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The Envelopes of B[e] Stars

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Abstract. Our current understanding of B[e] envelopes, obtained through a variety of techniques including spectral studies, polarization studies, and interferometric studies, is summarized. While the hybrid spectra of B[e] stars strongly suggests the presence of a dense equatorial zone (or disk), and a more normal stellar wind, accurate knowledge of the density and velocity structure of the envelope is still lacking. We highlight the importance of using reflection nebula, which can allow us to look at the illuminating B[e] star from a different direction, to provide additional geometrical constraints on the B[e] envelope. Radiation pressure is expected to play a key role in formation of the envelope, but the actual "disk" generating mechanism has not yet been identified. Four mechanisms for disk formation are discussed: the bistability mechanism, wind-compressed disks, centrifugal ejection, and magnetic fields.

1. Introduction

B[e] stars are objects whose spectra are characterized by strong Balmer emission, low excitation permitted lines, narrow [Fe II] and [O I] lines in the optical, and an IR excess due to hot dust (e.g., Lamers et al. 1998). It is really a phenomenon, and thus stars in the class can have diverse properties and histories. Lamers et al. (1998) classified the B[e] stars into 5 broad groups, which, in addition to the B[e] defining characteristics, have the following properties:

1. Supergiant B[e] stars (sgB[e]): These are characterized by $L > 10^4\, L_\odot$, P Cygni or double peaked emission profiles, N/C> 1, and small photometric variability. The enhanced N/C ratio criterion is interesting, since if full CNO processed material were present, [O I] could be weak and possibly difficult to detect. Whether the variability criterion should remain is questionable, since there is also increasing evidence that at least some sgB[e] stars are variable (e.g., van Genderen & Sterken 2002).

2. Herbig AeB[e] stars (HAeB[e]): These are associated with star-forming regions, show evidence for infall and variability, and have $L < 10^{4.5}\, L_\odot$.

3. Central stars of Planetary Nebulae (cPNB[e]): Their spectra show high excitation forbidden lines (e.g., [OIII], [SII], [NeIII]) indicating the presence of a nebula. Their luminosities are low ($L < 10^4\, L_\odot$).

4. Symbiotic B[e] (SymB[e]) stars: These show evidence of a cool star with evidence for TiO absorption in the visual, and a late type spectrum in the

IR. They are also associated with star-forming regions and typically have $L < 10^{4.5}\, L_\odot$.

For many stars it is unclear to which group they belong — they are therefore given the classification unclB[e].

Due to their hybrid spectra it is generally assumed that B[e] stars have two distinct emitting regions — a "fast" polar wind giving rise to strong UV resonance lines and an equatorial disk in which the narrow forbidden lines, molecular emission (when present) and dust emission arises (Zickgraf et al. 1985).

In this review we will primarily concentrate on sgB[e] stars. As radiation pressure is expected to play an important role in the formation of at least part of the circumstellar envelope of B[e] stars, we will first give a brief review of our current understanding of mass loss in massive stars. Then, since to understand mass-loss rates from these stars it is necessary to understand the geometry of the circumstellar material, we will summarize what is known about B[e] envelopes and how evidence on the geometry can be obtained. The limited information on sgB[e] mass-loss rates is then examined. Finally we discuss testing the B[e] paradigm, and proposed theoretical models for creating B[e] envelopes.

2. Mass Loss in "Normal" Massive Stars

It is generally accepted that mass loss in massive stars is determined by radiation pressure acting through bound-bound transitions in the UV and EUV. The line driving is statistical, and can be parameterized by two key parameters, k and α. The former is basically a normalization factor related to the number of driving lines, while α describes the slope of the line distribution (or the ratio of optically thick to thin lines). The parameter α is of crucial importance since the force due to a thick line is proportional to the velocity gradient, while the force due to an optically thin line is independent of the velocity gradient.

It is customary to write the acceleration due to lines, g_{line}, in the form

$$g_{line} = M(t) g_{elec} = k t^{-\alpha} g_{elec} \tag{1}$$

where g_{elec} is the acceleration due to radiation acting on the electrons, $M(t)$ is the force multiplier, and t is an optical depth parameter which is inversely proportional to the local velocity gradient ($t = n_e \sigma V_{th} dr/dV$; Castor et al. 1975).

Due to the pioneering work of Castor et al. (1975); Abbott (1980, 1982); Pauldrach et al. (1986); Kudritzki et al. (1987) and others (see review by Kudritzki & Puls 2000) we can make quantitative predictions for mass loss in massive stars. In an extensive study, Vink et al. (2000, 2001) investigated the dependence of mass-loss rates on luminosity, effective temperature, gravity, and metalicity. Since it is less dependent on the stellar and wind driving parameters, we use the modified wind momentum (Kudritzki et al. 1995) to discuss the mass-loss rates.

The modified wind momentum, Π, is defined by $\Pi = \dot{M} V_\infty \sqrt{R_*}$ where we measure $\dot{M}$ in $M_\odot\,\mathrm{yr}^{-1}$, V_∞ in $\mathrm{km\,s^{-1}}$, and R in $R_\odot$. For stars above a $T_{\rm eff}$ of approximately 27,500 K, Vink et al. (2000) find

$$\log \Pi = -12.12\,(\pm 0.26) + 1.826\,(\pm 0.044) \log\,(L/L_\odot) \tag{2}$$

which illustrates the simple, and strong, dependence of mass-loss rate on luminosity. Vink et al. (2000) showed that Eq. (2) provides an excellent fit to both the theoretical mass-loss rates, and to the observed mass-loss rates. At temperatures lower than 27,500 K (approximately) a different fitting formula needs to be adopted, since the dominant ions driving the flow change. This is the bistability discussed by Lamers & Pauldrach (1991) and Vink et al. (1999). This mechanism will be discussed further when we consider B[e] winds.

The excellent agreement found by Vink et al. (2000) is no longer apparent. Extensive observational (Eversberg et al. 1998; Kramer et al. 2003) and theoretical evidence (Owocki et al. 1988; Feldmeier et al. 1997) exists that winds are clumped. As a consequence mass-loss rates derived from Hα, and radio fluxes, will overestimate the true mass-loss rates. More recently, spectroscopic empirical evidence (Massa et al. 2003; Fullerton et al. 2005), and results from detailed spectroscopic analyses (Crowther et al. 2002; Hillier et al. 2003; Bouret et al. 2003, 2005), strongly suggests that wind mass-loss rates are being consistently overestimated — possibly by factors of 2 to 5, or more. For a fuller discussion on clumping and mass-loss rates of O stars, see the review by Hillier (2005).

There is also evidence that low luminosity stars have much lower mass-loss rates than expected (Martins et al. 2004, 2005). This might be a real effect, or may be an artifact of the models, due to a lack of understanding of the structure of low density winds, and/or the importance of X-rays in determining the ionization structure.

It should also be noted that we still don't fully understand mass loss in Wolf-Rayet (W-R) stars (e.g., Hillier 2003, but see Gräfener & Hamann 2005), or the highly variable mass loss observed in luminous blue variables (LBVs) but see Vink & de Koter (2002). Winds in W-R stars are also known to be highly clumped (e.g., Robert 1994; Lépine et al. 1996; Lépine & Moffat 1999; Hillier 1991; Hillier & Miller 1999).

3. The Structure of B[e] Envelopes

Evidence for disks and non-spherical envelopes for B[e] stars is substantial. The simple presence of heterogeneous spectral features (e.g., both very broad and narrow emission lines) argues for multiple emitting regions. Likewise the presence of molecules and dust argues for a dense region shielded from UV radiation (i.e., a disk). Importantly, speckle observations of the B[e] star MWC 349 A (now believed to be a B[e] supergiant), have revealed evidence for an edge-on disk (Danchi et al. 2001; Hofmann et al. 2002).

Intrinsic polarization provides unambiguous evidence for a departure from spherical symmetry — if intrinsic polarization is detected the system must depart from spherical symmetry. In B[e] stars continuum polarization can arise from electron scattering, dust scattering or both. Electron scattering is wavelength independent but wavelength dependent absorption processes can introduce a wavelength dependent polarization (e.g., Wood et al. 1997). Polarization by dust scattering is intrinsically wavelength dependent. A major difficulty with polarization studies is extracting the intrinsic polarization from the observed polarization signal which also contains a contribution (sometimes the dominant component) due to the interstellar medium.

Most B[e] stars show intrinsic polarization (Zickgraf & Schulte-Ladbeck 1989; Oudmaijer & Drew 1999), as evidenced, for example, by polarization structure across Hα. In the Zickgraf & Schulte-Ladbeck (1989) sample five of the eight stars showed intrinsic polarization, as did all four B[e] stars in the Oudmaijer & Drew (1999) sample. Oudmaijer & Drew (1999) found that the polarization signature of each star was unique, making it hard to draw general inferences. For HD 45677 (unclB[e]) both dust and electron scattering were invoked to explain the observed polarization.

Limited polarization observations can be misleading. Schulte-Ladbeck et al. (1994) analyzed observations of the LBV AG Carinae, and showed that the observations were consistent with an axisymmetric geometry. Moreover, the derived polarization axis was consistent with that of the optical nebula. As the polarization was shown to flip sign, the system had to change from prolate to oblate, or alternatively, optical depth effects were important. However, more recent observations (Leitherer et al. 1994; Davies et al. 2005) showed more erratic polarization changes with no preferred axis.

In some cases UV observations show direct evidence, through the presence of a P Cygni absorption profile, for a fast wind: $V_\infty \sim 1000$ to $2000\ \mathrm{km\,s^{-1}}$. An excellent example is provided by R 126. In the optical, emission lines indicate "expansion" velocities of order $100\,\mathrm{km\,s^{-1}}$ and less, while evidence for velocities in excess of $1000\,\mathrm{km\,s^{-1}}$ is seen in the P Cygni absorption components of UV resonance lines. It was R 126 that led Zickgraf et al. (1985) to devise their classic disk/fast wind scenario for B[e] stars. As Zickgraf et al. (1985) note, the observed fast wind terminal velocity is comparable to that of some B supergiants (e.g., ϵ Ori, B0Ia).

The origin of broad Hα profiles in B[e] stars is somewhat more problematic. In the Hα montage for galactic B[e] supergiants presented by Zickgraf (2003) $V_{\mathrm{FWHM}} < 300\,\mathrm{km\,s^{-1}}$. These widths can be interpreted in different ways: they could represent, for example, outflow velocities in a "slow" wind. Alternatively they could represent rotational velocities in a Keplerian-like disk or a "slowly" expanding disk like wind. As the Hα profiles are often double peaked, it is generally thought that they originate in a disk-like structure. However, as the observations of IRC +10420 show, this is not necessarily the case (Humphreys et al. 2002, Sect. 6.). Interestingly, the Hα velocity widths are similar to those observed for LBVs such as AG Carinae (Leitherer et al. 1994), P Cygni (Najarro et al. 1997), and η Carinae (Hillier et al. 2001).

While considerable advances have been made in our understanding of B[e] envelopes, much still remains to be done. It is still generally unclear, for example, whether the disks exhibit Keplerian rotation, or are outflowing. For Be stars evidence strongly suggests that the disks in those stars are dominated by rotation (Porter & Rivinius 2003). Disk opening angles are still uncertain, especially since it is unclear whether inferences for one object are also applicable to other B[e] stars. Further, it is commonly assumed that B[e] stars are axisymmetric. Is this assumption better, or worse, than the assumption of spherical symmetry for stars such as P Cygni?

3.1. sgB[e] Mass-Loss Rates

While there is some information on sgB[e] mass-loss rates, the situation is far from satisfactory. Many mass-loss estimates have been derived from H line fluxes (Stahl et al. 1983; Shore & Sanduleak 1983; McGregor et al. 1988; Zickgraf et al. 1989; de Freitas Pacheco 1998). Such estimates of supergiant mass-loss rates, which show considerable scatter, range from approximately 10^{-6} to 10^{-4} $M_\odot\,yr^{-1}$. An important assumption in these calculations is that all the Hα emission arises in a stellar wind, and not a rotating disk. Since distances to galactic B[e] are poorly determined, there are additional uncertainties in their mass-loss rates, since their inference from spectroscopic analysis typically scales as $d^{1.5}$.

In some cases we can observe the fast wind in the UV, and estimate, through standard means, the polar mass-loss rate. For R 126, Zickgraf et al. (1985) estimated $V_\infty = 1800\,\mathrm{km\,s^{-1}}$ and $\dot{M} = 10^{-6}$ to $10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$ for the polar wind, while theoretical estimates by Bjorkman (1998) suggest $V_\infty = 650\,\mathrm{km\,s^{-1}}$ and $\dot{M} = 4.6 \times 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$.

More problematical is the mass-loss rate in the equatorial region. The determination of these parameters depends on both the opening angle of the disk, and the disk outflow velocity, both of which are usually poorly known. Zickgraf (1992) infers disk-opening angles of around 20° to 40° based on statistics of those stars for which fast winds are observed. He estimates density contrasts of 100 to 1000 between the polar wind and the disk. In such circumstances the disk outflow dominates the mass loss. Zickgraf et al. (1986) estimated mass-loss rates of order $5 \times 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ for Hen S 22 and R 82 with disk outflow velocities of 60 to $80\,\mathrm{km\,s^{-1}}$.

4. Testing the B[e] Paradigm

How well does the basic model of Zickgraf et al. (1985) explain B[e] stars? Using this model, Oudmaijer et al. (1998) studied the unclassified B[e] star HD 87643. Although no quantitative comparisons were undertaken, they found that a polar wind and optically thick disk could qualitatively explain the spectroscopic and polarimetric observations. Interestingly, they also invoked a wind driven by radiation pressure from the disk.

Porter (2003) tested both the Keplerian disk model and the outflow model. While both models could have dust formation neither model could explain the observed IR spectral energy distribution.

Kraus & Lamers (2003) have investigated the ionization structure of B[e] supergiant winds. Fast polar winds tend to remain ionized out to large radii, provided the density is not too high. However in the high density equatorial winds, H can become neutral just above the stellar surface. In this region molecules and dust could potentially form. These models confirm that the basic disk-wind scenario can explain the observed emission line strengths in B[e] stars. An important distinction between O stars and B stars is that B stars have significantly less photons capable of ionizing H. This simple fact could explain the absence/rarity of O[e] stars.

A kinematic investigation of B[e] stars was undertaken by Zickgraf (2003). He concluded that while rotation may be important in the inner regions of the envelope, outflow velocities dominate the outer regions. Zickgraf (2003) showed that observed profile shapes could be reasonably well matched by profiles computed assuming optically thin lines and a latitudinal dependent wind.

5. Theoretical Considerations

Various mechanisms have been proposed to explain the B[e] phenomenon. A key requirement of all such mechanisms appears to be the necessity of producing a dense equatorial region (or disk) which produces the forbidden lines, and the dust emission. Below we discuss four mechanisms that may play a role: magnetic fields, rotation and wind-compressed disks, centrifugal ejection, and the bistability mechanism.

5.1. Rotation and Wind Compressed Disks

An important insight into the structure of stellar winds in the presence of stellar rotation was made by Bjorkman & Cassinelli (1993). They made the simple realization that forces in the wind are radial, and thus angular momentum parallel to the rotation axis is conserved. Consequently material leaving the star will be confined to an orbital plane, which passes through the center of the star, and the origin of the material that leaves the star. If the radial velocity dominates, particles will stream out along radial paths. However as the rotation rate increases, the streamlines become more curved. For sufficiently high rotation velocities, the streamlines will cross the equator. Since this will occur in both hemispheres, an increase in density will occur at the equator giving rise to a *wind-compressed disk*.

Unfortunately the model was found not to provide a viable explanation for Be disks — the densities were too low and the disk outflow velocities were too large (e.g., Porter & Rivinius 2003). Further, additional physics complicates the simple picture.

First, the effective gravity, the effective temperature, and the radiative flux vary with latitude, such that the star is hotter at the pole (e.g, von Zeipel 1924; Maeder 1999). The closer the star is to breakup, the greater the contrast between the pole and the equator. As a consequence $\dot{M}$ and V_∞ will vary with latitude. Second, the star is non-spherical. For a star rotating close to breakup, the equatorial radius is 1.5 times the polar radius. Third, the radiation can provide a non-radial force which, while small, can inhibit the flow of material towards the equator (Owocki et al. 1996). Finally we note that for stars very close to the Eddington limit, the latitudinal dependence of the effective surface gravity (i.e., the surface gravity including the effects of both radiation pressure and rotation) is complicated (Maeder & Meynet 2000).

5.2. Ionization Effects and the Bistability Mechanism

The lines that drive the flow, and their location with respect to the radiative flux, is controlled by the ionization structure. Consequently if there is a change in the ionization structure at the base of the flow, mass-loss rates and terminal velocities might change abruptly. This is the bistability jump, first found by Lamers & Pauldrach (1991). As $T_{\rm eff}$ decreases below 25,000 K, the mass-loss rate increases by a factor of five while the terminal velocity falls by a factor of two. The cause is a change in ionization from Fe IV to Fe III. This effect is observed although theoretical estimates of the locations of the jumps, while reasonable, are not in perfect agreement with observation. Interestingly, Vink & de Koter (2002) claim that S Doradus-like mass-loss variations are driven by Fe IV to Fe III and Fe III to Fe II ionization changes.

The bistability mechanism has been invoked by Cassinelli & Ignace (1997) and Pelupessy et al. (2000) to provide a formation mechanism for disks in B[e] stars. Because the star is gravity darkened, it is possible that the equator is on one side of the bistability (slow wind), while the pole is on the opposite side (fast wind). With this mechanism it is possible to get a density contrast of about 10 between the equator and the pole. This appears too low to explain B[e] disk models, but it might be possible to invoke additional mechanisms. For example, Curé & Rial (2004) and Curé (2004) have pointed out that there is a slow acceleration solution to the momentum equation, with correspondingly higher densities, when the star is rotating above 75% critical. The physics behind this solution is discussed by Owocki (2006). Curé et al. (2005) have used this model to explain B[e] disks, however they neglect gravity darkening. This, and 2D effects, need to be investigated in order to address the viability of the proposed mechanism.

5.3. Centrifugal ejection

If B[e] stars are rotating close to breakup, it may be possible to eject material from the star into a rotating disk, as originally proposed for Be stars by Struve (1931). As noted by many authors, simple energetic considerations show that it is much easier to put material into orbit from a rapidly rotating star. This mechanism, and candidate processes (radiation, pulsation, and magnetic fields) for the actual mass ejection in Be stars, has recently been discussed by Owocki (2005).

5.4. Magnetic Fields

Magnetic fields add a great deal more complexity and freedom into models of stellar winds, and consequently investigation into the role of magnetic fields in massive stars is still in its infancy. In radiation-magnetohydrodynamic models you potentially need to allow for the influence of line driving, which is dependent on the velocity and ionization structure of the envelope, for the effects of rotation, for a magnetic axis which could be offset from the rotation axis, and for the effects of a magnetic field whose topology is not necessarily simple. Investigations into the role of magnetic fields in OB stars have been undertaken, for example, by Cassinelli et al. (2002) and ud-Doula & Owocki (2002).

ud-Doula & Owocki (2002) showed that the key parameter controlling the dynamical influence of the magnetic field is η, the ratio of the magnetic energy density to the kinetic energy density:

$$\eta(r,\theta) = \frac{B^2/8\pi}{\rho v^2/2} \tag{3}$$

Although expressed somewhat differently, a similar expression is obtained for the magnetic rotator model discussed extensively by Lamers & Cassinelli (1999). For a dipole configuration, Eq. (3) reduces to

$$\eta_* = \frac{B(90^\circ)^2 R_*^2}{\dot{M} V_\infty}$$
$$= 0.19 \left(\frac{B(90^\circ)}{100\,G}\right)\left(\frac{R_*}{10\,R_\odot}\right)^2 \left(\frac{1\times10^{-6} M_\odot/\mathrm{yr}}{\dot{M}}\right)\left(\frac{1000\,\mathrm{km\,s^{-1}}}{V_\infty}\right) \quad (4)$$

(ud-Doula & Owocki 2002). When η_* is < 0.1, the dynamical influence of the magnetic field is relatively small. However, when $\eta_* > 1$, the magnetic field plays a crucial role in the wind dynamics. In particular, when the magnetic field is strong the wind is constrained to flow along the field lines, potentially giving rise to a thin, slowly outflowing disk in the equatorial plane of the magnetic field (ud-Doula & Owocki 2002).

As can be seen from Eq. (4), the magnetic fields required for η_* to be > 1 depend on both R_* and $\dot{M}$. Typically magnetic field strengths of 10 to a few 100G are required. The detection of magnetic fields in O stars, the presumed progenitors of sgB[e] stars, is extremely difficult. Two O stars have been found to have high magnetic field strengths: θ^1 Ori C ($B = 1.1 \pm 0.1$ kG, Donati et al. 2002), and HD 191612 ($B = 220 \pm 38G$ [$B_{\mathrm{Dip}} \sim 1.5$kG], Donati et al. 2006). In these cases the magnetic field will dominate the wind dynamics as probably evidenced by the spectral peculiarities of the two stars (Donati et al. 2002, 2006). Since it is usually believed that magnetic field strengths will decline with age, it is unclear whether magnetic fields could play an important role in sgB[e] stars.

6. Views by Aliens

Since the circumstellar disks around B[e] stars are not spherically symmetric, it is highly desirable to view the stars from other directions. Fortunately this is feasible in some cases by using reflected starlight.

An excellent example of where a reflection nebula has been used to study a wind from different viewing directions is η Carinae. The expanding homunculus scatters light to us allowing us to view η Carinae from a variety of directions (e.g., Hillier & Allen 1992), providing direct evidence for a fast, latitudinal dependent, polar wind (Smith et al. 2003). The latitude dependent Hα profiles (measured from around 40° to 90°; Fig. 1) show three important aspects: (1) The redward extension is very similar at all locations, and with the exception of spectra of the central star, the emission strengths are virtually identical. (2) There is a P Cygni profile whose strength increases towards the poles, and whose characteristic velocity increases from around 400 to 600 km s^{-1}. (3) There is shallow absorption in the blue wing extending up to 1000 km s^{-1}.

The characteristic increase in velocity of the P Cygni absorption is easily explained by invoking a latitude dependent wind whose velocity is higher at the pole, a configuration expected for a rapidly rotating star (e.g., Cranmer & Owocki 1995; Owocki et al. 1996). The other characteristics, namely the similar emission profiles and the high velocity absorption are not so easy to explain. The latter is interesting since we also see evidence for such velocities in central star spectra at some epochs (Davidson et al. 2005). Simple models, with a simple

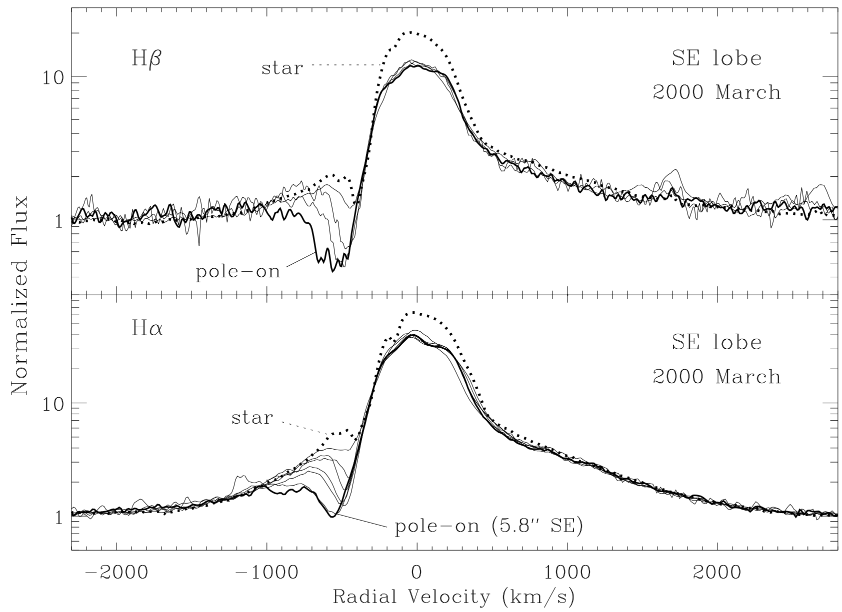

Figure 1. Illustration of the variation of Hα with latitude for η Carinae. Profiles have been shifted in velocity to allow for the wavelength shift introduced by the dust scattering. From Smith et al. (2003; reproduced by permission of the AAS).

latitudinal velocity variation, or a latitudinal density and velocity variation, tend to show changes in both the emission line strengths and the red edge (Fig. 2).

Part of the difficulty in understanding the profiles may be due to the complex ionization structure of the wind. In many LBVs hydrogen recombines in the outer envelope. However, for relatively small changes in the stellar or wind parameters (e.g., $T_{\rm eff}$ or $\dot{M}$) hydrogen may remain fully ionized (e.g., Najarro et al. 1997). Consequently the ionization structure of a latitudinal dependent wind may be quite complicated. In η Carinae, hydrogen must recombine (in a significant fraction of the outer wind) if we are going to get strong Fe II emission, as is observed.

Other examples of reflection nebulae exist, and these need to be exploited to obtain directional data on B[e] stars. S 22 is a sgB[e] star which is surrounded by an extended reflection nebula (Chu et al. 2003). The Hα profile varies across the reflection nebula indicating an anisotropic wind. AG Carinae has a nebula which shows starlight scattered by dust (Nota et al. 1995), and hence could be used to study AG Carinae from different directions. HD 87643 (unclB[e]) is another example of a B[e] star with a reflection nebula (Surdej et al. 1981). Humphreys et al. (2002) used the reflection technique to study directional information on the wind of the post-red supergiant IRC +10420. In that case they conclude that the Hα, while showing aspect variations, comes from a roughly spherical outflow. Interestingly, the Hα profile shows a double peaked profile — a structure usually taken to indicate the presence of a disk.

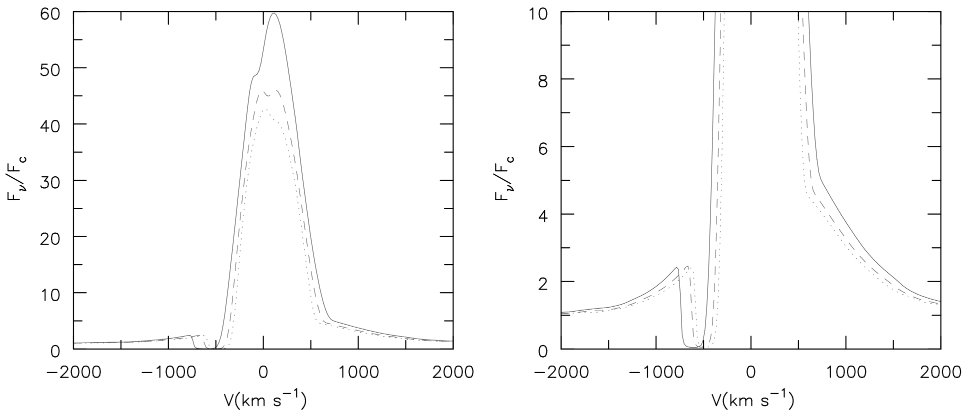

Figure 2. Illustration of the variation of Hα with latitude [0° (solid), 45° (dashed), and 90°] for a 2D model for η Carinae. The polar terminal velocity is 30% higher, and the density a factor of 2 higher than at the equator.

How is our understanding of individual B[e] stars affected by our particular observing sightline? In η Carinae there is substantial evidence that our sightline is peculiar — the reddening along our sight line is well above that expected from the intervening interstellar medium. Conversely, directions towards the pole appear to suffer less reddening (Hillier & Allen 1992). The system appears to have a built-in coronagraph that allows the forbidden lines to be so prominent in ground-based spectra, and hence to generate the characteristic η Carinae spectrum. In how many other systems do similar effects occur?

7. Conclusion

Through improved observations, and through theoretical investigations, considerable progress is being made towards understanding the B[e] phenomenon. With the computer power now available it will be possible to construct more advanced 2D models capable of allowing reliable spectroscopic analysis. Results from such analyses should provide new impetus, and importantly, new constraints, for theoretical studies concerned with the formation of B[e] circumstellar envelopes. New interferometric observations and polarization observations, and studies of reflected spectra, will play an important role in providing additional observational constraints.

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References

Abbott, D. C. 1980, ApJ, 242, 1183

Abbott, D. C. 1982, ApJ, 259, 282

Bjorkman, J. E. 1998, in ASSL Vol. 233, B[e] stars, ed. A. M. Hubert & C. Jaschek (Dordrecht: Kluwer), 189

Bjorkman, J. E., & Cassinelli, J. P. 1993, ApJ, 409, 429

Bouret, J.-C., Lanz, T., & Hillier, D. J. 2005, A&A, 438, 301
Bouret, J.-C., Lanz, T., Hillier, D. J., Heap, S. R., Hubeny, I., Lennon, D. J., Smith, L. J., & Evans, C. J. 2003, ApJ, 595, 1182
Cassinelli, J. P., Brown, J. C., Maheswaran, M., Miller, N. A., & Telfer, D. C. 2002, ApJ, 578, 951
Cassinelli, J. P., & Ignace, R. 1997, in ASP Conf. Ser. Vol. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. J. G. L. M. Lamers (San Francisco: ASP), 166
Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, ApJ, 195, 157
Chu, Y.-H., Chen, C.-H. R., Danforth, C., Dunne, B. C., Gruendl, R. A., Nazé, Y., Oey, M. S., & Points, S. D. 2003, AJ, 125, 2098
Cranmer, S. R., & Owocki, S. P. 1995, ApJ, 440, 308
Crowther, P. A., Hillier, D. J., Evans, C. J., Fullerton, A. W., De Marco, O., & Willis, A. J. 2002, ApJ, 579, 774
Curé, M. 2004, ApJ, 614, 929
Curé, M., & Rial, D. F. 2004, A&A, 428, 545
Curé, M., Rial, D. F., & Cidale, L. 2005, A&A, 437, 929
Danchi, W. C., Tuthill, P. G., & Monnier, J. D. 2001, ApJ, 562, 440
Davidson, K., Martin, J., Humphreys, R. M., Ishibashi, K., Gull, T. R., Stahl, O., Weis, K., Hillier, D. J., Damineli, A., Corcoran, M., & Hamann, F. 2005, AJ, 129, 900
Davies, B., Oudmaijer, R. D., & Vink, J. S. 2005, A&A, 439, 1107
de Freitas Pacheco, J. A. 1998, in ASSL Vol. 233, B[e] stars, ed. A. M. Hubert & C. Jaschek (Dordrecht: Kluwer), 221
Donati, J.-F., Babel, J., Harries, T. J., Howarth, I. D., Petit, P., & Semel, M. 2002, MNRAS, 333, 55
Donati, J.-F., Howarth, I. D., Bouret, J.-C., Petit, P., Catala, C., & Landstreet, J. 2006, MNRAS, 365, L6
Eversberg, T., Lépine, S., & Moffat, A. F. J. 1998, ApJ, 494, 799
Feldmeier, A., Puls, J., & Pauldrach, A. W. A. 1997, A&A, 322, 878
Fullerton, A. W., Massa, D. L., & Prinja, R. K. 2005, ApJ, 637, 1025
Gräfener, G., & Hamann, W.-R. 2005, A&A, 432, 633
Hillier, D. J. 1991, A&A, 247, 455
Hillier, D. J. 2003, in IAU Symp. 212, A Massive Star Odyssey: From Main Sequence to Supernova, ed. K. van der Hucht, A. Herrero & C. Esteban (San Francisco: ASP), 70
Hillier, D. J. 2005, in ASP Conf. Ser. Vol. 332, The Fate of the Most Massive Stars, ed. R. Humphreys & K. Stanek (San Francisco: ASP), 219
Hillier, D. J., & Allen, D. A. 1992, A&A, 262, 153
Hillier, D. J., Davidson, K., Ishibashi, K., & Gull, T. 2001, ApJ, 553, 837
Hillier, D. J., Lanz, T., Heap, S. R., Hubeny, I., Smith, L. J., Evans, C. J., Lennon, D. J., & Bouret, J.-C. 2003, ApJ, 588, 1039
Hillier, D. J., & Miller, D. L. 1999, ApJ, 519, 354
Hofmann, K.-H., Balega, Y., Ikhsanov, N. R., Miroshnichenko, A. S., & Weigelt, G. 2002, A&A, 395, 891
Humphreys, R. M., Davidson, K., & Smith, N. 2002, AJ, 124, 1026
Kramer, R. H., Cohen, D. H., & Owocki, S. P. 2003, ApJ, 592, 532
Kraus, M., & Lamers, H. J. G. L. M. 2003, A&A, 405, 165
Kudritzki, R.-P., Lennon, D. J., & Puls, J. 1995, in Science with the VLT, ed. J. R. Walsh & I. J. Danziger (Berlin: Springer-Verlag), 1246
Kudritzki, R. P., Pauldrach, A. W. A., & Puls, J. 1987, A&A, 173, 293
Kudritzki, R.-P., & Puls, J. 2000, ARA&A, 38, 613
Lamers, H. J. G. L. M., & Pauldrach, A. W. A. 1991, A&A, 244, L5
Lamers, H. J. G. L. M., & Cassinelli, J. P. 1999, Introduction to Stellar Winds, (Cambridge, UK: Cambridge University Press)

Lamers, H. J. G. L. M., Zickgraf, F.-J., de Winter, D., Houziaux, L., & Zorec, J. 1998, A&A, 340, 117
Leitherer, C., Allen, R., Altner, B., Damineli, A., Drissen, L., Idiart, T., Lupie, O., Nota, A., Robert, C., Schmutz, W., & Shore, S. N. 1994, ApJ, 428, 292
Lépine, S., & Moffat, A. F. J. 1999, ApJ, 514, 909
Lépine, S., Moffat, A. F. J., & Henriksen, R. N. 1996, ApJ, 466, 392
Maeder, A. 1999, A&A, 347, 185
Maeder, A., & Meynet, G. 2000, A&A, 361, 159
Martins, F., Schaerer, D., Hillier, D. J., & Heydari-Malayeri, M. 2004, A&A, 420, 1087
Martins, F., Schaerer, D., Hillier, D. J., Meynadier, F., Heydari-Malayeri, M., & Walborn, N. R. 2005, A&A, 441, 735
Massa, D., Fullerton, A. W., Sonneborn, G., & Hutchings, J. B. 2003, ApJ, 586, 996
McGregor, P. J., Hyland, A. R., & Hillier, D. J. 1988, ApJ, 324, 1071
Najarro, F., Hillier, D. J., & Stahl, O. 1997, A&A, 326, 1117
Nota, A., Livio, M., Clampin, M., & Schulte-Ladbeck, R. 1995, ApJ, 448, 788
Oudmaijer, R. D., & Drew, J. E. 1999, MNRAS, 305, 166
Oudmaijer, R. D., Proga, D., Drew, J. E., & de Winter, D. 1998, MNRAS, 300, 170
Owocki, S. 2005, in ASP Conf. Ser. Vol. 337, The Nature and Evolution of Disks Around Hot Stars, ed. R. Ignace & K. G. Gayley (San Francisco: ASP), 101
Owocki, S. 2006, in ASP Conf. Ser., Stars With the B[e] Phenomenon, ed. M. Kraus & A. S. Miroshnichenko (San Francisco: ASP), in press
Owocki, S. P., Castor, J. I., & Rybicki, G. B. 1988, ApJ, 335, 914
Owocki, S. P., Cranmer, S. R., & Gayley, K. G. 1996, ApJ, 472, L115
Pauldrach, A., Puls, J., & Kudritzki, R. P. 1986, A&A, 164, 86
Pelupessy, I., Lamers, H. J. G. L. M., & Vink, J. S. 2000, A&A, 359, 695
Porter, J. M. 2003, A&A, 398, 631
Porter, J. M., & Rivinius, T. 2003, PASP, 115, 1153
Robert, C. 1994, Ap&SS, 221, 137
Schulte-Ladbeck, R. E., Clayton, G. C., Hillier, D. J., Harries, T. J., & Howarth, I. D. 1994, ApJ, 429, 846
Shore, S. N., & Sanduleak, N. 1983, ApJ, 273, 177
Smith, N., Davidson, K., Gull, T. R., Ishibashi, K., & Hillier, D. J. 2003, ApJ, 586, 432
Stahl, O., Wolf, B., Zickgraf, F.-J., Leitherer, C., Bastian, U., & de Groot, M. J. H. 1983, A&A, 120, 287
Struve, O. 1931, ApJ, 73, 94
Surdej, A., Surdej, J., Swings, J. P., & Wamsteker, W. 1981, A&A, 93, 285
ud-Doula, A., & Owocki, S. P. 2002, ApJ, 576, 413
van Genderen, A. M., & Sterken, C. 2002, A&A, 386, 926
Vink, J. S., & de Koter, A. 2002, A&A, 393, 543
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 1999, A&A, 350, 181
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2000, A&A, 362, 295
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574
von Zeipel, H. 1924, MNRAS, 84, 665
Wood, K., Bjorkman, K. S., & Bjorkman, J. E. 1997, ApJ, 477, 926
Zickgraf, F.-J. 1992, in ASP Conf. Ser. Vol. 22, Nonisotropic and Variable Outflows from Stars, ed. L. Drissen, C. Leitherer, & A. Nota (San Francisco: ASP), 75
Zickgraf, F.-J. 2003, A&A, 408, 257
Zickgraf, F.-J., & Schulte-Ladbeck, R. E. 1989, A&A, 214, 274
Zickgraf, F.-J., Wolf, B., Leitherer, C., Appenzeller, I., & Stahl, O. 1986, A&A, 163, 119
Zickgraf, F.-J., Wolf, B., Stahl, O., & Humphreys, R. M. 1989, A&A, 220, 206
Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., & Klare, G. 1985, A&A, 143, 421