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SUDDEN RADIATIVE BRAKING IN COLLIDING HOT–STAR WINDS

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RESUMEN

Cuando los vientos de dos estrellas calientes chocan, su interacción se centra en el punto donde los flujos del momentum se equilibran. Sin embargo, en sistemas WR+O, el desequilibrio en los flujos del momentum *corpóreo* puede ser suficientemente extremo como para impedir una colisión standard tipo vientos de frente. Por otra parte, una componente importante del flujo del momentum total en vientos de origen radiativos es acarreado por *fotones*. Entonces, si la región de interacción de los vientos tiene suficiente opacidad de dispersión, puede reflejar fotones estelares y dar origen a importantes términos radiativos en el balance del momentum. Estos términos radiativos resultarían en un frenado adicional del viento.

Usamos un cálculo radiativo-hidrodinámico para mostrar que tal frenado radiativo puede ser un efecto importante en muchas clases de choques de vientos en estrellas calientes. Caracterizado por una repentina desaceleración del viento más fuerte en la vecindad de la estrella con viento más débil, puede permitir un balance de presión de viento que de otra manera resultaría imposible en muchos sistemas WR+O con separaciones menores de algunos cientos de radios solares. También debilita mucho la fuerza del choque y la concomitante producción de rayos-X. Demostramos la importancia de este efecto usando V444 Cygni como un ejemplo característico. También derivamos una teoríia analítica general de aplicación a un amplio rango de binarias, ofreciendo predicciones simples de cuando el frenado radiativo debería jugar un papel importante.

ABSTRACT

When two hot-star winds collide, their interaction centers at the point where the momentum fluxes balance. However, in WR+O systems, the imbalance in the *corporeal* momentum fluxes may be extreme enough to preclude a standard head-on wind/wind collision. On the other hand, an important component of the total momentum flux in radiatively driven winds is carried by *photons*. Thus, if the wind interaction region has sufficient scattering opacity, it can reflect stellar photons and cause important radiative terms to enter the momentum balance. This radiative input would result in additional braking of the wind.

We use a radiative-hydrodynamics calculation to show that such radiative braking can be an important effect in many types of colliding hot-star winds. Characterized by sudden deceleration of the stronger wind in the vicinity of the weak-wind star, it can allow a wind ram balance that would otherwise be impossible in many WR+O systems with separations less than a few hundred solar radii. It also greatly weakens the shock strength and the encumbent X-ray production. We demonstrate the significant features of this effect using V444 Cygni as a characteristic example. We also derive a general analytic theory that applies to a wide class of binaries, yielding simple predictions for when radiative braking should play an important role.

Key words: **BINARIES: CLOSE — STARS: MASS LOSS — STARS: WOLF-RAYET**

1. INTRODUCTION

Just as binary systems in general offer unique opportunities to constrain stellar masses, colliding winds offer a unique laboratory to study hot-star wind momentum and energy fluxes. An important class of these systems is WR+O binaries, which involve extremely massive winds and large luminosities. Much recent work has focused on modeling the collision of these winds, and it is often more or less taken for granted that such a collision occurs. Yet a curious puzzle arises in the case of fairly close WR+O systems, such as V444 Cygni and γ Velorum: using standard stellar parameters, the momentum flux of the WR wind should completely overpower the O wind and result in a collision with the O photosphere. At present, there seems to be little observational evidence that this in fact occurs. Indeed, in V444 Cygni, evidence (e.g., Corcoran et al. 1993; Marchenko et al. 1994) suggests that a wind/wind interaction does occur between the stars. If this is true, then are the WR wind momentum fluxes severely overestimated, or does another source of momentum help bolster the O wind?

2. RAM PRESSURE BALANCE IN WR+O SYSTEMS

In order to allow a sufficient momentum-flux density (ram pressure) to hold off the WR wind, it is often assumed that the O wind reaches terminal speed immediately at the surface of the O star. This is computationally convenient, but severely overestimates the stopping power of the O wind. As shown in Fig. 1, the assumption of a constant-velocity O wind overestimates the peak ram pressure by a factor more than 5, assuming a standard ($\beta = 0.8$) O-wind velocity law: $v(r) = v_o(1 - R_o/r)^\beta$. Also shown in the figure is the incident momentum flux from a WR companion, modeled after the V444 Cygni system along the line of centers. The assumed ratio of the asymptotic momentum fluxes is

$$P_{wr/o} \equiv \frac{\dot{M}_{wr} v_{wr}}{\dot{M}_o v_o} = 10, \tag{1}$$

and the binary separation is 4 O-star radii. It is clear from the figure that the factor 5 overestimate of the O wind ram pressure is crucial for inferring that a wind/wind momentum balance can exist along the line of centers; a more realistic O wind model would be totally overwhelmed by the WR momentum flux.

Indeed, it is straightforward to express the maximum $P_{wr/o}$ that will allow a ram balance, as a function of the binary separation and the assumed β-law for the O wind. Noting that ram balance involves equating ρv^2 in the two winds and assuming the WR wind has reached its terminal speed v_{wr}, the result is

$$P^{ram}_{wr/o} = \frac{4\beta^\beta}{(2+\beta)^{2\beta}} \frac{(d-1)^{2+\beta}}{d^\beta}, \tag{2}$$

where $d = D/R_o$ is the binary separation in O-star radii. Taking $\beta = 0.8$ as standard, then for V444 Cygni $d = 4$ implies $P^{ram}_{wr/o} = 1$, and for γ Vel at periastron, $d = 9$ implies $P^{ram}_{wr/o} = 7$. The commonly assumed momentum ratios in both of these systems, and in many other WR+O binaries, are well in excess of these limits. Thus the very existence of a wind/wind collision along the line of centers is untenable in purely hydrodynamic models.

Figure 1 also indicates that the momentum flux density corresponding to the O-star luminosity substantially exceeds that of the wind, especially near the surface. This is typical for two reasons: first, most O stars exhibit larger asymptotic momentum fluxes in their radiation than in the winds driven by that radiation; second, this dominance of the radiative momentum becomes even stronger in the region where the wind is still accelerating. Finally, there is yet a third reason why radiative momentum is potentially more effective than corporeal momentum: photons scatter elastically so can deposit up to twice their initial momentum when they backscatter, whereas dissipative winds "stick". Figure 1 is intentionally suggestive of the idea that the O-star radiative momentum flux would be fully capable of holding off the WR wind if sufficient opacity existed to reflect the photons. After all, in many cases the O star is brighter than the WR core that initially expelled the massive wind.

3. RADIATIVE BRAKING VS. TERMINAL-SPEED INHIBITION

The above argues that the O-star radiation can have a significant impact on the wind/wind collision. This general possibility was already explored by Stevens & Pollock (1994), who examined its potential for reducing the WR-wind terminal speed. But such terminal speed "inhibition" is a completely distinct phenomenon from

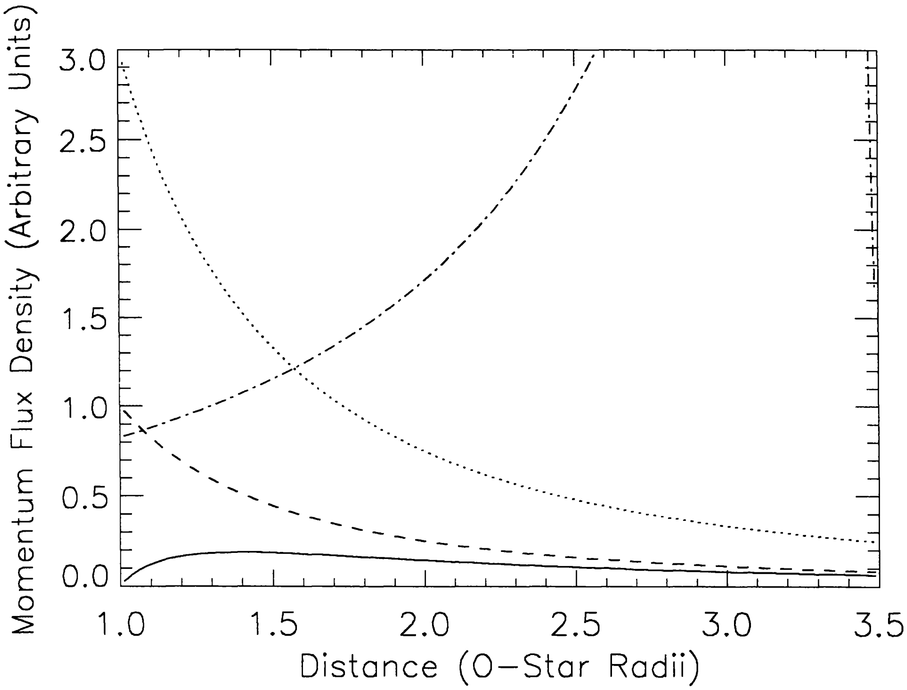

Fig. 1. A comparison of the momentum flux densities in the O wind (solid curve) and WR wind (dot-dash curve) of our V444 Cygni model. The dashed curve is the momentum flux density from the O wind under the unrealistic assumption of constant speed, and the dotted curve shows the momentum flux density from the O-star continuum.

the radiative "braking" explored here. Whereas inhibition operates in the region of initial acceleration near the WR core, radiative braking occurs near the O star, in the vicinity of the crossing between the O-star radiative momentum flux and the WR wind flux in Fig. 1. Since terminal-speed inhibition must occur in a region where the WR flux is strong and the O flux is diluted by distance, it can only have a substantial impact in binaries where the ratio of the binary separation to the WR core radius is not large. Radiative braking does not suffer from this limitation, so has significance for a wider class of systems.

However, in these winds the dominant mechanism for coupling the radiative momentum to the matter is through line opacity, which, to be effective, requires a nonzero velocity gradient. Such a gradient allows the Doppler-shifted lines to cover a greater portion of the stellar spectrum, and so yields a greater photon reflection. Though the impingent WR wind initially has a nearly constant speed, once radiative braking begins, there develops a negative velocity gradient which, through the enhanced Doppler shift, leads to a strong line force that maintains the deceleration. Thus radiative braking exhibits the same "bootstrapped" quality as all CAK winds (Castor et al. 1975), and requires that the velocity gradients and the radiative forces be solved self-consistently to determine when and where it will actually occur.

4. SELF-CONSISTENT CAK CALCULATION

The self-consistent WR-wind decelerating velocity law $v(r)$ can be approximated by integrating

$$\frac{1}{2}\frac{d}{dr}v^2 = \frac{L_o \kappa_{es}}{4\pi(1+\alpha)cr^2} k \left(\frac{1}{\kappa_{es}\rho v_{th}}\frac{dv}{dr}\right)^{\alpha}, \tag{3}$$

which represents the time-steady force balance along the line of centers, with r the distance to the center of the O star. Here L_o is the O-star luminosity, κ_{es} is the free-electron scattering opacity per gram for solar abundance, and ρ is the mass density. The radiative force is approximated using the CAK k, α parametrization, defined for solar-abundance thermal speed v_{th}. The finite disk correction is approximated by the factor $1/(1+\alpha)$, appropriate for a plane-parallel braking layer close to the O star.

The balance expressed in eq. (3) is solely between the WR wind deceleration and the radiative force from the O continuum; all other forces (including orbital terms) are neglected for simplicity. The form is similar to the usual CAK force balance in the accelerating O wind, but because it now applies to the decelerating WR wind, the density variation is somewhat different,

$$\rho = \frac{\dot{M}_{wr}}{4\pi(D-r)^2 v}, \tag{4}$$

where $\dot{M}_{wr}$ is the WR mass-loss rate and D is the binary separation. From this we see that, as in the normal CAK form, all velocity dependence in eq. (3) enters through dv^2/dr, and so is independent of the *sign* of the velocity. Therefore, radiative braking is essentially CAK acceleration in reverse, with the boundary condition set by the incident WR wind instead of the normal critical point conditions.

A primary advantage of eq. (3) is that it can be readily integrated to yield a simple analytic expression for the decelerating velocity law

$$v(r) = v_{wr}\sqrt{1 - \xi\,(D/r-1)^{(1+\alpha)/(1-\alpha)}}, \tag{5}$$

where

$$\xi \equiv \frac{(1-\alpha)}{(1+\alpha)^{(2-\alpha)/(1-\alpha)}} \frac{L_o \kappa_{es}}{4\pi G M_{wr} c} \left(\frac{L_o}{\dot{M}_{wr} c v_{th}}\right)^{\alpha/(1-\alpha)} \frac{v_*^2}{v_{wr}^2}\, k^{1/(1-\alpha)}. \tag{6}$$

Here M_{wr} is the WR mass, v_{wr} is the WR wind speed incident to the interaction region, and we have defined the speed parameter

$$v_* \equiv \sqrt{\frac{2GM_{wr}}{D}}. \tag{7}$$

Apparently, ξ is the key parameter for determining the importance of radiative braking, and k is the basic unknown. If we assume k is that which would be required to drive the WR mass-loss rate originally, then

$$\xi = \frac{1}{\alpha^{\alpha/(1-\alpha)}(1+\alpha)} \left(\frac{L_o}{L_{wr}}\right)^{1/(1-\alpha)} \frac{v_*^2}{v_{wr}^2}. \tag{8}$$

5. WHEN AND WHERE DOES BRAKING OCCUR?

Although the scale of the deceleration from eq. (5) is formally R_o, in practice the nonlinear character of the radiative force creates an ever-steepening braking law, and most of the final braking occurs in a narrow layer; hence our term "sudden" braking. By setting the WR wind speed to zero, eq. (5) can be solved for the "braking radius"

$$r_{rb} = \frac{D}{1+\xi^{(\alpha-1)/(\alpha+1)}}. \tag{9}$$

When $r_{rb} > R_o$, radiative braking occurs outside the O photosphere and can allow the O wind to support a wind/wind collision with the greatly slowed WR wind. Such a wind/wind collision might not otherwise be possible in many cases, as discussed above.

An important parameter is the separation for which $r_{rb} = R_o$, which we denote D_{rb}. From eqs. (6) and (9), we can see that D_{rb} solves the transcendental relation

$$D_{rb} = R_o\left[1 + \left(\frac{D_{rb}}{\eta R_o}\right)^{(1-\alpha)/(1+\alpha)}\right], \tag{10}$$

where $\eta \equiv \xi D/R_o$ is a constant independent of the separation D. Whenever $D > D_{rb}$, radiative braking can prevent collision of the WR wind with the O-star photosphere, so D_{rb} sets the relevant separation scale.

6. RADIATIVE BRAKING IN V444 CYGNI

As a specific example of the theory, consider V444 Cygni, a close WN5+O6 III-V binary. We choose the typical parameters $\dot{M}_{wr} \cong 8\times10^{-6} M_\odot/\ \mathrm{yr}^{-1}, R_o \cong 10 R_\odot$, $L_o \cong 2.3\times10^5 L_\odot$, and $M_o \cong 27$ (Marchenko et al.

1994). We simulated three values for the CAK k parameter, $k = 0.15, 0.3$, and 0.8, which represent respectively the characteristic k for the O wind, an intermediate k, and the k that would have been needed to drive the WR mass-loss in the first place. We arbitrarily take $\alpha = 0.6$, a characteristic O-star value.

The respective results of eq. (9) give $r_{rb}/R_o = 0.66, 0.94$, and 1.44, from which we predict that radiative braking should occur in V444 Cygni only if the WR wind opacity is intrinsically high. This expectation can also be expressed by comparing D to D_{rb}; here $D/R_o = 4$, and the respective values from eq. (10) are $D_{rb}/R_o = 6.8, 4.4$, and 2.6.

To test the validity of the 1D analytic analysis, we carried out 2D simulations including the gravitational and radiative forces from both stars, in the Sobolev approximation. Fig. 2 shows the results given our V444 Cygni parameters with the three k values from above. There is good general agreement with the analytic predictions.

The simulations further show that, when the larger k values are used, the WR wind is held off the O-star photosphere, and the bow shock is noticeably wider. This suggests that observational determinations of the global shock geometry, including the presence or absence of a photospheric collision, and the bow-shock opening angle, could provide useful constraints on the coupling between the O spectrum and the WR wind material. Recent work by Marchenko et al. (1994) suggests that the half-angle of the bow shock in V444 Cygni is surprisingly large (about 70 degrees), and there appears to be no evidence of a photospheric collision. This makes V444 Cygni a prime candidate for radiative braking, and suggests that the opacity of the WR wind must be intrinsically high.

7. APPLICATION TO A BROAD CLASS OF HOT-STAR BINARY SYSTEMS

Let us now apply these analytic formulae to a broad range of binary systems. By appropriate scaling of D and $P_{wr/o}$, it is possible to classify the importance of radiative braking in terms of these two parameters. One first requires $D/D_{rb} > 1$ (see eq. [10]) if radiative forces are to prevent a photospheric collision, so we take D/D_{rb} as our scaled separation parameter.

Second, if there is to be no ram balance without braking, one also needs $P_{wr/o} > P_{wr/o}^{ram}$ (from eq. [2]). We do not scale to $P_{wr/o}^{ram}$, however, because it depends on D, so would not be constant for eccentric binaries. Instead, we define the scale of $P_{wr/o}$ to be $P_{rb} \equiv 4\beta^{\beta}(D_{rb}/R_o)^2/(2+\beta)^{2+\beta}$, which is $P_{wr/o}^{ram}$ evaluated at D_{rb} in the limit $D_{rb} >> R_o$. This is chosen to transform the requirement $P_{wr/o} > P_{wr/o}^{ram}$ into the homologous form $P_{wr/o}/P_{rb} > (D/D_{rb})^2$.

Next, we locate all example binaries in a single diagram over the scaled $\{P,D\}$ plane. Figure 3 shows results for the 8 indicated systems, with eccentric binaries exhibiting a range in D/D_{rb}. As described above, radiative braking is critical for achieving a ram balance whenever $D/D_{rb} > 1$ and $P_{wr/o}/P_{rb} > (D/D_{rb})^2$, which is the region between the solid curves in the diagram. In deriving the values of D_{rb}, we arbitrarily take $\alpha = 0.5$ in all models (as argued should be characteristic of WR winds by Gayley 1995), and fix k by applying eq. (8).

Table 1 summarizes the parameters used. The terminal speeds are in km/s, and all other units are solar. Key references were, for V444 Cygni (WR 139): Marchenko et al. (1994) and St.-Louis et al. (1993); for γ Vel

TABLE 1
APPROXIMATE BINARY PARAMETERS

	V444	γ Vel	WR 22	WR 42	WR 79	CV Ser	CX Cep	Iota Ori
$P_{wr/o}$	8.6	43	67	120	25	210	21	85
D	40	200–400	160–560	60	54	130	25	100–270
R_o	10	21	12	10	10	10	9	10
L_{wr}/L_o	0.6	2.2	8	1	0.6	1.3	0.3	13
M_{wr}^{eff}	7	8	40	8	4	8	18	35
v_{wr}	1800	1520	1000	2000	2270	1000	2000	2500
η	1.5	3.8	3.2	2.2	1.8	3.3	0.7	6
R_{rb}	12	23–45	18–63	12	11	15	13	8–18
D_{rb}	32	190	91	46	38	73	17	111
P_{rb}	1.5	9.6	7.2	2.9	2.1	6.8	0.58	11

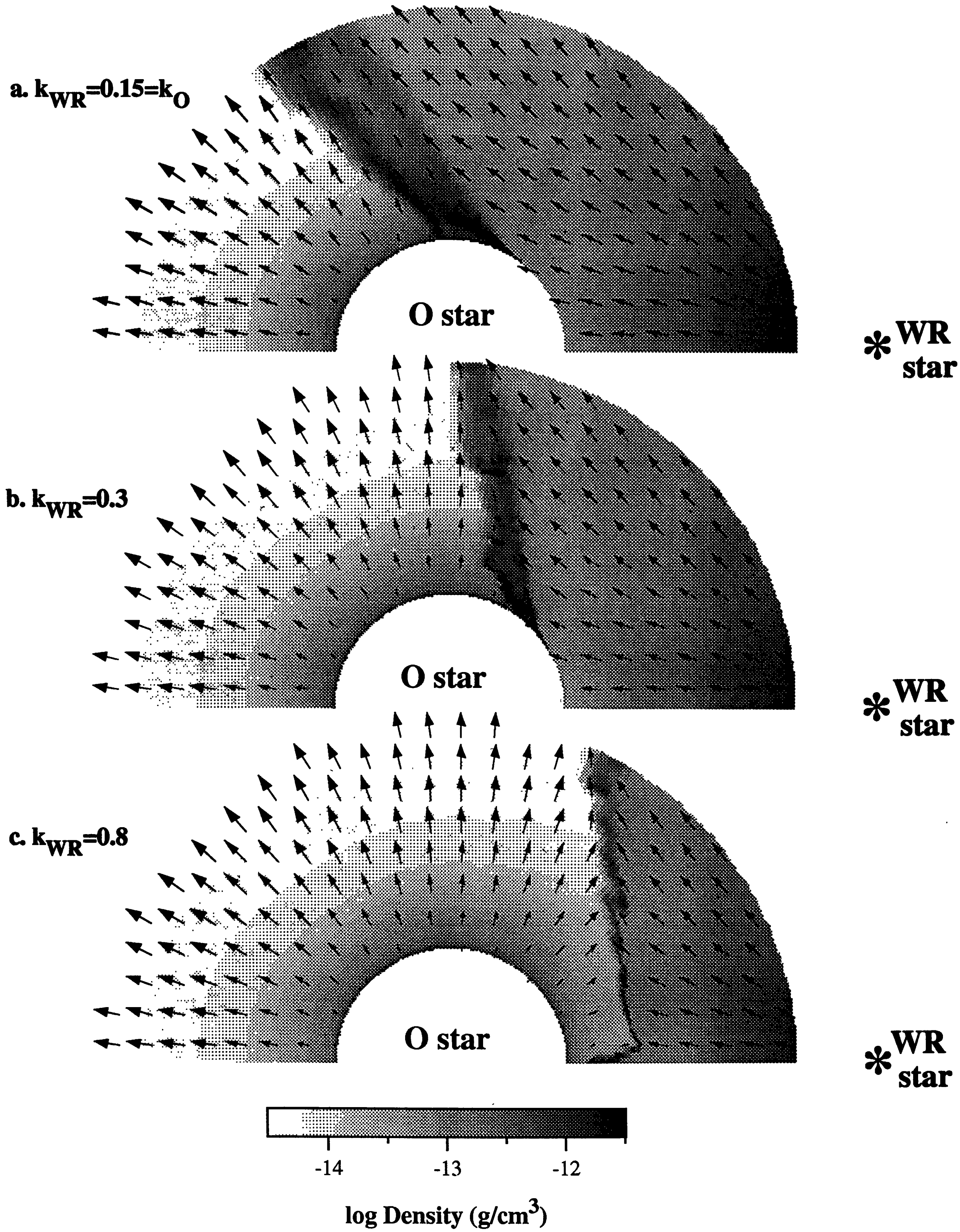

Fig. 2. Bow shock density structure in our 2D hydrodynamic simulation of V444 Cygni for $k = 0.15$, 0.3, and 0.8. The onset of radiative braking is evident.

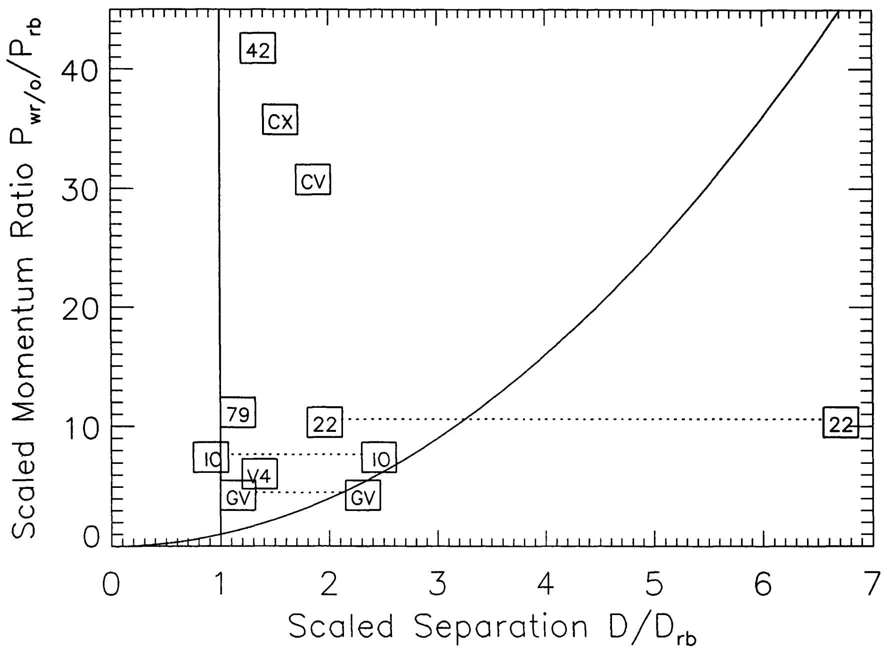

Fig. 3. Homologous scaling of the 8 binary models in Table 1, showing the radiative braking domain lying between the solid curves, defined in the text. An obvious two-letter code signifies each binary, and eccentric binaries sample a range of separations.

(WR 11): St.-Louis, Willis, & Stevens (1993); for WR 22 (HD 92740): Rauw et al. (1996); for WR 42 (HD 97152): Schulte-Ladbeck (1989); for WR 79 (HD 152270): van Beveren (1993) and Luhrs (1996); for CV Ser (WR 113): Massey et al. (1981) and St.-Louis et al. (1993); for CX Cep: Lewis et al. (1993); and for Iota Ori: Stevens & Pollock (1994) and Penny et al. (1994). Also of use were general relations in Howarth & Prinja (1989), Prinja et al. (1990), Hamann et al. (1993 and 1995), de Loore & van Beveren (1994), Maeder (1994), and Smith et al. (1994).

Though the parameters are sometimes uncertain by up to a factor of 2, the examples here do illustrate the potentially widespread importance of radiative braking in WR+O binaries with separations less than a few hundred solar radii. By this criterion, promising candidates not considered here include WR 21, WR 47, WR 127, WR 151, and WR 153. In the SMC, it is also likely that the WN3+O6 6.5-day binary R31 (Hutchings et al. 1993) will be a good candidate to observe the effect at lower metallicity.

We also treated Iota Ori, an O+B binary where the O star assumes the role of the WR in our analysis, to indicate that radiative braking is not limited solely to WR+O systems. The prevailing requirement is simply a large imbalance in the momentum-driving efficiencies of stellar components at separations of order 100 $R_\odot$. Additional O+B candidates include HD 53975 (Gies et al. 1994).

8. CONCLUSIONS

We have explored the ramifications of a new phenomenon, radiative braking, and propose it as a mechanism for allowing wind/wind collisions to exist in many systems that would otherwise suffer direct photospheric collision. In systems like V444 Cygni, γ Vel, and WR22, braking can only occur if the WR wind exhibits an intrinsically high opacity to to external illumination by an O spectrum. The apparent absence of photospheric collision and the presence of a widened bow shock are potentially significant clues that strong radiative braking is operating. An important future challenge for confirming this effect will be to find a more direct diagnostic of its presence, perhaps akin to atmospheric eclipse effects in isolated lines (Auer & Koenigsberger 1994) or pseudo-continua (Koenigsberger 1988). Further elaboration of the radiative braking phenomenon will be given in an upcoming journal paper (Gayley et al. 1996).

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