MODELING MASS LOSS FROM B[e] STARS

J.P. CASSINELLI, R.E. SCHULTE-LADBECK, C.H. POE*, and M. ABBOTT

Department of Astronomy
University of Wisconsin-Madison
475 N. Charter Street
Madison, WI 53706

**High Altitude Observatory*
NCAR
P.O. Box 3000
Boulder, CO 80307-3000

1. Introduction

It has been suggested by Zickgraf et al. (1986) that the outer atmosphere of some B[e] stars has a two-component structure: a fast, radiation-driven wind from the pole, and a dense, slow outflow from the equator. This is also the basic picture investigated by Poe, Friend, and Cassinelli (1989) (hereafter PFC) to explain the momentum problem associated with Wolf-Rayet stars. Here we apply the PFC multiforce wind theory to model the B[e] outflow phenomenon.

The theory requires that the B[e] stars rotate rapidly, i.e., $\omega = v/v_{crit}$ greater than about 0.5, where

$$v_{crit} = \sqrt{\frac{GM(1-\Gamma)}{R}} \qquad (1)$$

M and R are the stellar mass and radius and Γ is the ratio of the luminosity to the Eddington maximum luminosity; $\Gamma = k_F L/(4\pi c\, GM)$ with k_F being the flux mean opacity.

We have investigated two general questions. 1) Can B[e] stars be rotating near critical speed, and if so, 2) what constraints can be placed on the parameters that determine the two-component flow structure?

2. Near-Critical Rotation of B[e] Stars

We have used information regarding the density distribution of non-rotating stars to investigate the possibility that $\omega > 0.5$ for luminous post-main sequence stars. The results are shown in Figure 1, where the size of the dots is proportional to ω. Our main conclusion is this: high ω values can only occur after the star has undergone substantial mass loss. Stars evolve back to the left in the HR diagram from the Humphreys -

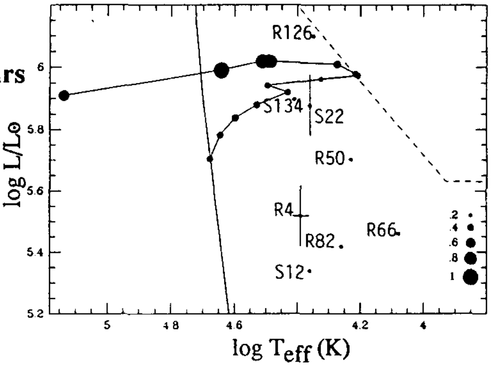

Figure 1: This HR diagram shows the track of a rotating 60 $M_\odot$ star and the positions of observed B[e] stars.

K. Davidson et al. (eds.), Physics of Luminous Blue Variables, 121–125.

Davidson limit after they have lost at least 40% of their initial mass. In this lowered mass, overly luminous state, v_{crit} is reduced, and ω can be increased as is shown in Figure 1.

We infer the following: a) B[e] stars are in the post Humphreys-Davidson part of their evolutionary track, and are moving to the left in the HR diagram, b) the B[e] stars are possibly the precursors of rapidly rotating Wolf-Rayet stars, and c) the B[e] stars are not an extrapolation, to high luminosity, of classical Be stars, but require a pre-existing major mass-loss phase.

3. Theoretical Constraints on the B[e] Winds

We have applied the PFC theory and used limits on the surface magnetic field as derived from the analysis of Maheswaran and Cassinelli (1988).

The wind theory of PFC accounts for three forces to drive the equatorial flow: the line-radiation force of the Castor, Abbott, and Klein (1975, CAK) theory, the effects of a finite-sized disk, and the centrifugal and magnetic forces. The effects of all of these forces can best be illustrated in a diagram of mass-loss rate ($\dot{M}$) vs. terminal wind speed (v_∞), as is shown in Figure 2a. The solid lines show the dependence of $\dot{M}$ and v_∞ on rotation rate and surface magnetic fields, B, ranging from 0 to 500 Gauss. Several interesting limits and boundaries can be discerned. There is a minimal mass-loss rate that is set by the Friend-Abbott (1986, FA) line-driven wind theory; increasing ω leads to larger $\dot{M}$. The asymptotic behavior of $\dot{M}$ vs. v_∞ for the magnetic cases can be rather well described by the Michel velocity, v_M, of "fast magnetic rotator" (FMR) theory (Hartmann and MacGregor 1982),

$$v_\infty \approx v_M = \left(\frac{(R^2 B_o)^2\, \Omega^2}{\dot{M}}\right)^{1/3} \qquad (2)$$

where B_o is the radial component of the magnetic field at R, and $\Omega^2 = GM(1\text{-}\Gamma)/R^3$. Lines satisfying equation (2) are shown in Figure 2b and demonstrate that the radiation and magnetic fields needed to explain the wind properties can be derived from rather simple considerations.

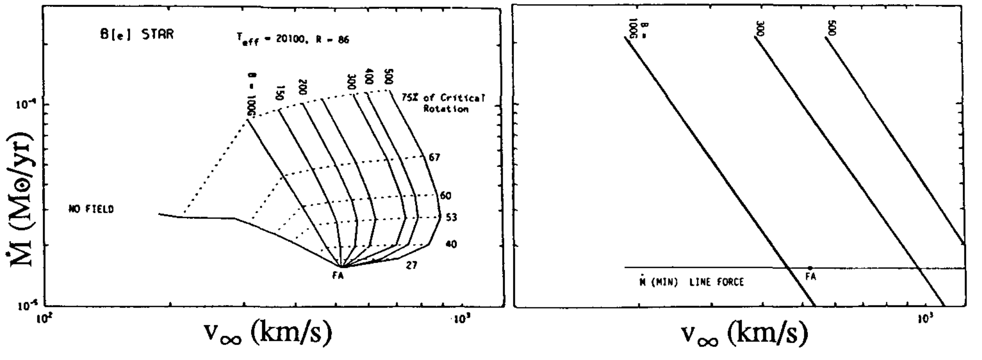

Figure 2a and b: Mass-loss rate versus terminal wind speed for different rotation rates and magnetic field strengths calculated numerically (left side) and using equation (2) (right side).

Constraints on the magnetic fields in the winds of rotating stars have recently been described by Maheswaran and Cassinelli (1988). They point out that rapid rotation leads to circulation currents in the stellar-interior envelope. If the circulation currents are faster than the Alfvén speed, the magnetic field becomes submerged below the stellar surface. This means that either the surface field is essentially zero or is greater than a certain lower limit. There is also an upper limit on the field beyond which hydrostatic structure is drastically modified. The allowed non-zero values for B_0 are shown in Figure 3. Combining these limits with the results of Figure 2a gives rise to Figure 4.

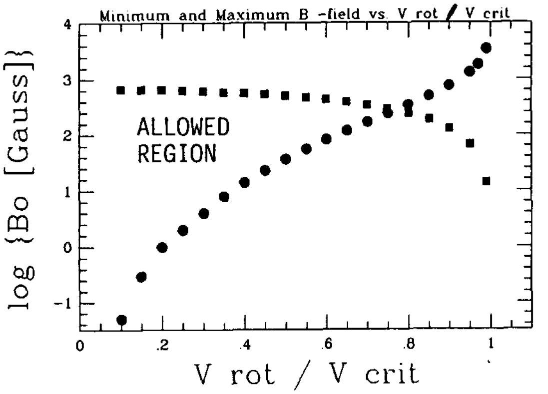

Figure 3: The logarithm of the magnetic field strength as a function of the rotation rate. The allowed region of values is indicated.

We conclude that there are two allowed types of equatorial flow:

1) $B_0 = 0$ and one has the no-field rotationally-driven outflow that was first analyzed by Castor (1979) in conjunction with CAK line forces. Note that for this type of flow v_∞ decreases as $\omega = v_0/v_{crit}$ increases. Or,

2) B is in the range allowed by Figure 3 and the equatorial flow is determined by the PFC analysis.

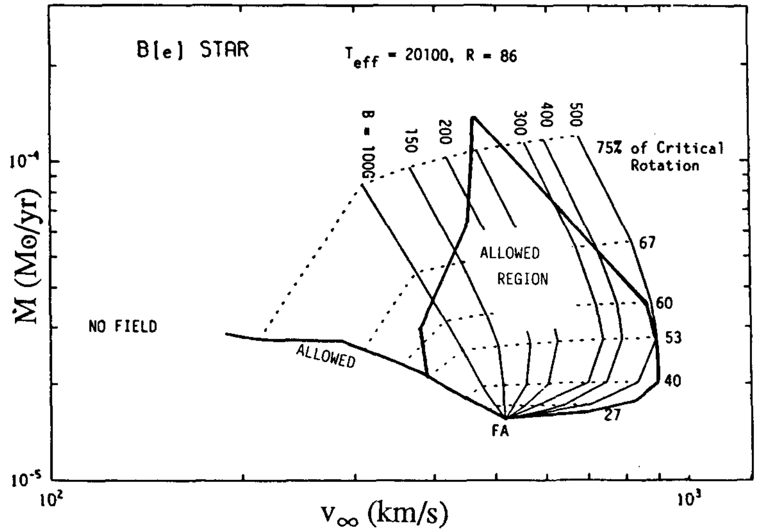

Figure 4: The numerical solutions for mass-loss rate versus terminal wind speed are shown for the same models as in Figure 2a, with the allowed values of the magnetic field indicated.

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The density and velocity structure for our model with $T_{eff} = 20,100$ K and $R = 86\ R_\odot$ is shown in Figure 5a. Note that the polar terminal speed is not as high as the observed about 1500 km s^{-1} in R126. The speed is increased for $T_{eff} = 40,000$ K (Figure 5b). This temperature is higher than indicated by the continuum of R126. However, we think that it is quite plausible that the effective temperatures of B[e] stars have been underestimated because of extended atmosphere effects. The extended equatorial region may well provide the radiation that flattens the continuum, giving rise to a lower temperature estimate.

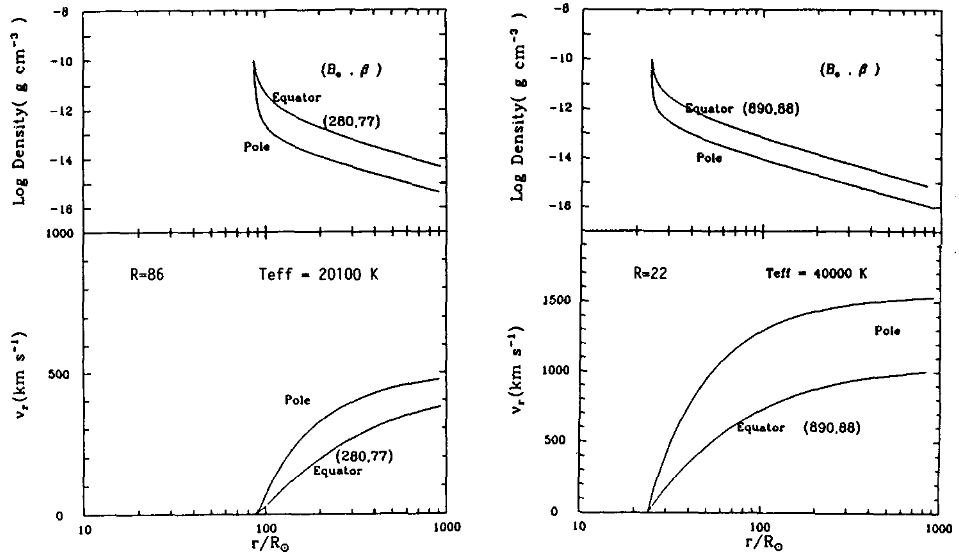

Figure 5a and b: The logarithmic density and velocity structure of two models are shown. The outflow from the cooler star (left panel) is slower than the one from the hotter star (right panel).

We should also comment on the evidence for 900 K dust in R126 (Zickgraf et al.). Using the Mathis, Rumpl and Nordsieck (1976) grain model, we find that even for the 20,100 K model the grain temperature exceeds 900 K all the way to 2000 R, where the density shown in Figure 5a has fallen below the minimal value of 10^{-17} gm cm^{-3} needed for grain growth. The fact that grain growth occurs requires that the outflowing material be optically thick. This will only happen if there is a strong density enhancement as suggested for the equatorial zone of a two-component model. We consider the ongoing grain formation to be added evidence that the flow from B[e] stars is not spherically symmetric.

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References

Castor, J.I. (1978), in: IAU Symp. **83**, eds. P.S. Conti and C.W.H. de Loore (Dordrecht:Reidel), p.175.
Castor, J.I., Abbott, D.C., and Klein, R.I. (1975), Ap. J., **195**, 157.
Friend, D.B. and Abbott, D.C. (1986), Ap. J., **311**, 701.
Hartmann, L. and MacGregor, K.B. (1982), Ap. J., **259**, 180.
Maheswaran, M, and Cassinelli, J.P. (1988), Ap. J., **335**.
Mathis, J., Rumpl, , and Nordsieck, K.H. (1976), Ap. J., **217**, 425.
Poe, C.H., Friend, D.B., and Cassinelli, J.P. (1989), Ap. J., **336**.
Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., and Appenzeller, I. (1986), Astron. Ap., **163**, 119.

DISCUSSION

Henrichs: What is the thickness of the disk in your model?

Cassinelli: We are solving the wind momentum equation in the equatorial plane and along the polar axis. Since we are not doing a 2-dimensional solution, I cannot answer your question from theoretical considerations. However, recall that Zickgraf estimated the equatorial zone in R 126 to have a half-angle of 15°.

Shore: If the envelope is differentially rotating and torus-like, then all bets are off concerning gravity darkening. It is generally true, however, that the measured rotational velocity (*v sin i*) will be quite a bit less than the true velocity.

Vanbeveren: When a rotating star is losing mass as a consequence of angular momentum loss it will slow down -- even a contracting star. Then what is the mechanism that brings the star to break-up velocity in your model?

Cassinelli: The stars lose about 40% of their mass while in the neighborhood of the Humphreys-Davidson limit, before they enter the B[e] phase. I did not say that this pre-B[e] mass loss was caused by angular-momentum-driven winds. However, the mass loss has the effect of increasing the ratio v_ϕ/v_{crit} during the final evolutionary movement to the left in the H-R diagram. This is because $v_{crit} = \sqrt{GM(1-\Gamma)/R}$ is reduced by a factor of about 2, because M is smaller and Γ is larger than when the star was evolving to the right in its early post-main-sequence evolution.

Schulte-Ladbeck, Zickgraf, Cassinelli, Appenzeller

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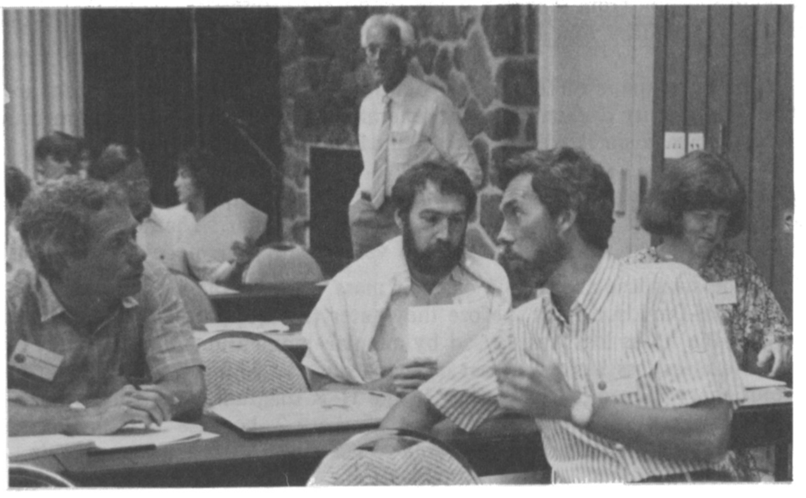

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