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ON THE WIND STRUCTURE OF THE WOLF-RAYET STAR IN V444 Cyg

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RESUMEN

Se deduce la ley de velocidades en el viento de la estrella Wolf-Rayet (WN5) V444 Cyg a partir de las observaciones fotométricas de Kron y Gordon (1943) y del análisis de la curva de luz de Kopal y Shapley (1946). Estos resultados sugieren una velocidad constante en las regiones internas del flujo ($1.6 \lesssim r/R_{WR} \lesssim 3.1$), y una aceleración en regiones más externas ($3.1 \lesssim r/R_{WR} \lesssim 7.7$). Esto podría ser consistente con el modelo de viento con condensaciones (Lucy 1982*b*). Se sugiere que los resultados aparentemente contradictorios obtenidos por Cherepashchuk (1975) y Hartmann (1978) para la estructura de viento de V444 Cyg se pueden reconciliar mediante este tipo de modelo de viento con ley de velocidades no-monotónica.

ABSTRACT

The velocity law in the wind of the WN5 star in V444 Cyg is deduced from the photometric observations of Kron and Gordon (1943) and the light curve analysis of Kopal and Shapley (1946). A constant velocity wind region in the inner portions of the flow ($1.6 \lesssim r/R_{WR} \lesssim 3.1$), with a subsequent acceleration ($3.1 \lesssim r/R_{WR} \lesssim 7.7$), is implied. This could be consistent with a multiply non-monotonic wind model (Lucy 1982*b*). It is suggested that the apparently conflicting results for the V444 Cyg wind structure obtained by Cherepashchuk (1975) and Hartmann (1978) may be reconciled by a non-monotonic wind model.

Key words: MASS LOSS – STELLAR WIND – STARS-WR

I. INTRODUCTION

Stellar winds have their most extreme manifestation in the Wolf-Rayet (WR) stars, which have large terminal speeds (~ 2000 km s^{-1}) and estimated mass-loss rates $\dot{M} \sim 10^{-5}$ $M_{\odot}$ yr^{-1} (Barlow, Smith, and Willis 1981). One of the basic problems in understanding the WR phenomenon has been the determination of the driving forces responsible for these winds. Although radiation pressure on spectral lines can be shown to be the dominant mechanism driving the mass loss from OB stars (Abbott 1982), the standard model of line driven winds (Castor, Abbot, and Klein 1975) does not seem capable of explaining the winds from WR stars. Recently, however, Friend and Castor (1983) have presented a model of a radiation driven stellar wind with overlapping spectral lines which seems to be more efficient in ejecting matter than the previous models. Alternative mechanism for powering, or at least initiating, the flow (Sreenivasan and Wilson 1982; Cassinelli 1981) which rely on the deposition of mechanical energy at the base of the wind have not been fully developed.

There is as yet no evidence favoring any one of the proposed mechanisms, since from an observational standpoint, there is very little information concerning the wind structure in WR stars. The first attempt at deriving the detailed wind structure of a WR star can be attributed to Kopal and Shapley (1946 hereafter KS). They analyzed the Kron and Gordon (1943) photometric data obtained during primary eclipse in the WN5 + O6 system V444 Cyg and derived the opacity distribution in the WR wind. In addition, they demonstrated that the primary opacity source in the WR wind is electron scattering. However, although they computed electron densities, they did not comment on the implied density distribution.

In subsequent studies of this system, apparently contradictory results have been presented. Specifically, Hartmann (1978) has modeled the IR eclipse of the WR component by the O-star concluding that the WR wind has a decelerating or constant velocity distribution in the regions of large electron scattering optical depths; that is, in the inner portions of the wind, close to the WR core. It could be argued that such a velocity distribution could result from perturbations of the WR outflow by wind-wind collisions (Prilutskii and Usov 1976; Koenigsberger and Auer 1984). However, a similar velocity law was deduced by Hartmann and Cassinelli (1977) from IR continuum modeling of the WN5 + compact companion system HD 50896 (Firmani *et al.* 1980) where strong wind-wind interactions are not expected to occur. Thus, there is strong evidence for a constant velocity (or decelerating) wind in the dominant IR emitting regions. In addition, as stated by Hartmann, in order to accommodate the large terminal speeds observed, an acceleration must occur beyond the constant velocity region. Also, an acceleration is presumably required between the WR core and the constant velocity zone, so as to initiate the flow. This wind structure is quite different from that predicted by standard line radiation pressure driven models. Thus, the IR results would seem to support the idea of driving mechanisms other than radiation pressure. In contrast, Cherepashchuk (1975) has concluded from an analysis of the optical continuum light curves of V444 Cyg that the volume absorption coefficient in the WR wind has a dependence of $\kappa(r) \propto r^{-n}$ with $n = 2.5 - 3.1$. This exponent implies a velocity distribution $v(r) \propto r^k$ with $k = 0.5 - 1.1$ That is, a flow with a linear velocity distribution. In a subsequent investigation, however, Cherepashchuk, Eaton, and Khaliullin (1980, 1984), and Cherepashchuk (1982) state that this acceleration occurs between the core and $12R_\odot$, with a constant velocity prevailing at larger distances, implying a wind structure in confortable agreement with standard radiation pressure models. However, this assertion is based on the opacity distribution derived from *UV* observations with OAO-2, and is inconsistent with the opacity distributions derived for longer wavelengths, as is clearly visible if one plots the data in Cherepashchuk, Eaton and Khaliullin's (1984) Table 6. In fact, the average of the opacity distributions for their data at $\lambda < 7512$ A results in an opacity distribution $\kappa(r) \propto r^{-n}$ with $n = 2.8 \pm 0.3$, where the error is derived from the dispersion about the average value. Hence, these subsequent results imply a linear velocity law out to at least $\approx 20\ R_\odot$, consistent with Cherepashchuk's (1975) conclusion. It is worth recalling that since scattering is the dominant opacity source in the WR wind (KS; Cherepaschuk 1975), the opacity distribution should be wavelength independent (at least until the free-free opacity becomes important at IR wavelengths).

Given the above considerations, a further analysis of the existing information on V444 Cyg's wind structure can be fruitful. In this spirit, we take a new look at the results obtained by Kopal and Shapley (1946) from an analysis of the photometric observations of Kron and Gordon (1943).

Thus the purpose of this paper is to compare the wind structure implied by the Kopal and Shapley investigation with the apparently conflicting velocity distributions derived by Cherepashchuk (1975) and Hartmann (1978). We will conclude that a non-monotonic wind structure is a possible solution for the discrepancy.

II. THE CONTINUUM OPTICAL DEPTH DISTRIBUTION

A major advantage of studying binary systems such as V444 Cyg is that, given the orbital parameters, the optical depth through the WR wind along the line-of-sight to the O-star can be obtained empirically. Thus, no assumptions are necessary in order to derive an optical depth distribution from appropriate observations. This empirically derived structure can be compared with model predictions.

In this section we derive the expected electron scattering optical depth distributions as a function of impact parameter for the proposed monotonic velocity laws in the WR wind: a) $V = V_0$, a constant velocity distribution, which is that obtained by Hartmann; and b) $V \propto r$, a linear velocity law, as proposed by Cherepashchuk. We will then compare these predictions with the derived optical depth distribution of Kopal and Shapley.

a) *Expected τ_{es} Distribution.*

Because electron scattering is the dominant opacity source in the WR wind (KS; Cherepashchuk 1975), the expected optical depth along the line of sight to the O-star, through the WR wind, can easily be computed, given the velocity distribution. We will use the usual p-z coordinate system (see c.f. Castor 1970). The impact parameter, p, is the distance of closest approach to the WR core of the line-of-sight to the O-star, and is computed from the orbital phase, given the orbital separation and inclination. The z-axis lies along the line of sight to the WR core.

Due to the extended nature of the WR atmosphere, once the O-star begins its passage along the far side of the orbit, it is occulted by increasingly larger columns of WR wind material, in what is referred to as an "atmospheric eclipse" (KS). The atmospheric eclipse becomes important at emission line frequencies long before it is evident in the continuum (Koenigsberger and Auer 1984). That is, small column densities are sufficient to produce observable effects in the emission lines and different portions of the wind are responsible for the absorption at different wavelengths within the line, due to the velocity gradient in the wind.

The situation in the continuum is different, however, since electron scattering is wavelength independent. At a given orbital phase, ϕ, in which the O-star is on the far side of the WR, the continuum optical depth due to electron scattering is given by

$$\tau_{es}(\phi) = \int_{-\infty}^{+z_{orb}} \sigma_T\, n_e(r)\, d\bar{z} \qquad (1)$$

where σ_T is the Thompson cross section, and $n_e(r)$ is the electron density at a radial distance r from the WR core, with $r = (p^2 + z^2)^{1/2}$. The upper limit of integration, $Z_{orb} = (a^2 - p^2)^{1/2}$ is the z-coordinate of the orbital position of the O-star at the impact parameter under consideration, where a is the orbital separation.

The electron density and the velocity distribution in 'inds are related by the conservation of mass flow quation:

$$n_e(r)\, v(r)\, r^2 = \text{constant}.$$

Using this equation with the two proposed velocity .ws, equation (1) becomes:

$$\tau_{es}(\phi) = \tau_{es}(P) = \sigma_T N_0 R_{WR} \times$$

$$\times \begin{cases} \int_{-\infty}^{+Z_{orb}} \frac{dZ}{(P^2 + Z^2)}, & \text{for } V = V_0, \\ \int_{-\infty}^{+Z_{orb}} \frac{dZ}{(P^2 + Z^2)^{3/2}}, & \text{for } V \propto r; \end{cases}$$

'here all distances are now in units of the WR core radius, R_{WR}; that is, $P = p/R_{WR}$, $Z = z/R_{WR}$ and N_0 is the lectron number density at R_{WR}. The integration results 1:

$$\tau_{es}(P) = \sigma_T N_0 R_{WR} \times$$

$$\begin{cases} P^{-1}\left[\tan^{-1}\left(\frac{(A^2 - P^2)^{1/2}}{P}\right) + \frac{\pi}{2}\right], & \text{for } V = V_0 \\ P^{-2}\left[1 + (1 - P^2/A^2)^{1/2}\right], & \text{for } V \propto r. \end{cases}$$

herefore, to a first approximation, a constant velocity ıw should produce an electron scattering optical depth istribution $\tau \propto p^{-1}$ while a linear velocity law results ı $\tau \propto p^{-2}$.

b) *Observed Optical Depth*

In Figure 1, we plot ln τ as a function of ln p (in olar units), using the data given in KS's Table 8, which 'e will denote as τ_{KS}. We have adopted an orbital sepaıtion of a = 35.8 $R_\odot$. It is immediately evident that τ_{KS} does not obey a unique power law distribution. In articular, for the inner regions of the wind this distribuıon can be divided into two segments with different ıopes:

$$\tau_{KS}(p) \propto p^{-0.9}, \quad 4 \lesssim p \lesssim 8\, R_o,$$

$$\tau_{KS}(p) \propto p^{-2.2}, \quad 8 \lesssim p \lesssim 16\, R_o,$$

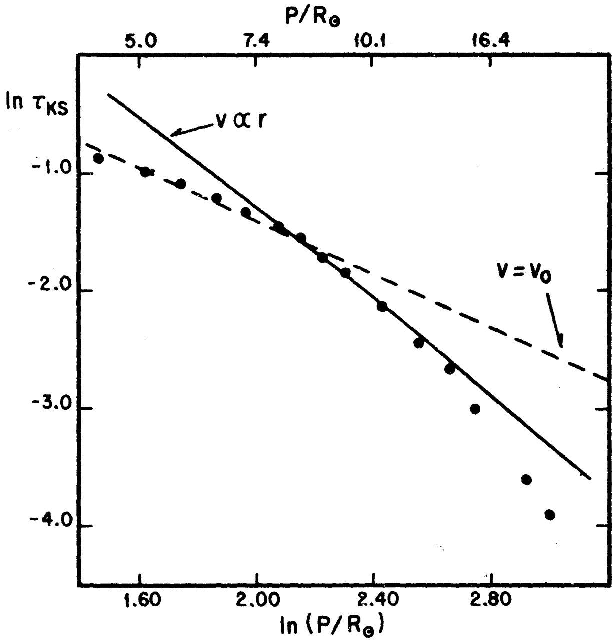

Fig. 1. Optical depth distribution (dots) derived by Kopal and Shapley for the WR wind of V444 Cyg. Electron scattering optical depths predicted by a constant (dashed) and a linear (continuous curve) velocity laws are superposed. The corresponding electron densities at the WR core surface are $N_0 = 9 \times 10^{12}$ cm^{-3} for the constant velocity law and $N_0 = 1.2 \times 10^{12}$ cm^{-3} for the linear law.

The expected τ_{es} distributions from a constant and a linear velocity distributions have been superposed on the data, as indicated. Thus, adopting the KS optical depth as the actual electron scattering optical depth distribution, one is led to conclude that the WR wind velocity is constant between ∿ 4 $R_\odot$ (1.5 R_{WR}) and 8 $R_\odot$ (3.1 R_{WR}) with an acceleration v(r) ∝ r taking place between 8 $R_\odot$ and at least 20 $R_\odot$ (6 R_{WR}). The more pronounced acceleration suggested by the points at p $\gtrsim$ 16 $R_\odot$ is not considered significant since fluctuations in very small values of τ produce very large fluctuations in ln τ.

The KS optical depths rely on the solution of the light curve at primary eclipse. For comparison, we have derived the optical depth distribution directly from the data listed by Kron and Gordon (1943, Table 3), using

$$\tau_{KG}(p) = -\ln\left[\left(\frac{1+f}{1-\xi}\right) \times \right.$$

$$\left. \times\ 10^{-\frac{1}{2.5}[\Delta m(\phi_0) - \Delta m(\phi)]} - \frac{f}{(1-\xi)}\right] \qquad (2)$$

Here $\Delta m(\phi)$, $\Delta m(\phi)$ are the Kron and Gordon magnitude differences at phase ϕ, and at elongation ϕ_0, respectively; $f = L_{WR}/L_0$ is the luminosity ratio, and ξ is the fraction of O-star surface physically occulted by the WR core (uniform brightness accross the O-star disk is assumed). Two O-star radii have been used in the analysis: $R_o = 4.2 R_\odot$, as adopted by KS, and represented by open circles, and $R_o = 9.6\ R_\odot$, the currently accepted value (Kron and Gordon 1950). The resulting optical depth distribution (denoted τ_{KG}) for $R_o = 4.2\ R_\odot$ does not differ at all from that of KS for impact parameters between 7.5 $R_\odot$ and 16.5 $R_\odot$, as one can see in Figure 2, where the curves are the same as in Figure 1. Since we have merely converted the magnitude differences recorded by Kron and Gordon to optical depths, we are limited to the available range in impact parameters, while KS have the benefit of their light curve solution. Thus, the τ_{KG} distribution (Figure 2) does not extend to the smaller p's that KS's does. Even so, a flattening of the distribution is evident for $p \lesssim 8\ R_\odot$. Furthermore, one can see that a larger radius for the O-star accentuates the flattening, producing a visible effect even at $p \sim 10\ R_\odot$. On the other hand, however, the divergence from a linear velocity law at $p \gtrsim 16\ R_\odot$ is no longer present.

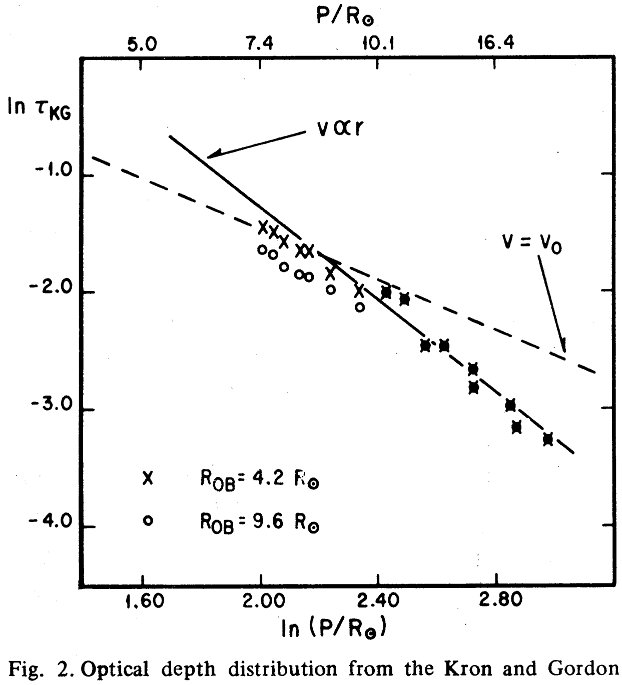

Fig. 2. Optical depth distribution from the Kron and Gordon data using equation (2) with $m(\phi_0) = -0.096$ and $f = 0.245$, and rescaled to match the values in Figure 1. Curves are the same as in Figure 1.

We have repeated this analysis exactly using the data published in Cherepashchuk, Eaton and Khaliullin's (1984), Table 1 for the λ2980 A and λ4250 A light curves. The optical depths, τ_{CEK} were computed using:

$$\tau_{CEK} = -\ell n \left[\frac{1+f}{1-\xi} \; \frac{L(\phi)}{L(\phi_0)} \; - \; \frac{f}{1-\xi} \right]$$

where $L(\phi)$ and $L(\phi_0)$ are the light at phases ϕ and at elongation ϕ_0, respectively. The other symbols are the same as in equation (2). The averages, over impact parameter (± standard deviations) are plotted in Figure 3. The eye-drawn fit to this data corresponds to a $v \propto r$ velocity distribution, at least for $p \lesssim 20\ R_\odot$. In addition, there is evidence once again for a flattening of the velocity law at $p \lesssim 9\ R_\odot$.

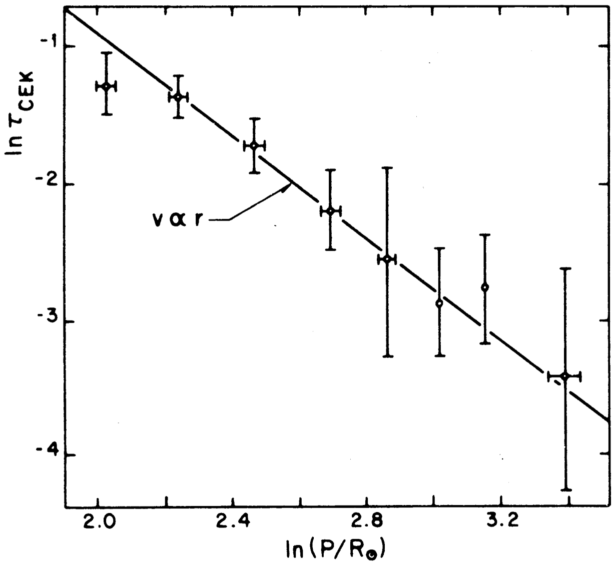

Fig. 3. Average optical depth distribution from the Cherepashchuk, Easton, and Khaliullin (1984) data for λ4250 A and λ2980 A (Table 1). Error bars correspond to the standard deviation.

Thus, we conclude that, at least between 8 $R_\odot$ and 20 $R_\odot$, the flow in the WR wind can be approximated by a linear velocity distribution, while a constant velocity is implied for the region $4 \lesssim r/R_\odot \lesssim 8$. An acceleration is presumably also required very close to the WR core (2.6 $R_\odot$) to initiate the flow.

III. DISCUSSION

The above scenario provides the possibility of reconciling the contradictory results quoted for V444 Cyg's wind velocity structure. That is, from a qualitative standpoint, a non-monotonic velocity distribution as implied by the Kopal and Shapley (1946) analysis is consistent with both a constant velocity law (Hartmann 1978) in regions of large electron densities and a linear velocity law (Cherepashchuk 1975) further out. Indeed, according to Hartmann's results, the WR wind velocity is constant, or decelerating, in the regions of large electron scattering optical depths, and in order to accomodate the large observed terminal speeds, an acceleration must occur beyond the constant velocity wind regions. According to the KS analysis, this acceleration occurs at $r \approx 8\ R_\odot$, closer to the WR core surface than contemplated by the IR models (Hartmann 1978; Hartmann and Cassinelli 1977); however, if the wind is indeed clumpy (see below), then the effects of a filling factor which increases with radius would have to be taken into account in the IR analysis (Hartmann, private communication). Hence, the scenario for the WR wind velocity structure which we deduce consists of a wind with three regions: the first, lying between the WR core and at most 4.3 $R_\odot$, for which we have no information, but in which the initial acceleration must take place; the second, at 4.3 $R_\odot \lesssim r \lesssim 9.0$ $R_\odot$, where the wind flows at an approximately constant velocity; and the third, at $r \gtrsim 9.0$ $R_\odot$ where once again the velocity law steepens and can be approximated by a linear ($V(r) \propto r$) law. In terms of the WR core radius, $R_{WR} = 2.9$ $R_\odot$, these regions lie at $1.0 \lesssim r/R_{WR} \lesssim 1.6$, $1.6 \lesssim r/R_{WR} \lesssim 3.1$ and $3.1 \lesssim r/R_{WR}$, respectively.

This velocity distribution is remarkably similar to the velocity law constructed by Hamann (1980) to fit the line profiles of ζ Pup. Hamann's "taylored" velocity law (shown in his Figure 2) has an initial acceleration between the surface of the Of core and ~ 1.3 R_*, a plateau of nearly constant velocity at $1.3 \lesssim r/R_* \lesssim 3$, and a subsequent steepening of the velocity law for $3 \lesssim r/R_*$. Thus, this is independent evidence pointing to the non-monotonic nature of velocity laws in the winds of these stars. Furthermore, the similarity in the velocity structures seems to suggest that similar mechanisms are responsible for WR and Of star winds. Clearly, the extended acceleration region at $r/R_* \gtrsim 3$ contradicts the classical radiation pressure driven wind models, although it may be explained with the more sophisticated models which take into account multiple scattering in lines. In addition, one may speculate that the contribution from the secondary radiation field mentioned below may not be insignificant.

It is important to emphasize that the description of the winds of hot stars in terms of a smooth, monotonic velocity distribution is an oversimplification. In particular, it has been shown that a wind driven by radiation pressure on lines is unstable (Nelson and Hearn 1978; MacGregor, Hartmann, and Raymond 1979; Carlberg 1980) and that, for large enough mass loss rates, it will depart seriously from radial flow long before it reaches a height equal to the stellar radius (Kahn 1981). This has led to the clumpy or multiply non-monotonic wind model, the properties of which have been explored by Lucy and White (1980) and Lucy (1982*a*, 1982*b*, 1983). Unfortunately, the expected velocity law has not been derived, though Lucy (1982*b*) conjectures that a plateau may exist in the velocity law at $V \sim 0.75$ V_∞. This plateau would be imposed by changes in the line opacity and acceleration produced by the secondary radiation field generated by the interaction between the clumps and the ambient gas. It is tempting to speculate that the constant velocity wind region implied by Figure 1 corresponds to the proposed plateau. This may not be a totally unreasonable speculation if the instabilities in the line driven wind do indeed develop at a distance of one stellar radius (Kahn 1981), since for the case of V444 Cyg this distance corresponds to $r \sim 5$ $R_\odot$.

In conclusion, we find that the contradictory results derived for the wind structure of the WR in V444 Cyg can be reconciled, provided that a more sophisticated scenario (than a monotonic velocity law, for instance) for the wind is adopted. The qualitative agreement between the empirically-deduced velocity distribution (Figures 1, 2 and 3) and that which may be expected from a multiply non-monotonic wind model (Lucy 1982*b*) is encouraging.

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