THE B[e] STARS

F.-J. ZICKGRAF
Landessternwarte Königstuhl
D-6900 Heidelberg 1

ABSTRACT. B[e] supergiants show evidence for a non-spherical two-component stellar wind. The general appearance and the physical properties of the suggested disk-like configuration are discussed. The high mass-loss rates, the surprisingly large number and the location in the H-R diagram make these stars important for the understanding of the post-main-sequence evolution of massive stars.

1. Introduction

In the Magellanic Clouds (MCs) presently 10 B[e] supergiants are known: three in the SMC and 7 in the LMC (Stahl et al. 1983, 1984, 1988, Zickgraf et al. 1985, 1986, 1988). Apart from several individual characteristics they show the following common properties

- optical spectra dominated by strong Balmer emission lines (some stars with P Cygni profiles) with Hα equivalent widths of the order of 10^2 to 10^3 Å;
- narrow, low-excitation metallic emission lines like FeII, [FeII] and [OI];
- strong infrared excesses due to thermal reradiation of circumstellar dust ($T_{dust} \approx 1000$ K, $R_{dust} \approx 300\ R_\star$).

In contrast e.g. to the S Dor variables the B[e] supergiants show *no* striking photometric variations (at most $0.^m1$ to $0.^m2$). Spectroscopic variations are also very weak with the exception of Hen S 18 in the SMC which shows a strongly variable HeIIλ4686 emission line (cf. Shore et al. 1987, Zickgraf et al. 1988).

2. The two-component wind model

R 126 in the LMC can be regarded as the proto-type of the B[e] supergiants. Its spectrum has been described by Zickgraf et al. (1985) as *hybrid*, meaning the simultanous presence of broad UV resonance absorption lines of CIV, SiIV, and NV indicating expansion velocities of about 1600 km s^{-1} and very narrow FeII, [FeII]

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and [OI] emission lines with typical line widths of several 10 $\mathrm{km\,s^{-1}}$. Hen S 18 in the SMC is another example of this kind. Sharp emission lines of FeI, FeII, [FeII], and [OI] (FWHM $\approx$ 20 to 60 $\mathrm{km\,s^{-1}}$) are contrasted by broad P Cygni absorption components of the Balmer lines ($v_\infty \approx$ -750 $\mathrm{km\,s^{-1}}$). Obviously two different environments of line formation are required to produce such spectra. Zickgraf et al. 1985 suggested a two-component wind model consisting of a hot and fast line-driven (Castor et al. 1975) normal OB star wind in the polar region and a dense , cool and slowly expanding wind in the equator zone forming an *excretion* disk. The disk is the site of dust condensation and the formation of the low excitation lines. The molecular band emission of TiO and/or CO observed in some B[e] supergiants (Zickgraf et al.1988, McGregor et al. 1988) is also supposed to originate in the disk.

Individual characteristics of the B[e] supergiants are explained by taking into account different angles of aspect. Whereas R 126 is an example of a pole-on seen star, R 50 in the SMC represents the edge-on case showing no evidence for a high velocity wind component. Its line spectrum exhibits properties similar to a shell star (cf. Zickgraf et al. 1986) with Beals type III P Cygni profiles of the Balmer lines and sharp absorption features of singly ionized metals, both indicating a low expansion velocity.

The fast wind component is visible in seven out of ten B[e] supergiants either in the UV or in the visual wavelength region. Only in two stars (R 50 in the SMC and R 82 in the LMC) no evidence of a fast wind is found. One star is an intermediate case (R 4 in the SMC). With the assumption of the same overall geometry for all B[e] supergiants and randomly distributed inclination angles this small statistics allow to estimate the solid angle of the disk to about 20 to 30 % of the full sphere corresponding to a disk opening angle of 20° to 40°. Note, that White and Becker (1985) derived a disk opening angle of this size for the galactic B[e] supergiant MWC 349 from VLA observations.

Near IR excess in the J-band and Hα emission-line strength allow to derive the emission measure *EM*. It was found to be of the order of 10^{62} $\mathrm{cm^{-3}}$ for all objects of the sample (cf. Zickgraf et al. 1988). With a disk geometry as suggested above and a disk radius $R_{disk} \approx 300\ R_\star$ densities of several 10^9 $\mathrm{cm^{-3}}$ were derived. A similar result was independently obtained by McGregor et al. (1988) from CO emission.

The ratio of the mass flux densities f_{disk} and f_{pole} in the different wind components can be estimated as follows. Assuming for the excretion disk the above given density, a mean radius of $10^2\ R_\star$, and $v_{exp} = 20$ $\mathrm{km\,s^{-1}}$ and taking the polar wind to be a normal OB star wind with mass loss rate and flux density given by the relations of Lamers (1981) values of f_{disk}/f_{pole} of the order of 50 were estimated. With a ratio of the expansion velocities of $v_{pole}/v_{disk} \approx 20$ the density ratio between disk and polar wind is typically 10^2 to 10^3 (cf. Zickgraf et al. 1988).

The total mass-loss rate $\dot{M}_{tot}$ is determined by the mass outflow in the excretion disk. For Hen S 18 in the SMC e.g. mass-loss rates of $\dot{M}_{disk} \approx 4\ 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$ and $\dot{M}_{pole} \approx 4\ 10^{-6}\ \mathrm{M_\odot\ yr^{-1}}$ for the two wind components were obtained, i.e. $\dot{M}_{tot} \approx \dot{M}_{disk}$. $\dot{M}_{tot}$ is comparable to that of LBVs, however, it appears not to be variable but rather stable.

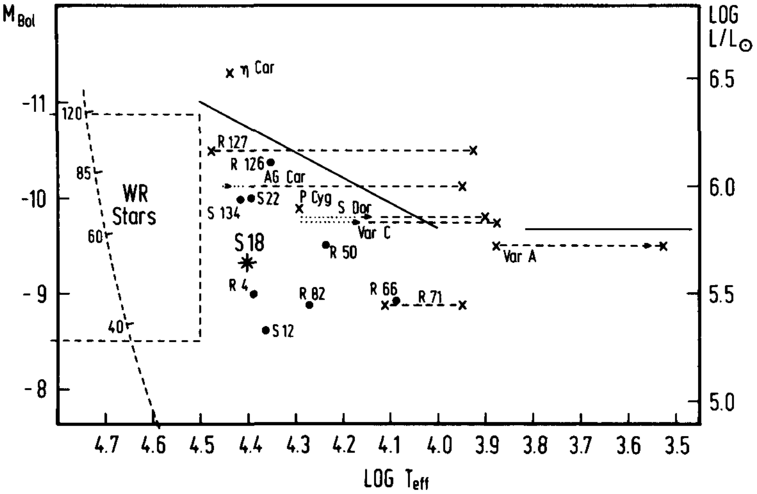

Figure 1: H-R diagram showing the location of the B[e] supergiants and the LBVs (×)

In the H-R diagram the B[e] supergiants and S Dor variables are located nearly in the same region (see Figure 1). Note the large number of B[e] supergiants compared to the S Dor type stars. In the SMC e.g. no S Dor variables are known, whereas already three B[e] supergiants have been found in this galaxy. Due to the surprisingly large number, the high mass-loss rates and the location in the H-R diagram the B[e] supergiants are certainly an important evolutionary stage of massive stars.

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DISCUSSION

Shore: (1) It is gratifying to see that the mass-loss results that you are deriving from optical data agree with results from the ultraviolet. We find C III] and Si III] both giving densities of 10^8--10^{10} cm^{-3} in some of the emission-line stars. HD 38489, S 18/SMC, and S 131/LMC are good examples of this. (2) Here is a crazy, toy, model. There must be massive systems with large mass ratios between components. What happens if one star is evolving through the supergiant region while the other is still on its way to the main sequence? Ablation, making the companion look something like a comet, should produce many of the same effects one sees in B[e] stars. This is not the same as the model we proposed for S 18/SMC (Shore, Sanduleak, & Allen 1987, *Astr.&Astrophys.* **176**, 59) nor that which I have suggested for R Aqr with an accreting companion sitting in the wind of a massive star, perhaps in an elliptical orbit. We might ask: What are the environmental effects of massive stars when less massive stars are formed nearby?

Walborn: Conti *et al.* have argued observationally that mass ratios near unity are favored for massive stars, and that very large ratios are rare.

Shore: So are LBV's.

Henrichs: What supports the excretion disk against gravity in your picture?

Zickgraf: It is supported by radiation pressure, probably due to opacity in the lines of ionized metals, similar to the mechanism suggested for S Dor winds.

Friedjung: There are good reasons for supposing that disks exist around these stars, but their nature is uncertain. A few years ago we suggested that S 22 has an excretion disk (Bensammar *et al.* 1983: *Astr.&Astrophys.* **126**, 427). Though this interpretation is less likely now, we must remember that we do not understand very well the disks supposed to exist around normal Be stars. Winds can come from both the central star and the disk. Moreover, some disk regions may be optically thick and such disks may be heated by radiation from the central star; so your density may not represent the whole disk.

Lamers: The spectral energy distributions of B[e] stars are very similar to those of classical Be stars. In classical Be stars, the IR excess is due to free-free emission (see, *e.g.*, Waters 1986, *Astr.&Astrophys.* **162**, 121). How do you know that the far-IR excess of B[e] stars is due to dust?

Zickgraf: The far-IR energy distributions can be fit well by black-body curves with temperatures around 1000 K. At wavelengths greater than 2 or 3 μm they are clearly different from free-free emission.

Conti: Does any observer have any information on rotational velocities of B[e] stars? Are they indeed rapid?

Zickgraf: The lack of photospheric absorption lines in B[e] supergiants makes it practically impossible to determine their $v \sin i$.