Dynamics and variability of winds in WR+O binaries

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Abstract.   The presence of a nearby O star offers the potential for studying the response of a Wolf-Rayet wind to external irradiation from a well-understood UV source. The O starlight offers not only a passive diagnostic probe, but also the potential for a dynamical interaction whose nature relates directly to fundamental issues of how WR winds are driven. It may even decelerate the WR wind prior to the wind/wind interaction, an effect we term *radiative braking*. We report on recent progress in WR+O wind-wind interaction models that incorporate the influence of the O starlight on the incident WR wind, and also the effect of the WR starlight on the acceleration of the O-star wind. A recurrent theme is the importance of feedback between the line force and the gas dynamics, and the leveraging that results.

1.   Introduction

A particularly useful probe of the connection between a Wolf-Rayet star and its wind appears in the form of close WR+O binaries. Not only is the binarity useful for constraining the mass of the system, but it also provides an excellent opportunity to compare and contrast the spectral luminosity of equidistant stars in different stages of evolution. That these two luminosities are typically of the same order is a significant point we will return to.

In addition to these general advantages, the presence of an O star in the WR wind provides a direct diagnostic probe of that wind, via wind eclipses (Auer & Koenigsberger 1994) and bow-shock emission features (Lührs 1997; Stevens & Howarth 1999). However, perhaps the most exciting application of the proximity of the O star comes from the potentially important dynamical influences of its radiant momentum on the WR wind itself (Usov 1990). After all, wind-wind interactions require a transverse momentum balance, and O starlight typically carries more momentum than its associated massive wind. What determines the overall momentum coupling coefficient between a WR wind and external irradiation, and is it strong enough to introduce totally new dynamics to the wind geometry? Can the strength of the coupling shed light on the issue of how the WR wind was radiatively accelerated in the first place? Here we summarize recent results on the various dynamical phenomena that may be expected in WR+O binaries with orbital periods of a few days to a few months, and how these issues may help understand the resolution of the so-called WR 'momentum problem'.

2. The Wolf-Rayet 'Momentum Problem'

It was mentioned above that WR luminosities are often inferred to be similar to O stars. However, WR winds tend to be significantly more massive and hence carry a greater momentum flux than their hydrogen-rich O-star counterparts. In many cases, observations suggest that WR wind momentum fluxes are greatly in excess of the momentum flux in the radiation fields that drive them (*e.g.*, Puls 1987; Schmutz *et al.* 1989; Hamann *et al.* 1993). This can only be explained in terms of multiple scattering from a strongly blanketing array of spectral lines (Springmann 1994; Gayley, Owocki & Cranmer 1995). To achieve this blanketing, the observed ionization stratification plays an essential role in filling spectral gaps (Lucy & Abbott 1993), and as yet unknown processes may be required to yield sufficiently rich ionization strata (Schmutz 1997).

This sketches some key aspects of the present state of conventional thought on the WR momentum problem, but recurring questions that remain highly uncertain include: why are Wolf-Rayet mass-loss rates so high in the first place, what role does clumping (Moffat & Robert 1994) play in causing these rates to be overestimated, and whether or not additional lifting mechanisms such as large-amplitude oscillations (Glatzel *et al.* 1993) are needed to assist in the initial levitation of dense WR winds. As emphasized in the Owocki & Gayley contribution to these proceedings, a key challenge to purely radiation-driven models for WR winds is to identify sufficent wind line opacity to adequately blanket the stellar flux spectrum (Lucy & Abbott 1993).

One of the main difficulties in the study of WR winds is that the lowest layers where mass loss is initiated and supersonic acceleration takes place may be completely obscured behind an optically thick cloud of entrained free electrons. Thus one of the advantages of studying WR+O binaries is that the O star presents a potent source of light outside the obscuration of the free electrons, so the dynamical response of WR wind material to UV illumination can be observed. This in turn may shed insight into the curiously efficient deposition of momentum in these winds, and help resolve the issues raised above.

3. The radiative braking paradigm

The most important issue for the dynamics and expected variability in interacting winds is the nature and geometry of the bow shock separating the two winds. This requires an understanding of the relevant transverse momentum fluxes which must balance. Fig. 1 depicts the possible status of the various terms in the momentum flux along the line of centers between the stars, including the ram pressure of the incident WR wind, the opposing ram pressure of the O wind, and the momentum flux of the O starlight, for parameters roughly consistent with a model of the close binary V444 Cygni (Owocki & Gayley 1995).

The key point from the figure is that due to the finite distance required for the O-star wind to reach terminal speed, it is never able to reach sufficient ram pressure to hold off the WR wind and prevent a direct collision with the O-star photosphere. However, the *radiant* momentum would be sufficient to achieve a balance, if a large fraction of the O starlight could be scattered in a sufficiently compact deceleration regime inside the WR wind. Note that if 'sudden braking'
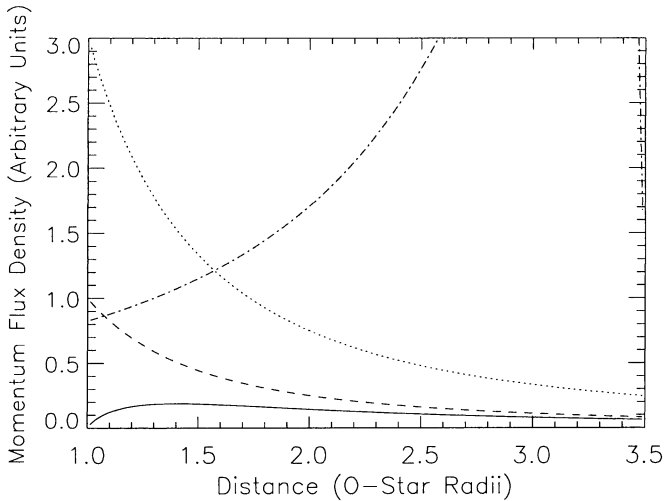
Figure 1.   Curves of momentum-flux density near the O star for a schematic model of V444 Cygni. The dot-dashed curve is for the incident WR-wind ram pressure, the solid curve is for the O-star wind, and the dotted curve is for the O starlight. The dashed curve shows how the O-star wind ram pressure artificially increases if it is assumed to reach terminal speed immediately upon leaving the surface.

of the wind did occur, this might provide sufficiently broad Doppler-shifting of optically thick wind lines to achieve such a highly efficient interaction. Once the WR wind has been slowed by the radiative interaction, it then achieves a greatly weakened ram balance with the O-star wind, generating a weaker shock and lower temperatures in the shocked WR wind.

Note that due to the presence of the O-star wind, it is not actually necessary to radiatively decelerate the wind into the subsonic domain. Such a complete deceleration might be unstable to forming shocks anyway (as argued by J. Dyson in the Summary Talk of these Proceedings). But note that the radiative instability actually has the opposite sign, and damps small-scale perturbations, in the radiative-braking geometry.

Fig. 2 compares results of 2D hydrodynamical simulations of V444 Cygni with (lower panel) and without (upper panel) strong radiative braking. As predicted in the simple line-of-centers analysis of figure 1, without radiative braking the WR wind simply crashes into the O-star surface; but when it is included, it allows a wind-wind shock ahead of the O-star core, with a much wider bow-shock angle.

4.   Radiative braking as a WR wind in reverse

The steady-state inertial requirements, typically expressed as $v\partial v/\partial r$, are independent of the sign of v, and hence are insensitive to the direction of time. An appealing aspect of the braking model, along the line of centers between the stars, is that it represents in effect a CAK-type process (Castor, Abbott & Klein 1975) with time running backward. The difference from the CAK model
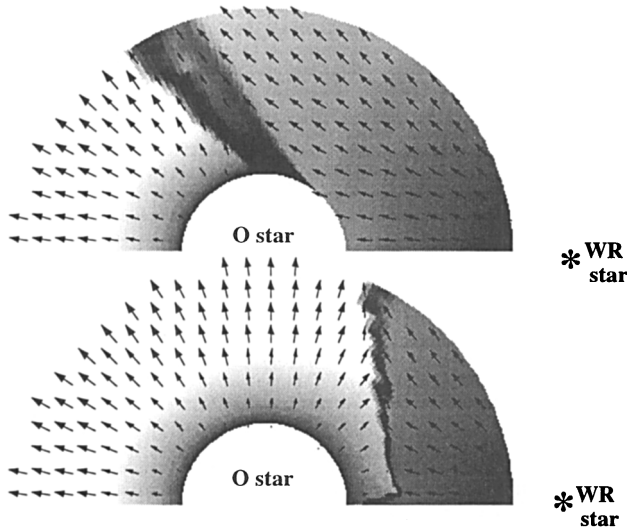
Figure 2.   2D hydrodynamical simulations of the wind-wind interaction for V444 Cygni with (*lower panel*) or without (*upper panel*) strong radiative braking. The level of gray denotes density, and the arrows represent flow vectors. (The dip in the interaction front along the line-of-centers is a numerical artifact of the assumption of 2D axisymmetry.)

is that the mass flux is externally constrained in braking models. Steady-state line-driven winds always experience dynamical feedback because the force explicitly depends on the acceleration, but CAK-type winds experience additional feedback because the mass-loss rate must be determined simultaneously with the dynamics. The braking process includes the dynamical feedback, but not the mass-flux self-consistency complication. This makes it convenient for focusing on the purely kinematic effects of the line forces.

One potentially interesting way that substantial radiative braking might affect the wind dynamics is that it implies nearly an order of magnitude increase in the wind density as the velocity slows. This density increase will have a sharper gradient than in a standard stellar wind model, so will lead to elevated recombination rates that will likely set up an ionization gradient. This could in turn induce a second ionization stratification over this narrow layer in the WR wind, which in turn might assist in promoting the spectral coverage needed for efficient reflection of the incident radiation. Such stratification-induced momentum deposition may lead to further insights into how ionization stratification may have assisted the original acceleration of the WR wind.

5.   Leveraging and force 'dressing'

We can be more quantitative about the role of dynamical feedback in producing the steep character of radiative braking. The simplest model for radiative braking applies the CAK parametrization of the line force. If we define r as the distance to the center of the O star, and assume r is much less than the binary
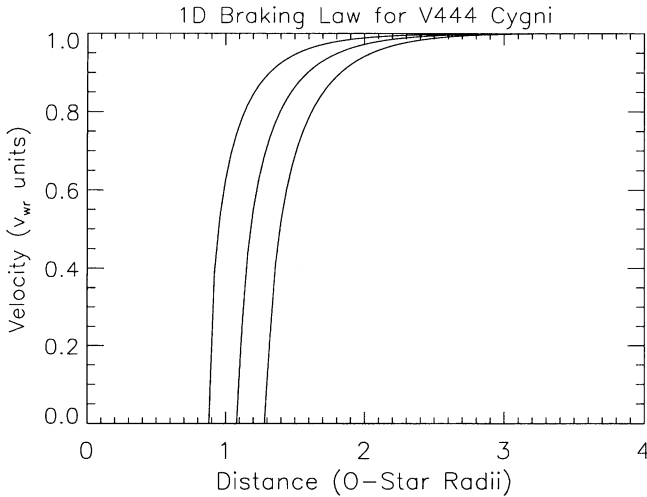
Figure 3.   Solutions to eq. (1) in the text are depicted for varying values of the force coefficient C, to show the steep character of the deceleration. The model is intended for V444 Cygni, and the braking may or may not prevent a collision with the O-star photosphere, depending on the strength of the coupling. The force coefficient varies over the figure by a total factor of 5. Referral to Fig. 1 shows that about half of the 'available' O-star radiant momentum flux is being used to produce the braking.

separation D (again for simplicity of form), then the deceleration along the line of centers (neglecting orbital effects and all forces other than line scattering of O starlight) can be equated to the radiative line force per unit mass:

$$v\frac{\partial v}{\partial r} \;=\; \frac{C}{r^2}\left(v\frac{\partial v}{\partial r}\right)^{\alpha},$$ (1)

where $v\partial v/\partial r$ is the steady-state acceleration, and C is a constant that scales with the O-star luminosity and the mass flux and line density in the WR wind. The $(v\partial v/\partial r)^{\alpha}$ on the right describes the way Sobolev opacity depends on the local acceleration after integrating over a line ensemble, and the $1/r^2$ factor comes from the inverse-square falloff of the O-star radiative flux.

    An advantage of the simplicity of eq. (1) is that it admits a trivial solution which can be integrated to find $v(r)$ in closed form. In the limit $r \ll D$, the result for a canonical value of the CAK exponent $\alpha = 2/3$ (Puls 1987, though may be smaller for lower metallicity; Puls *et al.* 1996) is

$$\frac{v(r)}{v_\infty} \;=\; \sqrt{1 \,-\, \frac{2C^3}{5v_\infty^2}r^{-5}}.$$ (2)

Solutions for varying values of C are shown in Fig. 3.

    It is clear that the deceleration increases quickly after a certain point is reached, and this sudden braking is due to the steep r^{-5} dependence in eq. (2). The large exponent can be traced in part to the dynamical feedback that allows the acceleration to depend on a force that in turn depends on acceleration. The

large exponent of the constant C has similar roots, and this extreme sensitivity confirms the usefulness of radiative braking as a well-leveraged probe of line opacity in WR winds.

It is worth developing the concept of leveraging a bit further, as it is a fundamental aspect of steady-state line driving. If we write eq. (1) simply in the form $A = f(A)$, with $A \equiv v \partial v / \partial r$, we can then imagine adding a small test force Δ to $f(A)$, and ask what will be the self-consistent shift in the acceleration, dA. Thus we solve

$$A + dA = f(A + dA) + \Delta, \tag{3}$$

which to lowest order in Δ gives

$$dA = \frac{\Delta}{1 - f'}, \tag{4}$$

where f' is the derivative of f at A. The factor $1/(1 - f')$ can be interpreted as a kind of force 'dressing', in that any test force Δ that we attempt to add gets augmented by this factor. In the case of the radiative force used here, this factor becomes $1/(1 - \alpha)$, which also gives the power of C seen in eq. (2). Thus the radiative force effectively 'dresses' itself, meaning that changes in the line driving induce changes in acceleration which ultimately alter the driving force itself. This effect causes the steepness and the sensitivity of the braking solution, and recurs in many contexts where a fixed mass flux is driven in steady state. In cases where $f' > 1$, the dressing factor is negative, which actually occurs in the subsonic portion of a CAK wind.

6.   The differences between braking, inhibition, and ablation

The sudden radiative braking effect is quite separate from the radiative inhibition effect described by (Stevens & Pollock 1994), and the two may often occur in combination (Pittard 1998). Radiative inhibition refers to the reduction in the initial acceleration of one wind due to the radiative flux of a nearby companion, whereas braking refers to the deceleration of that wind as it approaches closer to the companion. A third effect can also be discussed in this context, which accounts for the fact that companion starlight will be reflected in the photosphere beneath the wind being inhibited. This effect was not included in the initial inhibition studies, and can be expected to reduce inhibition slightly. It may have an even more important application for lower luminosity surfaces, which can actually mimic higher luminosity stars by reflecting the continuum of hot nearby companions. This can in turn lead to an increased mass loss from the secondary, an effect termed line-driven ablation (Gayley & Owocki 1999).

To what extent a given hydrodynamic simulation will exhibit these effects often depends on the degree to which the line-driving mechanism is allowed to realize the potential richness of its own dynamical response. For example, radiative inhibition deals only with changes in the overall flux moment of the radiation field, whereas the ablation effect has a nonradial character that depends sensitively on the non-isotropic quality of line-of-sight velocity gradients. The 'sudden' quality of radiative braking is sensitive to the well-known high degree of dynamical feedback present in line-driven winds, while more technical

issues involving the bifurcation between the inhibition regime and the braking layer require the inclusion of transverse velocity gradients inherent in any spherically expanding flow. Experience with even the simplest models of dynamically and geometrically self-consistent line driving quickly instills respect for the ever-expanding complexities of this surprisingly inscrutable mechanism.

7. Diagnostics of phase-locked variability in interacting winds

Interacting winds are often detected by looking for phase-locked variability. Unfortunately, close binaries are likely to be tidally locked, so phased variations due to stellar rotation are difficult to distinguish from orbital phase variations. Fortunately, the conical bow-shock structure produces an observable signature in the form of variable peaks in optically thin line diagnostics (Lührs 1997), and progress continues toward their quantitative interpretation (Stevens & Howarth 1999). Also, orbital variations in X-ray luminosity have been observed in WR+O binaries (Corcoran *et al.* 1993), which is expected if wind/wind collisions result in substantial shock heating and an orbitally varying fraction of this emission is re-absorbed (Pittard & Stevens 1997). There may even be a connection between colliding winds and the Struve-Sahade effect (Gies, Bagnuolo & Penny 1997).

What then are the expected diagnostics of radiative braking? A formal study of this question has yet to be undertaken, but a preliminary analysis indicates that for radiative braking to be prevalent, a large fraction of the O starlight that impinges on the braking region must be reflected. This implies that UV starlight observed in the blanketed portion of the WR spectrum should be augmented by an observable amount when the line of sight passes through the 'hole' cut in the WR wind within a spectral gap in the normal O-star wind spectrum. This signal might also exhibit sharp variations due to eclipsing by the O-star itself. Excellent phase coverage may be required, but it is certainly possible that existing archives already contain spectral diagnostics of the radiative braking effect. Also, optically thin emission-line diagnostics might include a radiative-braking signal alongside the Lührs (1997) phased peaks. An alternative approach is to identify diagnostics that indicate that the WR wind is colliding with the O-star photosphere, and then use the absence or presence of these signatures as indirect evidence for or against radiative braking.

Our simplified analysis here has focused on the line of centers connecting the stars, but radiative momentum deposition may occur throughout the interaction region extending several O-star radii to both sides of the line of centers. In the transverse regions, the radiative force acts to steer the WR wind away from the O star, as illustrated in Fig. 2. This widens the bow-shock cone, and alters the geometry of the wind-wind collision. As such, it may be expected to alter the magnitude and energy of the X-rays generated in ways that require detailed modeling to characterize. It might be expected that the hardest X-rays will be truncated by radiative braking, since the strongest shocks are avoided, but the change in the geometry of the bow shock might actually serve to increase the yield of softer X-rays. Unfortunately, the geometry of the bow shock is also affected by unknown parameters such as the mass-loss rate of the O star, so additional spectral diagnostics will be needed to map out the velocity structure in the interaction region and determine whether or not radiative braking occurs.

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Discussion

Koenigsberger: We analyzed the atmospheric eclipse-effects in V444 Cyg (Auer & Koenigsberger, 1994 ApJ 436, 859) and the discrepancy between our model calculation and the observed line-profile changes were interpreted as due to wind-wind collisions. Perhaps we should go back and check whether this is more likely due to radiative braking and thus have some observational evidence for this effect.

Gayley: That's a very interesting possibility. Wind-eclipse data might provide just the kind of detailed diagnostics we need to understand the possibility of radiative braking.

Walder: You have quite convincingly argued for radiative breaking. However, your argument of a significant reduction of the X-ray production in the central region is not very convincing to me. It's hard to believe that sudden radiative breaking, which slowes down a highly supersonic wind by a factor of ten on a relatively small spatial scale, is a smooth and subtle process. Rather, instabilities like in the acceleration process are likely to appear, which will generate, probably weaker, X-rays.

Gayley: You are right that the X-ray ramifications are unclear at present. Probably the biggest issue is how radiative braking would alter the bow-shock geometry, which might actually increase X-ray production. As for instabilities, they could probably not

convert a large fraction of the wind kinetic energy into X-rays. Note that the radiative instability actually becomes stabilizing in the time-reversed environment of radiative braking.

Moffat: In a given WR+O binary, with an observed opening angle θ, it is not easy to know whether braking has occurred, since to do this, one needs accurate values for the mass loss rates and wind speeds at the points of collision of both stellar winds. I doubt whether these are well known in WR+O binaries, unfortunately.

Gayley: I agree, this is a big problem. The geometry of the bow-shock is an ambiguous constraint when the momentum ratio of the winds is not known. Since the cone angle might be altered by braking, we need a separate diagnostic for the braking, so we can reach a consistent picture for all the wind parameters simultaneously.