THE STELLAR WIND VELOCITY FUNCTION FOR RED SUPERGIANTS DETERMINED IN ECLIPSING BINARIES

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ABSTRACT

We discuss the potential for direct measurement of the acceleration of stellar winds from the supergiant component of Zeta Aurigae-type binary stars. The aberration angle of the interaction shock cone centered on the hot star provides a measure of the velocity of the cool star wind at the orbit of the secondary. This is confirmed by direct observations of stellar wind (P Cygni) line profile variations. This velocity is generally smaller than the final (terminal) velocity of the wind, deduced from the P Cygni line profiles. We discuss the contrast between these results and previously published supergiant wind models. We consider the implication on the physics of energy source dissipation predicted in the theoretical models.

Subject headings: stars: eclipsing binaries — stars: late-type — stars: supergiants — stars: winds

1. INTRODUCTION

Thirty years ago, Deutsch (1956) demonstrated that the low speed wind from a Her never exceeds the escape velocity throughout its observable regime, implying that energy (and momentum) deposition must continue to many stellar radii. In recent years, however, researchers have tended to adopt velocity functions for stellar winds in late-type supergiants for which energy deposition is confined to a thin shell at the base of the flow (Cassinelli 1979) and the wind velocity is constant for the rest of the flow (e.g., Che, Hempe and Reimers 1983). Their motive for adopting such a velocity profile was that the combination of large mass fluxes and low final wind velocities require energy or momentum deposition below the sonic point in the flow (Leer and Holzer 1980). In contradiction to this popular model, we present evidence for continuous acceleration of stellar winds over a large range of heights.

Zeta Aurigae systems are eclipsing binaries with a hot main-sequence companion orbiting a cool supergiant star. The hot star's light has been used as a probe to explore the extended atmosphere of the supergiant primary (Wright 1970; Stencel et al. 1979). Recent high-resolution ultraviolet spectroscopy of these systems made possible by the International Ultraviolet Observatory (IUE, see Bogess et al. 1978a, b), has resulted in direct observational evidence for an accretion shock in four systems: Zeta Aurigae (Chapman 1981), 22 Vulpeculae (Ahmad and Parsons 1985), 32 Cygni (Ahmad 1986), and 31 Cygni (Reimers and Che-Bohnenstengel 1986; Ahmad 1987). The shock is due to the interaction of the primary wind with the companion or its wind and results in a column of material accreting onto the secondary. Because the orbital velocity of the components in these systems is known, the phase offset from secondary minimum, or aberration angle, at which the shock and/or accretion column are observed implies, by vector combination, the velocity of the supergiant’s wind at the orbit of the B star ($v_w$). When taken together with the “terminal velocity” of the wind ($v_T$), estimated by the velocity of the short wavelength edge of the P Cygni profile near secondary minimum, this provides us with two points of the wind velocity as a function of radial distance from the supergiant.

In this paper we apply this procedure to Zeta Aur-type systems to provide a direct measure of the velocity function of winds of their late-type primary components. We also present arguments that direct spectroscopic observations of the stellar wind itself confirms the value of $v_w$ inferred from the accretion shock aberration angle. Finally, we note that these observations have the important implication that, at least in these systems, stellar wind acceleration is not confined to a thin shell near the surface of the emitting star. We suggest some implications for energy deposition which could lead to an understanding of the physics of stellar wind acceleration and conditions in the outer atmospheres of late-type supergiants.

II. ABBERRATION ANGLE

At the secondary minimum only material outside the orbit of the B star will contribute to the absorption wing of the P Cygni profile which is formed by the supergiant wind scattering the hot dwarf continuum. The velocity of maximum absorption provides an estimate of the terminal velocity.

Ahmad, Chapman, and Kondo (1983, hereafter ACK) developed a model for the accretion interaction region in the prototype, ζ Aur (the ACK model; see Fig. 4 of that paper or Fig. 1 of Ahmad 1986 for a schematic diagram of the model). They estimated an aberration angle of about 35° due to the motion of the secondary through the primary's wind. A monthly monitoring of the system (Ahmad 1986) suggests a similar value of $32 ± 2°$. Because the orbital velocity of the secondary in ζ Aur is only about $37 \text{ km s}^{-1}$ in the rest frame of the primary at the time the accretion column is observed, this aberration angle implies that the supergiant wind velocity at the orbit of the B star is

$$v_w = \frac{37}{\tan 32 ± 2°} = 59 ± 5 \text{ km s}^{-1}. \quad (1)$$

All errors quoted are estimated 1 σ standard errors.
The secondary star in ζ Aur is far from the base of the primary wind flow, being about 13 stellar radii from the surface at the time of the accretion column observation. Yet the value of $v_p$ calculated in equation (1) is less than the maximum observed velocity of the supergiant wind. This latter terminal velocity, $v_p$, can be estimated from the velocity of the shock wavelength edge of the absorption wing of the Mg II spectral lines near secondary minimum (when only material outside the orbit of the dwarf star will contribute to the absorption). We get $v_p = 72 \pm 15$ km s$^{-1}$. The wind velocity, $v_w$, at this large an orbital separation appears to be close to the terminal velocity, $v_p$. We have, however, chosen a very liberal estimate of the standard error for $v_p$, namely 40% of the “stochastic velocity,” as discussed below.

In the case of 22 Vul, the velocity of maximum absorption of Mg II near secondary minimum implies $v_p = 160 \pm 20$ km s$^{-1}$. Given the shock cone half-width in 22 Vul of about 7° (Ahmad and Chapman 1986), the data of Ahmad and Parsons (1985, 1986) implies an aberration angle of 31° ± 2°. Then we may calculate from equation (1) that for 22 Vul, $v_w = 106 \pm 8$ km s$^{-1}$. The B star in 22 Vul is about 6 stellar radii from the primary, and there appears to be a dramatic acceleration of the wind far from the primary’s surface.

The error estimate we have given for $v_p$ is simply 40% of the “stochastic velocity” (effective turbulent velocity) of the absorption wing (Che, Hempe, and Reimers 1983). If the wind is at its terminal velocity at every point outside the hot star orbit (contrary to our thesis), the only error is the uncertainty in the determination of the velocity of maximum absorption (estimated by the quoted error). If, on the other hand, our thesis is correct, then the velocity of maximum absorption will be smaller than the actual terminal velocity and the quoted error is too large on the minus side—which is the domain of interest to our thesis. Even given this liberal error estimate, the terminal velocity greatly exceeds the calculated wind velocity at the B star companion in 22 Vul. This analysis reveals a measurable wind acceleration beyond the orbit of the B star and outside any hypothetical “thin shell” around the primary.

Reimers and Che-Bohnenstengel (1986) comment on the fact that their model synthesizing the Fe II and Si II lines shows a peculiar lack of intermediate velocity material, and they hypothesize both a thick acceleration zone and an artificial second region of acceleration near the orbit of the secondary. We argue that the single thicker yet acceleration zone which their model produces is an artifact of ignoring the gravitational effects of the secondary. The effect of the omission of the companion star's gravitational effects is that high-velocity disturbed wind is being observed near the B star, corresponding to a distance from the K star at which the undisturbed wind actually is at intermediate velocities. We shall show in the next section that direct observations of the 22 Vul Mg II line exhibit variations consistent with our analysis.

Application of the ACK model to the third case, 32 Cygni, is somewhat complicated by the smaller inclination angle of that orbital axis to the line of sight. (Zeta Aur and 22 Vul are virtually edge-on systems.) Assuming an inclination angle of 78° (Schroeder 1985), we can calculate, as before, from the data obtained by Ahmad (1986) that $v_p = 39 \pm 4$ km s$^{-1}$, corresponding to an aberration angle of $37° \pm 3°$. The velocity of the peak absorption near secondary minimum suggests $v_p = 90 \pm 15$ km s$^{-1}$. The implied acceleration beyond the dwarf star orbit is again dramatic. Consistent with this conclusion, Schroeder (1985) found that thickening the acceleration zone makes it easier to reproduce the density distribution of 32 Cyg derived from a curve of growth analysis.

We have also applied this analysis to observations of 31 Cyg. Che-Bohnenstengel and Reimers (1986) and Ahmad (1987) both conclude that the aberration angle is somewhere between 15° and 42°. The failure to detect Mg II at either of these phases (Ahmad 1987) implies that the actual aberration is near the center of this range. Combining this with the fact that the detected lines (C IV and Si IV) are somewhat stronger in the observations at 15° (Che-Bohnenstengel and Reimers 1986), we estimate the aberration angle at $27° \pm 4°$, which implies $v_w = 71 \pm 14$ km s$^{-1}$. From an inspection of the Mg II absorption wing near secondary minimum (Ahmad 1987), we find $v_p = 80 \pm 8$ km s$^{-1}$, in good agreement with the value obtained from Che, Hempe, and Reimers (1983) study of the Fe II and Si II lines.

III. EMPIRICAL DETERMINATIONS

If the analysis of the preceding section is correct, we may reasonably ask whether the inferred velocity function may not have some directly observable effects on the P Cygni profile? Such effects have been observed. Comparisons of secular variations in the Mg II resonance line spectrum can be used to directly measure the projected velocity of the wind at the orbit of the hot companion in such systems.

Measurements in the case of ζ Aur (Ahmad 1986) show that absorption at the calculated undisturbed wind velocity (region B in Fig. 1) decreases when absorption at the disturbed wind velocity (region A in Fig. 1) increases, confirming the ACK model value (Ahmed, Chapman, and Kondo 1983). That is, the greater the distortion in the Mg II profile due to the presence of accreting material (region A), the less is the absorption due to undisturbed wind at velocities $v_w < v < v_p$ (region B).

Observations (Ahmad and Parsons 1987) of 22 Vul indicate the presence of more shortward shifted absorbing material outside of the obscuration phase (i.e., obscuration of the secondary by the accretion column) than during the obscuration phase (Fig. 2). The velocity of this material coincides with the calculated undisturbed wind velocity, $v_w$, after allowing for projection effects.

The case of 32 Cyg is complicated by its higher inclination angle and some peculiar transient effects, and we are therefore unable to check our calculated velocity in that case by the direct observation of the accretion column. Nor can we check the calculated velocity for 31 Cyg as the Mg II accretion column absorption has not yet been directly observed in that system (Ahmad 1987).

The analysis summarized in the preceding paragraphs is virtually model independent. We make only one assumption: that the difference in flux at the inferred wind velocity for the short period that the line of sight passes through the disturbance in the wind is due to a decrease in the amount of absorbing material (irrespective of cause) rather than an increase in emission. The latter possibility is farfetched. We can conceive of no reasonable geometrical effect that can increase emission over a narrow range of phase angles only. It is conceivable that some time-dependent, nongeometrical effect (e.g., variations in the supergiant stellar wind) alters the absorption line wings in a manner that coincidently mimics the variations expected from the shock cavity. While this cannot be ruled out without further observations for repeatability of the phenomena (now
The accretion column absorption appears stronger at the time of weaker absorption at the undisturbed wind velocity. "A" marks the velocity of absorption due to the accretion column, "B" marks the velocity of the undisturbed wind (corrected for projection effects).

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profile with phase are not sufficiently dramatic to support such a conclusion. We suggest that an additional observational constraint is needed to resolve this problem because the actual wind velocities cannot be accounted for. They conclude that it must be that the wind is quickly accelerated to its terminal velocity (within a stellar radius of the surface) and then remains essentially flat.

In § II we pointed out that the presence of the secondary causes not only a shock in the wind, but also a gravitational distorsion to the velocity function. Wind approaching the secondary from the primary will be additionally accelerated; wind passing near the secondary will be deflected toward it, and wind beyond the secondary will be retarded. We have already suggested this effect may distort the velocity functions obtained from line synthesis. In principle it could radically alter the structure of the shock cone. There is no reason to believe it can affect aberration angle, however.

Notwithstanding the validity of our analysis, a related problem is whether the secondary may be responsible for the observed velocity function, making it inapplicable in the case of single late-type supergiants. It is conceivable, after all, that the secondary may play a role in the acceleration of the wind whether through magnetic effects, radiation effects, or indirectly through the generation of dust particles by some interaction with the primary. Although arguments can be made that none of these effects could be important in themselves, they could conceivably account for the additional energy and/or momentum input implied by our analysis. We think this unlikely, however, as acceleration of the wind by the dwarf should result in an asymmetry of the wind profile about the point of origin of the wind: the supergiant. Variations of the Mg II P Cygni profile with phase are not sufficiently dramatic to support such a conclusion. We suggest that an additional observational constraint be made by comparing the Mg II emission line profiles of these stars during primary eclipse against the profiles in single stars resembling their primaries. The data to perform such a study exist in the IUE archives but is beyond the scope of the present paper.

V. IMPLICATIONS FOR STELLAR WIND THEORY

A stellar wind is accelerated to escape velocity at some distance from the surface and then is assumed to settle to some final "terminal velocity." In the recent past, model makers have assumed that the wind is quickly accelerated to its terminal velocity (within a stellar radius of the surface) and then remains essentially flat. The systems discussed in the preceding sections pointedly contradict this picture as can be seen from Table 1. In all three cases our study indicates that the velocity of the wind at the distance of many stellar radii remains well below the terminal velocity, \( v_T \).

This conclusion has important implications for stellar wind acceleration models. In Figure 3 we plot the observed velocities (relative to terminal velocity) as a function of distance from the primary (in units of primary stellar radial) in the systems under discussion. The primary stellar radius determined from eclipse data has been used except in the case of 32 Cyg for which, due to its large inclination, the spectroscopic radius is preferred. The ratio of radial velocity to terminal velocity differs significantly from unity. Che, Hempe, and Reimers's (1983) model for \( \zeta \) Aur is plotted as a dashed line on Figure 3 and does not match the plotted observations. Neither does the Hartmann and Avrett (1984) model for \( \alpha \) Ori (Ahmad and Stencel 1986).

In Figure 3 we also plot theoretical models with and without damping (Hartmann and MacGregor 1980). Those curves suggest that one problem with the standard models is the assumption of a short scale length for the dissipation of the source of energy input. Ahmad and Kuin (1987), however, have found that simply increasing the dissipation length is insufficient to resolve this problem because the actual wind velocities (as opposed to the relative wind velocities shown in Fig. 3) cannot be accounted for. They conclude that it must be that the dissipation length changes with radius. Such an effect could arise from leakage of Alfvén waves (see Davila 1985).

### TABLE 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Zeta Aur</th>
<th>22 Vul</th>
<th>32 Cyg</th>
<th>31 Cyg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supergiant mass ( (10^{33} , \text{g}) )</td>
<td>16</td>
<td>8.6</td>
<td>38:</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>Supergiant radius ( (10^{12} , \text{cm}) )</td>
<td>7.0</td>
<td>3.8 ± 1.5</td>
<td>13.8</td>
<td>11.2</td>
</tr>
<tr>
<td>Orbital separation ( R ) ( (\text{in} , 10^{17} , \text{cm}) )</td>
<td>87</td>
<td>22</td>
<td>69</td>
<td>171:</td>
</tr>
<tr>
<td>( v_w ) ( (R , \text{in} , 10^{17} , \text{cm}) )</td>
<td>59 ± 5</td>
<td>106 ± 8</td>
<td>39 ± 4</td>
<td>71 ± 14</td>
</tr>
<tr>
<td>( r_w ) ( (\text{km} , s^{-1}) )</td>
<td>6</td>
<td>9.6 ± 4</td>
<td>0.5 ± 3</td>
<td>0.5 ± 3</td>
</tr>
<tr>
<td>Estimate from Mg II abs. peak</td>
<td>72 ± 15</td>
<td>160 ± 20</td>
<td>90 ± 15</td>
<td>80 ± 8</td>
</tr>
<tr>
<td>Estimate from Fe ii/Si ii models</td>
<td>...</td>
<td>160 ± 20</td>
<td>&gt;30</td>
<td>80:</td>
</tr>
</tbody>
</table>

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* Supergiant mass is uncorrected for inclination. We note that Schroeder 1985 adopts a value for the mass of 32 Cyg about half of Wright's 1970 value quoted here.

* Supergiant radii are inferred from spectral type.

* The orbital separation is the separation of the components at the time of observation of the accretion column.

* Wind velocity is the velocity determined from the aberration angle of the shock at the distance from the primary given in the "orbital separation" line.

* The terminal velocity from Mg II absorption edge is that estimated in the text.

* The terminal velocity from Fe ii/Si ii models are taken from Che, Hempe, and Reimers 1983 for 32 Cyg and 31 Cyg and from Che-Bohnenstengel and Reimers 1986 for 22 Vul.

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Stellar Wind Velocity Function

One obvious conclusion from our work is that substantial acceleration of the wind must continue beyond any suborbital sonic point which may be required by the large mass-loss rates. The sonic point is the critical point only in the absence of such complicating factors as magnetic fields and turbulence. We note a parallel to models for high-speed wind streams in the Sun (Munro and Jackson 1977; Ahmad and Webb 1978). Evidence for significant energy deposition in cool star winds far from the surface was demonstrated as far back as 1956 (Deutsch 1956). The thin zone acceleration model is incompatible with the ultraviolet observations of 22 Vul, 32 Cyg, and ζ Aur. We suggest that energy (and momentum) deposition may result in continued acceleration beyond the orbit of the B star. A proposal for such deposition by an Alfvén wave mechanism has been put forward by Kuin and Ahmad (1987).

A reevaluation of the acceleration of late-type supergiant winds in the light of the conclusions expressed here may shed light on supergiant magnetic fields and the physics of Alfvén wave dissipation. Ahmad and Kuin (1987) suggest that allowing for leakage of Alfvén waves back to the surface through refraction could resolve the discrepancy in the case of 22 Vul, but that the ζ Aur velocity function appears incompatible with the large mass-loss rate derived even in the presence of leakage. Because the same mechanisms which accelerate stellar winds may, in closed magnetic fields, result in coronal heating, insights may also be gained into those processes, for which no dissipation model exists (Ionson 1985).

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