{-1}) of the Herbig B[e] star V380 Ori. Notice the many permitted and forbidden Fe II emission lines and the strong Hα (6563 Å) emission. The inverse P Cygni profile of Hβ (4861 Å) shows evidence of infall. (from de Winter & van den Ancker, Private Communication)

Table 2. The HAeB[e] stars.

Name	Spectral type	log L_* [$L_\odot$]	reference[1]
Stars with strong [Fe II] lines:			
He 2–446	B:[e]	–	ddW
HK Ori	B/G:[e]p	–	ddW
R Mon	B0[e]	3.78	ddW
V380 Ori	B9[e]+sh	2.06	vdA
Stars with possible or weak [Fe II] lines:			
HD 85567	B5Vne	>2.54	vdA
HD 200775	B2/3eq	3.90	vdA
MWC 1080	B0eq	4.64 – 5.33 [2]	vdA
V594 Cas	B8:eq	4.34	vdA
V1686 Cyg	B2/3e	3.56	ddW
Stars with unclear classification[3]			
HD 87643	B[e]	4.2-4.9	McGregor et al. (1988a), §7.2: sgB[e]?
MWC 349A	B[e]	4.5-5.2 [4]	Cohen et al. (1985), §7.2: sgB[e]?

[1] ddW = de Winter (1996); vdA = van den Ancker et al. (1998).
[2] For MWC 1080 two luminosity estimates are given as both the distances 1 and 2.2 kpc are used in the literature.
[3] These stars also satisfy the criteria of other B[e] classifications.
[4] This star is brighter than the limit of criterion B1. However the extinction and the distance are uncertain.

a hot compact object. The class of symbiotic stars has been defined by Kenyon (1986). These objects are often surrounded by a nebula. The presence of the cool star is obvious from the TiO bands in the spectrum and the hot component manifests itself by the production of high ionization lines, such as He II lines. If the optical spectrum is highly obscured, or if the cool star is not bright enough, the TiO bands may be absent in the visual spectrum. In that case features in the IR part of the spectrum may indicate the presence of a cool companion. Symbiotic stars are irregular photometric and spectroscopic variables. Near maximum light the spectrum shows Balmer emission lines as well as permitted and forbidden emission lines of low excitation metals (Ciatti 1982). Because of this characteristic, many object in the list of stars which show the B[e] phenomenon by Allen & Swings (1976) also appear in lists of symbiotic stars. We propose a spectral type designation of "SymB[e]" for these stars.

Fig. 6 shows the spectrum of the symbiotic star PU Vul, which has been studied in detail by Andrillat & Houziaux (1994). The figure shows the permitted emission lines of H I, O II, O III as well as the forbidden emission lines of [Fe II] and [O III]. The range of the TiO bands is shown.

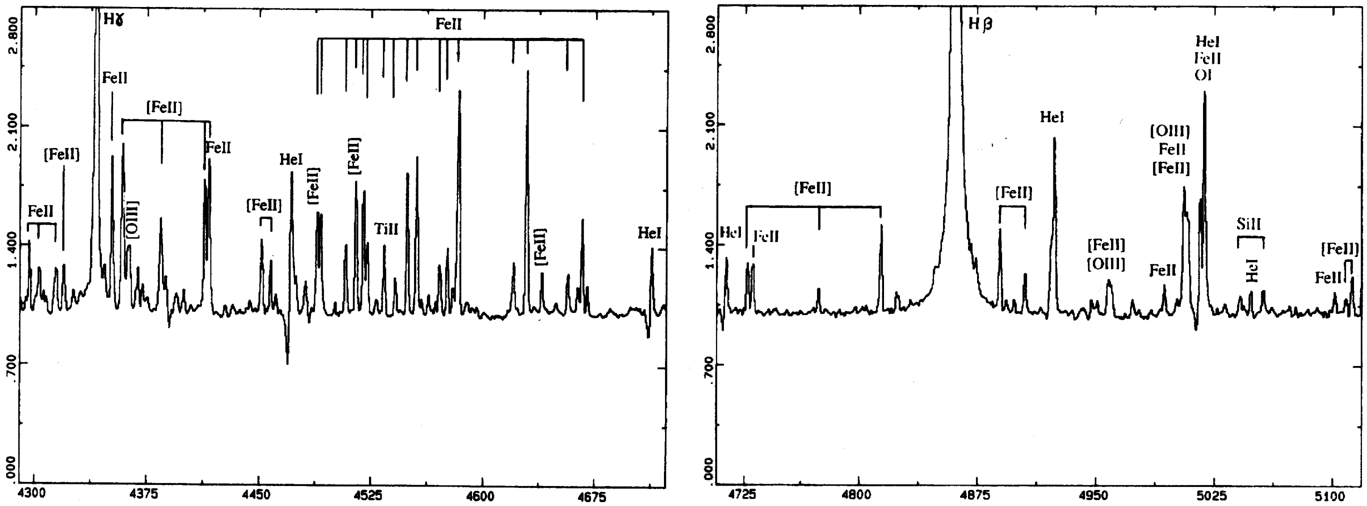

Fig. 5. The optical spectrum of the cPNB[e] star HD 51585 (OY Gem) from 4300 to 5100 Å. Notice the strong Hβ emission, the many permitted emission lines and the forbidden emission lines of [Fe II]. (from Jaschek et al. 1996)

Table 3. Compact planetary nebulae B[e] or cPNB[e] stars

Name	PK number	Spectral type	log L_* [$L_\odot$]	reference
Hb 12	111-02 1	?		Hyung & Aller (1996)
He 2-34	274+02 1	B[e]		Cahn et al. (1992)
He 2-90	305+01 1	?e	3.00	Costa et al. (1993)
He 2-139	326-01 1	B[e]		Stenholm & Acker (1987)
He 2-1312	334-07 1	?		Preite Martinez et al. (1991)
He 3-1475	–	B[e]	4.34	Riera et al. (1995)
M 1-26	358-00 2	?	4.59	Gorny et al. (1997)
M 2-9	010+18 2	B[e]	2.82	Gorny et al. (1997)
Mz 3	331-01 1	B0		Acker et al. (1992b)
OY Gem = HD 51585	–	B0[e]	4.90	Parthasarathy & Pottasch (1989)
V 704 Cen	311+03 1	B[e]	3.78	Mikojalewska et al. (1997)
Vy 2-2	45-02 1	B[e]		Van de Steene & Zijlstra (1994)
Unclear classification[1]:				
V 1016 Cyg		B[e]		Acker et al. (1992a); SymB[e]?

1: This object also satisfies the criteria of other B[e] classifications.

6.1. The criteria for SymB[e] stars

Based on these observations we propose the class of Symbiotic B[e] stars or "SymB[e] stars".

Primary criteria

A1: The star shows the B[e] phenomenon.
A2: The visual spectrum shows evidence for a cool star, in particular the TiO band (unless the cool star is heavily obscured).
A3: The presence of a late type stellar spectrum in the near infrared.

All symbiotic stars and slow novae show forbidden emission lines at some stage. Therefore almost all symbiotic stars are also SymB[e] stars. A catalogue of symbiotic stars with their spectra has been published by Allen (1984) and contains 115 objects. For this reason we do not give the list of the SymB[e] stars.

7. Unclassified B[e] stars or "unclB[e] stars"

Apart from the four classes of stars discussed above, there are stars showing the B[e] phenomenon that cannot be classified into one of these groups because they do not clearly fit the criteria of these classes. Well known examples of these are: HD 45677, HD 50138, HD 87643 and MWC 349A. Their parameters, from Zorec (1998), are listed in Table 4. The distances of HD 45677 and HD 50138 were measured with the HIPPARCOS satellite, so the luminosities are fairly well known (van den Ancker et al. 1998). The distances of HD 87643 and MWC 349A are

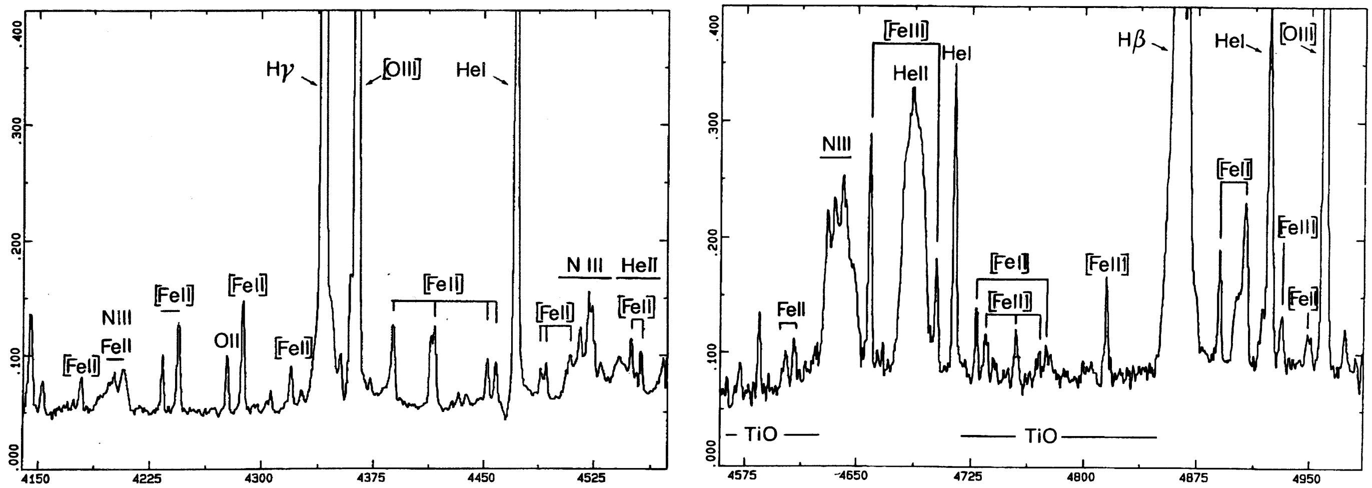

Fig. 6. The spectrum of the Symbiotic B[e] star PU Vul between 4150 and 4950 Å. Notice the bands of TiO from the cool companion, the permitted emission lines from high ionization stages such as He II and N III and the forbidden emission lines from [Fe II] to [O III]. (from Andrillat & Houziaux, 1994)

Table 4. Four typical "unclassified B[e] stars"

Name	Spectral type	log $T_{\rm eff}$	log $L/L_\odot$
HD 45677	B2V:	4.357	3.18
HD 50138	B6III-IV	4.123	2.85
HD 87643	B4II:	4.176	4.19
MWC 349A	O9:III:	4.462	5.23

determined by an iterative method, using the energy distribution from the UV to the far-IR and taking into account the emission and absorption effects of the gaseous and dusty circumstellar envelopes. The spectrum of HD 45677 is shown in Fig. 7

These stars clearly show the B[e] phenomenon. They also show some of the characteristics of the pre-main sequence HAeBe stars, defined by Herbig (1960), Allen & Glass (1975) and Finkenzeller & Mundt (1984). However they do not appear in the list of HAeBe stars by Thé et al. (1994) because either there is doubt about their association to nebulosities, or there is insufficient spectroscopic evidence to clearly assign the HAeB[e] status. We discuss the four stars as examples for unclassified B[e] stars.

7.1. HD 45677 and HD 50138: stars not associated with nebulae

Both stars have a photospheric like visible energy distribution from which the MK spectral type can be derived as listed in Table 4 (Zorec et al. 1998). From this classification we might consider them as "main sequence B[e] stars". Difficulties in assigning an evolutionary stage were discussed by Israelian et al. (1996) and de Winter & van den Ancker (1997) for HD 45677 and by Jaschek & Andrillat (1998) for HD 50138. Spectroscopic and polarimetric data discussed in Schulte-Ladbeck et al. (1992), Bopp (1993), Grady et al. (1993, 1994), Morrison & Beaver (1995), Pogodin (1997) and Vaidya & Schulte Ladbeck (1995) and Vaidya et al. (1994) for HD 45677 and HD 50138, suggest that both stars should possibly be considered as massive Herbig Be stars with an accreting circumstellar disk. This suggests a pre-main sequence evolutionary stage. The parallaxes clearly show that HD 45677 and HD 50138 are not in the southern filament of the Orion and Monoceros system of molecular clouds towards which they project in the sky (Maddalena et al. 1986, Zorec 1998). Hence, they are isolated objects, but located in the Gould belt plane between the Orion and Vela complexes.

Although the isolation of HD 45677 and HD 50138 apparently violates the criteria for HAeBe candidates, Grinin et al. (1989, 1991) discuss the existence of isolated HAeBe stars. Among the outstanding characteristics of these isolated HAeBe stars is an irregular Algol-like light variation with enhanced linear polarization and "blueing" effects at the deep minima produced by scattered light in a circumstellar dusty envelope seen edge-on. Up to now such Algol-like photometric variations and "blueings" were not detected in HD 45677 (de Winter & van den Ancker 1997) nor in HD 50138. These arguments suggest that HD 45677 and HD 50138 may be isolated pre-main sequence HAeBe stars (which would put them in the class of HAeB[e] stars), but the evidence for this is not conclusive and there are counter arguments.

The visual and near-IR spectroscopic characteristics of HD 45677 and HD 50138 are similar to those of "classical" Be stars, which suggests that they might be considered as a kind of extreme examples of classical Be phenomena. In particular, Paschen line emission is frequently seen up to higher members than in the Balmer series, similar to classical Be stars (Jaschek 1998). The Hα emission of HD 45677 and HD 50138 is much stronger than in classical Be stars and in HAeBe stars of similar spectral types. An additional distinction between the unclassified B[e] stars and the HAeBe stars is the slope of the infrared energy distribution at $\lambda \gtrsim 2.2\mu$m. For most HAeBe stars the spectral slope is $\lambda F_\lambda \sim \lambda^{-4/3}$, as expected for an optically thick

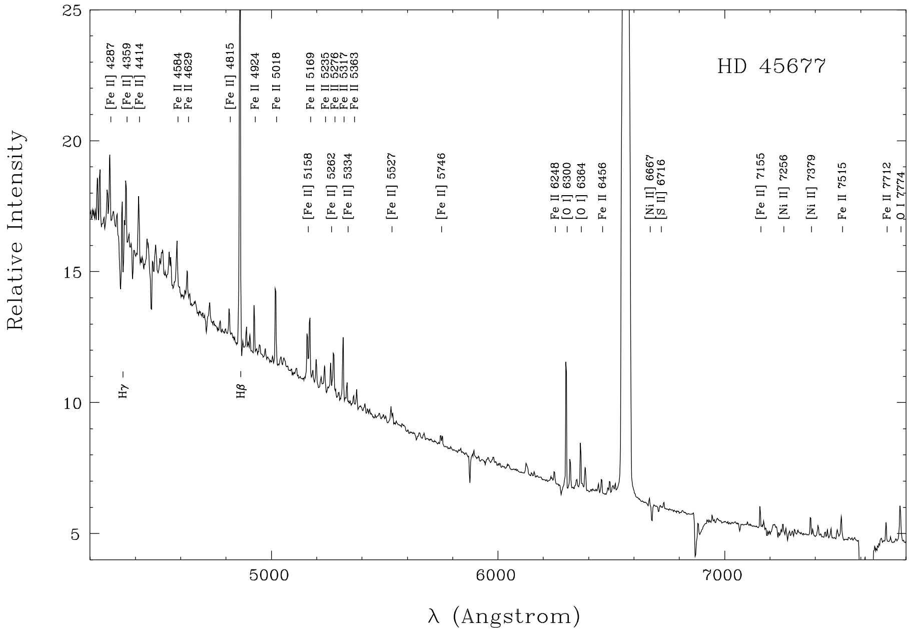

Fig. 7. The 4200 – 7800 Å low resolution spectrum (1.80 Å pixel^{-1}) of the unclassified B[e] star HD 45677. The spectrum is dominated by forbidden emission lines and by the strong Hα emission. There is no evidence for infall in the optical spectrum, but there is clear evidence in the UV spectrum. A higher resolution spectrum shows that many of the stronger lines are double-peaked, as in Be-stars. (from de Winter & van den Ancker, 1997)

circumstellar disc (Hillenbrand et al. 1992), while for these unclassified B[e] stars the slope is $\lambda F_\lambda \sim \lambda^{-0.4\pm0.3}$.

We conclude that the stars HD 45677 and HD 50138 show some characteristics of HAeB[e] stars and of extreme Be stars. Their luminosities indicate that they are possibly some kind of main sequence objects. Therefore these stars are as yet unclassified B[e] stars.

7.2. HD 87643 and MWC 349A: stars associated with nebulae

HD 87643 and MWC 349A show the B[e] phenomenon and they are associated with nebulae. Yet, their classification as pre-main sequence HAeB[e] stars is uncertain because there is no spectroscopic evidence for infall.

HD 87643 is embedded in a reflecting nebula (Henize 1962, van den Bergh 1972, Surdej et al. 1981). The star was originally classified as a P Cygni type star and even a nova-like star (Carlson & Henize 1979). From IUE spectra McGregor et al. (1988a) and Shore et al. (1990) assigned an effective temperature of 15000 K to HD 87643. A distinctive peculiarity of HD 87643 is the presence of a strong, low ionization wind (de Freitas Pacheco et al. 1985, Lópes et al. 1992). P Cygni line profiles are observed in many species, indicating outflows up to 1400 km s^{-1} (Surdej et al. 1981, Shore et al. 1990) and 1800 km s^{-1} (Oudmaijer et al. 1998). The estimated bolometric luminosity indicates that this star should be a bright giant (Zorec 1998; Oudmaijer et al. 1998).

The evolutionary state of MWC 349A is unknown. The star is associated with a surrounding dense cloud of gas and dust (Baldwin et al. 1973). Andrillat et al. (1996) assigned a spectral type B to this star. On the basis of its spectrum Ciatti et al. (1974) classified this star as a young planetary nebula. However, Hamann & Simon (1986, 1988) found spectroscopic characteristics similar to young stellar objects. It can however not be very young, because it has an evolved companion, MWC 349B, of spectral type B0 IIIe. Also, the r^{-2} radial structure of the circumstellar disk in the orbital plane implies that the star should not be a pre-main sequence object (Cohen et al. 1985). These authors derived a distance of 1.2 kpc and a luminosity of 3×10^4 $L_\odot$. From velocity measurements of the maser lines Thum et al. (1992) derived a mass of $M = 34 \pm 2$ M$_\odot$ for the central object. Thus it could also be a massive evolved object.

We conclude that HD 87643 and MW 349A show some characteristics of pre-main sequence stars (e.g. forbidden emission lines, evidence for disks, nebulosity) but there is no evidence for infall. The slope of the infrared energy distribution of these two stars is much slower than for most HAeBe stars (Hillenbrand et al. 1992), suggesting a different type of circumstellar disk. Moreover, the companion of MWC 349A excludes a very young age as the luminosity does for HD 87643. Therefore these stars are as yet unclassified B[e] stars.

7.3. Unclassified B[e] stars

The unclassified B[e] stars are listed in Table 5, based on de Winter & Pérez (1998).

8. Summary and conclusions

The class of stars that is presently classified as B[e] stars is obviously very heterogeneous and comprises objects of large difference in mass and in evolutionary phase. Moreover the physical mechanism that produces the characteristic forbidden emission lines can be very different in the different objects: e.g. from an outflowing disk to the presence of a hot companion. Despite these large differences, the physical conditions of the circumstellar line emitting region and the dust emitting region are rather homogeneous. Therefore we propose the use of the term ”stars with the B[e] phenomenon” rather than ”B[e] stars”.

Table 5. Unclassified B[e] stars

Name	Spectral type	reference[1]	Remark[2]
AS 119	B8/9[e]	dWP	
AS 269	B[e]	AS	SymB[e]?/Bin?
CD–42°11721	B0[e]p	dWP	[Fe II] var?
HD 45677	B2V:[e]	§7.1	extreme Be?
HD 50138	B6III-IV[e]	§7.1	extreme Be?
HD 51585	B[e]q	dWP and Ar	SymB[e]?/Bin?/cPNB[e]?
HD 87643	B4II[e]	§7.2	sgB[e]?/HAeB[e]?
HD 326823	B1.5[e]	dWP	
He 2–461	B[e]	AS	
He 2–79	B[e]	AS	
He 2–91	B[e]	AS	Plan. neb?
He 3–52	B[e]	AS	
He 3–847	B6/A0:[e]	dWP	
He 3–1138	B8Ia[e]	dWP	LBV?
He 3–1191	B0:[e]	dWP	Post-AGB?
MWC 17	B[e]	AS	SymB[e]?/Bin?
MWC 84	B[e]	AS and Ch	cPNB[e]?
MWC 342	B[e]	AS	SymB[e]?/Bin?
MWC 349A	O9:III:[e]	§7.2	sgB[e]?/HAeB[e]?
MWC 623	B[e]	AS and ZS	SymB[e]?/Bin?
MWC 645	B[e]	AS	
MWC 819	B[e]	AS	
MWC 922	B[e]	AS	
MWC 939	B[e]	dWP	[Fe II] var?
PN M 1–92	B0.5IV[e]	AS	
SS 73–170	B[e]	dWP	
Th 35–27	B[e]	dWP	
V 1016 Cyg	B[e]	Acker et al. (1992a)	SymB[e]?/cPNB[e]?

[1] Ar = Arkhipova (1989); AS = Allen & Swings (1976); Ch = Chkhikvadze (1970); ddW= de Winter (1996); dWP = de Winter & Pérez (1998); ZS = Zickgraf & Stahl (1989)
[2] Remarks based on other sections of this paper and on de Winter & Pérez (1998)

The heterogeneity of this class of stars results in confusion when the characteristics of the stars are studied or discussed without a clear separation into the different evolutionary stages. Therefore we proposed to divide the group into five categories, with a name that is related to their evolutionary phase:
(a) sgB[e]: supergiants which show the B[e] phenomenon.
(b) HAeB[e]: pre-main sequence stars that show the B[e] phenomenon.
(c) cPNB[e]: compact planetary nebula stars that show the B[e] phenomenon.
(d) SymB[e]: symbiotic stars that show the B[e] phenomenon.
(e) unclB[e]: unclassified stars that show the B[e] phenomenon.
These five classes and their primary and secondary criteria have been discussed in Sects. 3, 4, 5, 6 and 7. The stars that fall into these classes have been listed, except for SymB[e] stars. The list of SymB[e] stars is almost the same as the list of symbiotic stars published by Allen (1984).

Some stars satisfy the criteria for more than one of the classes sgB[e], HAeB[e], PPNB[e] or SymB[e]. In that case the evolutionary phase is unclear, and the star should be assigned to class unclB[e].

In many cases the uncertainty about the nature and evolution phase of the unclB[e] stars is due to their unknown distance and the resulting unknown luminosity. In other cases a detailed spectroscopic or photometric study has not been made yet. Trigonometric parallaxes or cluster parallaxes for these stars would be very useful. Kinematical studies of unclB[e] stars might show their relation to nearby molecular clouds, if they are very young stars. Detailed spectroscopic studies might show infall, indicative of a pre-main sequence phase. The IR energy distribution can give information about the dust distribution. Dust formed in outflows, e.g. from sgB[e] stars, tends to have an r^{-2} density distribution, where r is the distance from the stellar center. On the other hand, dust in accretion disks or in Keplerian disks has a flatter density distribution. A study of the dust spectroscopic features, e.g. based on IR-spectroscopy with *ISO*, will reveal the nature of the dust. Since the ratio of crystalline to amorphous silicate circumstellar dust generally appears to increase with age of the stars, a small fraction of crystalline dust might be indicative of a young evolutionary phase (L. Waters, Private Communication).

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