THE STRUCTURE OF THE CIRCUMSTELLAR MATERIAL IN BE STARS

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Abstract. We review observations that are relevant for the determination of the structure and geometry of the circumstellar envelopes of Be stars. Evidence is summarized suggesting that Be stars have rotating discs. Infrared and radio continuum and line measurements and their interpretation are discussed.

1. Introduction

One of the controversial issues in trying to understand the nature of Be stars has been the question of the geometry of their circumstellar envelopes. Extensive discussions in the literature can be found (e.g. Slettebak & Snow 1987). In this review we discuss recent observations which we believe are relevant to the question of the structure of Be star envelopes. The conclusion that can be drawn from these studies is that the envelopes of Be stars are very likely rotationally flattened rather than being (roughly) spherically symmetric, and hence the term *disc-like* would be appropriate. However the detailed structure (velocity field, both rotational and radial; density, radial and in the z direction) remains quite uncertain despite considerable efforts.

2. Optical Emission Lines

The strength and shape of emission lines in the optical spectra of Be stars are important tools to constrain the geometry of their envelopes. This has been investigated in some detail by Dachs and coworkers (Dachs *et al.* 1986; 1992; Hanuschik 1987, 1989) using high resolution and high S/N spectra of Balmer lines and of Fe II emission lines. These studies show that there is a correlation between the FWHM of Hα, its strength and $v \sin i$ (Dachs *et al.* 1986). Such a correlation strongly points to rotation as being the cause of the line broadening in Be star discs and also suggests that the geometry should be highly non-spherical. More recently, Hanuschik (these

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Proceedings) showed that a correlation between the FWHM and $v \sin i$ also exists for the Fe II lines.

Both the Hα line and the Fe II lines are found to be (much) wider than the rotation of the underlying star would permit. For Hα, part of the line width can be explained by electron scattering, which produces broad, weak emission wings that can easily extend to $\pm$ 1000 km s^{-1}. However even when electron scattering is included the Hα line width in many Be stars exceeds the value expected on the basis of $v \sin i$. This additional broadening was explained by Hummel & Dachs (1992) as a radiative transfer effect in very optically thick lines, where the line photons tend to escape from the line by slightly shifting their frequency (non-coherent scattering) thus broadening the observed line. However such an explanation cannot account for the observed widths in the optical Fe II lines, that also are systematically wider (by about 20 per cent) than expected on the basis of $v \sin i$ (e.g. Hanuschik these Proceedings). Therefore the inner regions of the discs of Be stars may rotate more rapidly than the underlying star, perhaps being in Keplerian orbits. If this is the case, some angular momentum transfer is necessary, and it might solve the problem of the dynamical support of the gas in the disc. Alternately, the $v \sin i$ values of *all* Be stars may be underestimated by some 20 per cent. However this would imply that several stars actually rotate at their Keplerian speed.

3. Hydrogen IR Recombination Lines

The recent improvement in IR detector technology allows us to observe the H I and He I recombination lines of Be stars the near-IR and mid-IR with high spectral resolution and high S/N. These lines are important diagnostic tools because they cover a large range in wavelength and line strength, and thus probe different layers of the envelope. Furthermore the underlying photospheric absorption lines are weak and we get a better view of the disc emission. In Fig. 1 we show the Brγ lines of ψ Per and 59 Cyg, taken in July of 1992 with the CGS4 spectrograph, UKIRT, Hawaii. Both profiles look different from what would be expected from a rotating, roughly Keplerian disc which is optically thin.

In ψ Per the Brγ profile shows peculiar wings that suggest that the bulk of the emission is superimposed on a plateau with a width of $2 \times v \sin i$. The shape of the wings rules out an origin in terms of electron scattering, since that will only produce smooth features. The wings disappear in Brα, probably because the optical depth of the line and the free-free continuum increase to the point that the layers in which this emission is formed are blocked from view. Because the wings are symmetric they are probably located near the surface of the star in the disc. Interestingly, the Hα line of ψ Per has a width which is comparable to the Brγ total width, but does not

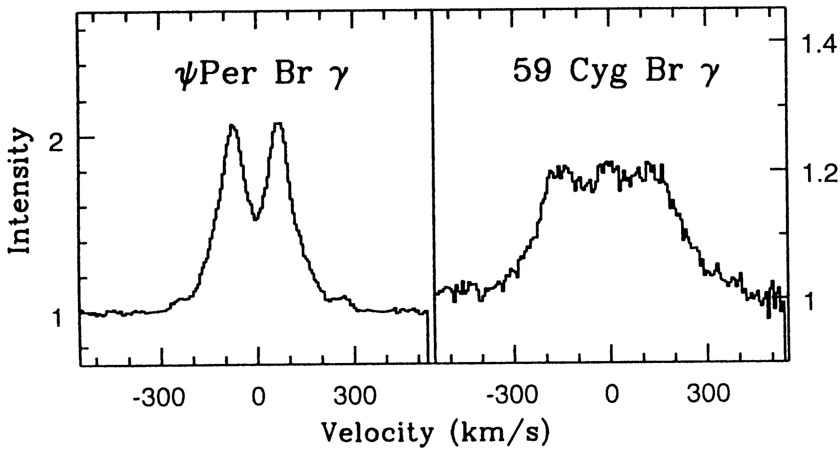

Fig. 1. **High-resolution, high S/N Brγ lines for ψ Per and 59 Cyg. Notice the plateau in ψ Per and the broad emission in 59 Cyg.**

show the plateau.

The Brγ profile of 59 Cyg is most peculiar. The emission is weak, i.e. the star has a weakly developed disc. The width of the line is about 810 km s^{-1} which considerably exceeds $2\times v \sin i$ ($v \sin i$ = 260 km s^{-1}, Slettebak 1982). Since the emission is weak it is unlikely that the broadening is due to electron scattering and must be due to doppler broadening. The symmetry of the line then points to rotational broadening. This implies that either the star rotates much faster than thought up to now, or that the disc rotates faster than the star. If this is the case then angular momentum must be transferred to the gas in the disc. The line profile also strongly deviates in shape from what is expected for a low-density disc. The flat top, with even a hint for *three* peaks, cannot be explained in terms of a rotating Keplerian disc. Flat-topped profiles are expected for optically thin spherical winds with constant outflow velocity, but that situation probably does not apply in this case.

4. The Infrared and Radio Continuum

The increase in sensitivity of (sub-)mm and radio telescopes in the past five years has resulted in the detection of a few IRAS-bright Be stars at those wavelengths. The first detection was of the B5 Ve star ψ Per at 6 cm using the *VLA* (Taylor *et al.* 1987). This detection demonstrates that the extent of Be star envelopes can be very large indeed, and that the term 'wind' for the high-density part of the envelope seems appropriate at least in some cases. The spectral slope of the continuum was found to be significantly steeper

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than that found from IRAS data.

A subsequent more extensive *VLA* survey of 22 IRAS-selected Be stars at 2 cm resulted in the detection of another 5 Be stars (Taylor *et al.* 1990) covering the spectral range from B0.5 to B8. In almost all cases the spectral index found from the radio measurements was significantly steeper than that from IRAS 12 to 60 μm data, typically $S_\nu \propto \nu^\alpha$ with $\alpha \approx$ 0.6-1 in the IRAS data and >1 in the radio. Therefore a *turnover* in the spectrum must occur somewhere between the IR and radio. A *VLA* radio survey of Be stars by Apparao *et al.* (1991) did not yield detections.

The position of the turnover was investigated by Waters *et al.* (1991) who reported the detection of the 6 Be stars, previously detected with the *VLA*, at wavelengths of 0.8 and 1.1 mm using the *JCMT* Bolometer UKT14. The turnover in the spectral index occurs in the sub-mm wavelength range for most of the stars, except perhaps for γ Cas whose turnover was found roughly at 60 μm.

It is important to recognise that the steepening of the radio spectrum is quite contrary to the behaviour expected for a wind flowing out and reaching a terminal velocity. In the case of a spherically symmetric outflow or an outflow in a disc with constant opening angle a spectral index of 0.6 is expected (e.g. Wright & Barlow 1975). The origin of the steepening of the spectral index is as yet not well understood. Taylor *et al.* (1990) suggest several possibilities, such as recombination at large distances from the star, re-acceleration or a change in geometry.

Model calculations of the ionisation/excitation equilibrium in circumstellar discs around B stars indicate that the degree of ionisation stays roughly constant or increases slightly outwards (Waters *et al.* 1991), suggesting that recombination cannot explain the observations. Similar conclusions were also found by Poeckert & Marlborough (1982) using their model. However all calculations so far assumed a constant temperature, which may not be a very realistic approximation.

Chen *et al.* (1992) have interpreted the shape of the IR to radio continuum in terms of an additional acceleration of the gas at large distance from the star, and found that the driving force, which they called F_x, should be very small near the star but should dominate all other forces at distances beyond 10-100 R_*. It is not clear however what the nature of this force could be. Chen *et al.* (1992) suggest that stellar UV continuum radiation, unable to penetrate deep into the disc near the star where densities are high, could succeed in doing so at larger distance, especially if the disc near the star is very thin in the z direction. Marlborough *et al.* (1993) suggest that in Be stars the force F_x dominates all other forces at a smaller distance from the star than in shell stars.

Could the turnover be the result of a change in geometry? Indeed slab models have steeper continuum slopes than models with a diverging geome-

TABLE I

Effect of geometry on the slope of the excess flux ratio Z_ν

n	spherical	pole-on slab	edge-on slab
2	0.67	0.50	0.33
2.5	0.50	0.40	0.25
3.0	0.40	0.33	0.20
3.5	0.33	0.29	0.17
4.0	0.29	0.25	0.14

try with the same density gradient (e.g. Cassinelli & Hartmann 1979; Waters 1986a). In Table 1 we compare the expected slope of the excess flux ratio $Z_\nu = F_\nu^{tot}/F_\nu^*$ as a function of the optical depth parameter E_ν (Waters 1986a), where $E_\nu \propto \lambda^2(g+b)$, for a simple disc model and for a slab model using a power-law density distribution $\rho(r) \propto r^{-n}$. The slab models are capable of reproducing the observed mm-cm slope for n = 2, i.e. a constant outflow velocity model.

The consequence of this interpretation would be that the discs of Be stars have an inner region which has a diverging geometry (in order to explain the flat IRAS continuum slope) and an outer region which is more slab-like. The question then arises what causes such a change in geometry, at a relatively large distance from the star. We will come back to this point in Sect. 7.

The near-IR energy distribution of a large sample of Be stars was studied by Dougherty *et al.* (1994) using the simple disc model of Waters (1986a). The IR excesses were derived by constructing optical-IR colour-colour diagrams for normal stars using the Geneva system and the ESO JHKL system (Dougherty *et al.* 1993), and by comparing the observed colours of Be stars to these intrinsic colour-colour relationships. We show the excess colour-colour diagrams in Fig. 2. Panel (a) shows the effect of different density gradients ($\rho(r) \propto r^{-n}$, n=2,2.5,..,5) for pole-on discs (solid lines) and edge-on discs (n = 3,4; dotted lines). Panels (b) to (d) show the effect of disc radius, opening angle and disc temperature for edge-on models. For small excesses or at short wavelengths the emission is optically thin and so no information on the density structure can be obtained. However for a significant fraction of stars the optical depth in the disc at the L-band is already significant (large K-L colour excess). Comparison of models and observations shows that the simple model can describe the near-IR excess of Be stars in most cases, but that the value of the density gradient parameter n is larger than about 3. This is steeper than the value found by Waters *et al.* (1987) from IRAS data but agrees reasonably well with the range of slopes found from

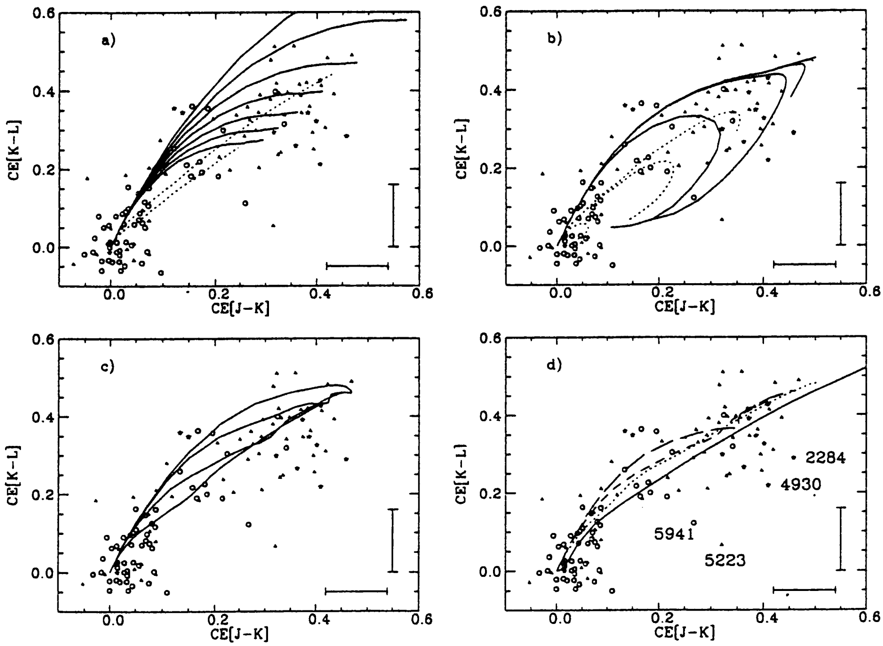

Fig. 2. Near-IR excess colour-colour diagram for Be stars (taken from Dougherty *et al.* (1994)). See text for details.

the mm-radio continuum. Dougherty *et al.* (1994) show that part of this effect may be due to the assumption that the disc is viewed pole-on. Some stars fall significantly below the model curves for any reasonable choice of the density distribution. These stars may have a different disc geometry (e.g. slab-like), or a small outer disc radius.

In summary the near-IR slope of the continuum energy distribution *and* the mm-radio continuum may point to a steeper spectral index than the IRAS data. As discussed above, this may be related to changes in geometry in combination with changes in the density/velocity gradient.

5. Mass Loss Rates

The mass loss rates of Be stars are quite uncertain because of our poor knowledge of the wind geometry and ionisation structure. The latter uncertainty especially affects the UV mass loss rates derived from e.g. Si IV and C IV (for a review see Snow 1987). The equatorial mass loss rates are mainly based on the IR excess (Waters 1986a; Waters *et al.* 1987) and are uncertain because of the unknown opening angle of the disc and the initial outflow velocity $v(r = R_*)$, which were fixed to 15 degrees and 5 km s^{-1} respectively. This initial velocity was based on estimates derived from detailed fitting of the Hα line of a limited number of Be stars (in particular γ Cas and ϕ Per) by Poeckert & Marlborough (1978a; 1979).

In the case of γ Cas the initial velocity of 7 km s^{-1} probably is overestimated considerably. This is because the Hα line profile that was used by Poeckert & Marlborough was taken when the star was in a phase when the Violet peak of the emission line was weaker than the Red one. Such a line profile can be explained with a rotating and expanding disc. However the shape of the Balmer emission lines in γ Cas is affected by the cyclic V/R variability, in which phases with V>R and V<R alternate on a timescale of several years (e.g. Doazan *et al.* 1987). The V/R variability probably results from one-armed spiral density waves that propagate in the disc (Okasaki 1991; Papaloizou *et al.* 1992; Savonije & Heemskerk 1993). Indeed, Telting *et al.* (1993) have shown that the V/R variations in γ Cas do not affect the radial density structure of the disc strongly. Therefore the velocity law in γ Cas cannot be derived from Hα unless the effects of such density waves on the line profiles are taken into account.

The effect of a high initial outflow velocity on the Hα line was already pointed out by Poeckert & Marlborough (1978b) who used their γ Cas model but assumed an inclination angle of 90 degrees (for γ Cas the inclination angle was taken at 45 degrees). The resulting line shows a P Cygni profile, which is hardly ever observed in Be stars that are assumed to be viewed edge-on, suggesting that the radial outflow velocity in the γ Cas model is too high.

An analysis of the infrared recombination lines of ψ Per by Zijlstra *et al.* (in preparation) showed that in order to reproduce the shape of the line profiles, an expansion velocity of less than about 1 km s^{-1} at $r = R_*$ is required, i.e. more than a factor 5 lower than assumed by Waters *et al.* (1987). This would result in IR mass loss rates that are a factor 5 lower; for ψ Per it would reduce to 2.5 10^{-9} $M_\odot$/yr, compared to an UV mass loss rate of 8 10^{-11} $M_\odot$/yr (Snow 1981). Note however that in the analysis of Waters *et al.* (1987) a total opening angle of the disc of 30 degrees was used. Reducing this opening angle would result in an increase of the equatorial mass loss rate.

Can the mass loss rates from the UV and from the IR be roughly equal? Such a question is difficult to answer given the uncertainties noted above. The X-ray luminosities observed in Be/X-ray binaries indicate that the *mass flux* near the neutron star must be considerably higher than expected on the basis of the UV mass loss rates (Waters *et al.* 1988).

6. The Wind Compressed Disc Model

The wind compressed disc (WCD) model developed by Bjorkman & Cassinelli (1993; see also J. Bjorkman these Proceedings) predicts the formation of a very thin disc in the equatorial regions of rapidly rotating stars that have radiation-driven winds. This idea is very attractive because for the first time a model is able to explain the existence of discs quantitatively by using properties of hot stars that are well understood. The numerical calculations of Owocki *et al.* (1993) confirm the analytical calculations by Bjorkman & Cassinelli (1993). These theoretical developments as well as advances in observational techniques strongly suggest that Be stars indeed have discs.

However, the WCD model does have some serious difficulties in explaining the observed properties of Be stars (some of these were already pointed out by Bjorkman & Cassinelli). The main difficulty is the predicted density in the disc, which is a factor 100 lower than observed. Also the infall of material inside the stagnation point, with outflow beyond the stagnation point, does not agree with observations of line profile shapes of optical and IR HI recombination lines. These line profiles clearly point to a rotating disc without strong radial motions. A third difficulty is the opening angle of the disc, which is of the order of 1 degree. Such thin, dense discs would show a very strong dependence of IR excess on inclination, which is not observed (e.g. Dougherty *et al.* 1991; Waters 1986b). It would also be difficult to explain the statistics of shell stars, which require opening angles of the order of 10 degrees (Hanuschik these Proceedings).

The steady-state WCD model by definition is unable to explain the strong variability in Be stars. A critical test of the WCD model will be a determination of the rate of increase of the emission measure of the disc during an outburst of a Be star such as the ones observed in μ Cen by Baade *et al.* (1988), since in the WCD model the disc is fed by the radiation-driven wind (we thank L. Kaper and J. Telting for pointing this out). If the rate of increase of the mass in the disc cannot be accounted for, another mass loss mechanism must be effective in Be stars.

7. The Geometry of Be-star Discs

Be stars have now been imaged directly in the Hα line (see Vakili these Proceedings) and in the radio (Dougherty & Taylor 1992). In the case of ψ Per the alignment between the optical and radio images is very good, and also the position angle of the linear polarisation is perpendicular to the semi-major axis of the intensity distribution. These observations strongly support the disc-like geometry of Be star envelopes.

Useful information about the geometry of Be star discs can also be obtained from a comparison of the emission in e.g. Hα and the near-IR.

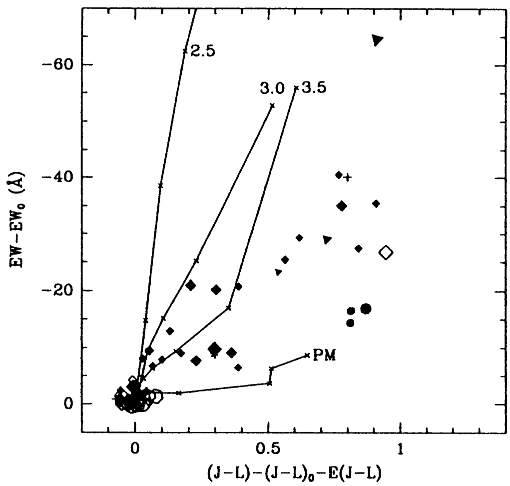

Fig. 3. Correlation between Hα excess emission and (J-L) colour excess (taken from van Kerkwijk *et al.* 1994). The solid lines are the model curves for the disc model with different radial density gradients, and the PM model. Both models have difficulty explaining the observations

Many studies have shown that a correlation between IR excess and Hα line strength exists (e.g. Ashok *et al.* 1984; Dachs *et al.* 1988) but only a few attempts have been made to reproduce quantitatively the observed correlations.

Kastner & Mazzali (1989) used a pole-on slab model to calculate Hα line flux and near-IR excess, and found that they can reproduce the observed correlations quite well. It is not clear however what the effects of a different inclination angle would be on their results. More recently, van Kerkwijk *et al.* (1994) have used two models, the disc model introduced by Waters (1986a) and the Poeckert & Marlborough (1978a; PM) model, to calculate theoretical correlations between IR excess and Hα emission (Fig. 3), and compared them to simultaneously obtained optical and near-IR data. They find that the disc model produces *much too strong* Hα emission for reasonable choices of the density gradient parameter n, and that the PM model gives *much too weak* Hα emission. Since the near-IR and Hα probe quite different regions in the disc it is obvious that in both models the density/velocity structure is wrong. The disc model has too much material at large distance, the PM model too little. The fact that the disc model produces too much Hα is consistent with the fact that it also predicts too much mm and cm radiation.

The WCD model may have a strong effect on the geometry of an (existing) disc. The collimating effect of the fast radiation-driven wind near the star, which in the WCD model is responsible for *producing* the disc, may, in the

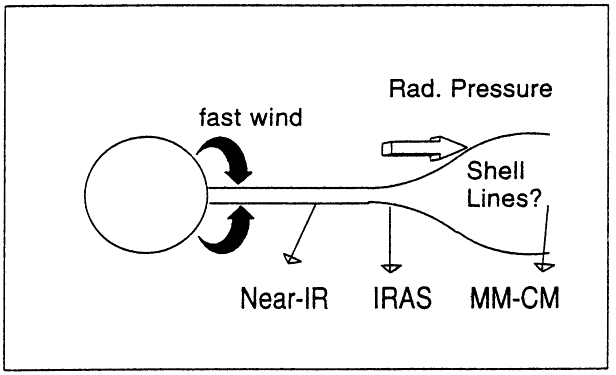

Fig. 4. A possible geometry of Be star discs. Near the star the disc is thin and confined because of the collimating effect of the polar wind. At some distance the disc flares (not necessarily to the same thickness as the stellar radius) and the gas is accelerated radially by the strongly forward peaked radiation field.

case of an *existing* disc produced by some other mechanism, cause this disc to be effectively confined to regions very close to the equatorial plane. At larger radial distance from the star this confinement is much less efficient and therefore the disc may flare. When this happens, the radiation force from the central star, which is strongly forward peaked, can accelerate the gas which is flaring out. The resulting geometry is sketched in Fig. 4, and we call this model the wine-bottle model (not to be confused with so-called wine-bottle Hα line profiles).

Such a model would produce a continuum energy distribution which is rather steep in the near-IR, would flatten somewhat when the disc opens up, and would steepen again when the gas is accelerated to a terminal velocity. As discussed in Sect. 4, such an energy distribution would not be inconsistent with observations. However detailed model calculations are required to verify this. A flaring of the disc would also circumvent the difficulty of the statistics of shell stars, since the shell absorption lines could be formed in the region where the disc begins to flare out. The model is consistent with the observations of Be/X-ray binaries, since it can have both an inner region dominated by rotation (where the Hα line is formed) and an outer region dominated by expansion (where the neutron star is located).

Acknowledgements

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References

Apparao, K.M.V., Rengarajan, T.N., Tarafdar, S.P. and Ghosh, K.K.: 1991, *Astron. Astrophys.* **229**, 141.

Ashok, N.M., Bhatt, H.C., Kuhlkarni, P.V. and Joshi, S.C.: 1984, *Mon. Not. Roy. Astr. Soc.* **211**, 471.

Baade, D., Dachs, J., can de Weygaert, R. and Steeman, F.: 1988, *Astron. Astrophys.* **198**, 211.

Bjorkman, J.E. and Cassinelli, J.P.: 1993, *Astrophys. J.* **409**, 429.

Cassinelli, J.P. and Hartmann, L.: 1979, *Astrophys. J.* **212**, 488.

Chen, H., Marlborough, J.M. and Waters, L.B.F.M.: 1992, *Astrophys. J.* **384**, 604.

Dachs, J., Hanuschik, R., Kaiser, D. and Rohe, D.: 1986, *Astron. Astrophys.* **159**, 276.

Dachs, J., Engels, D. and Kiehling, R.: 1988, *Astron. Astrophys.* **194**, 167.

Dachs, J., Hummel, W. and Hanuschik, R.W.: 1992, *Astron. Astrophys. Suppl.* **95**, 437.

Doazan, V., Rusconi, L., Sedmak, G., Thomas, R.N. and Bourdonneau, B.: 1987, *Astron. Astrophys.* **182**, L25.

Dougherty, S.M., Taylor, A.R. and Clark, T.A.: 1991, *Astron. J.* **102**, 1753.

Dougherty, S.M. and Taylor, A.R.: 1992, *Nature* **359**, 808.

Dougherty, S.M., Cramer, N., van Kerkwijk, M.H., Taylor, A.R. and Waters, L.B.F.M.: 1993, *Astron. Astrophys.* **273**, 503.

Dougherty, S.M., Waters, L.B.F.M., Burki, G., Cramer, N., van Kerkwijk, M.H. and Taylor, A.R.: 1994, *Astron. Astrophys.* in press.

Hanuschik, R.W.: 1987, *Astron. Astrophys.* **173**, 299.

Hanuschik, R.W.: 1989, *Astrophys. Space Sci.* **161**, 61.

Hummel, W. and Dachs, J.: 1992, *Astron. Astrophys.* **262**, L17.

Kastner, J.H. and Mazzali, P.A.: 1989, *Astron. Astrophys.* **210**, 295.

Kogure, T.: 1990, *Astrophys. Space Sci.* **163**, 7.

Marlborough, J.M., Chen, H. and Waters, L.B.F.M.: 1993, *Astrophys. J.* **408**, 646.

Okasaki, A.T.: 1991, *Publ. Astr. Soc. Japan* **43**, 75.

Owocki, S.P., Cranmer, S.R. and Blondin, J.M.: 1993, *Astrophys. J.* in press.

Papaloizou, J.C., Savonije, G.J. and Henrichs, H.F.: 1992, *Astron. Astrophys.* **265**, L45.

Poeckert, R. and Marlborough, J.M.: 1978a, *Astrophys. J.* **220**, 940.

Poeckert, R. and Marlborough, J.M.: 1978b, *Astrophys. J. Suppl.* **38**, 229.

Poeckert, R. and Marlborough, J.M.: 1979, *Astrophys. J.* **233**, 259.

Poeckert, R. and Marlborough, J.M.: 1982, *Astrophys. J.* **252**, 196.

Savonije, G.J. and Heemskerk, M.H.M.: 1993, *Astron. Astrophys.* **276**, 409.

Slettebak, A.: 1982, *Astrophys. J. Suppl.* **50**, 55.

Slettebak, A. and Snow, T.P.: 1987, *Physics of Be Stars: IAU Colloquium 98*, Cambridge Univ. Press: Cambridge.

Snow, T.P.: 1981, *Astrophys. J.* **251**, 139.

Snow, T.P.: 1987, in Slettebak, A. and Snow, T.P., eds., *Physics of Be Stars: IAU Colloquium 98*, Cambridge Univ. Press: Cambridge, 250.

Taylor, A.R., Waters, L.B.F.M., Lamers, H.J.G.L.M., Persi, P. and Bjorkman, K.S.: 1987, *Mon. Not. Roy. Astr. Soc.* **228**, 811.

Taylor, A.R., Waters, L.B.F.M., Bjorkman, K.S. and Dougherty, S.M.: 1990, *Astron. Astrophys.* **231**, 453.

Telting, J.H., Waters, L.B.F.M., Persi, P. and Dunlop, S.R.: 1993, *Astron. Astrophys.* **270**, 355.

Van Kerkwijk, M.H., Waters, L.B.F.M. and Marlborough, J.M.: 1994, *Astron. Astrophys.* submitted.

Waters, L.B.F.M.: 1986a, *Astron. Astrophys.* **162**, 121.

Waters, L.B.F.M.: 1986b, *Astron. Astrophys.* **159**, L1.

Waters, L.B.F.M., Coté, J. and Lamers, H.J.G.L.M.: 1987, *Astron. Astrophys.* **185**, 206.

Waters, L.B.F.M., Taylor, A.R., van den Heuvel, E.P.J., Habets, G.M.H.J. and Persi, P.: 1988, *Astron. Astrophys.* **198**, 200.

Waters, L.B.F.M., van der Veen, W.E.C.J., Taylor, A.R., Marlborough, J.M. and Dougherty, S.M.: 1991, *Astron. Astrophys.* **244**, 120.
Wright, A.E. and Barlow, M.J.: 1975, *Mon. Not. Roy. Astr. Soc.* **170**, 41.

Discussion

Friedjung: As a non-member of the Be community, I would like to be clear about your assumptions when you determine disc densities and mass loss rates. Are you sure that all the hydrogen of the disc is ionized? If you have enough matter, all will not be ionized by radiation from the star.

Waters: The observed IR excess gives information about the ionized part of the envelope only. The fact that some Be stars, even of late B spectral type, are detected in the radio, suggests that a significant fraction of the envelope remains ionized out to large distances from the star. If a large amount of neutral material were present, one would expect to see emission from neutral metals (Fe I, Ni I, etc.) and also the formation of dust grains. Such things are not generally observed.

Kogure: What is the essential difference between ordinary Be and shell stars? It is evident that the discs of shell stars are optically thicker than those of Be stars, but what determines the structure of these two types of stars?

Waters: The shell stars may simply be Be stars with a very dense disc seen at inclination angles close to 90°. Possibly shell stars have a different disc structure in that the disc flares out relatively close to the star so that a large fraction of the stellar disc is covered by material from the disc even at moderate inclination angles, resulting in deep absorption lines.

Kogure: I would like to stress the importance of analysing the lines of the higher members of the Balmer series. These lines provide useful information on the envelope structure of shell stars (Kogure 1990).

Polosukhina: What do polarization observations tell us?

Waters: The linear polarization observed in Be stars indicates that the scattering electrons are distributed in a non-spherically symmetric manner. As such, polarization places important constraints on the geometry, but in many cases the solution is not unique (model dependant). See K. Bjorkman (these Proceedings) for more detail.

Hanuschik: I would like to bring to your attention observations of the Fe II λ5317 shell line in *o* Aqr in 1989 October. Shell lines are sensitive tracers of the *radial* component of the velocity field in the disc. Now, the profile of this line is the narrowest feature we have ever observed in a Be/Be-shell star. It is unresolved at the 6 km s^{-1} instrumental resolution. The full Doppler width of iron at 10^4K being about 4 km s^{-1}, the residual range for any radial motion (inflow/outflow) in front of the star is only 1 or 2 km s^{-1}! This is a very tough upper limit for any outflow model.

Waters: The Hα and IR hydrogen recombination lines of ψ Per also indicate that there is only a very small radial motion, although the IR continuum suggests that $v(r)$ increases roughly as $\sqrt{r}$.

Owocki: How can one reconcile the evidence you mention (e.g. in X-ray binaries) for outflow of the order of $\sim$ 100 km s^{-1} in the outer disc with observations of narrow circumstellar Fe lines with very low outflow velocity ($<$ 10 km s^{-1})?

Waters: Shell lines clearly indicate much lower radial outflow velocities than the Be/X-ray binaries suggest. The Be/X-ray binaries known so far, however, have early spectral type (in the range O9–B2III) and radiation pressure exerted by the central star may have a significant effect on the radial outflow of these stars. This is consistent with the fact that γ Cas has the steepest IR to radio continuum of the objects detected so far. I would expect, if radiation forces play a role, that later B-type stars should have significantly lower outflow velocities than earlier types and also that it depends on the density in the disc.

Saraswat: I have two comments regarding Be/X-ray binaries:

(1) We have used the "short" period Be/X-ray binary 4U1907+09 to test the predictions of the "ellipsoidal" model proposed by Doazan & Thomas. We find this model is unable to predict the X-ray luminosity of this binary. The neutron star lies in the coronal/wind region where the density is low and the wind velocity is high. Hence the X-ray luminosity predicted by this model is lower by several orders of magnitude.

(2) The disc model can explain the X-ray light curve of this source. However, we find that the disc is *not* continuous with a uniform density, but the Be star ejects multiple *rings* with different initial density values and gradients. Also these rings have different outflow velocities (in the range 100–250 km s^{-1}). One could say that the Be star ejects "puffs" of matter.

Waters: The nature of 4U1907+09 is not clear. It may be a supergiant system rather than a Be/X-ray binary.