WINDS FROM ROTATING WOLF-RAYET STARS: THE WIND-COMPRESSED ZONE MODEL

J.P. CASSINELLI, R. IGNACE AND J.E. BJORKMAN
Department of Astronomy, The University of Wisconsin, Madison, WI, U.S.A.

Abstract. Theoretical models for Wolf-Rayet winds that include the effects of rotation and magnetic fields are discussed. These are of two types: magnetic rotator models and wind compression models. The magnetic rotator models are examples of equatorial expulsion models, typically requiring large rotation rates to produce significant equatorial density enhancements. Wind- compression models are introduced here as an application of the two-dimensional Wind-Compressed Disk (WCD) model that has recently been developed for Be stars. An equatorial disk forms because of the supersonic confluence of the flow from the upper and lower hemispheres of the star. In the application to WR stars, we suggest that disk formation is not required, and instead a less extreme example that we call a wind-compressed zone (WCZ) may suffice. Because the winds of WR stars have a geometrically extended acceleration region, or a "slow" velocity law, there can be compressions by an order of magnitude, even with moderate stellar rotation rates of about 16% critical. Magnetic flux conservation is then used to estimate the enhancement of the field strength that occurs because of the equatorial wind-compression. We consider an application of the model to explain the occurrence of polarization and dust formation among only some WR stars. Finally, we consider the WR + compact companion system WR 147, and suggest that the enhanced accretion in a WCZ could help explain the large X-ray emission.

1. Introduction

This paper is concerned with theoretical models that can explain an equatorial enhancement of density in a Wolf-Rayet wind. There are indications from observations that at least some WR stellar winds are asymmetrically distributed about the star (Schulte-Ladbeck *et al.* 1991, and these proceedings).

The equatorially enhanced winds are of two main types that we call *equatorially expelled*, and *wind-compressed*. Equatorial expulsion models are those in which the material is spun out from the equator of a star as a result of rapid rotation; the amount of material can be significantly enhanced if there is a magnetic field present. An example for the WR stars is the magnetic rotator model of Poe, Friend & Cassinelli (1989). The expulsion models for hot stars are basically one-dimensional in that the equations are solved for the equatorial flow alone, and the wind from the polar regions is assumed to be that expected from a non-rotating star.

Wind-compressed models are two-dimensional; flow from higher latitudes is brought toward the equator as a result of the interplay between gravity and rotation. The wind from both hemispheres converges toward the equator and a wind-compression results. If the flow speed perpendicular to the equator is supersonic, then a pair of shocks form above and below the equator.

K. A. van der Hucht and P. M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, 191–202.

Between the two shocks, the post-shock cooling creates a *very* dense disk, called the wind-compressed disk (WCD). Our discussion here is based on the WCD model for Be stars as has recently been developed by Bjorkman & Cassinelli (1993), Owocki, Cranmer & Blondin (1994), and Bjorkman (1994). In these Be star models, it is essential that the wind-compression produce shocks so that there is a 2–3 order of magnitude increase in the density, *i.e.*, an equatorial disk. This disk is necessary to explain the strong Balmer emission lines, IR continua excesses, and intrinsic polarization, while using only the relatively low mass-loss rate of Be stars. In the case of the WR models discussed in §3, we do *not* need to form a disk; the density compression without the equatorial shocks is adequate, so we call these models "wind-compressed zone" (WCZ) models to emphasize the difference from the Be stars.

The existing WCD models do not involve magnetic fields; however, for the purposes of this review, we have computed the enhancements of the magnetic field in a compressed wind model for the special case of weak field strengths. The presence of magnetic fields is of interest for several reasons. Magnetic fields can play a role in accelerating particles to relativistic energies in the wind shocks (White & Chen 1992). Surface fields could also help explain the tendency of WR stars to eject matter in the form of blobs, as has been inferred from polarization observations (Moffat & Robert 1992). If the fields are sufficiently strong, they can help drive a strong wind either by magnetic rotator effects (Poe *et al.* 1989), or by Alfvén wave driving enhancements (Koninx & Hearn 1992; dos Santos *et al.* 1993).

2. Magnetic rotator models

In two previous IAU symposia on WR stars, Cassinelli (1982, 1991) discussed magnetic rotator wind models, with the primary focus on explaining the WR "wind momentum problem".

The WR picture proposed by Poe *et al.* (1989) involves two components: the equatorial region, in which material is expelled from the equator of the star by the very rapid rotation, and a polar component, in which the wind is basically driven by the line-driving wind mechanism of Friend & Abbott (1986). The Poe *et al.* model required a rotation rate of $\omega = 87\%$ critical to match observational constraints. Taylor & Cassinelli (1992) calculated the polarization expected from such a model and argued that if WR winds are to be explained by the magnetic rotator model, the polar wind would have to be much stronger than that provided by line-driven wind theory. The polar wind must be denser to provide "cancellation" of the polarization produced in the equatorial component. In the context of the magnetic rotator model, the cancellation is required to explain why only a fraction of WR stars show strong line depolarization (the primary evidence for a rotationally distorted wind structure).

The magnetic field that can be used in rotating WR models must be in one of two domains as derived by Maheswaran & Cassinelli (1992). The values of the allowable magnetic field for WR parameters are shown in Cassinelli (1992). At a fast rotation rate of $\omega = 80\%$ critical, the two allowed ranges of the magnetic field are: $10^3 < B < 10^5$ and $B < 10$ Gauss. The high range is of interest for accelerating iron nuclei to cosmic ray energies in the supernova shocks present at the termination of the WR phase (Biermann & Cassinelli 1993), while fields in the the low range can play a role in the production of the non-thermal radio emission from WR stars (Abbott *et al.* 1986; Bieging *et al.* 1989; White & Chen 1992). At slow rotation rates of $\omega < 20\%$ critical that will be of interest in our WCZ model, the high and low ranges merge.

3. Wind-compression: two-dimensional models

The wind-compressed disk model differs in important ways from other rotational models. First of all, the disk does not arise from matter expelled from the equatorial zone of the star. Instead, it results from material originating over a wide range of latitudes on the star. Second, the star does not have to be rotating at speeds near the critical rotation speed, which was the case in the magnetic rotator and other purely equatorial models; for Be stars rotation speeds of half the critical speed may be sufficient for disk formation.

The tendency for the flow to converge toward the equatorial plane can be illustrated by considering a fluid element originating at some latitude above the equator. Since the forces acting on the fluid element are radial, the outflowing material remains in an orbital plane, and the azimuthal velocity is determined by conserving the angular momentum of the fluid element after it leaves the stellar surface. Figure 1 shows two trajectories of material flowing from the sonic point outward. In case (b) the radial forces are so large as to cause the flow to move outward and quickly develop a nearly radial trajectory. This is considered to be the case in O star winds. Case (a) shows a more interesting trajectory, in which the outward radial forces do not dominate the flow close to the star, so the trajectory bends around the star, bringing the material down toward the equator. If trajectories cross the equatorial plane, an equatorial wind-compressed disk forms.

The dependence of the flow trajectories on the velocity law has led us to consider the application of WCD concepts to the WR winds. There are arguments and models indicating that the radial velocity laws of WR stars tend to be slower than is the case for O stars, and the terminal speeds are lower. Cassinelli (1991) noted that in winds driven by multi-scattering lines, the acceleration persists over a wider range in radius. Observational evidence

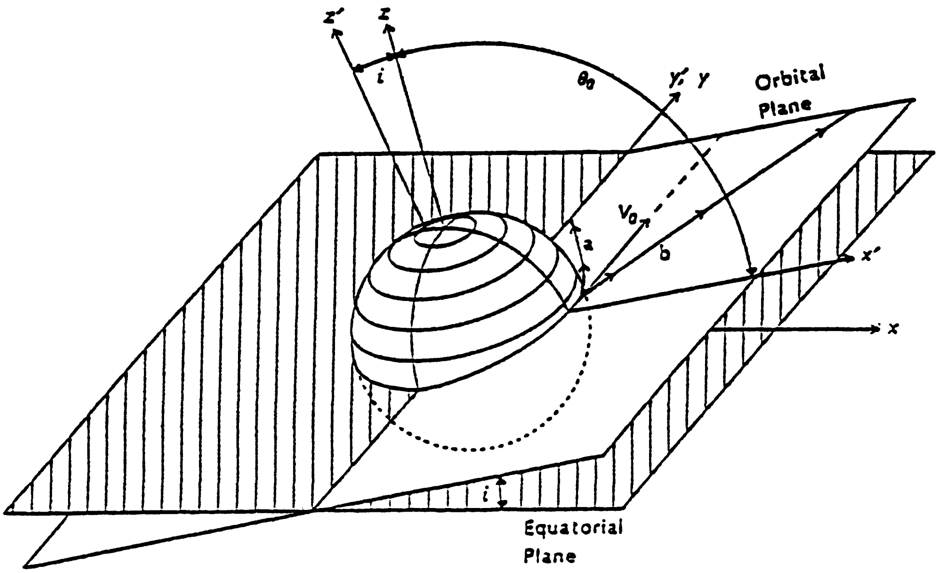

Fig. 1. This Figure shows trajectories in the orbital plane for a stream line originating at polar angle θ_o. The trajectory labeled (a) is one that would occur in a star with a high rotation rate, and a slowly accelerating wind. Conditions that lead to a preponderance of this type of stream line also lead to significant equatorial compression of the wind. The trajectory labeled (b) is for a slow rotator and fast wind acceleration. There is little tendency for the flow to form significant equatorial wind-compression in this case.

for the slow acceleration of WR winds has been presented by Koenigsberger (1990). This tendency for slow acceleration has also been found in the recent multi-scattering wind models by Springmann (1994) and Gayley, Owocki & Cranmer (1994). Whether or not multi-scattering is capable of fully explaining the high wind momenta of WR stars, the results of multi-scattering suggest that slowly accelerating winds are possible. Here we consider a kinematic description of the wind and investigate the wind-compression that results from the rotation of the star.

We use the "β velocity law" that is commonly used in studies of hot star winds:

$$v(r) = v_o + (v_\infty - v_o)(1 - R_o/r)^\beta , \qquad (1)$$

where v_o is the velocity at the base of the flow, R_o, which we take to be the sonic radius. The higher the β, the slower the increase of $v(r)$ toward the terminal speed, v_∞. For the rapidly accelerating winds of O stars, the velocity exponent, β, has a small value of about 0.5 to 0.8. For the more slowly accelerating velocity laws associated with WR winds, we assume that β has a higher value of 2 to 3.

https://doi.org/10.1017/S0074180900201952 Published online by Cambridge University Press

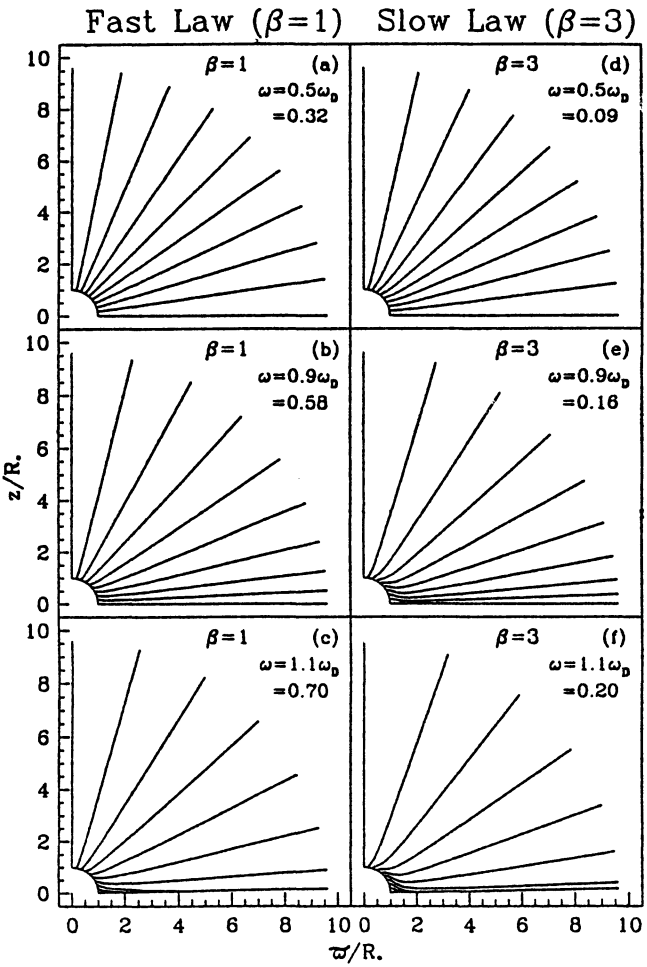

Fig. 2. Stream lines for various values of the rotation rate $\omega = v_{rot}/v_{crit}$. The stream lines originate at 10° increments in latitude, and the separation between the stream lines is an indication of the density in the wind. The ϕ-component of the motion is not shown. The left side of the Figure shows results for a star with a fast velocity law ($\beta = 1$). The right side shows results for a much slower velocity law ($\beta = 3$). On each panel we list the rotation rate both as a fraction of the disk formation rate, ω_D, and as a fraction of the critical rotation speed. The value of ω_D is 0.64 and 0.18 for the fast and slow laws, respectively.

The compression of material toward the equator is illustrated in Figure 2 for a WN5 star, for which $R_o = 3.7\,R_\odot$, $\dot{M} = 10^{-4.31}\ M_\odot yr^{-1}$, and $v_{crit} = 645\,km\,s^{-1}$ (Hamann, Koesterke & Wessolowski 1993). Note that there is less wind-compression for the faster velocity law. Panel (a) best represents the case for the O stars, which have high speed winds and a fast acceleration to the terminal speed. Panel (c) is the best representation of the Be stars,

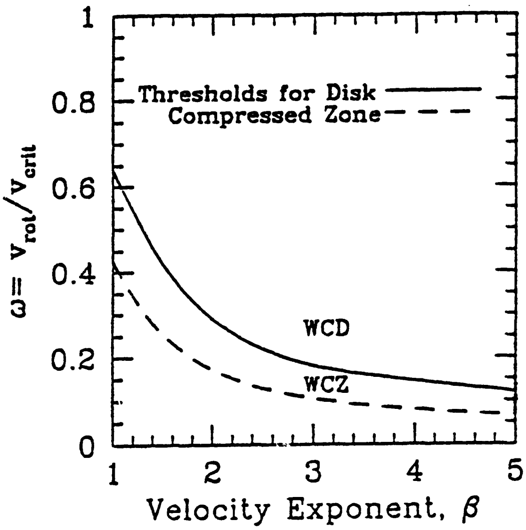

Fig. 3. Rotation rate ω required for wind compression *vs.* the velocity law exponent β. The upper curve corresponds to ω_D (the threshold value for forming a wind-compressed disk). Along the lower of the two curves, rotation will produce a factor of 3 compression in the equatorial density at large radii.

which have slower winds. Note that the flow lines terminate as they enter the equatorial plane; this is what leads to the disk in the WCD model of Be stars. Panel (e) represents our WCZ model for WR winds. The wind acceleration law is slow, and even though a disk does not form, there is significant compression near the equatorial plane. As can be seen in panel (e), a rotation rate of 16% critical is sufficient to produce a significant wind-compression.

Given a radial velocity law, it is possible to find the threshold stellar rotation rate, ω_D, that leads to disk formation. The upper curve in Figure 3. shows ω_D versus the velocity law exponent β. As the velocity law becomes slower, disk formation becomes more likely. In the case of WR stars, it is not necessary that disk formation occur; a moderate enhancement of the density is sufficient for the applications that we discuss. Since emission processes often are proportional to n^2, a factor of 3 enhancement in density is sufficient to increase the emission by about an order of magnitude. The lower curve in Figure 3. shows the rotation speed required to increase the equatorial density by a factor of 3 over the polar wind. Note that for a $\beta = 3$ velocity law, a rotation speed of only about 10% critical should be sufficient for the rotation to cause significant observational effects. We can use this Figure to distinguish two types of wind-compression models. For stars having an ω and β that places them in the upper region, a wind-compressed disk will form and there can be a density contrast $(\rho_{\rm eq}/\rho_{\rm pole})$ of perhaps two orders of magnitude. For stars that lie in the zone between the two curves, there will be a wind-compressed zone, in which the equatorial compression can be observationally significant.

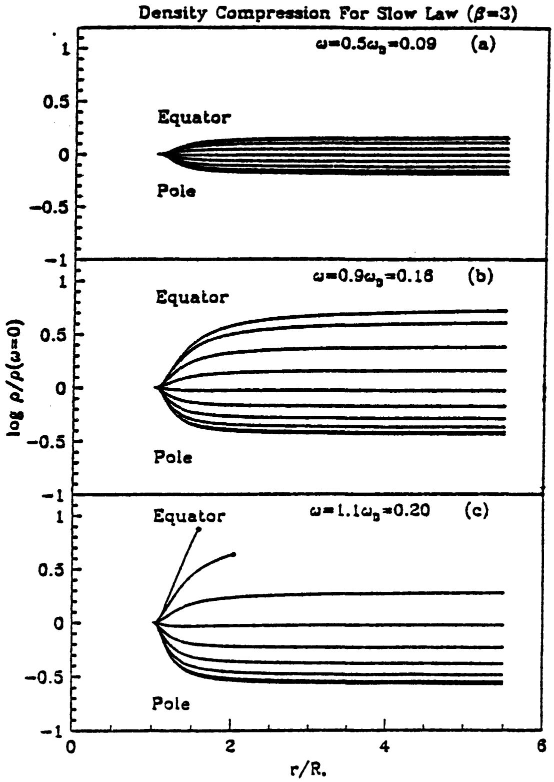

Fig. 4. Ratio of the density in wind-compressed models to that of non-rotating models as a function of distance from the star for stream lines originating in a sequence of latitudes with a separation of 10°. Shown are three rotation rates given both in terms of the disk forming rotation, ω_D, and in terms of critical rotation speed. All panels correspond to a slow velocity law with $\beta = 3$. In the lower panel, dots mark the termination of stream lines entering the disk, where the density increases by $\sim$ 2 orders of magnitude.

Figure 4 shows the major increase in the density contrast as the rotation rate increases from 9% critical to 20% critical. Note from the second panel that even at a rotation rate of 16% critical, there will be a contrast in the density from equator to pole of a factor of almost 20. This is sufficient to have an effect on polarization calculations. A comparison of the three panels shows that the density contrast increases rapidly in going from a rather slow rotation rate of 9% critical to a model that will have a WCD disk, at 20% critical. This result shows, in sharp contrast to the magnetic rotator model, that interesting equatorial enhancements can be attained at relatively low rotation speeds.

Since it is likely that there is a distribution of the number of WR stars with rotation rate, $N(\omega)$, the sensitivity to small changes in rotation rate may explain several peculiar properties of WR stars. First, only some WR stars show polarization while most do not. Perhaps only the WR stars in the tail of the $N(\omega)$ distribution show significant polarization. Second, only some WC8 stars show evidence for dust in their winds, whereas nearly all of the cooler WC9 stars have dust (Williams, these proceedings). Perhaps in the case of the WC8 stars, the density enhancement associated with being at the high rotation rate end of $N(\omega)$ is required for the dust formation, so only those WC8 stars have dust.

Given that binary stars are a major topic at this conference, we should mention the application of the wind-compression on binary systems. Churchwell *et al.* (1992) have considered the binary system WR147 (WN8), which shows both thermal and non-thermal radio emission and is a strong X-ray source. They found that, to explain the hard X-ray emission as a result of the accretion of wind material from the WR star onto a compact companion, the wind can not be spherically symmetric. This is because at the large distance inferred for the companion from the WR star ($\sim 4\,000\ R_*$), a spherically symmetric wind has too little mass flux. Instead, they suggested that the wind structure is more like the magnetic rotator structure of Poe *et al.* (1989), that could possibly provide a density enhancement over the spherical model by a factor of about 30 to explain the X-ray luminosity, but it requires unrealistically high rotation rates. If instead we consider a WCZ model of a WN8 star that has a mass loss rate of 4.2×10^{-5} $M_{\odot}yr^{-1}$, and a polar wind terminal velocity of $900\,km\,s^{-1}$, we find an X-ray luminosity that is of the same order as observed if the WR star has a rotation rate close to ω_D, which is approximately 0.21 for WR147. If the star is rotating fast enough to form a disk (WCD), we find an X-ray luminosity that is 3 orders of magnitude higher than is observed. This estimate assumes that all stream lines entering the equatorial plane remain there, that the conversion of gravitational energy to X-ray luminosity is 100% efficient, and that the neutron star is in the equatorial plane of WR147. The large derived X-ray luminosity is thus an upper limit that can be greatly reduced by relaxing these assumptions.

Finally, we note that since very small rotation rates can lead to wind compression zones in stars with slowly accelerating winds, there should be other applications of the WCD/WCZ model. Luminous Blue Variables are associated with nebulae that are aspherical and axially symmetric (Hester, in preparation; Leitherer *et al.* 1994). B[e] stars are another class of B supergiants that show polarization and spectral evidence for asymmetries. Wind-compression might also occur in late-type giant and supergiant stars. For these stars, it has long been known that the winds accelerate slowly to terminal velocities much smaller than the escape speed at the surface of the star, so even very small rotation rates should result in equatorial wind-compression. This could lead to the equatorial ring around SN 1987A and to the rotational asymmetries seen in planetary nebulae (Balick 1987).

4. Magnetic fields in the WCZ model of WR winds

Very strong fields in the kilo-Gauss range are required to drive the winds of WR stars by the magnetic rotator model. However, because of wind compres-

https://doi.org/10.1017/S0074180900201952 Published online by Cambridge University Press

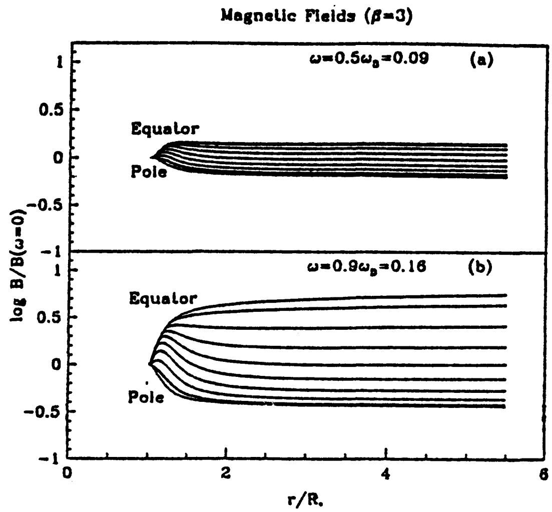

Fig. 5. The effects of the wind compression on magnetic fields for a $\beta = 3$ velocity law at low rotation rates. The stream lines are the same as used in Figure 4.

sion, much smaller fields might have interesting observational consequences. Rather than discussing the full set of magneto-hydrodynamic equations, we choose to employ the result of slow magnetic rotator theory (Cassinelli 1991) that weak magnetic fields do not change the flow structure derived from the non-magnetic models. This does not mean that the field lines are identical to the flow stream lines in the non-magnetic case. The field lines are rooted in the stellar envelope at the base of the wind. As a result, magnetic fields follow what are commonly called "streak lines" (Currie 1980). A streak line is the locus of elements of matter that are released sequentially from the *same point* on the star, whereas a stream line is the track followed by a single element of matter. In magnetic rotator models, the difference between stream and streak lines is often explained using the analogy to a phonograph record. The flow of a single element of matter is like the nearly-radial track of the needle, while the magnetic field follows streak lines that are like the grooves in the record. Note that the field is frozen into the flow; there can be no crossing of the field lines. In a *co-rotating* frame of reference, the streak lines are identical to the stream lines. It is therefore straightforward to find streak lines once one transforms the known ϕ-velocity component in the non-rotating case, V_ϕ, to that in the rotating frame, v_ϕ, via the relation, $v_\phi\,(r) = V_\phi\,(r) - r\Omega\sin\theta$, where Ω is the angular speed of the star and θ is the co-latitude.

To derive the field strength from a WCZ model, we have computed the components of velocity at all radii along a stream originating at given polar angle θ_0 on the surface of the star, using the equations in Bjorkman & Cassinelli (1993), but accounting for an initial radial velocity, a, taken to be the sound speed. The components of the velocity vector have been transformed to the rotating frame of reference. Along a flow tube of variable cross-sectional area $d\mathbf{A}$, the conservation of mass takes the form, $F_M = \rho\mathbf{v} \cdot d\mathbf{A} = constant$. Magnetic flux freezing applies the additional constraint that $\Phi = \mathbf{B} \cdot d\mathbf{A} = constant$. Since $\mathbf{B} \propto \mathbf{v}$ in the rotating frame, we combine these two expressions to derive the magnitude of the field along the tube,

$$\mathbf{B} = \rho\mathbf{v}\frac{\Phi}{F_M}, \tag{2}$$

where Φ and F_M are assumed known at the stellar surface, $r = R$. This result shows that $\mathbf{B}$ is proportional to ρ, so the magnetic field also shows an equatorial amplification. Because of the compression of the flow toward the equator in the WCZ model, the field decreases more slowly than r^{-2} (the non-rotating case). Figure 5 shows the strength of the field normalized to the field in the non-rotating case. We see that rotationally induced wind-compression can cause more than an order of magnitude enhancement of the field (a factor not accounted for by Maheswaran & Cassinelli (1992) in their derivation of allowed field strengths in WR stars). The magnitude of the field in the wind is likely to be of special interest in interpreting the radio spectra of WR stars that show non-thermal emission. Also, White & Chen (1992) have shown that fields of moderate size can lead to the acceleration of particles to relativistic speeds and to the possible subsequent emission of gamma rays by the WR stars.

5. Summary

The main focus of this paper has been to consider the effects of rotation in a two-dimensional picture of WR stellar winds. We have been led to the idea that the wind-compressed zone model, as opposed to a WCD model, may be sufficient to describe the properties of WR winds. It is found that there can be density and magnetic field amplifications by an order of magnitude relative to those in the polar regions of WR stars, even when the rotation rate is of moderate size ($\omega \approx 16\%$ critical). Equatorial wind compression models may be able to explain the magnitude and occurrence of polarization in WR stars, and the occurrence of dust formation in WC8 stars. In the case of WR + compact companion binary systems, the model can lead to a significant enhancement in X-ray production. Wind-compression may also be important in other classes of stars that have moderate rotation rates and slowly accelerating winds.

Acknowledgements

We thank Edward Churchwell for discussions regarding WR147 and Wlodzimierz Kluzniak for discussions regarding magnetic fields.

References

Abbott, D.C., Bieging, J.H., Churchwell, E.B., Torres, A.V. 1986, *ApJ* **303**, 239
Balick, P.L. 1987, *AJ* **94**, 671
Bieging, J.H., Abbott, D.C., Churchwell, E.B. 1989, *ApJ* **340**, 518
Biermann, P.L., Cassinelli, J.P. 1993a, *A&A* **277**, 691
Bjorkman, J.E., Cassinelli, J.P. 1993b, *ApJ* **409**, 429
Bjorkman, J.E. 1994, in: L. Balona, H. Henrichs & J.M. Le-Contel (eds.), Pulsation, Rotation and Mass Loss in Early-Type Stars, *Proc. IAU Symp. No. 162* (Dordrecht: Kluwer), in press
Cassinelli, J.P. 1982, in: C.W.H. de Loore & A.J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, *Proc. IAU Symp. No. 99*, (Dordrecht: Kluwer), p. 173
Cassinelli, J.P. 1991, in: K.A. van der Hucht & B. Hidayat (eds.), Wolf-Rayet Stars and Interrelations with other Massive Stars in Galaxies, *Proc. IAU Symp. No. 143* (Dordrecht: Kluwer), p. 289
Cassinelli, J.P. 1993, in: L. Drissen, C. Leitherer & A. Nota (eds.), Nonisotropic and Variable Outflows from Stars, *ASP Conf. Series* **22**, 134
Churchwell, E.B., Bieging, J.H., van der Hucht, K.A., Williams, P.M., Spoelstra, T.A.Th., Abbott, D.C. 1992, *ApJ* **393**, 329
Currie, I.G. 1974, Fundamental Mechanics of Fluids (New York: McGraw-Hill), p. 41
dos Santos, L.C., Jatenco-Pereira, V., Opher, R. 1993 *ApJ* **410**, 732
Friend, D.B., Abbott, D.C. 1986, *ApJ* **311**, 701
Gayley, K.G., Owocki, S.P., Cranmer, S.R. 1994, *ApJ* in press
Hamann, W.-R., Koesterke, L., Wessolowski, U. 1993, *A&A* **274**, 397
Koenigsberger, G. 1990, *A&A* **135**, 282
Koninx, J.P.M., Hearn, A.G. 1992, *A&A* **263**, 208
Leitherer, C. *et al.* 1994, STSCI preprint series no. 809
Owocki, S.P., Cranmer, S., Blondin, J. 1994, *ApJ* **424**, 887
Maheswaran, M., Cassinelli, J.P. 1992, *ApJ* **386**, 695
Moffat, A.F.J., Robert, C. 1993, in: L. Drissen, C. Leitherer & A. Nota (eds.), Nonisotropic and Variable Outflows from Stars, *ASP Conf. Series* **22**, 203
Poe, C.H., Friend, D.B., Cassinelli, J.P. 1989, *ApJ* **337**, 888
Springmann, U.W.E. 1994, *A&A* in press
Taylor, M., Cassinelli, J.P. 1992 *ApJ* **401** 311
Schulte-Ladbeck, R.E. 1994, these proceedings
White, R.L., Chen, Wan 1992, *ApJ (Letters)* **387**, L81

DISCUSSION:

Pollock: Wouldn't the most obvious observational consequence of a WCD shocked disk be a very strong X-ray source unobscured by an overlying wind?

Cassinelli: We have ROSAT observations of B and Be stars and while most of the X-rays on Be stars seem to be arising in the wind, we are finding the overall Be stars X-ray luminosity to be higher. The extra X-rays may arise from this infall shock rather than in the compression shock.

https://doi.org/10.1017/S0074180900201952 Published online by Cambridge University Press

Owocki: 1. Regarding the last question, the wind compression shocks tend to be much lower velocity amplitude, < 100 km/s, which would emit more EUV than X-ray. (Strong shocks can, however, occur in the inner disk *infall*).
2. Recent multi-line scattering models have extended acceleration, but still $\beta \approx 1$ in the inner wind. This is only theory, of course, and is at odds with high β values inferred for blobs.
3. In computing your wind compression factors, did you use the "modified wind compression" starting at the sonic velocity rather than zero velocity?
Cassinelli: 2. We both have to rely on observational studies that determine β. It may be difficult because the winds are so thick and many of the wind diagnostic lines are saturated. Also the binary star observations are probing this wind velocity at a fairly large distance from the star. Finally the velocity law derived for the blob derived by Carmelle Robert, Tony Moffat and others, does not necessarily hold for the non blobbed wind. Nevertheless, I hope that observers really focus on deriving more information on the velocity law.
3. Yes, we did use the modified WCD equations. The changes were described in Bjorkman (1994).
Moffat: From blob motion analysis (Lepine, PhD thesis in progress), one needs not just large β's as you mentioned ($\beta \sim 3$) but *really* large values ($\beta \geq 10$). However, the stellar core radii needed for a simultaneous fits to the β-law are unrealistically high ($R^* \geq 30\ R_\odot$). Thus, it seems that the β-law is not a good approximation for the true expansion of WR winds. We hope to derive an empirical law from blob trajectories.
Casinelli: We are using the beta velocity law as a convenient way to study the differences between fast and slowly accelerating winds. Although I have chosen to focus on the beta = 3 case in my presentation, I am not saying that any particular value is crucial for the study. The main conclusion is that if a star has a wind with a velocity that increases somewhat slowly as it flows from a star with a moderate rotation rate, the star will have an equatorially enhanced density distribution. I am glad to hear that you are attempting to find the real velocity distribution in WR winds from your studies of blob trajectories. I would like to see the velocity law derived from a broad range of observations. It is the expansion within a few stellar radii from the surface that is especially important for producing the equatorial wind compression.
Cherepashchuk: Rotation of the WR wind does have some consequence on the position and orientation of shock in WR +O binaries. Could you calculate this effect? Using the method of Shore and Brown applied for V444 Cyg it could be possible to compare this effect with observations and derive observational constrains on the value of ω.
Cassinelli: That is a very good idea! It should be rather straightforward to do those calculations, since we know v, P, B at all points in a WCZ model.
Hill: In Be stars there are episodes of disk formation. In this model, why is that and why not for WR stars?
Cassinelli: There might be instabilities that lead to the loss of the disk in Be stars. There are both inflows and outflows in the Be disks in the Owocki, Cranmer & Blondin hydrodynamical version of the WCD model. So with two loss channels, small changes in the mass inflow from the polar regions of the star might have major consequences in regards to the density in the disk. As for the WR stars, I would just say that in the WCZ model we are not trying to form a disk, just a compression in the equatorial region. So the compression properties in the WR star winds and Be star disks can be quite different. Perhaps the variability in the WR stars can be attributed to the presence of a magnetic field, that appears to be present in some WR stars, as evidenced by their non-thermal radio emission.

https://doi.org/10.1017/S0074180900201952 Published online by Cambridge University Press