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The Connection with B[e] stars

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Abstract. The characteristics of the various types of B[e] stars are discussed and compared with those of classical Be stars. Both groups of stars are characterized by the presence of emission lines in their spectra, in particular of hydrogen. However, there are also significant differences between these classes. Classical Be stars lack hot circumstellar dust and strong forbidden low-excitation emission lines, which are typical characteristics produced by B[e]-type stars. While classical Be stars are a rather uniform group of early-type stars, B[e]-type stars form a quite heterogeneous group, very often of poorly known evolutionary status, comprising such diverse types of objects as near main-sequence objects, evolved low-mass proto-planetray nebulae and massive evolved hot supergiants. Even pre-main sequence Herbig Ae/Be stars sometimes find their way into the group of B[e] stars. However, despite these dissimilarities classical Be stars and B[e]-type stars, share a common property, namely the non-sphericity of their circumstellar envelopes.

1. Introduction

The existence of classical Be stars has been recogized for more than a century. The history of B[e] stars on the other hand is much shorter. About 30 years ago Geisel (1970) first reported a correlation between stars for which the continua exhibit excess radiation at infrared wavelengths $> 5\mu$m and stars having spectra which exhibit low-excitation emission lines. This marked the beginning of the investigation of the enigmatic class of B[e] stars although then these stars were not yet know under this acronym. At about the same time Wackerling (1970) and Ciatti et al. (1974) also realized the existence of a group of hot emission line objects with "abnormal" spectra and forbidden emission lines for which they introduced the designation BQ[ ] stars. Allen & Swings (1972) and in particular Allen & Swings (1976) systematically investigated this new class of stars which they described as peculiar hot emission line stars with infrared excesses. They found that these stars "... form a group spectroscopically discerned from normal Be stars and planetary nebulae..." which contains "objects ranging from almost conventional Be stars to high density planetary nebulae". The dominant spectral features were found to be emission lines of singly ionized iron. The final step towards the B[e] stars was made by P. Conti during the general discussion in the 1975 IAU symposium entitled "Be and Shell Stars." He suggested that " ... A second class of objects would be those B-type stars which show forbidden emission lines and I would suggest that we classify these as B with a small e in brackets B[e], following the notation for forbidden lines" (Conti 1976).

In the following sections I will first describe in more detail the defining characteristics of what nowadays we call "B[e]" stars, and then consider the various object classes which constitute the inhomogeneous group of B[e] stars. Finally, I will discuss in some detail the connection between B[e] stars and classical Be stars.

2. Defining characteristics of B[e] stars

Extensive infrared surveys of galactic early-type emission line stars, e.g. by Allen (1973), (1974), and Allen & Glass (1975), revealed that two populations of emission line stars exist: (a) emission-line stars with normal stellar infrared colours comprising the classical Be stars and other types of objects like normal supergiants, Luminous Blue Variables (LBVs), and S-type symbiotics; and (b) "peculiar" emission-line stars with IR excesses due to hot circumstellar dust.

Following Conti's suggestion the latter group of peculiar and dusty Be stars is now usually called B[e] stars, i.e. they are early-type emission lines stars with low-excitation lines, forbidden lines, and hot dust visible in the near and mid infrared.

As we will see in the next section a more precise statement is that these stars show the "B[e] phenomenon" which is characterized by spectroscopic properties and by the continuum energy distribution as follows:

1. Spectroscopic characteristics:
   - 1.1 strong Balmer emission lines;
   - 1.2 low-excitation permitted emission lines, predominantly of singly ionized metals, e.g. Fe II;
   - 1.3 forbidden emission lines of [Fe II] and [O I];
   - 1.4 higher ionization emission lines can be present, e.g. [O III], He II;
2. continuum energy distribution:
   - 2.1 Continuum distribution of an early-type star in the visual(/UV);
   - 2.2 strong near/mid infrared excess due to hot circumstellar dust with temperatures around $T \sim 500 - 1000\,\mathrm{K}$.

Stars showing the B[e] phenomenon form a distinct group of objects in $(J-H)-(H-K)$ and $(H-K)-(K-L)$ diagrams (cf. Fig. 1). One can therefore state that in connection with forbidden emission lines hot dust is *the* defining characteristic of B[e] stars. Hence, a star with forbidden emission lines but without thermal emission due to hot circumstellar dust (such as LBVs in certain phases), should not be classified as B[e] star. With respect to classical Be stars the presence of circumstellar dust is a distinctive feature because these stars definitely lack this property.

Linear polarization measurements showed that B[e] stars of all sub-types defined in the next section are characterized additionally by a non-spherical

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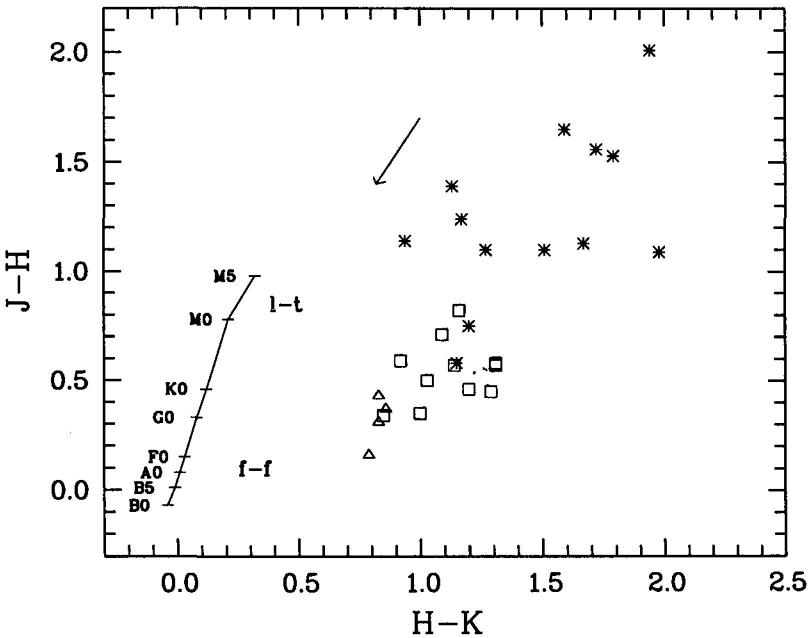

Figure 1. $(J-H)-(H-K)$ diagram for B[e]-type stars. The different symbols denote B[e] stars in the Milky Way (asterisks), in the LMC (squares) and in the SMC (triangles). The location of stars with normal colours is indicated by the solid line. "f-f" denotes the approximate location of stars with IR excess due to $f-f$ emission from stellar winds. "l-t" marks the area occupied by objects with late-type companions. The arrow gives the reddening line for $A_V = 3$.

distribution of circumstellar scattering particles. Intrinsic polarization was observed e.g. by Coyne & Vrba (1976), Barbier & Swings (1982), Zickgraf & Schulte-Ladbeck (1989), and Schulte-Ladbeck et al. (1992). Oudmaijer & Drew (1999) obtained spectropolarimetry of B[e] and Herbig Be stars. They detected non-sphericity by polarization changes across the Hα emission line in all B[e]-type stars of their sample.

In classical Be stars polarization is due to Thomson scattering in the ionized circumstellar disk. Two scattering mechanisms are responsible for the observed polarization of B[e] stars: scattering by dust particles and Thomson scattering anaolgous to classical Be stars. Both mechanisms may contribute simultaneously in B[e] type stars (cf. Zickgraf & Schulte-Ladbeck 1989)

As discussed by Lamers et al. (1998) the characteristics of the B[e] phenomenon can also be formulated in terms of physical conditions:

(a) The strong Balmer emission lines imply very large emission measures (EM) of the singly ionized gas above the stellar continuum forming region. Typically, for a supergiant B[e] star (see below) with Hα luminosities of 10^{37} to $10^{38}\,\mathrm{erg\,s^{-1}}$, the EMs are on the order of 10^{62} to 10^{63} cm^{-3}. For

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less luminous stars, such as pre-main sequence B stars showing the B[e] phenomenon, the emission measure is about 10^{57} cm^{-3}.

(b) The presence of emission lines of low-ionization metals like Fe II indicates a temperature of $\sim 10^4$ K in the emitting region.

(c) The presence of forbidden emission lines of low excitation metals such as [Fe II] and [O I] indicates a geometrically extended envelope so that there is a large amount of low density gas. Applying the diagnostics described by Viotti (1976) leads to densities of the [Fe II] emitting region of $N_e < 10^{11}\,\mathrm{cm}^{-3}$.

(d) According to Bjorkman (1998), infrared excesses from cool dust ($T_{rmd} = \sim$500-1000 K) indicate a circumstellar density of $\rho \geq 10^{-18}\,\mathrm{gm\,cm}^{-3}$ at distances where the dust temperature can equilibriate (≥ 500 to $1000\,\mathrm{R}_*$).

Taking into account that the circumstellar environments of B[e] stars are non-spherical, these conditions are consistent with circumstellar densities on the order of 10^9 to $10^{10}\,\mathrm{cm}^{-3}$. This is supported also by 2.3 μm CO overtone emission observations by MacGregor et al. (1988a,b) who derived similar densities for the molecular emission regions. The existence of dust is most likely related to the existence of molecules. The formation of molecules in turn drives the condensation of dust particles. Both types of matter require high densities. In contrast, the envelopes of Be stars may have densities too low to allow condensation of dust particles.

3. B[e] stars: a stellar melange

The definition of B[e] stars as given in the previous section describes certain physical conditions in terms of excitation and density in the circumstellar environment rather than intrinsic object properties. Because similar circumstellar conditions can prevail in the surroundings of objects belonging to intrinsically different classes it is not surprising that "B[e]" stars do **not** form a homogenous group of objects, but rather a melange of various classes.

This was already realized by Allen & Swings (1976) who distinguished three groups of peculiar Be stars with infrared excesses, namely (a) group 1: few emission lines, not always forbidden lines, almost conventional Be stars, (b) group 2: "most distinctive group", spectra with permitted and forbidden Fe II emission, and (c) group 3: additionally emission lines of higher ionization stages ($IP >$ 25eV). The phenomenological grouping indicated that B[e] stars are not a unique class of objects but comprise members of different classes which share the common property of showing the B[e] phenomenon (for a detailed discussion of the various object classes cf. Zickgraf 1998).

Actually, it would be desirable to determine the intrinsic stellar parameters in order to find the position of the B[e] stars in the H-R diagram. This would permit one to constrain the likely evolutionary status and therefore determine the objects' B[e] classification types. However, in practice this turns out to be difficult or even impossible. In many cases photospheric absorption features are absent or at most weakly discernible. It is therefore difficult to determine

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reliable effective temperatures. In many cases only the stellar continuum energy distribution allows to estimate the star's $T_{\rm eff}$, yielding rather uncertain results. Interstellar reddening increases the problem. Likewise, unknown distances lead to uncertain luminosities. Therefore the evolutionary status of many B[e] stars is unknown. Zorec (1998) collected distances and luminosities for galactic B[e]-type stars in order to establish the H-R diagram for galactic B[e] stars. But even with known $T_{\rm eff}$ and L values, B[e] stars often offer obstacles to a determination of their evolutionary status, as I will discuss below for some near-main sequence objects.

In some cases more or less reliable information about the evolutionary status can be obtained. Some stars were found to represent objects in a post-main sequence phase of the evolution of massive stars. Others are obviously intermediate mass pre-main sequence Herbig Ae/Be stars, while still others are in late stages of the evolution of low-mass stars.

As an important result of the Workshop on B[e] stars held in Paris, 1997, Lamers et al. (1998) discussed an improved classification of B[e] stars and suggested several different subclasses of B[e] stars:

a) evolved high-mass stars with $L \geq 10^4 L_\odot$: B[e] supergiants → sgB[e]

b) intermediate mass pre-main sequence stars: Herbig Ae/Be stars → HAeB[e] in particular: *isolated* HAeB[e]

c) evolved low-mass stars: Compact low-excitation proto-planetary nebulae → cPNB[e]

d) D-type symbiotic stars → symB[e]

e) "unclassified" B[e] stars → unclB[e]

As a further possible class one can add a group of main-sequence or near-main sequence stars, MSB[e], which could represent a link with classical Be stars.

Lamers et al. stressed that a unique classification is not always possible because the assignment to a class is typically ambiguous. It is therefore not surprising that their group of stars of type unclB[e] is the largest.

4. The connection: B[e] vs. Be

In this section I will discuss in more detail the connection between Be stars and the two subclasses of low-luminosity B[e] stars and high-luminosity B[e] supergiants. The dividing line between both classes is set around $L \simeq 10^4\,L_\odot$.

4.1. Low-luminosity/(near)-MS B[e] stars

In the H-R diagram constructed by Zorec (1998) several B[e] stars are found close to or on the main sequence. These stars are of particular interest to resolving the question of their connection with classical Be stars. Among these objects are e.g. MWC 84, and HD 51585, which were classified as cPPNB[e] by Lamers et al. (1998), and HD 163296, HD 31648, and HD 190073 which are probably HAeB[e]-type stars. They belong to classes which are not related to classical Be stars.

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This is different for the two B[e] stars HD 45677 (FS CMa) and HD 50138. In the H-R diagram they are located in the same region as classical Be stars, and they exhibit spectroscopic similarities with this class. For these two near-main sequence objects parallaxes are known from HIPPARCOS (cf. Zorec 1998) and therefore their distance and luminosity are well known.

HD 45677 This is one of the best-studied galactic B[e] stars. Allen & Swings (1976) describe HD 45677 as a kind of "proto-type" of their group 2 (s. above) and hence it is often regarded as a "proto-type" B[e] star. Its spectral type is B2(III-V)e. The spectrum was described in detail e.g. by Swings (1973), de Winter & van den Ancker (1997), and by Andrillat et al. (1997). A detailed NLTE analysis by Israelian et al. (1996) yielded the stellar parameters $\log g = 3.9$ and $T_{\rm eff} = 22\,000\,{\rm K}$.

Swings (1973) discussed the emission line spectrum of HD 45677. He found double-peaked Fe II emission lines with a line splitting of $\Delta v = 32\,{\rm km\,s^{-1}}$, and single-peaked forbidden [Fe II] lines. He interpreted the observations in terms of a rotating equatorial disk. The non-spherical environment is confirmed by visual and UV polarization data, which indicate that the star is viewed edge-on through a dusty disk (Coyne & Vrba 1976, Schulte-Ladbeck et al. 1992). The existence of a disk should be correlated with a high stellar rotational velocity for which Swings & Allen (1971) had estimated in fact $v \sin i \approx 200\,{\rm km\,s^{-1}}$ which would be comparable with velocities measured for classical Be stars. The NLTE analysis of Israelian et al. (1996), however, yielded only $v \sin i \approx 70\,{\rm km\,s^{-1}}$. It remains therefore unclear whether rapid rotation is responsible for the formation of the disk.

Although the distance of HD 45677 is known its evolutionary status is still under discussion. The location in the H-R diagram suggests that it is near the main sequence. In this respect it could be considered as an extreme Be star. However, Grady et al. (1993) detected mass accretion in IUE spectra which indicates that it is still in a pre-main sequence phase of evolution, i.e. a Herbig Be star of the type HAeB[e]. This classification is somewhat doubtful because no association with a nebula is present. de Winter & van den Ancker (1997) therefore interpreted the observations in view of the isolated position in the sky in terms of a young object, but not in the sense of being pre-main sequence. It should be noted, however, that the isolated location does not necessarily contradict a Herbig Be classification. Grinin et al. (1989, 1991) discuss the existence of isolated Herbig stars, of which HD 45677 could be a member.

HD 50138 HD 50138 was considered by Allen & Swings (1976) as a group 1 object and they described this star as a kind of extreme Be star. For recent studies cf. Pogodin (1997) and Jaschek & Andrillat (1998). Its spectral type is B6III-IV, and in the H-R diagram it is located close to the main sequence. Houziaux (1960) determined a rotational velocity of $v \sin i \approx 160\,{\rm km\,s^{-1}}$. Like HD 45677 it is not associated with a nebula, but exhibits spectral and polarimetric characteristics similar to young stellar objects. It could therefore also be a HAeB[e]-type star.

The conclusion for the (near)-main sequence B[e] stars is that their $T_{\rm eff}$ and L are comparatively well known, and that in some respects they are similar to Be stars. Like the latter group, they posses disk-like circumstellar structures and

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may also rotate rapidly – although this question is not yet settled. However, their evolutionary status is still a controversial issue. Despite their well known distances and effective temperatures, it is still not clear whether they are a kind of extreme Be stars or, alternatively, pre-main sequence HAeB[e] stars. The problem is that near the location of these stars in the H-R diagram the birthline of Herbig stars reaches the main sequence (Palla & Staller 1993) and hence a separation of true main sequence from pre-main sequence objects is difficult.

4.2. B[e] supergiants vs. Be stars

As discussed in the previous section, galactic B[e] stars are a mixture of different classes. Only for a few of these B[e] stars luminosities are known to be as high as those of supergiants, like e.g. CPD-52°9243 (Swings 1981, Winkler & Wolf 1989), MWC 300 (Wolf & Stahl 1985), MWC 349A (Cohen et al. 1985), GG Car (McGregor et al. 1988a, Lopes et al. 1992), HD 87643 (Oudmaijer et al. 1998), and MWC 137 (S 266) (Esteban & Fernandez et al. 1998).

However, despite many efforts the classification remains often uncertain, and confusion with other classes is still an issue, e.g. as for the stars MWC 300, HD 87643, MWC 349A, and MWC 137. These stars have alternatively been classified as HAeB[e]-type stars with lower luminosities than supergiants (cf. references in Lamers et al. 1998).

For extragalactic B[e] stars the situation is different. Until now the only galaxies in which B[e] have been found (except our Milky Way) are the Magellanic Clouds (MCs). Presently 15 B[e] supergiants known in the MCs. For a list of these stars cf. Lamers et al. (1998). Compared to the Milky Way the advantage of the MCs is that their distances are well known and hence the luminosities of the B[e] stars are also known. The location of the B[e] stars in the H-R diagram indicates that they are evolved massive post-main sequence objects. Most of the sgB[e] in the MCs have luminosities on the order of $L \approx 10^5 - 10^6$ $L_\odot$ (e.g. Zickgraf et al. 1985, 1986, 1989). Recently, the luminosity range was extended downward to $L \approx 10^4 L_\odot$ (Zickgraf et al. 1992, Gummersbach et al. 1995) suggesting that a transition to lower-luminosity near-main sequence objects could exist.

Spectroscopically, B[e] supergiants are characterized by hybrid spectra. This term describes the simultaneous presence of broad (1000-2000 $\mathrm{km\,s^{-1}}$) high excitation absorption features of N V, C IV, and Si IV in the satellite UV, or of He I in the visual wavelength region indicative of a hot high velocity wind component. At the same time narrow ($\lesssim 100\,\mathrm{km\,s^{-1}}$) B[e]-type low-excitation emission-lines of Fe II, [Fe II], and [O I] are observed, a fact which suggests a cool, slow wind component. Likewise, molecular emission bands of TiO in the visual and CO overtone bands in the near infrared are observed (Zickgraf et al. 1989, McGregor et al. 1988b). These observations indicate the presence of two wind regions with basically different physical conditions.

The observed properties were explained by an empirical model by Zickgraf et al. (1985). These authors invoked a two-component stellar wind with a bipolar wind structure. In the polar region a fast radiation-driven CAK-type wind, similar to those of normal OB supergiants, prevails. This component exhibits velocities $\sim 1000-2000\,\mathrm{km\,s^{-1}}$. In the equatorial region region a slow, cool, and dense wind is present with outflow velocites on the order of $\sim 100\,\mathrm{km\,s^{-1}}$. The

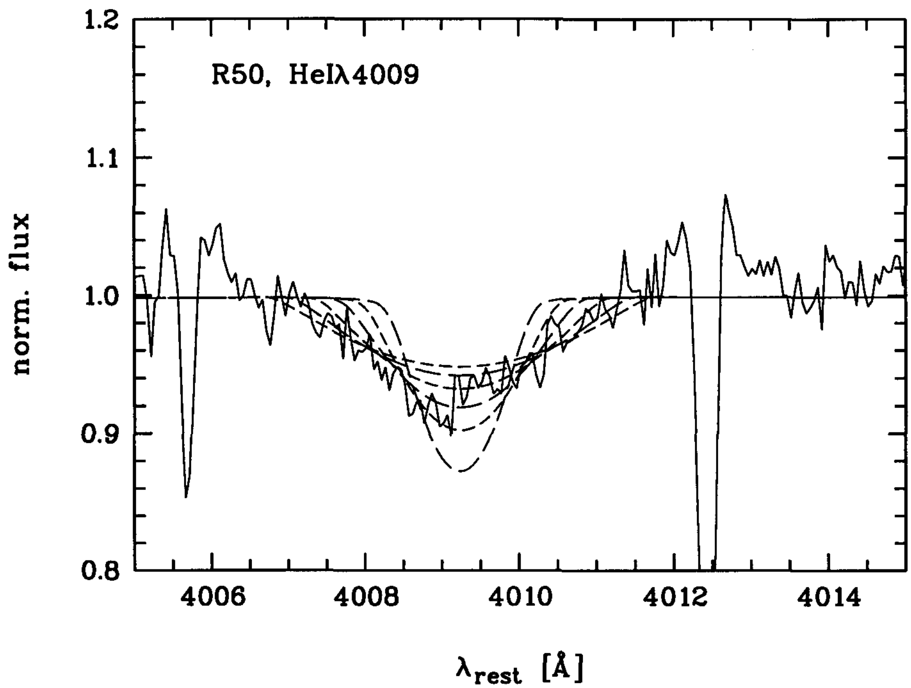

Figure 2. Section of the spectrum of R 50 in the SMC (spectral resolution ~ 20 000). Overplotted are rotationally broadened synthetic line profiles of He Iλ4009Å for rotational velocities between 75 km s^{-1} and 200 km s^{-1} in steps of 25 km s^{-1}. The best fit yields $v \sin i \simeq 150\,\mathrm{km\,s^{-1}}$.

equatorial outflow is concentrated in a disk-like configuration, similar to models for classical Be stars. However, in classical Be stars the polar wind is significantly less pronounced due to these stars' lower luminosities. Likewise, supergiants are closer to the Eddington limit. They have values of $\Gamma = 1-(g_{\rm eff}/g_{\rm grav}) \geq 0.3-0.5$. Therefore even moderate rotation of 100-200 km s^{-1} is near the break-up velocity (Zickgraf et al. 1996). In fact there is an indication for fast rotation for at least one case of a B[e] supergiant, namely R 50 in the SMC. This star rotates with a velocity on the order of $v \sin i \simeq 150\,\mathrm{km\,s^{-1}}$ (cf. Fig. 2) and thus at $\gtrsim$ 60% of its break-up velocity.

Linear polarization measurements support the assumption of non-spherical circumstellar environments for B[e] supergiants. Magalhaes (1992) and Schulte-Ladbeck et al. (1993) detected intrinsic polarization in several B[e] supergiants. Schulte-Ladbeck & Clayton (1993) obtained spectropolarimetry of Hen S22 in the LMC and detected intrinsic polarization due to electron scattering in a circumstellar disk.

5. Summary

The group of B[e] stars is an inhomogeneous class of objects comprising intrinsically different classes characterized by permitted and forbidden low-excitation line emission and hot circumstellar dust. In contrast, classical Be stars are more or less normal B stars with photospheric absorption lines and superimposed Balmer emission lines, plus occasionally Fe II emission lines. B[e] stars in many cases show no or only weak photospheric absorption lines. Forbidden lines on the other hand are not typical for classical Be stars. Likewise, circumstellar dust signatures are not found in classical Be stars but are a defining characteristic of B[e] stars. High stellar rotational velocities as in classical Be stars are found in a few cases of B[e] stars, but not much information is available or else is controversial, as in the case of HD 45677. A common characteristic of B[e] and classical Be stars is certainly the non-sphericity of their circumstellar envelopes. Both groups appear to possess disk-like envelopes which for B[e] stars, but not for classical Be stars, are dense enough to allow dust formation.

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Discussion

P. Harmanec: 1. What is known about the variability of B[e] stars? 2. How did you derive the luminosities of B[e] stars used to plot particular stars into the HR diagram? Cannot these luminosities and also $v \sin i$ values refer to

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optically thick inner parts of their envelopes (i.e. pseudophotospheres) rather than genuine photospheres?

F.-J. Zickgraf: 1. For several galactic B[e] stars variability has been observed. The B[e] supergiants in the Magellanic Clouds, however, in general do not show pronounced variations. An exception is R 4, which is a kind of B[e]/LBV-type star. 2. This question should be answered by J. Zorec who derived the stellar parameters.

J. Zorec: The key parameter for luminosity estimation is the stellar distance. The method used to derive the distance of some stars with the B[e] phenomenon is published in the proceedings of the "B[e] stars" workshop (eds. A.M. Hubert and C. Jaschek). The basic assumptions I made are: (a) The spectrum of the star underneath the circumstellar gas and dust envelope, determined using either the BCD spectrophotometry or excitation arguments for the observed intensity of visible emission lines, is assumed to correspond to a "normal-like" stellar energy distribution. (b) There is an emission component in the visible continuum spectrum resembling the one observed in classical Be stars. The amount of this emission, and the intrinsic reddening that is associated with it, are estimated from the second component of the Balmer discontinuity, as in classical Be stars. (c) I took into account the UV-visible dust absorption due to the circumstellar dust envelope and the corresponding re-emission of energy in the far-IR. (d) The interstellar absorption as a function of the distance in the direction of the star was determined as carefully as possible. Then, from an iterative procedure to get a description of the amount of energy absorbed and re-emitted by the gas-dust circumstellar envelope, which is also consistent with the excitation produced by the underlying object, it is possible to obtain an estimate of the circumstellar dust $E(B-V)$ component as well as the interstellar $E(B-V)$ and consequently the stellar distance.

The energy integrated over the whole spectral range is a quantity which is treated in each iteration step. So, when you stop the iteration you also get the right apparent bolometric luminosity which can be straightforwardly transformed into an absolute bolometric luminosity. The method produced distances which are quite comparable with the distances obtained from HIPPARCOS parallaxes, when they existed.

P. Najarro: In your color-color viewgraph there seems to be a clear separation between emission line stars and B[e]. I was wondering if some of the B[e]s on the lower edge of your diagram could just be LBV like stars (e.g. HD316285 and R4) with such dense winds that the bound-free and free-free emission from the wind could simulate the B[e] IR excess. A good way to test it would be to overplot the color-color values for W-R stars. Have you tested that?

F.-J. Zickgraf: No, I have not compared the IR colours of B[e] supergiants with those of W-R stars. However, it seems difficult to produce such excesses with (f-f)-(f-b) emission as observed in the B[e] region of the $(J-H)-(H-K)$ diagram.

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