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# COLLIDING WINDS IN MASSIVE BINARIES INVOLVING WOLF-RAYET STARS

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## RESUMEN

Las estrellas Wolf-Rayet se destacan por sus vientos muy fuertes y calientes. Su presencia en sistemas binarios puede, por lo tanto, llevar a fuertes colisiones de vientos, las que se manifiestan como distorsiones bien definidas de las líneas espectrales, que además dependen de la fase. Recíprocamente, las variaciones de los perfiles pueden usarse para determinar las propiedades de la colisión de vientos, así como de los vientos en sí y hasta de la propia órbita. Examinamos la situación actual concerniente a colisión de vientos de estrellas WR en sistemas WR + O, WR + WR y WR + c.

## ABSTRACT

Wolf-Rayet stars are notorious for their very strong, hot winds. Their presence in binary systems can therefore lead to strong wind collisions, that manifest themselves as well-defined, phase-dependent distortions of the spectral lines. Turning this around, profile variations can be used to determine properties of the wind collision, as well as the winds and even the orbit itself. We review the present situation regarding colliding winds for WR stars in WR + O, WR + WR, and WR + c systems.

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

## 1. WHY STUDY COLLIDING WINDS IN MASSIVE BINARIES?

Massive, hot stars stand out for their strong, radiatively driven winds. For example, main sequence hot stars follow the relation $\dot{M} \propto L^{1.6}$ (e.g., Howarth & Prinja 1989; for a given luminosity $L$, supergiants have even stronger winds). Therefore, one would expect to find strong wind interaction effects in massive close binaries. The interest of such effects is manifold:

- in their own right, as a high-energy phenomenon;
- as a source of excess emission (+ absorption) compared to single stars, both in continuum and lines;
- to probe winds of hot stars (e.g., strong X-ray production from the collision is relatively simple to analyse, to obtain element abundances; shock cone angles can lead to estimates of the relative mass-loss rates of the two stars);
- to constrain the orbit and masses (e.g., identify non-perturbed lines, best for deriving the RV orbit; the behavior of the excess shock emission can lead to a reliable estimate of the orbital inclination, which when combined with the RV orbit, can yield the masses);
- as a source of strong instability and turbulence.



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## 2. COLLIDING WINDS INVOLVING WR STARS

### *2.1. Why Study (Colliding Winds in Systems with) WR Stars?*

Wolf-Rayet stars distinguish themselves from normal (e.g., main sequence, massive) stars in the following ways:

- They have the largest sustained mass-loss rates among stable, luminous stars, making colliding winds most obvious.
- They possess highly enriched winds, which allow one to trace directly the products of nucleosynthesis in the stellar cores.
- They represent the last phase in the evolution of all massive stars, before they explode as supernovae.
- They provide important impact (energy, enrichment) in starbursts and galactic evolution.

### *2.2. Types of Massive Binaries with WR Components*

Assuming that all O stars can evolve into WR stars, the most likely scenario (at least in the solar neighborhood) for massive binaries is:

$$O + O \rightarrow WR + O \rightarrow c + O \rightarrow c + WR \rightarrow c(+)c,$$

where c refers to a compact (relativistic) companion [(+) means that two such stars rarely end up being in a *bound* system]. If the original secondary star is a B star, the c + WR phase may never occur, depending on the importance of mass transfer to the B star. However, WR + B (or later) systems appear to be quite rare, if they occur at all (see below). If the initial masses of the two O stars are similar, it is feasible (in rare cases) that the two stars can evolve nearly in tandem to yield a WR + WR pair. Thus we are left with 3 types of (population I) WR binaries:

- WR + OB, observed in some 43% of WR stars (e.g., Moffat et al. 1986), e.g., V444 Cyg;
- WR + WR, observed only rarely, e.g., HD 5980(?);
- WR + c, observed only rarely, Cyg X-3 being the only reasonably sure case so far (but see below).

In this review we discuss all three cases.

## 3. THEORY AND MODELLING

### *3.1. Simple Analytic Theory*

Usov (1995) derives simple expressions to locate the contact surfaces and the two associated shock fronts, curved by orbital motion. The contact surface along the line joining the stars is located at distance $D/(1+\eta^{1/2})$ from the center of the WR star, where D is the orbital separation between the centers of the stars and the momentum flux ratio $\eta = (\dot{M}v_\infty)_{OB}/(\dot{M}v_\infty)_{WR}$. The asymptotic half opening angle of the shock cone, that wraps itself around the weaker-wind O star, $\theta(degr) = 120(1-\eta^{2/5}/4)\eta^{1/3}$, while the cone thickness is of order $\theta$ for the adiabatic case (normally for long orbital periods) and small for efficient cooling (short periods).

### *3.2. Numerical Simulations*

Two-dimensional hydrodynamic simulations for WR + O systems have been carried out mainly by Stevens et al. (1992). These basically confirm the simple theory and provide much more detail (e.g., turbulence, time dependence). Three-dimensional simulations have also now been started (Walder 1995). Clearly, both analytic and numerical methods are necessary and complementary.

### *3.3. Lührs' Model of Line Profiles from the Shock Zone*

Lührs (1991, 1995, 1996) has derived a very simple but extremely useful model of the emission line radiation expected from the cooling shocked material flowing along the shock cone, in the case of a circular orbit. The model is purely geometric, without dealing with the physical emission mechanisms. As illustrated in Fig. 1, line

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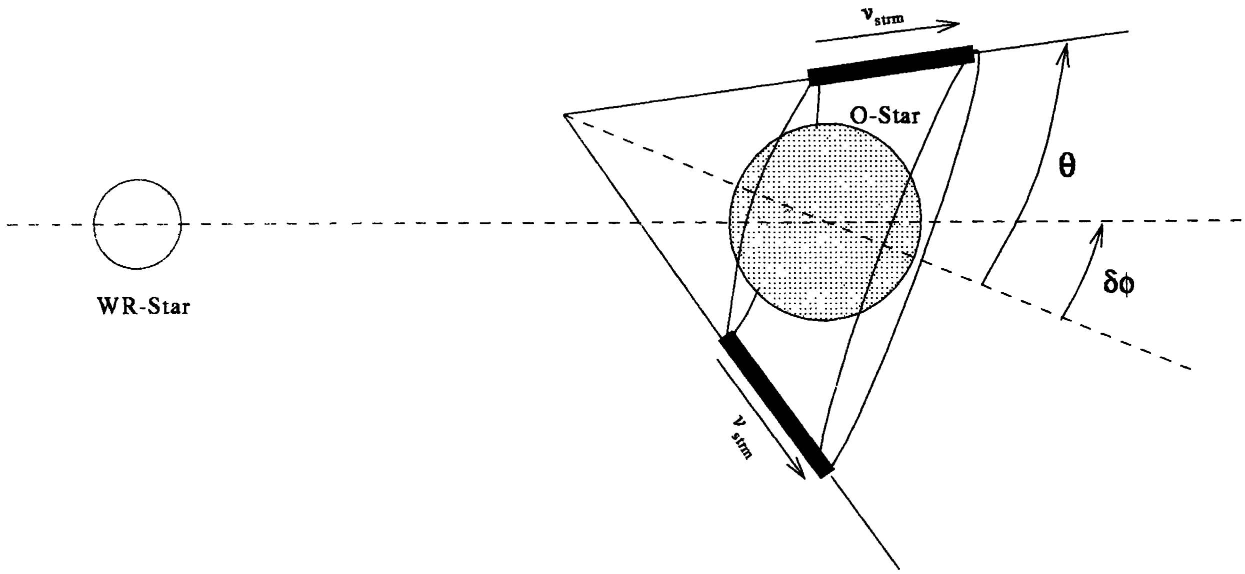


Fig. 1. Sketch in a WR + O system of the elementary basis for Lührs' model of optically thin line emission arising from a uniform, thin sheath along an idealized cone of opening half-angle $\theta$, axis deviation $\delta\phi$, and (constant) streaming velocity $v_{strm}$ along the cone.

emission is assumed (plausibly, to good approximation) to arise in a uniform, optically thin sheath on a thin cone. For a *physically* thin sheath, the emission line intensity as a function of radial velocity $v$ can be written as:

$$I(v)dv = (I_{tot}/\pi)dv/\sqrt{v_*^2 - (v-\bar{v})^2},$$

for $\bar{v} - v_* \leq v \leq \bar{v} + v_*$. Note that the integral of $I(v)$ over all allowed $v$ gives $I_{tot}$.

In the above expression for $I(v)$, one has:

$$v_* = v_{strm} \sin\theta\sqrt{1 - \sin^2 i \cos^2(\phi - \delta\phi)},$$

$$\bar{v} = v_{strm} \cos\theta \sin i \, cos(\phi - \delta\phi),$$

compared to the orbital radial velocity of the WR star:

$$v_{orb} = V_o + K_{WR} \sin\phi,$$

where $i$ is the orbital inclination, $\theta$ is the cone half-angle, $\phi$ is the orbital phase (= 0 when the WR star passes in front), $\delta\phi$ is the coriolis-caused rotation of the cone axis due to the orbital motion of the O star (cf., Fig. 1), and $v_{strm}$ is the (assumed constant) streaming velocity of line-emitting material in a sheath along the shock cone. The expressions $v_*$ and $\bar{v}$, respectively, are the resulting half-width (more precisely: half the velocity separation between the two peaks, e.g., in Fig. 2) and mean velocity of the shock-cone emission profile.

In Fig. 2 we show an example emission-line profile arising in the shock cone according to Lührs' model, for the above equations, as well as for the more realistic case of emitting material distributed between two cone half-angles (i.e., parabolic density distribution, peaking half way between the two surfaces, where the density falls to zero). Note how the asymmetry between the two peaks increases for thicker cones. Fig. 3 illustrates Lührs' (1996) model of phase-dependent profile variations for two extreme values and one intermediate value of both orbital inclination and cone half-angle. Notice how well-separated double peaks are most clearly seen when a wide shock cone is viewed broadside, while the profiles narrow when one is looking more and more *along* the shock cone axis.

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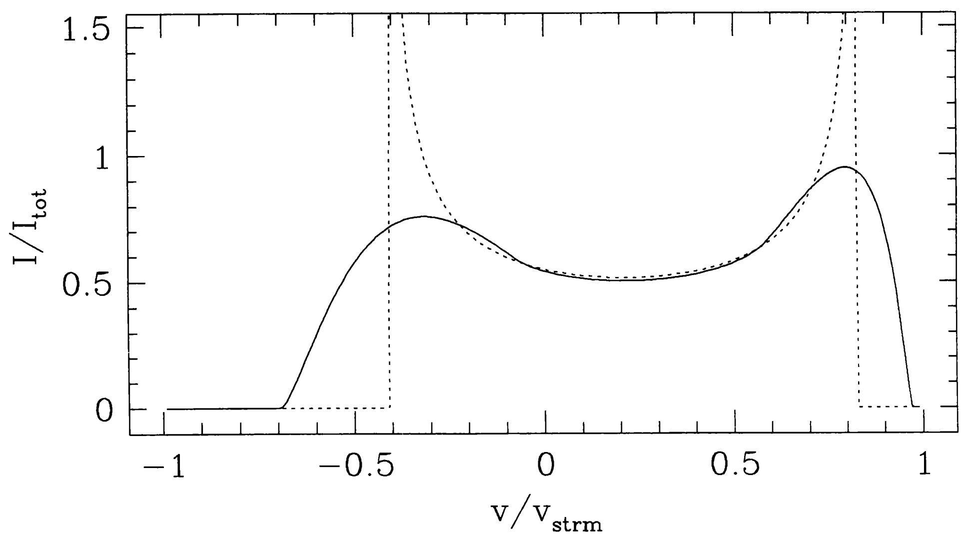


Fig. 2. Example of an emission profile from the shock cone as in Fig. 1, based on the model of Lührs, for $\delta\phi = 0$, $i = 35^o$, and $\phi/2\pi = 0.17$. The dashed profile, which diverges at its edges, refers to a thin sheath at $\theta = 40^o$, while the smoother, full-line profile refers to a parabolic density distribution of line-emitting plasma, centered at $\theta = 40^o$ and falling to zero at $\theta = 20^o$ and $60^o$. The area under each curve is normalized to unity.

## 4. PHASE-DEPENDENT OBSERVATIONS OF COLLIDING WINDS IN WR BINARIES

Concerning the observed excess flux arising in the shock cone, it is useful to divide the discussion into continuous emission and line emission. Both are useful, but the latter does have the extra advantage of providing Doppler, thus spatial (with a simple model) information.

### *4.1. Continuum Emission*

Most continuous emission seen from shock-cones occurs in X-rays, IR, and radio.

In X-rays, Corcoran (1996) discusses the situation for O + O and WR + O binaries. Among the latter, the best studied systems are $\gamma$ Vel, HD 193793 (WR140), and V444 Cygni. Especially the first two cases show clear, strong modulation due to phase-dependent visibility of the hot bow shock.

In the IR, Williams (1996) shows convincingly that a number of long-period, WC + O systems with eccentric orbits reveal phase-dependent IR emission from wind-collision created and heated dust. WN + O systems apparently lack the proper elements (e.g., Carbon) to form observable dust.

In the radio, non-thermal excess emission is seen to arise in the shock region, and is modulated by phase-dependent visibility, as for X-rays (Williams 1996). WR140 and $\gamma$ Vel are the only WR + O systems we are aware of that clearly show such radio emission.

### *4.2. Spectral Lines*

Spectral lines in WR stars have been studied in detail so far only in the UV, optical and IR domains. Phase-dependent line variations in WR binaries have been carried out mainly in the UV and optical (St-Louis 1995). Note that the UV work uses *IUE*, where one is limited to low S/N. Such UV data thus concentrate on the more obvious variations in the absorption edges, mainly of resonance lines. For example, Shore & Brown's (1988) analysis of UV lines in the eclipsing binary V444 Cygni leads to an estimate of the cone half-angle of $\theta \sim 30^o$, based mainly on variations of the strong C IV 1550Å absorption edge, as the faster O-star wind seen inside the shock zone sweeps across the line of sight.

However, in many ways, the optical (and even the IR in some cases: see below) is more useful than the UV for studying WR wind collisions: not only is it easier to obtain frequent, high S/N data, but one can also

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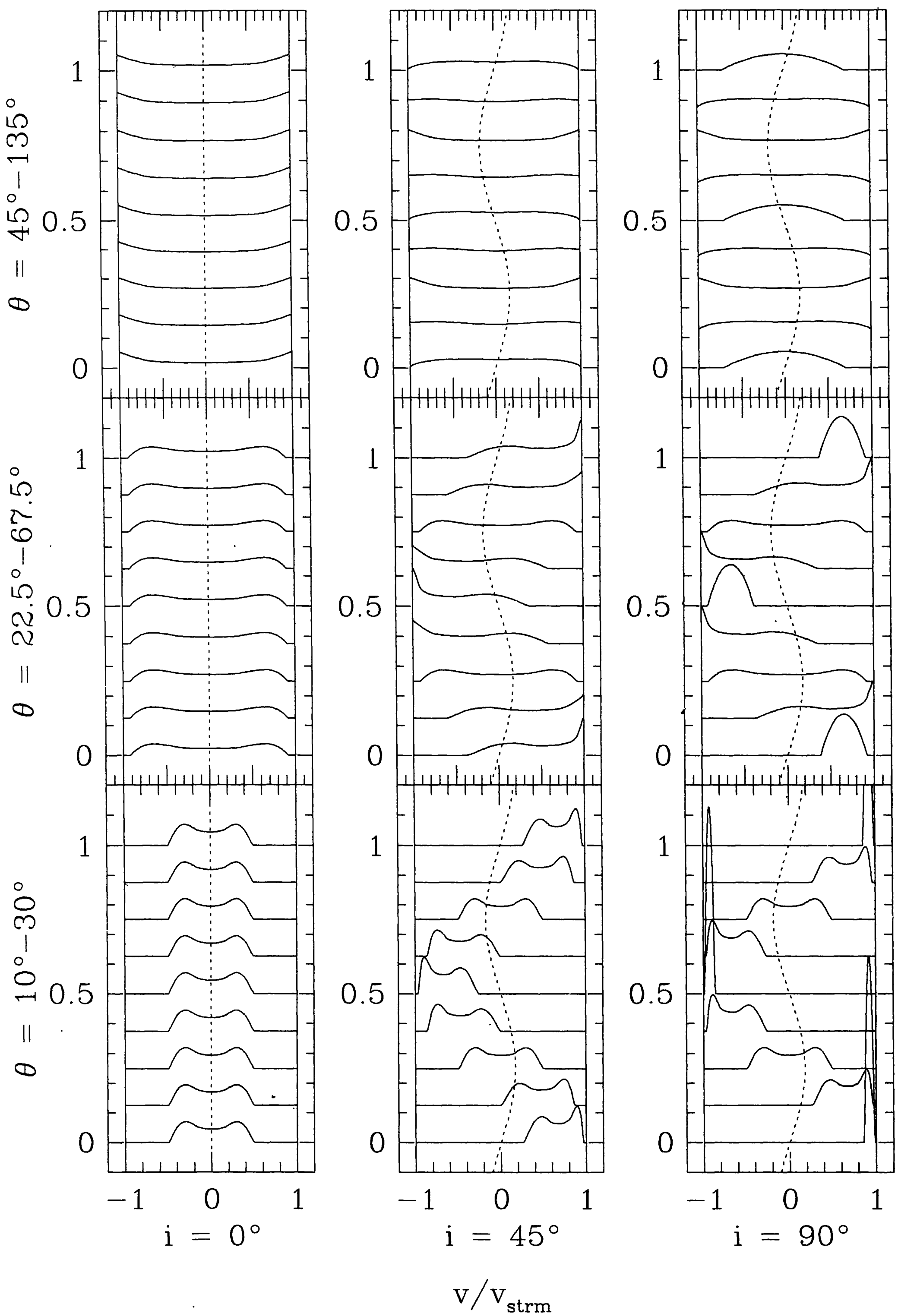


Fig. 3. Illustration of phase-dependent shock-cone emission-line profile variations, based on the model of Lührs (1996), for 3 different values (over a nearly complete range) of orbital inclination and cone opening half-angle. All profiles are normalized to the same area under the curve. We choose an angular cone thickness which is equal to the mean cone half-angle, e.g., $30^o - 10^o = 20^o = (30^o + 10^o)/2$. The dashed curve depicts the RV orbit of the WR component (true orbital speed $0.2v_{strm}$).

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study more readily many ***subordinate*** lines of various ionization and excitation levels, thus allowing one to better probe the environment, both in emission and absorption lines, nearer the bow shock head. We now divide up the discussion according to the nature of the companion to the WR star.

### *4.2.1. WR + O Systems*

As it turns out, one of the first studies of emission-line variations in a WR + O system, that now appears to be highly relevant to the wind-wind collision problem, is in the study of $\theta$ Mus (WC6 + O9.5I; note that the O-supergiant is a third star that does not participate in the observed 18-day orbit) by Moffat & Seggewiss (1977). These authors found very large RV variations in the C III 5696Å line, which lag $\sim 90^o$ out of phase with the smaller amplitude orbital variations of the much less perturbed doublet C IV 5802/12Å emission. Although these authors thought this was caused by streaming effects of excess WR wind material through $L_1$, we now believe (Hill et al. 1996) that this is a perfect manifestation of a cooling plasma flow along the wind collision shock cone, à la Lührs. The gas flow vectors are the same; it is the physics that is different and more plausible now.

Among other WR + O systems now (or being) studied optically, we have:

WN + O:
- CX Cep (Lewis et al. 1993)
- V444 Cygni (Marchenko et al. 1994, 1996b)
- CQ Cep (Marchenko et al. 1995)
- HD 193928 = WR141 (Eenens et al. 1996)
- HD 90657 = WR21 (Hill et al. 1996)

WC + O:
- HD 193793 = WR140 (Hervieux 1995)
- Sk $-69^o$104 = Br22(LMC) (Bartzakos et al. 1995, 1996)
- HD 152270 = WR79 (Lührs 1991, 1995, 1996; Hill et al. 1996)
- CV Ser (Antokhin et al. 1996)
- $\gamma$ Vel (St-Louis 1996)
- HD 97152 = WR42, $\theta$ Mus (Hill et al. 1996)
- HD 63099 = WR9, WR30a, HD 36521 = Br32(LMC), HD 36402 = Br31(LMC), Sk 188 = AB8(SMC) (Bartzakos et al. 1996)

We show as an example in Fig. 4, the double-peak variations in excess He I 4471Å emission observed by Marchenko et al. (1996b) in V444 Cygni. While this is a complicated system because it is eclipsing, the weak double peaks do behave in a way which is at least qualitatively compatible with the model of Lührs, with $i = 78^o$ (fixed), $\theta = 55^o, \delta\phi/2\pi = 0.03$, and $v_{strm} \approx 900$ km/s. The 14-day LMC binary WC4 + O system Br 22, on the other hand, shows very clear phase-dependent changes in C III 5696Å à la Lührs. This line emission arises uniquely in the shock cone of this star. In fact, the absence of this line in the WC component of Br22 led to a revision of the WC subclass from WC6 to WC4, no longer making it a unique case compared to all the remaining WC4 stars in the LMC (Bartzakos, Moffat, & Niemela 1995).

### *4.2.2. HD 5980: a WR + WR System?*

Breysacher & Westerlund (1978) first noted the remarkable variability in width of the emission lines in the brightest WR star in the SMC, HD 5980. Its emission lines were also noted to appear much too strong for its type (WN3 + OB), compared to the slightly *fainter* star AB6 = R31 = Sk 108 (also WN3 + OB). After its discovery as a deep eclipsing system in an elliptical orbit, Breysacher et al. (1982) found, still using photographic spectra, that the ***width*** variations in the strong He II 4686Å line in HD 5980 are strongly correlated with orbital phase, such that minimum width occurs near the two conjunctions (phases 0.00 = primary minimum and 0.36 = secondary minimum). More recently, Moffat et al. (1996) report on CCD spectra at various phases around the orbit in 1991 and 1992, well enough before the LBV eruption (Barba et al. 1995) to show the same width variations, with ***constant equivalent width.***

Following the work of Moffat et al. (1996), with $i = 86^o$ based on both polarization and light curve modulation as a function of orbital phase, the above equations (section 3.3) for the line half-width (which

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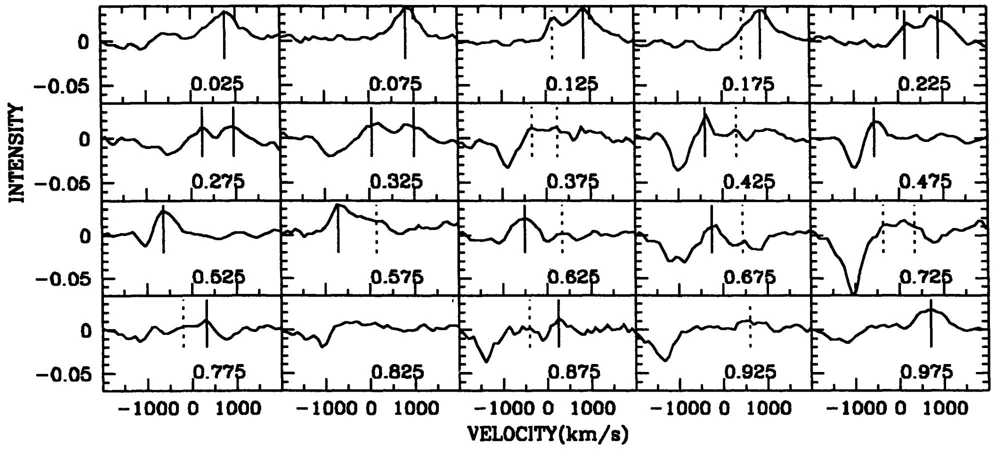


Fig. 4. Identification of the double peaks on the shock excess profile of He I 4471 in V444 Cygni (adapted from Marchenko et al. 1996b). Notice, in accordance with the model of Lührs, how the double peaks degenerate into one stronger peak near conjunctions ($\phi = 0.0$ and 0.5), for this nearly edge-on system.

cannot be negative!) and mean velocity of the excess shock cone emission in the case of a circular orbit, reduce to:

$$v_* \cong v_{strm} \sin\theta \, |\sin(\phi - \delta\phi)|,$$

$$\bar{v} \cong v_{strm} \cos\theta \, \sin(\phi - \delta\phi + 90^o).$$

These equations can be generalized to an elliptical orbit, by replacing $\phi$ by the true anomaly, etc. Note that the half-width will follow the orbit exactly (in shape but not amplitude), except for an abrupt change in slope twice during the orbit, when (for a circular orbit) $\sin(\phi - \delta\phi) = 0$. By characterizing the half-width (to within a nominal constant) by the easily measurable quantity FWHM, i.e., $FWHM \simeq const + 2v_*$, one can thus reconstruct the shape of the orbit (within a small shift $\delta\phi$) from the phase-dependent behavior of FWHM, by reflecting part of the FWHM curve about a line which passes through the point of abrupt slope change. Doing this for the 1991,92 He II 4686Å data of HD 5980, Moffat et al. (1996) (see Fig. 5) find values for the eccentricity ($e = 0.27 \pm 0.02$) and direction of line of nodes ($\omega = 128 \pm 3^o$) which are entirely compatible with the values obtained from the polarization and light curve fits. The mean velocity curve is less straightforward to fit, but Moffat et al. (1996) find a plausible fit of $\bar{v}(\phi)$ for amplitude $v_{strm}\cos\theta \cong 30$ km/s. Combined with $v_{strm} sin\theta \cong 535$ km/s from the fit in Fig. 5, Moffat et al. (1996) find $\theta = 87^o$ and $v_{strm} = 536$ km/s. If this model is correct, this means that we are dealing with two nearly equal winds that collide with contact surface lying in a nearly flat sheet. The low value of the streaming velocity is then also understandable, even for rapid winds. Such a violent collision between two nearly equal, strong winds makes plausible that fact that the major emission lines in HD 5980 (before becoming LBV) are completely dominated by phase-dependent varying emission from the shock cone. The strongly enhanced emission-line strengths in HD 5980 compared to AB6, as noted by Breysacher & Westerlund (1978), then also become understandable.

The above circumstances (high intrinsic luminosity, relatively weak intrinsic emission lines, equal winds) suggest that HD 5980 likely consists of two Of or Of/WNE (i.e., hot, luminous slash-) stars, rather than two intrinsically faint WNE stars, as proposed by Niemela (1988). It would also be more compatible with the large radii (Breysacher & Perrier 1991) and high masses (Niemela 1988) estimated for the two components. It also makes the recent evolution of one of the two massive components to an LBV phase more comprehensible in terms of our current knowledge of stellar evolution, which would not favor intrinsically faint (and presumably low-mass, like AB6 in the SMC: Moffat 1982a) WNE stars evolving *back* to become luminous LBVs. A test of this will not be possible however, until the current LBV phase has subsided and the system returns to what one would expect to be its normal state, as before the eruption.

Could the phase-dependent width variations be produced by any other means? If due to atmospheric eclipses of light from one star being scattered by passage through the strong wind of the other star, one would expect the *equivalent* width to drop dramatically and the mean RV curve to increase at conjunctions; however, this is clearly not seen. Alternatively, if the width variations are due to the back-and-forth anti-phased motion

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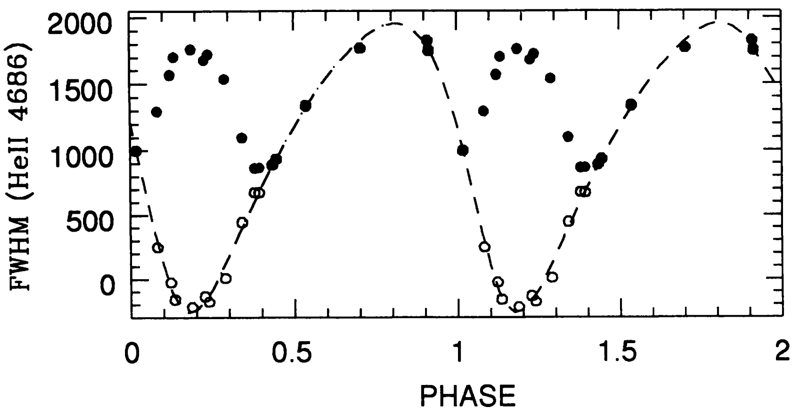


Fig. 5. FWHM (km/s) of the emission line He II 4686Å versus orbital phase (0.00 at primary light minimum, 0.36 at secondary light minimum) for HD 5980 (from Moffat et al. 1996). Filled circles refer to the original data; open circles are the original data in half the orbit reflected about the level 775 km/s, where the slope changes. The curve is a fit to the points, after reflection, according to an elliptical orbit (see text).

of the emission lines from two orbiting stars, one can derive an estimate (lower limit, actually) for the sum of the masses of the stars. Taking the total RV amplitude to be $K = (K_1 + K_2) \cong 2 \times 535 = 1070$ km/s, one finds

$$(M_1 + M_2)\sin^3 i = (1 - e^2)^{3/2} K^3 P = 2185 M_{\odot},$$

which is clearly highly improbable, within the realm of current knowledge about stellar masses.

#### *4.2.3. WR + c Systems*

Assuming the broad He lines in the near-IR spectrum of the heavily reddened 4.8-hour X-ray binary Cyg X-3 to arise in a WN component, this is the first truly convincing case of a WR + c system (van Kerkwijk 1995). However, because of extreme heating effects on the WR envelope, it is difficult to determine a reliable orbit in this case.

Among other WR + c candidates (e.g., Moffat 1982b; Marchenko et al. 1996a) have looked closely at the runaway system HD 197406 = WR148, on the basis of high-quality CCD spectra around the 4.3-day orbit. They find that mainly the intermediate-ionization lines of He II vary strongly with orbital phase, suggesting that *localized* heating of the WR wind occurs due to X-rays from accretion onto a relativistic companion or crashing of the WR-wind onto the surface of a low-mass, normal B-type star, whose stellar wind is essentially negligible.

Another one-time favorite WR + c candidate, the 3.76-day variable EZ CMa, shows clear rotating global wind structures (St-Louis et al. 1995). Although the origin of such perturbations is unknown, it seems difficult to account for them via an orbiting relativistic star, mainly because we do not see the reflex orbit of the WR star.

## 5. FUTURE PROSPECTS

Although many of the effects of wind collisions in massive stars are fairly subtle, the ready availability of efficient digital detectors now makes their detection and study on the basis of spectral line variability quite feasible. In the case of binaries involving the strong-wind WR stars, the effects of wind collision can even dominate over the WR wind itself. Nevertheless, CCDs have been used systematically for barely a decade, and there still remain numerous systems to be studied in this way. Among the most obvious things to look for now in these wind collisions, is how emission-lines of different ionization level behave. Possibly one will be able to map out the structure of the whole shock region, from the bow to areas far downstream.

Another aspect is to determine WR abundances using X-ray spectroscopy of million-degree plasma heated

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by wind collision. Such X-rays can only be spectroscopically probed using sufficiently high flux-rates at certain orbital phases in moderately long-period systems. This may, however, be more than just a challenge with present-day X-ray satellites.

On the theoretical side, although considerable progress is being made (e.g., wind braking before the collision in close WR + O systems – cf., Owocki & Gayley 1995; 3-D hydrodynamic simulations), more sophistication may be required to match reality, e.g., allowing for clumpy or rotationally flattened, globaly asymmetric winds before the collision; inclusion of magnetic fields.

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