RE-ANALYSIS OF CLOSE BINARY SYSTEMS

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Abstract. Line-forming regions around close binaries with strong winds ($\dot{M}/4\pi r_* v_\infty \gtrsim 10^{-4}\,\mathrm{g\,cm^{-2}}$) are large in extent compared with the stars, large enough to screen them. Their orbitally-modulated Doppler shifts can overestimate the mass function, because of a larger rotational lever arm. In particular, most of the black-hole candidates need not involve companions more massive than a neutron star.

The solar-wind problem is reconsidered. An extrapolation to Wolf–Rayet stars suggests that their winds are centrifugally driven. Their mass-loss rates tend to have been overestimated.

Seemingly single (massive) stars can hide a (compact) companion.

1. Introduction

Newton's laws, when applied to the Kepler problem, are among the most powerful tools for a determination of the orbital parameters and masses of binary systems. One observes the Doppler variations of emission and/or absorption lines, identifies them with certain co-orbiting objects (such as the two stars themselves, an accretion disk, a hotspot on the disk, or the like) and thus obtains the line-of-sight projection of the orbital velocity. This procedure would give reliable results if the lines were really emitted or absorbed by the surfaces of these objects.

For a known wind-mass-loss rate, temperature and radial velocity of the wind, one can calculate the photospheric radii of emission and absorption lines. (Insiders distinguish between so-called 'photospheric' and 'wind' lines depending on whether or not the lines are formed in the subsonic domain.) Line cross-sections (per atom) can be up to 10^{12} times larger than continuum cross-sections; consequently, the photospheric radii of the lines can be several 10 times larger than those of the continuum (Underhill and Fahey, 1986). (They would be $\leq 10^5$ times larger if the wind velocity was constant between the continuum photosphere and infinity, and if the wind was one-component in composition and excitation.) In other words: stars can have much larger radii – larger by an order of magnitude or more – when observed in the light of a strong line. In the case of a close binary, line photospheres can easily envelop the two stars which are, therefore, invisible in the line. In this case, the Doppler shifts of the lines are only indirectly related to the motion of the stars, and all inferences on the orbital parameters

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are inconclusive. At the same time, the following interpretations from the literature are called into question: (i) In the Cyg X-1 system, the He II line at 4686 Å is emitted in a neighbourhood of the inner Lagrangian point L_1. (ii) The Balmer emission lines in A 0620–00 come from the inner accretion disk. (iii) Enhanced line emission of cataclysmic variables stems from a hotspot where matter from the donor star intersects the accretion disk around the white dwarf.

That large line-forming regions occur among the best-studied close binaries is already indicated by the facts that (a) emission lines are often redshifted (on average), absorption lines are often blueshifted; (b) emission lines can brighten during occultations (of the continuum sources); (c) the amplitudes of the periodic Doppler shifts vary from line to line, and so do the systemic velocities (= average radial velocities); (d) there are often significant phase offsets between minimum light (due to occultation) and zero-radial velocity (w.r.t. the systemic velocity); (e) the lines' Doppler shifts are often far from periodic. In our understanding, fact (a) is a consequence of dominant (blueshifted) absorption on the approaching side, and fact (b) can be explained by modulated line self-absorption in the thick boundary layer of the winds between the two stars, see Figure 1. Figure 2 shows all mentioned effects except (b).

Historically, the conclusion that lines need not map close binary stars for mass-loss rates $\gtrsim 10^{-10} M_\odot \text{ yr}^{-1}$ – depending on composition, angular velocity, asymptotic wind velocity, and stellar radius – might have been drawn much earlier had not Wilson (1942) given strong arguments against a large extent of the line-emitting region. Wilson judged this extent by a comparison of the absorbed and emitted fraction in a P Cygni profile, overlooking the possibility that the absorption comes from an area which can be larger than the continuum photosphere. Wilson also concluded from the intensity ratio of neutral He-absorption lines with largely different lifetimes that the lines are formed inside a hardly diluted radiation field – a condition that is still satisfied inside the photosphere of the lines. Wilson (1942) could not convince Beals (1944), but his reservations apparently survived into the present. This despite the direct observation by Hanbury-Brown *et al.* (1970) who found a 4.5 times larger extent of γ Vel in the light of the 'weak' line C III 4650 Å. Even the recent survey by Abbott and Conti (1987) leaves the true size of the line-forming region unspecified and does not distinguish between radial and azimuthal velocities in the wind field.

We thereby arrive at another ambiguity in the interpretations: Are the observed Doppler shifts due to radial expansion or to (partial) corotation? Clearly, corotation at higher than Kepler speeds leads to radial expansion further downstream, at larger radial distances. But lines can form in an almost corotating zone, and mass-loss rates $\dot{M}$ inferred from radio-emission measures plus line-absorption edges can overestimate the true rates in proportion to $|v|/v_r$, by several others of magnitude. This uncertainty couples back into the determination of the line-emitting zone which should be evaluated self-consistently.

At the same time, corotation can be the cause for offsets between minimum light and zero-velocity shift. The implied centrifugal forces are much larger than radiation forces: the fact that Wolf–Rayet winds have higher estimated radial momenta than their

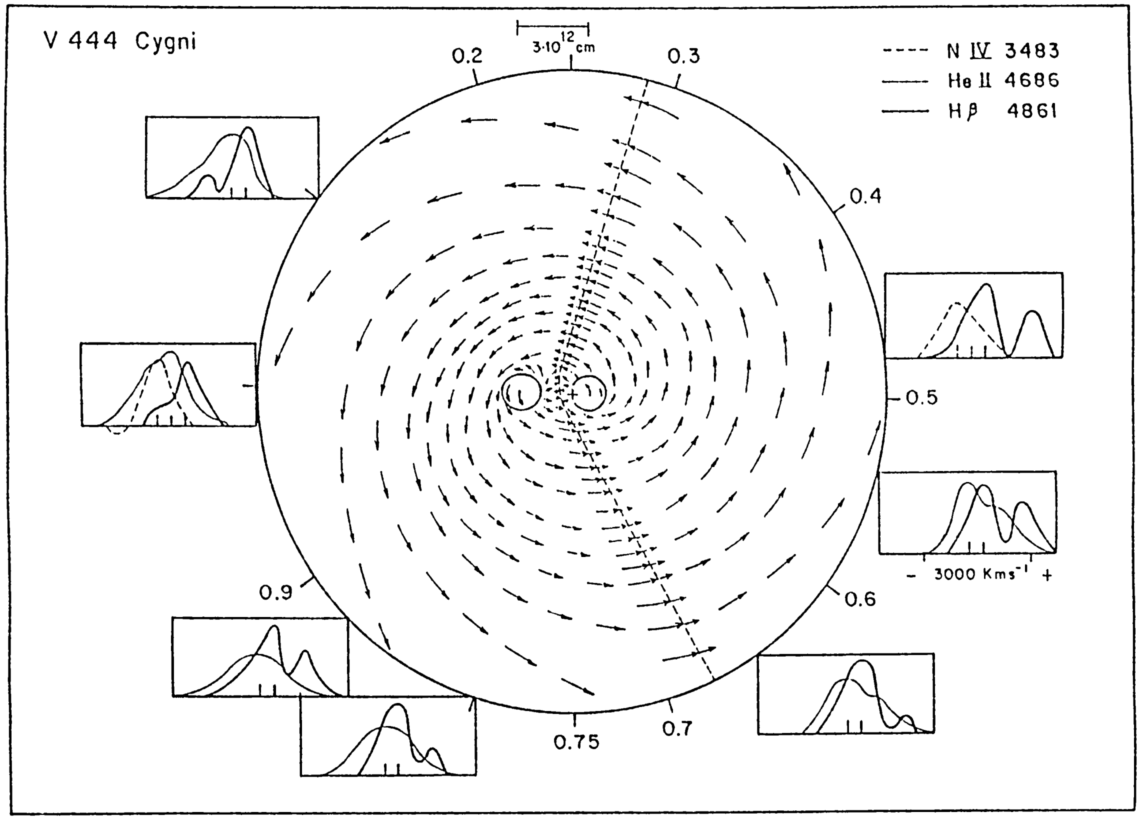

Fig. 1. Sketch of the proposed geometry of the wind zone around the Wolf–Rayet binary V444 Cyg drawn approximately to scale. The drawing shows a cut through the orbit plane. The O-star is assumed more massive and more luminous whereas the W–R star has the stronger wind. The two winds meet in a quasi-hyperboloidal boundary layer which is slightly offset in angle due to corotation. The drawing is based on the work by Ganesh *et al.* (1967) and Underhill and Fahey (1987). Further discussion can be found in the text.

radiation, by factors of 10 or more, cannot easily be understood without centrifugal driving.

When notice is taken of the large extent and partial corotation of the line-forming regions, stellar orbital-velocity estimates can shrink by a factor of 3, hence, the mass estimate of their companion can shrink by a factor of 3^2. In this way, several of the black-hole candidates lose their property of involving higher than neutron-star masses (cf. Bahcall, 1978; and Kundt and Fischer, 1989). We shall discuss two of them in Section 5.

Emission-line stars can radiate a significant fraction of their power in the form of lines. The lines, therefore, contribute significantly to their light curves. It then does not take surprise that conservative attempts at fitting the light curves of close binaries are unsatisfactory (Tjemkes *et al.*, 1986).

We shall estimate the extent of the line-forming regions in Section 2. In Section 3 we discuss corotation of the solar wind, as a testing ground for more rapidly rotating systems. Section 4 will be devoted to the corotation problem of close binaries, and Section 5 to a discussion of special systems.

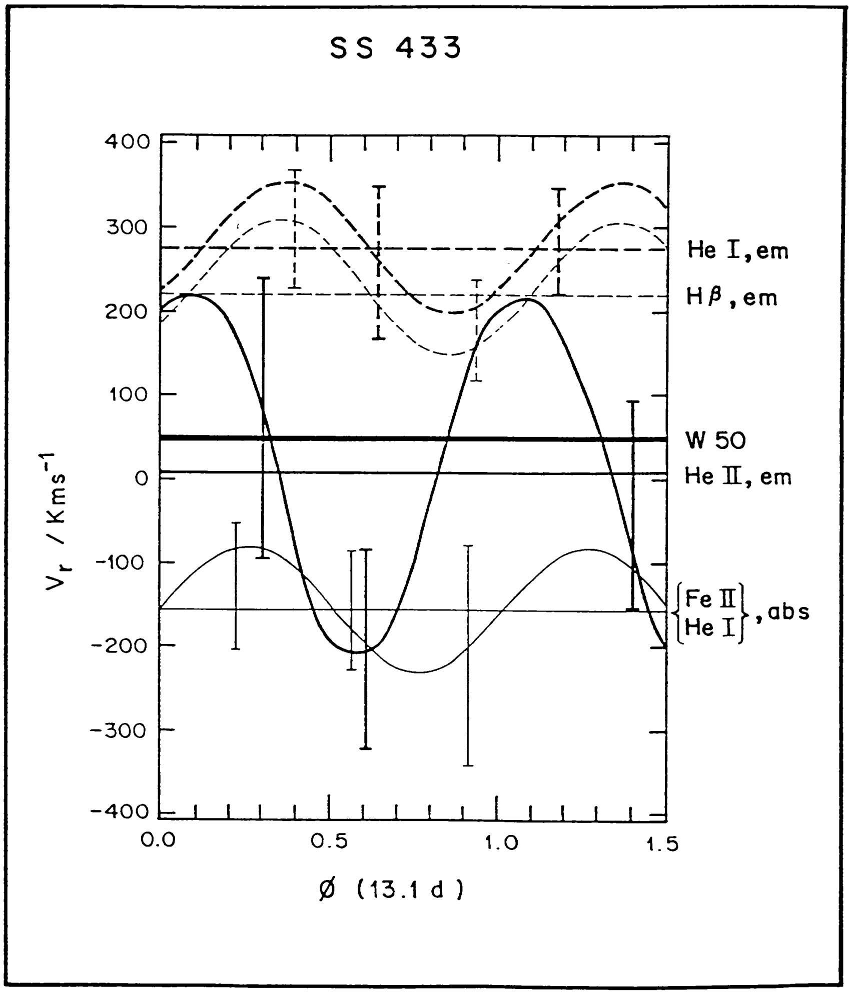

Fig. 2. Orbital radial-velocity variations of the emission and absorption lines of SS 433, based on Crampton and Hutchings (1981). Note the large intrinsic velocity spreads indicated by the error bars and the different systemic velocities.

2. The Line-Forming Regions

In this section we estimate the radial distance r_{line} out to which a wind zone is opaque in a resonance line. We shall do this in eight different ways, with the result that $r_{\text{line}}/r_* = 10^{1 \pm 0.5}$ holds for stars with strong winds.

The photosphere of a resonance line is defined as the sphere of radius r_{line} for which its optical depth towards infinity $\tau(\nu) = \int_r^\infty \kappa(\nu)\, \mathrm{d}s$ averages unity. Here the absorption coefficient $\kappa(\nu) = n\sigma(\nu)$ involves the frequency-dependent (and, hence, velocity-dependent) cross-section (Lang, 1974)

$$\sigma(\nu) = \sigma_{\mathrm{T}}\nu^4/[(\nu^2 - \nu_0^2)^2 + \nu^2(\Delta\nu)^2]\,, \tag{1}$$

whose peak exceeds the Thomson cross-section $\sigma_{\mathrm{T}} = (8\pi/3)\,(e^2/m_e c^2)^2 = 10^{-24.2}$ cm^2

by $(\nu/\Delta\nu)^2 \lesssim 10^{15}$ for optical frequencies. For all practical purposes, $\sigma(\nu)$ has to be averaged over frequencies. Averaging over one octave yields (Lang, 1974)

$$\langle\sigma\rangle = \nu^{-1}\int\sigma(\nu)\,\mathrm{d}\nu \approx gf\pi e^2\lambda/m_e c^2 \simeq 10^{-16.6}\,\lambda_{-4.5}\,\mathrm{cm}^2\,, \tag{2}$$

for optical wavelengths λ, $\lambda_{-4.5} := \lambda/10^{-4.5}$ cm, where the numerical value corresponds to a 'weighted oscillator strength' gf of unity. In the literature, the average cross-section $\langle\sigma\rangle$ is sometimes confused with the quantity $\int\sigma(\nu)\,\mathrm{d}\nu$ (which has a different dimension), as in Lang (1974). Its value exceeds the Thomson cross-section by $\lesssim 10^8$. Note that near resonance, $\sigma(\nu)$ is much larger than $\langle\sigma\rangle$: for a line of halfwidth $\beta\nu$, $(\beta < 1)$, $\sigma(\nu)$ exceeds $\langle\sigma\rangle$ by $\gtrsim \beta^{-1}$. Note that different parts of a spectral line are formed by different sheets inside the line photosphere; Doppler tomography could uncover them. But standard observations map the whole line-forming region which is approximately ellipsoidal in outline. We use the word 'line photosphere' in the same sense as Thomas Gold introduced the word 'magnetosphere'.

The radius r with $\tau(\nu) = 1$ now follows from

$$N(r) \approx nrZ = \sigma^{-1}\,, \tag{3}$$

where the critical column density N is related to the mass-loss rate $\dot{M}$ and (relative) abundance Z via

$$\dot{M} = 4\pi mnr^2u \approx 4\pi mNru/Z\,, \tag{4}$$

with u = radial velocity component. This yields

$$r(\tau(\nu) = 1) = \dot{M}\sigma Z/4\pi mu = 10^{13}\,\mathrm{cm}\,\dot{M}_{(-11)}Z/u_8\,, \tag{5}$$

for $\dot{M} = 10^{-11}\,M_\odot\,\mathrm{yr}^{-1} = 10^{15}\,\mathrm{g\,s}^{-1}$, mean cross-section $\sigma \approx 10^{-17}\,\mathrm{cm}^2$, $m = m_p$, and $u = 10^8\,\mathrm{cm\,s}^{-1} = 10^3\,\mathrm{km\,s}^{-1}$. Note that the (relative) abundance Z of a line-scattering atomic or ionic species can be small, of order 10^{-4} or significantly smaller, depending on the chemical composition of the stellar wind and its degree of ionisation and excitation (cf. Pauldrach, 1987).

But a (large) line-photospheric radius of 10^{13} cm is predicted, e.g., for $Z = 10^{-4}$, $u = 10^3\,\mathrm{km\,s}^{-1}$ and a modest (hydrogen) mass-loss rate of $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. Clearly, the strong winds of O- and Wolf–Rayet-stars must be opaque in their resonance lines out to many stellar radii, even if their mass-loss rates have been somewhat overestimated in the literature, and so should be the winds from many cataclysmic variables. (For abundances in WC stars see van der Hucht *et al.*, 1986).

As a second estimate of the line-photospheric radius $r_{\mathrm{line}} := r(\tau(\nu) = 1)$, let us compare it with the radius $r_* := r(\tau(\mathrm{cont}) = 1)$ of the continuum photosphere. From Equation (5) we get

$$r_{\mathrm{line}}/r_* = (\sigma Z/\sigma_{\mathrm{cont}})\,(u_{\mathrm{cont}}/u_{\mathrm{line}}) \approx 10^3\,Z_{-4}(u_{\mathrm{cont}}/u_{\mathrm{line}}) \tag{6}$$

because of $\sigma_T \lesssim \sigma_{cont} \approx 10^{-24}$ cm^2 (cf. Novotny, 1973; her κ equals σ/m). r_{line} would be intolerably large if the continuum-photospheric expansion velocity u_{cont} were comparable with the line-photospheric velocity u_{line}, as conceived, e.g., by Abbott and Conti (1987). We infer from Equation (5) that

$$u_{cont} = \dot{M}\sigma_{cont}/4\pi m r_* \approx 10^{6.5}\ \text{cm s}^{-1}\dot{M}_{(-7)} \tag{7}$$

for $\sigma_{cont} \approx 5\sigma_T$, $r_* \approx 10^{12}$ cm, $m = 4m_p$, and a (small) mass-loss rate of $10^{-7}\ M_\odot$ yr^{-1} to which we shall return in Section 4. When this value is inserted into Equation (6), together with $u_{line} = 10^{8.5}$ cm s^{-1}, we arrive at

$$r_{line}/r_* = 10Z_{-4}(u_{cont}/u_{line})_{-2}\ . \tag{8}$$

Should we have underestimated the mass-loss rate, the line-photosphere would grow beyond $10r_*$ for $Z \geq 10^{-4}$.

We favour a reduced mass-loss rate $\dot{M} \lesssim 10^{-6}\ M_\odot$ yr^{-1}, among others because of Hanbury-Brown *et al.*'s (1970) direct interferometric observation of the C III 4650 Å photosphere of the WC 8 star γ Vel, for which they found $r/r_* = 4.5$. This observation (of a non-resonance line), which seems to be so far unique, is certainly of crucial importance.

A fourth estimate of the size of the line-forming zone can be obtained from the area A required to radiate the peak power of the line (incoherently). This area scales as I/T where I is the (peak) intensity and T is the (excitation) temperature of the emission region. From this and $A \sim r^2$, one gets

$$r_{line}/r_* = (I_{line}T_{cont}/I_{cont}T_{line})^{1/2} \approx 10^{0.4}(T_{cont}/T_{line})^{1/2} \tag{9}$$

for an observed ratio $I_{line}/I_{cont} \approx 6$. This estimate is not stringent, but certainly consistent with $r_{line}/r_* \approx 10$.

A fifth estimate of r_{line}/r_* was given by Wilson (1942) by noting that the emission bands of the Wolf–Rayet binary HD 193576 show no blueshift during eclipses. He concluded that

$$r_{line}/r_* \gtrsim 4\ . \tag{10}$$

At the same time, Wilson pointed at an upper limit to the size of the line-forming region given by the absence of forbidden lines in HD 193576

$$r_{line} \lesssim 10^{13}\ \text{cm}/n_5 Z_{-1} \tag{11}$$

follows from the critical column density $N \approx nrZ \lesssim 10^{17}$ cm^{-2} and the maximum volume density n for forbidden lines. For $Z_{-1} \ll 1$, this constraint is not serious.

A seventh constraint comes from Shylaja's (1987) observation that the ratio of the radial-velocity amplitude of the emission lines N IV 4058 Å and He II 4686 Å for different WN binaries changes near an orbital period of 6 d, corresponding to a critical binary separation a of

$$a_{crit} = (GM/\omega^2)^{1/3} = 10^{12.4}\ \text{cm}\ M_{(1.5)}^{1/3}\ , \tag{12}$$

where $M_{(1.5)} := M/10^{1.5}\,M_\odot$. Apparently, the emission-line region of WN stars has an extent somewhat larger than this critical separation, corresponding to $r_{\rm line}/r_* \gtrsim 4$.

An upper limit on the extent of the line-forming region can be obtained as soon as one has a reliable estimate of the distance out to which the stellar winds can be forced into corotation by their frozen-in magnetic fields, cf. Sections 3 and 4. A corotating wind zone can amplify the orbital velocity in proportion to the lever arms w.r.t. the center-of-mass. The observed amplifications certainly do not exceed a factor of three, corresponding to line-forming radii smaller than three orbital separations, consistent with all the earlier estimates.

3. The Solar Wind

Ever since the pioneering work by Eugene Parker, the correct dynamics of the solar wind have been a problem of major concern. Here we are primarily interested in the extent to which magnetic fields can force the solar wind into corotation with the Sun. As far as we can see, this problem has not yet found an unanymous answer by theorists and observers: the theoretical predictions by Weber and Davis (1967, 1970) and Weber (1973) disagree with the (most recent) observations by Pizzo *et al.* (1983). As we are in need of a unique answer, we shall briefly review the state-of-the-art.

In their 1967 approach, Weber and Davis treat the solar wind as a one-fluid, non-viscous magnetized plasma with axial symmetry. The existence of a global solution for the toroidal velocity component, in the presence of a critical radius, fixes this critical 'Alfvén' radius $r_{\rm A}$ to be the preferred distance at which the radial velocity u overtakes the radial Alfvén velocity

$$B_r^2/4\pi\rho u^2 = 1 \quad \text{for} \quad r = r_{\rm A}\,. \tag{13}$$

Regularity implies that the angular momentum by mass L take the constant value

$$L = \omega r_{\rm A}^2\,, \tag{14}$$

and that the toroidal velocity component v_ϕ obey

$$v_\phi = \omega r(1 - u/u_{\rm A})/(1 - ur^2/u_{\rm A} r_{\rm A}^2)\,. \tag{15}$$

Within the Weber and Davis assumptions, this unique solution can be approximated by

$$v_\phi \approx \begin{cases} \omega r(1 - r/r_{\rm A}) \\ \omega r_{\rm A}/(1 + 2u_{\rm A}/r_{\rm A}\,\partial_r u_{\rm A}) \\ \omega r_{\rm A}^2(1 - u_{\rm A}/u_\infty)/r \end{cases} \quad \text{for} \quad r/r_{\rm A} \begin{cases} \ll \\ = \\ \gg \end{cases} 1\,. \tag{16}$$

It assumes its maximum near $r = r_{\rm A}/2$. The major part of the angular momentum is carried away by the magnetic field for $u_{\rm A}/u_\infty < 0.5$. As a warning, however, MacGregor and Friend (1987) have shown that $v_\phi(r)$ can behave quite different in the presence of yet another strong radial acceleration (like a radiation pressure gradient), though without the correct magnetic rigidity (Weber and Davis, 1970).

The required regularity of the radial velocity component u imposes further constraints. $u(r)$ turns out to be a monotonically increasing function, linear for $r \ll r_A$ and logarithmically growing for $r \gg r_A$. The ratio u_A/u_∞ is, therefore, ill-defined; Weber and Davis understand by u_∞ the value of u at the Earth's orbit, near $r = 10^2\, r_\odot \approx 4r_A$. Their numerical solution yields $u_A/u_\infty = 0.8$, whereas Parker's field-free solution yields $u_A/u_\infty \approx 0.65$. It is not clear to us whether or not the two models should agree better; an erroneous power of two – instead of four – of M_A in the last term of Equation (23) by Weber and Davis (1967) may simply be a printing error. Yeh (1976) likewise disagrees with their radial-velocity solution; see in particular his Figure 1. The angular-momentum loss $\dot{J}$, for a plausible extrapolation off the equatorial plane, amounts to

$$\dot{J} = (2/3)\omega r_A^2 \dot{M}\,. \tag{17a}$$

In their second paper, Weber and Davis (1970) include the viscous stresses in the presence of the magnetic field. The toroidal component v_ϕ now increases, near $r = 5r_A$, by as much as a factor of 6 compared with the earlier solution, but drops again beyond $5r_A$. The stronger rigidity caused by the viscosity has the effect that the net torque (exerted via the magnetic field) decreases by a factor of 0.6: i.e.,

$$\dot{J} \approx 0.4\omega r_A^2 \dot{M}\,. \tag{17b}$$

At the time of their writing, this second approximation appeared to correspond better to the measured solar-wind velocity field.

Unfortunately, Pizzo *et al.* (1983) measure a solar-wind velocity field which agrees much better with the first approximation, but moves the Alfvén radius in towards $r_A \approx 12r_*$ (instead of $24r_*$). We do not share their confidence in their results because they find the He-component to counter-rotate(!) whereas Weber's (1973) isothermal non-magnetized 2-fluid treatment – when generalized to partial corotation – wants it to rotate faster than the proton component, see also Metzler and Dryer (1978). (The $\mathbf{E} \times \mathbf{B}$-drift forces all components to move at the same speed perpendicular to $\mathbf{B}$.)

Reasons for doubting the results by Pizzo *et al.* are the large intrinsic scatter of their independent evaluations and the large uncertainty in determining the centroids of their velocity contours. Gyrations plus drifts of the different ions can offset their centroids (cf. Jokipii, 1987). Apparently, convergence between theory and observation has not yet been reached on this most important corotation problem.

We conclude that theoretical estimates of the maximum corotation velocity v_ϕ are very uncertain but can exceed $10\omega r_*$ or even $20\omega r_*$ for the Sun.

4. Centrifugally Driven Winds

It is widely believed that the winds of W–R stars are driven by radiation pressure acting on the lines. Yet the radial momentum of their winds has been estimated to exceed that of their radiation by at least a factor of 10, possibly a factor of 30 (Abbott and Conti, 1987). One argues that 'extensive multiple scattering' of the photons can remove the unbalance. But fleas jumping up and down in a matchbox cannot make it rise: multiple scattering cannot enhance the momentum transfer unless it took place either between the wind and a stationary component (such as a solid surface), or unless the stellar core were transparent. Neither of these two possibilities applies to the present situation.

We are, therefore, forced to find another driving mechanism, and propose (partial) corotation. This proposal is not new: Verbunt (1984) has used magnetic rigidity to explain significant angular-momentum losses of close binary systems, and Nerney and Suess (1987) have given it a thorough (though perhaps inconsistent) consideration (see also Poe *et al.*, 1989). Another hint at significant corotation is the fact that the spectral slope between radio and infrared frequencies asks for significant post-acceleration in the distant wind zone (Abbott and Conti, 1987). Such radial post-acceleration is a natural consequence of super-Keplerian corotation: toroidal velocities convert into radial velocities further downstream. Note that the implied magnetic fields are difficult to measure because in the line-forming region they are non-uniform and reduced, in proportion to r^{-2} (compared with surface values). A third hint at the relevance of centrifugal driving comes from the likely presence of (accretion) disks around Wolf–Rayet stars (Underhill, 1986) which keep the spin high. Are W–R stars contracting?

Once we allow for corotation, mass-loss determinations via radio-flux or IR measurements have to be revised downward because such measurements determine $\dot{M}/u_{\infty}$, not $\dot{M}$ itself, and absorption lines measure $v_{\parallel}$, not u. Figure 1 sketches our understanding of partial corotation, whereby 'corotation' encompasses both spin and orbital motion of the stars. Nerney and Suess (1987) do not discuss the possible inconsistency of their boundary condition, nor do they treat magnetic rigidity properly (Weber and Davis, 1970).

A crucial case is the system V444 Cyg whose orbital period P has been found to lengthen: $P/\dot{P} \approx 10^6$ yr (Cherepashchuk *et al.*, 1984). Does this lengthening imply a mass-transfer rate of some $10^{-5}\,M_{\odot}\,\mathrm{yr}^{-1}$? We are not convinced: a possible alternative explanation is a transformation of spin-angular momentum into orbital-angular momentum, like achieved by cog wheels. This transformation may overcompensate the angular-momentum losses implied by partial corotation of the escaping wind. The viscous coupling of the two corotating wind zones may be so efficient that mass-loss rates of order $10^{-5}\,M_{\odot}\,\mathrm{yr}^{-1}$ are not required. As the system gains orbital-angular momentum, the two stars continue spinning super-synchronously until their separation is large enough for decoupling.

5. Individual Binary Systems

This section discusses a few well-known close binary systems of various masses. Their common property is a sufficiently strong wind zone.

5.1. V444 Cyg

Figure 1 is a sketch of the WN5 + O6 binary V444 Cyg, of period $P = 4.21$ d, based on Underhill and Fahey (1987) and Ganesh *et al.* (1967). We urge observers to publish more – and more complete – data in this or a similar form, not merely radial velocities, in order to allow comparison of periodic fine structure in the lines with likely geometries.

The wind field in Figure 1 has been drawn according to the following plausible assumptions: between the two stars, there must be a contact discontinuity where the two ram pressures balance. This contact discontinuity would be spherical if ram pressures scaled exactly as r_i^{-2}, i.e., if velocity variations and directions could be ignored. At large distances, the two winds will move radially; their contact dscontinuity must then be a cone. Taken together, a hyperboloidal shape of the boundary layer is a plausible approximation, shifted in position towards the star with the (momentum-wise) weaker wind and illuminated by both stars. The axis of this hyperboloid is likely to be somewhat offset by corotation; such off-setting reveals itself by phase shifts (of order $2h$) of certain line light curves. Note that Figure 1 gives only a section through the orbital plane and that we observe the system along the generators of some perpendicular cone because of a non-zero inclination.

When one now makes the two further plausible assumptions that (i) the radiation by the boundary layer between the two winds dominates the modulated part of the light curves and radial velocities, because of its higher density, and that (ii) line self-absorption is stronger along the hyperboloid than transverse to it, one can arrive at a qualitative understanding of the red and blue line wings drawn in at the various phases. Of course, quantitative confirmation would ask for the solution of a rather involved radiation transport problem, more complicated than Pauldrach *et al.*'s (1985) spherically-symmetric solution (see also Pauldrach *et al.*, 1986).

5.2. Cyg X-1

The 9.7ab star HDE 226868 orbits in 5.6 d around an unseen object which has been conjectured to be a black hole since 1971 (cf. Bahcall, 1978). This conjecture is based on its large radial velocity amplitudes, in particular of absorption lines from H, He I, and He II. The velocity amplitudes are of order (70 ± 10) km s^{-1} whilst the (absorption and emission) lines have a FWHM of 220 km s^{-1}. Gies and Bolton (1986) have interpreted the absorption lines as though they came from the O star and the He II emission line as though it were emitted in a vicinity of L_1, assuming a mass-loss rate of order $10^{-5.5}\, M_\odot$ yr^{-1}. Their fit of He II is far from good. Our estimates of Section 2 show that both the star and the region between the two stars should be screened in the lines. Another difficulty is the phase offset (of 0.15) between zero (line-averaged) radial velocity and minimum *UBV* light.

Instead, the velocity amplitudes should be modelled as a feature of the distant wind zone, caused by an enhanced boundary layer of the winds from HDE 226868 and its unseen companion. This unseen companion may well be a neutron star with a relativistic (pair-plasma) wind orbiting around an almost reposing O star (Kundt and Fischer, 1989). The standoff shock may be at a distance of $\lesssim 10^{12}$ cm from the neutron star. The illuminated, corotating boundary layer does not radiate isotropically, thus giving rise to an orbital modulation of both the line shapes and intensities. Corotation of the wind out to several stellar radii can give rise to a mass function which overestimates the O star's orbital velocity by a factor of 3; hence, overestimates the mass of the unseen companion by a factor of 9. Cyg X-1 may well be a neutron-star binary.

5.3. SS 433

The highly variable X-ray and radio binary SS 433 with its relativistically moving hydrogen and helium emission lines, its radio and X-ray jets and its surrounding supernova shell W 50, has found various interpretations in the literature (cf. Kundt, 1981, 1987). Its optical flux has occasionally dropped by $\lesssim 3$ mag within one night, at constant *UBV* colours, showing that the underlying star cannot be more luminous than a B star. Most of the light can be switched on and off within hours.

The orbital variations of its observed emission and absorption lines (of period 13.1 d) are drawn in Figure 2, taken from Crampton and Hutchings (1980, 1981). Note the large error bars which are not due to measurement errors. The velocity amplitudes even vanished at a later observing epoch. Note also the largely differing systemic velocities none of which agrees (exactly) with the average velocity of the blue- and redshifted optical filaments in W 50. Clearly, the lines are formed in a distant wind zone whose geometry need not be very different from that drawn in Figure 1. The emission lines are redshifted due to preferred absorption on the approaching side, the absorption lines blueshifted for the same reason. SS 433 is a lovely testing ground for stellar wind models.

5.4. A 0620–00

The 1975 X-ray nova A 0620–00 has long since returned to quiescence, revealing a K-dwarf plus an accretion disk around some unseen object, with a period of 7.75 hr. McClintock and Remillard (1986) determined a mass greater than some 5 $M_{\odot}$ for the unseen object, thereby making it one of the best established black-hole candidates (see also Johnston *et al.*, 1989). This mass determination is supported by a good fit to a K4–K7V stellar absorption spectrum, by a coincidence within 1% of minimum light and zero-radial velocities, and by the neatly sinusoidal velocity variation (by (457 ± 8) km s^{-1}) of a spectral cross-correlation analysis. The lines have a FWHM of order 300 km s^{-1}, as expected for a K-dwarf.

A problem is posed by the strong and strongly variable Hβ and Hα emission lines, of FWHM = $10^{3.3}$ km s^{-1}, whose origin is attributed to the inner accretion disk because of the high implied velocities. But the inner accretion disk is expected to be optically thick and hot so that the Balmer lines could appear in absorption or be absent. Also, the size of the inner disk is insufficient to radiate the strong lines.

We prefer a very different interpretation: the wind of the K-star is expected to be weaker than the solar wind. If its companion is a massive disk surrounding a neutron star which drives a relativistic (pair-plasma) wind of power L, this relativistic wind will control the K-star's wind – like a wind-sack – for

$$L > \dot{M}vc \lesssim 10^{30}\ \mathrm{erg\ s^{-1}}\,. \tag{18}$$

On top of driving its relativistic wind, the (magnetized) neutron star will centrifugally expel matter from the inner disk at high velocities $v_{\rm disk} \lesssim 10^{3.5}$ km s^{-1} (Kundt and Fischer, 1989). This high-velocity wind from the disk is thought responsible for the broad Balmer lines. It is (orbitally) modulated by the revolving K-star's wind zone which stirs it at $\lesssim 470$ km s^{-1}.

5.5. DQ Her

Cataclysmic variables are not very different from A 0620–00 except that their compact object is a white dwarf rather than a neutron star. Their emission lines can have a velocity FWHM of order $10^{3.2}$ km s^{-1} which is not much smaller than the escape velocity from a white dwarf. Perhaps the rotating, magnetized white dwarf 'scrapes off' matter from the accretion disk and ejects it centrifugally from its corotating magnetosphere, as suggested for (some of) the binary neutron star X-ray sources by Kundt and Fischer (1988). The white-dwarf wind (of strength $\lesssim 10^{-10}\ M_\odot$ yr^{-1}) can thus confine its companion's thermal wind.

DQ Her, one of the most interesting cataclysmic variables (of period 0.194 d), was a slow nova in 1934. Hutchings *et al.* (1979) gave it a careful consideration, pointing out various difficulties of a conservative interpretation of the line variations. In particular, the putative hot spot in the accretion disk may be invisible in the lines. It may have to be replaced by a corotating boundary layer between the two winds. The velocity amplitude of some 200 km s^{-1} of the emission and absorption lines need not strictly coincide with that of the red-dwarf companion. Similar thoughts have been expressed by Drew and Verbunt (1985).

It will, therefore, be worth re-analysing the cataclysmic variables, among them SS Cyg (e.g., Cowley *et al.*, 1980). In particular, the 'superhump' outbursts of the SU UMa stars and their periodic modulations, at a period exceeding the orbital period by a few percent, may be due to almost corotation of centrifugally ejected disk matter (Krzeminski and Vogt, 1985).

5.6. Other close binaries

If some of the most famous binaries have to be re-interpreted, then what about the others? Why, for instance, does the 3.4 d O6.5f-star binary 3U 1700–377 not suggest a companion mass larger than that of a neutron star? Its wind has a FWHM of $10^{3.5}$ km s^{-1} and an orbital modulation of only (19 ± 1) km s^{-1}.

More generally, when we see no or only a modest velocity variation, how certain can we be that there is no companion? Whenever the companion's wind is comparatively weak, the binary wind zone will approach axial symmetry, and no orbital modulation is expected. All of the massive 'single' stars are likely to have hidden compact companions, both for formation reasons (Boss, 1988) and because there are so many high-velocity neutron stars in the Galaxy (Kundt, 1985).

It will certainly be worth re-discussing all of the high mass-loss systems, in particular the Wolf–Rayet binaries whose properties have been recently summarized by Willis (1982), Chiosi and Maeder (1986), Underhill (1986), and Abbott and Conti (1987). Their (partially) corotating wind zones pose difficult radiation-transport problems. Inclination effects ask for 3-*d* treatments. Our understanding of close binaries may still be at its beginning.

Note Added in Proof

Edward Geyer has informed us that stellar wind zones in (partial) corotation can already be found in O. Struve (1950), *Stellar Evolution*, Princeton Univ. Press, Figure 32 and below.

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