

B[e] Supergiants in the Magellanic Clouds

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Abstract. The B[e] supergiants in the Magellanic Clouds form a subgroup of 15 massive stars showing the B[e] phenomenon. The properties of the B[e] supergiants can be explained in terms of a two-component stellar wind model. From their position on the H-R diagram it is clear that B[e] supergiants are in a post-main sequence evolutionary stage. Recent observational results on several B[e] supergiants with relevance to the question of an evolutionary connection with the luminous blue variables are discussed.

1. Introduction

In the Magellanic Clouds (MCs) 15 stars showing the B[e] phenomenon have been found. They are supergiants in a post-main sequence evolutionary phase with luminosities in the range $\sim 4 \leq \log L/L_\odot \leq \sim 6$. B[e] supergiants are descendants of massive stars with initial ZAMS masses in the range $\sim 7 \leq M/M_\odot \leq \sim 85$. Eleven of the 15 MC B[e] supergiants are located in the LMC, 4 of them are members of the SMC. In Table 1 the 15 stars are listed. The H-R diagram is depicted in Fig. 1. It suggests two groups of B[e] supergiants, the high and the low luminosity objects with a separation around a luminosity of $\log L/L_\odot \sim 5$.

In the next section the general characteristics of the B[e] supergiants are summarised. The B[e] paradigm suggested for the B[e] supergiants is discussed in Sect. 3. The properties of the disk wind are summarised in Sect. 4. Stellar rotation is addressed in Sect. 5. The question of a possible B[e]-LBV connection will be discussed in Sect. 6 and, finally, this review is concluded in Sect. 7 by a summary and open questions.

2. Characteristics of B[e] Supergiants

2.1. Observational Results (Selection)

The infrared excesses of most B[e] supergiants were found serendipitously (e.g. Allen & Glass 1976; Glass 1977; Stahl et al. 1983, 1984; McGregor et al. 1988). IR surveys searching systematically for B[e] supergiants in the SMC and the LMC were carried out by Zickgraf et al. (1992) and Zickgraf (1993) leading to the detection of 5 further B[e] supergiants.

First high-resolution spectroscopic studies of MC B[e] supergiants were carried out in the early 1980s. The optical spectrum of Hen S22 was analysed by Friedjung & Muratorio (1980). They derived a mass loss rate of $\dot{M} \simeq 4 \times 10^{-6} - 5 \times 10^{-5} M_\odot \text{yr}^{-1}$. The FeII emission lines were attributed to a disk

Table 1. B[e] supergiants in the Magellanic Clouds. References are: 1 = Zickgraf et al. (1986), 2 = Zickgraf et al. (1996a), 3 = Gummersbach et al. (1995), 4 = Zickgraf et al. (1989), 5 = Zickgraf et al. (1992), 6 = Stahl et al. (1989).

star	spec. type	T_{eff} [K]	$\log L/L_{\odot}$	R [$R_{\odot}$]	ref.
R 4/SMC	B0[e]/LBV	27 000	5.0	14	2
R 50/SMC	B2-3[e]	17 000	5.7	81	1
AV 172/SMC	B8[e]Ib	11 000	4.5	45	5
Hen S 18/SMC	B0[e]	25 000	5.6	35	4
R 66/LMC	B0.5[e]	12 000	5.5	125	1
R 82/LMC	B0.5[e]	18 500	5.4	50	1
R 126/LMC	B0.5[e]	22 500	6.1	72	1
Hen S 12/LMC	B0.5[e]	23 000	5.3	30	1
Hen S 22/LMC	B0.5[e]	24 500	5.9	49	1
Hen S 35/LMC	B1[e]Iab	22 000	5.2	28	3
Hen S 59/LMC	B5[e]II	14 000	4.0	16	3
Hen S 93/LMC	B9[e]Ib	10 000	4.7	73	3
Hen S 111/LMC	B[e]	?	?	?	6
Hen S 134/LMC	B0.5[e]	26 000	5.9	45	1
Hen S 137/LMC	B6[e]Ib/II	13 000	4.2	26	3

with a radius of several $10R_{*}$ ($10^{13} - 3 \cdot 10^{14}$ cm). Optical spectra of R 50 and R 82 observed with high spectral resolution were discussed for the first time by Muratorio (1981). The analysis of FeII lines in the satellite-UV by Muratorio & Friedjung (1988) suggested that for R 50 and R 82 the line formation takes place in a dense disk. For R 66 and Hen S 22 line formation in a wind was suggested. An optical and UV study of Hen S 134 was carried by Shore & Sanduleak (1983). From the CIV λ 1550 Å doublet a mass-loss rate of $\dot{M} \simeq 2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ was derived. The UV spectrum of Hen S 18 was studied by Shore, Sanduleak & Allen (1987) yielding a mass-loss rate of $\dot{M} \gtrsim 1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. Furthermore, they found a nitrogen overabundance relative to the solar value of a factor of 3-5. The observation of CO 2.3 μm first-overtone emission bands of several B[e] supergiants by McGregor et al. (1988) allowed to derive densities in the molecular emission region of $\simeq 10^9 \text{ cm}^{-3}$. Detailed multi-wavelengths investigations of individual B[e] supergiants were carried out by Zickgraf et al. (1985, 1986, 1989, 1992, 1996a,b) and Gummersbach et al. (1995). The observations were interpreted in terms of a two-component stellar wind model originally suggested for R 126 by Zickgraf et al. (1985). For two stars, R 4 and Hen S 93, a model atmosphere analysis could be carried out (Gummersbach et al. 1995; Zickgraf et al. 1996a).

2.2. The Four B[e] Characteristics

Based on these observational results B[e] supergiants can be described by four characteristics:

1. The hot underlying continua and in some cases photospheric absorption features show that the stars are of spectral type B, most of them of early B-type.

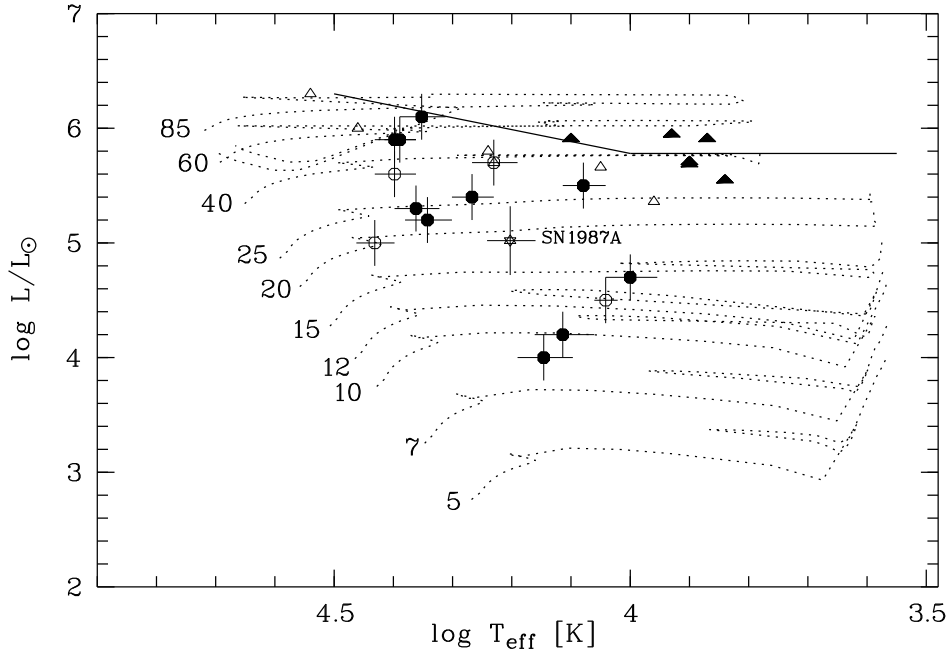


Figure 1. H-R diagram showing the location of the B[e] supergiants in the LMC (filled circles) and the SMC (open circles). Also shown are the 6 LBVs in the MCs (open triangles: minimum phase, filled triangles: maximum phase). The position of the precursor of SN 1987A is indicated. The solid line denotes the Humphreys-Davidson limit. Evolutionary tracks are from Schaller et al. (1992) for $Z = 0.008$.

2. The optical spectra are dominated by very strong Balmer emission lines. Equivalent widths of $H\alpha$ are as high as $\sim 1000 \text{ \AA}$.
3. The spectra display a hybrid character indicating the presence of two different wind components, a cool and a hot one. The cool wind component is responsible for the formation of low excitation emission lines of species like FeII, [FeII], [OI], and of molecules like TiO and CO in a few cases. The wind expansion velocities of the cool component are low, typically $v_{\text{exp}} \sim 100 \text{ km s}^{-1}$. The hot wind component is a normal radiation-driven CAK-type wind with high terminal velocities of up to $\sim 2000 \text{ km s}^{-1}$ as observed in OB stars.
4. The presence of hot circumstellar dust is revealed by a strong near IR excess. Dust temperatures are typically $T_d \approx 1000 \text{ K}$. While the spectral energy distribution beyond the J band is dominated by the thermal emission from the hot dust, the emission in the J band is dominated by free-free emission. Mass-loss rates estimated from the J excess are high, $\dot{M}_{ff} \simeq 10^{-4} M_{\odot} \text{ yr}^{-1}$.

3. The B[e] Paradigm

The observations summarised in the previous section led to the suggestion of a two-component stellar wind model for B[e] supergiants consisting of a fast and hot polar CAK-type wind and a slow and cool equatorial disk wind. Within

the framework of this model differences in the appearance of the stars are explained as effects of different viewing angles. The model is sketched in Fig. 2. Polarimetry, e.g. by Magalhães (1992) and Melgarejo et al. (2001), confirmed the presence of a non-spherical density distribution in the scattering circumstellar material. Melgarejo et al. (2001) concluded that electron scattering is causing the observed intrinsic polarisation. They could model the observed polarisation with a latitudinal density contrast and a radially constant electron density distribution.

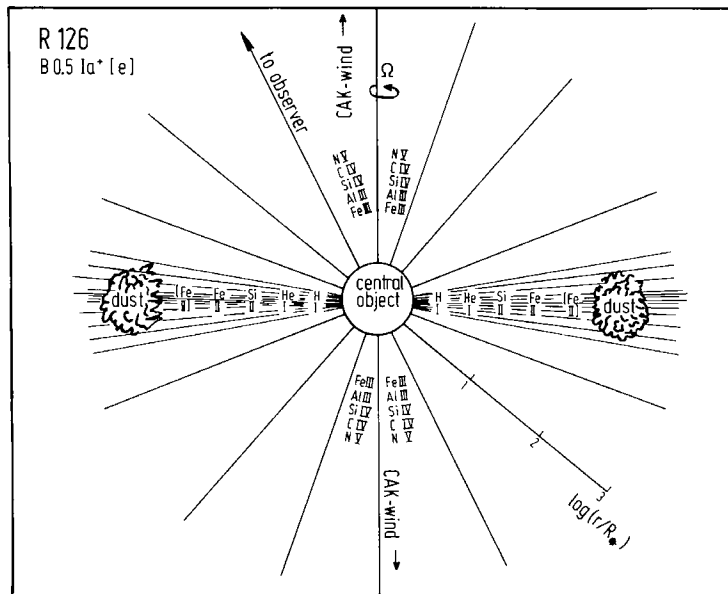


Figure 2. The two-component stellar wind model (adapted from Zickgraf et al. 1985).

An estimate for the “opening angle” of the disk may be obtained from a simple statistical argument. Three, maybe four, out of the eleven high-luminosity B[e] supergiants, i.e. those with $\log L/L_{\odot} \sim 5$, show edge-on characteristics. Assuming randomly distributed orientations of the symmetry axis then leads to an opening angle of $\simeq 30^\circ$.

4. Disk Wind

4.1. Absorption Lines

The slow equatorial disk wind of the edge-on stars Hen S 22 and R 82 in the LMC, and of R 50 in the SMC were studied by Zickgraf et al. (1996b) who used the FeII resonance absorption lines to measure the wind terminal velocities. They found $v_{\text{term}} = 50$ to 85 km s^{-1} for the three stars. Mass-loss rates for the disk wind, $\dot{M}_d$, were estimated from unsaturated FeII absorption lines (see Fig. 3). For Hen S 22 and R 82 $\dot{M}_d \gtrsim 6 \cdot 10^{-7} M_{\odot} \text{ yr}^{-1}$ and $5 \cdot 10^{-7} M_{\odot} \text{ yr}^{-1}$, respectively, were obtained. These estimates include the opening angle estimated above.

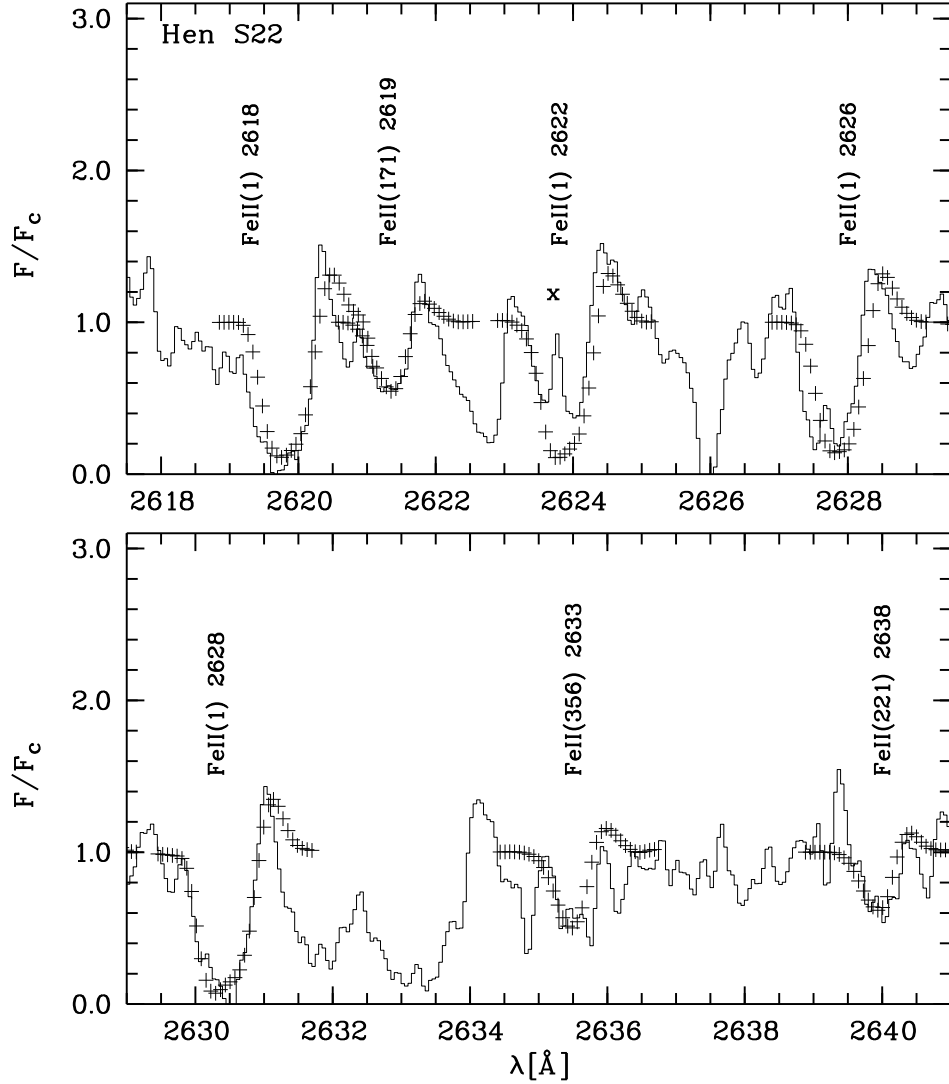


Figure 3. Section of the IUE spectrum of Hen S22. Absorption line profiles calculated for a radially expanding disk wind (opening angle 30°) are overplotted as crosses (from Zickgraf et al. 1996b).

4.2. Forbidden Emission Lines

The disk wind may also be studied using the profiles of the forbidden emission lines originating in the disk. Of particular interest are the lines of [FeII] and [OI]. These ions have the lowest excitation potential but high critical densities of $\sim 10^8 \text{ cm}^{-3}$ and $\sim 10^6 \text{ cm}^{-3}$, respectively. Therefore a cool line-formation environment is required which can have a high density. Such an environment is provided by the equatorial disk suggested by the two-component wind model. The observed line profiles all show at least some asymmetry usually with a

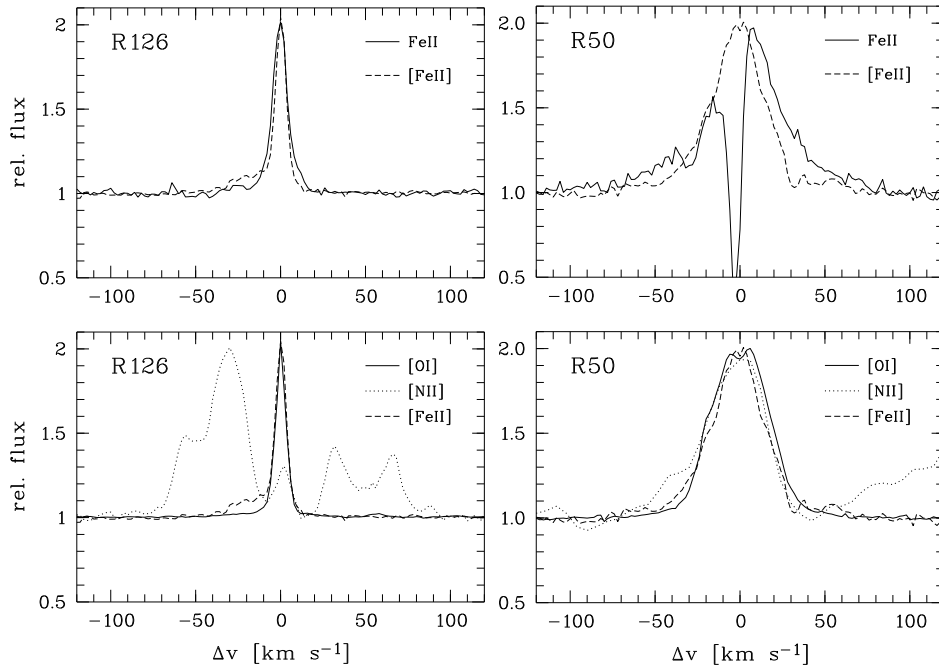


Figure 4. Permitted and forbidden lines of R 126 and R 50.

stronger blue wing. Edge-on stars like R 50 and Hen S 22 show double-peaked line profiles. Examples are shown in Figs. 4 and 5.

Optically thin lines of galactic B[e] stars were modelled by Zickgraf (2003) assuming a spherical radial outflow with a latitude-dependent outflow velocity, $v(\theta) = v_{\max} f(\theta)$ with θ being the angle between the polar axis and the velocity vector and $f(0^\circ) = 1$. From observations it follows that at the equator $f(90^\circ) = 0.05$ to 0.20 . This leads to an equatorial density enhancement of $\rho \propto r^{-2} v(\theta)$ and an emissivity j for a 2-level atom of $j(r, \theta) \propto \rho^2 \propto r^{-4} v(\theta)^{-2}$. A dust disk in the equatorial plane with an optical depth of τ_d absorbs partially the light from the lower part of the disk. Line profiles were calculated for various inclination angles i . These calculations showed that it is not necessary to invoke rotation of the line forming region in order to produce double-peaked profiles. They can be obtained for the radially expanding enhanced equatorial disk wind for moderate to large inclination angles i as shown in Fig. 6. A possible example for an intermediate inclination angle could be Hen S 134 which shows the fast wind component in the satellite-UV and split [OI] and [FeII] lines.

The profiles of lines with higher ionisation potential like [NII], [SIII] and [OIII] are different from the lower-excitation lines indicating different formation regions. A possible scenario could be a kind of a hot “corona” above the cool disk. In any case, the complex line profiles indicate that the geometry of the line forming region is more complicated than suggested by the simple disk model.

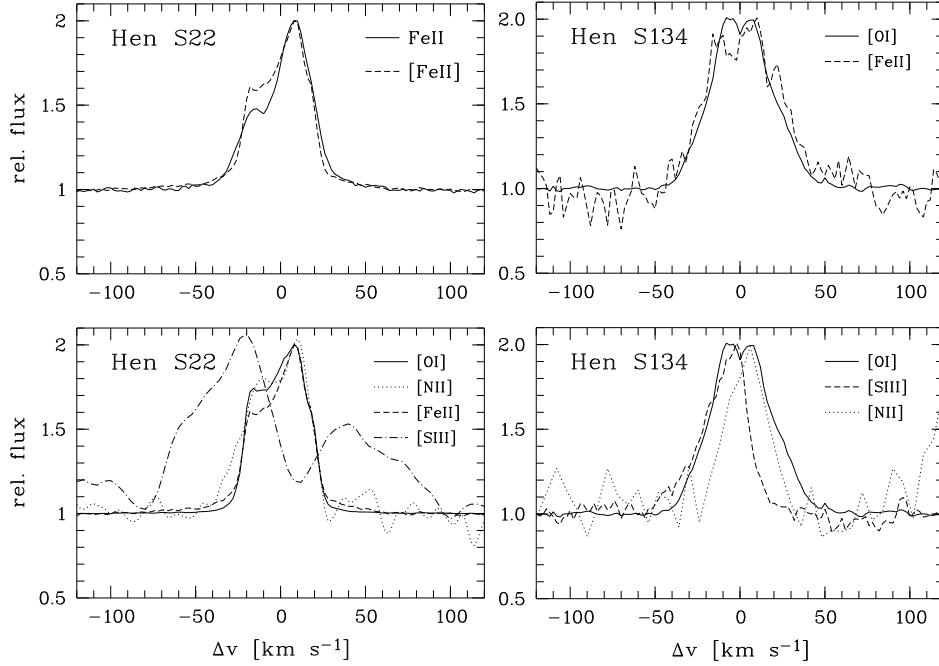


Figure 5. Permitted and forbidden lines of Hen S22 and Hen S134.

4.3. Summary: Two-Component Wind

The polar wind component shows all signs of a line-driven normal CAK-type OB stars wind. The equatorial disk wind with its surprisingly low velocity is more “exotic”. The ratio of equatorial to polar wind velocity is $v_{\text{eq}}/v_{\text{pole}} \simeq 0.05$ to 0.2 . Furthermore, the equatorial wind is cool and dense enough allow to dust formation. The density ratio is $\rho_{\text{eq}} \simeq 100 \dots 1000 \times \rho_{\text{pole}}$. However, because of the very uncertain mass loss rates in the disk wind these numbers for the density ratio should be taken with care. Finally, it should be noted that although (most) B[e] supergiants are early B-type stars the velocities of the disk winds are comparable to wind velocities of A-type hypergiants and LBVs.

5. Stellar Rotation vs. Critical Rotation

An important question for models of the disk formation is which role stellar rotation plays. In particular, the question is whether the rotation velocity is near the critical velocity as e.g. required by the bi-stable wind model of Lamers & Pauldrach (1991). This model requires $\Omega = v_{\text{rot}}/v_{\text{crit}} \simeq 0.8$, with the critical velocity given by $v_{\text{crit}} = (G(1 - \Gamma_{\text{rad}})M/R)^{1/2}$. Until now projected rotational velocities were published for only two stars, R 50 (Zickgraf 2000) and Hen S 93 (Gummersbach et al. 1995). Figure 7 shows photospheric absorption lines and rotationally broadened synthetic line profiles for R 50 and, in addition, for R 66 which has not been shown before. The results are summarised in Table 2. R 50

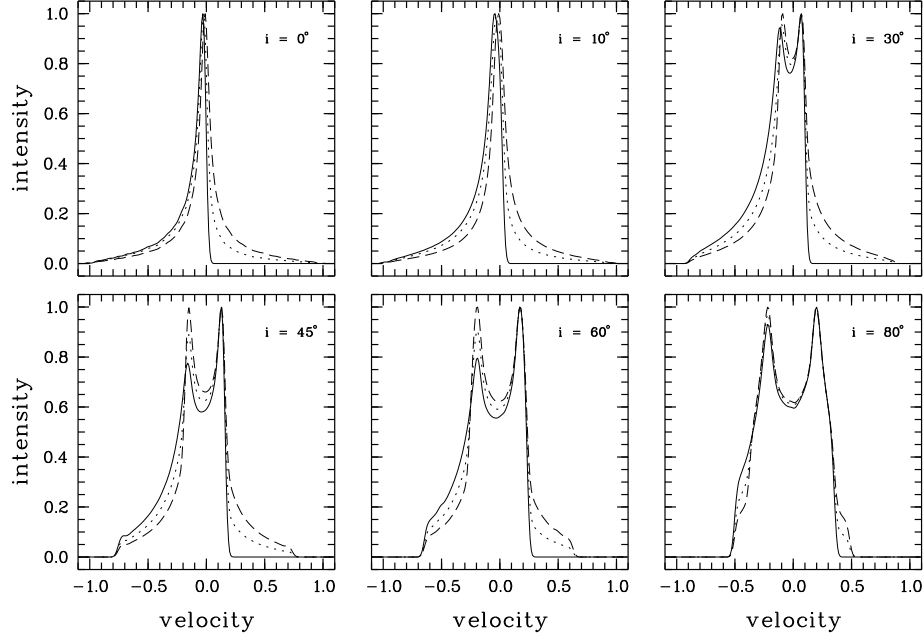


Figure 6. Emission line profiles calculated for an equatorially enhanced and radially expanding wind. Split line profiles occur for intermediate to large inclination angles (from Zickgraf 2003). The optical depth of the dust disk is 0.1, 1, and 1000 for the three profile types plotted as long dashed, short dashed and solid lines, respectively.

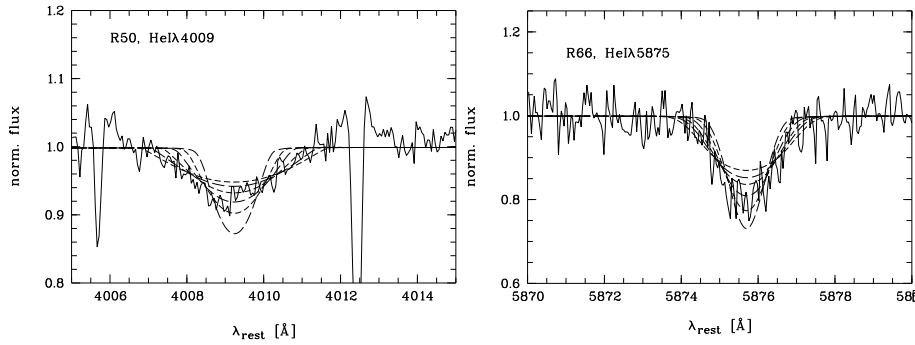


Figure 7. Projected rotational velocities, $v_{\text{rot}} \sin i$, of R 50 and R 66. The synthetic line profiles are shown for $v_{\text{rot}} \sin i = 75$ to 200 km s^{-1} in steps of 25 km s^{-1} and $v_{\text{rot}} \sin i = 30$ to 80 km s^{-1} in steps of 10 km s^{-1} , respectively. The best fit values are $v_{\text{rot}} \sin i = 150 \text{ km s}^{-1}$ and 50 km s^{-1} for R 50 and R 66, respectively.

Table 2. Projected rotational velocities $v_{\text{rot}} \sin i$, v_{rot} , critical velocities v_{crit} (in km s^{-1}) and Ω -ratios of three B[e] supergiants. The results for Hen S 93 were taken from Gummersbach et al. (1995).

	R 50	R 66	Hen S 93
inclination i	$\sim 60 - 90^\circ$	$\lesssim 60^\circ$	?
$v_{\text{rot}} \sin i$	≈ 150	≈ 50	≈ 65
v_{rot}	$\approx 150 - 175$	$\gtrsim 60$	$\gtrsim 65$
v_{crit}	~ 200	~ 140	~ 180
$\Omega = v_{\text{rot}}/v_{\text{crit}}$	$\approx 0.75 - 0.85$	$\gtrsim 0.45$	$\gtrsim 0.35$

appears to rotate near critical velocity ($\Omega \approx 0.8$), but also the other two stars have lower limits of Ω which indicate rather rapid rotation.

6. The B[e]-LBV Connection

6.1. Photometric Monitoring

The first B[e] supergiant found to show LBV-like photometric variability is R 4 in the SMC (Zickgraf et al. 1996a). Van Genderen & Sterken (1999, 2002) carried out an extensive photometric monitoring programme over many years in order to study the photometric behaviour of an extended sample of B[e] supergiants. The stars observed in the Walraven photometric system were R 126, Hen S 22 and R 66 in the LMC and Hen S 18 in the SMC.

As a result of the observations small variations in R 66 and R 126 of about $\Delta V_J \lesssim 0.08$ mag were found (here and in the following V_J denotes the Johnson V magnitude). Variability of this amount is typical for α Cygni variables and is possibly due to pulsations. Larger variations were found for Hen S 22 and Hen S 18.

Between 1989 and 1990 Hen S 22 showed variability of $\Delta V_J \lesssim 0.15$ mag. The variations suggest a quasi-periodic light variability with a timescale of 47 d. A long-term reddening trend, especially in Walraven $B - U$, is superimposed. The long-term cycle is about ~ 7 yr with an amplitude of $\Delta V_J \sim 0.04$ mag. Light and colour variations of Hen S 22 occurred in the sense that the star appeared redder when it was brighter. This was interpreted by van Genderen & Sterken (1999) as a low-amplitude S Dor cycle with a time scale of 7 yr, i.e. an S-SD phase in their nomenclature (N.B. $t < 10$ yr: S(hort)-SD phase, $t > 20$ yr: L(ong)-SD phase). Hen S 22 was therefore classified as LBV by van Genderen & Sterken (1999).

Hen S 18 exhibited larger variations of $\Delta V_J \approx 1$ mag. The variations occurred on three timescale: a) short-term variations with a timescale of days and $\Delta V_J \approx 0.1 - 0.2$ mag, b) medium-term variation on a ~ 150 days timescale with $\Delta V_J \approx 0.25 - 1$ mag, and c) long-term variation on a timescale of ~ 2 yr with $\Delta V_J \approx 0.7$ mag. However, to be LBV-like the photometric variability should be such that the star is bluer in minimum. This was not observed in most colours, except in Walraven $B - U$. For this colour the blueing effect was however too big to be

interpreted as LBV-like. Therefore van Genderen & Sterken (2002) concluded that Hen S 18 though being photometrically variable on various timescale the star cannot be classified as LBV based on its photometric characteristics. This leaves Hen S 22 as another B[e]/LBV candidate in addition to R 4.

6.2. The Binary System R 4 in the SMC

R 4 in the SMC was found by Zickgraf et al. (1996b) to be a binary system consisting of a B[e]- and an A-type component. As mentioned above the B[e] component exhibits LBV-like photometric variations and was therefore classified as B[e]/LBV-type. From the masses of the components and the evolutionary timescales Langer & Heger (1998) concluded that the binary system was originally a triple system in which two of the components had merged into the now observed B[e]/LBV component.

In a recent spectroscopic study by Pasquali et al. (2000) an extended circumstellar nebula was detected. This is the first evidence for an ejected nebula around a B[e] supergiant. The kinematical properties of the ejecta derived from the nebular emission lines indicate a cloverleaf shape of the nebula. The analysis of the long-slit spectra yielded a high ratio of $[\text{NII}]\lambda 6584/[\text{SII}]\lambda 6717$ indicative for N-enrichment in the nebula by a factor of 10. This finding is in agreement with photospheric CNO abundances determined by Zickgraf et al. (1996a) who found a N-overabundance and a C-underabundance as expected if CNO-processed material is exposed at the stellar surface. The size of the nebula of 2.4 pc, the dynamical age of 2×10^4 yr, and the N-enrichment thus allow the conclusion that R 4 is surrounded by an LBV-type nebula.

7. Summary & Open Questions

B[e] supergiants show clear evidence for non-spherical stellar winds. The working hypothesis of a two-component stellar wind with a normal OB-type radiation-driven wind near the poles and a slowly outflowing equatorial disk wind has quite successfully been used to explain many of the observed features of B[e] supergiants. Moreover, the presence of a non-spherical circumstellar environment has been confirmed by polarimetry. The formation of the equatorial disk could be caused by rapid stellar rotation. However, until now rotation velocities have been determined only for 3 B[e] supergiants. They are consistent with near critical rotation velocities. This would also allow the rotationally induced bi-stability mechanism to work.

B[e] supergiants are clearly in a post-main sequence evolutionary phase. It is, however, not clear whether they are on a red loop or a blue, i.e. post-red supergiant, loop. In two cases, R 4 and Hen S 18, CNO abundances could be determined indicating a nitrogen enrichment. The possible relation to other classes of evolved massive stars is also not clear. One or two of the B[e] supergiants exhibit LBV-type photometric variability. The binary R 4 was shown to possess an extended N-enriched nebula which is also in favour of an interpretation as LBV. Last but not least it should be mentioned that the cool hypergiant IRC +10420, which is in a post-red supergiant evolutionary phase, also exhibits circumstellar dust and forbidden emission lines.

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