1985A&A...148L...1P

Astron. Astrophys. 148, L1–L4 (1985)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

A radiation driven stellar wind model atmosphere for the Wolf-Rayet binary V 444 Cygni

A. Pauldrach, J. Puls, D. G. Hummer*, and R. P. Kudritzki

Institut für Astronomie und Astrophysik, Scheinerstrasse 1, D-8000 München 80, Federal Republic of Germany

Received February 14, accepted May 2, 1985

Summary: Using the stellar parameters of the WN5 component of the eclipsing binary V 444 Cygni determined by Cherepashchuk et al. (1984) from multi-color light curves, and employing an improved theory of radiatively-driven stellar winds, we have calculated models which yield an extended, supersonically expanding photosphere, with values close to those observed for the photospheric radius, the mass-loss rate and the terminal velocity. The radial distributions of velocity and density are also in close agreement with those obtained by Cherepashchuk et al. We regard this as strong evidence that the basic observational features of WR-stars can be reproduced by radiatively-driven wind theory if some previous simplifications in the theory are dropped and correctly determined stellar parameters are used.

Keywords: Wolf-Rayet star - stellar winds - stellar atmospheres

1. Introduction

The physical explanation of the atmospheres of Wolf-Rayet stars remains an outstanding problem. These objects are characterized by extremely dense stellar winds, with high mass-loss rates ($\dot{M} \approx 2\times10^{-5}$ $M_\odot$/yr, Bieging et al., 1982) and terminal velocities up to 3000 km/sec. The photospheres lie well out in the wind, where the flow is supersonic. No self consistent model atmospheres have yet been constructed which reproduced these basic observational features. As for the most promising explanation, radiatively-driven winds (see Lucy and Solomon, 1970, Castor, Abbott and Klein, 1975, Abbott, 1982a, and Abbott and Lucy, 1985), it is commonly believed that the radiation force due to the numerous metal lines is not sufficient to produce the high mass-loss rates (cf Abbott (1982b) and Cassinelli (1982)). The accepted values for radius and effective temperature of WR-stars yield mass-loss rates much smaller than observed, as radiative acceleration can produce winds with only $\dot{M}\, v_\infty \approx L/c$. As observed values of $\dot{M}\, v_\infty\, c/L$ lie in the range 20 to 50, the discrepancy is too large to be explained within this theory, even allowing for multiple scattering of photons in closely spaced clusters of lines.

In consequence, an additional mechanism is sought for the high mass-loss rates. However it cannot be excluded that the accepted effective temperatures and luminosities of WR-stars are simply too small. The determination of these temperatures from observational data are manifestly unreliable (Abbott and Hummer 1985). In a remarkable paper, Cherepashchuk et al. (1984, hereinafter: CEK) derive the structure of the expanding atmosphere and the physical characteristics of the WN5 component of the eclipsing WR binary V 444 Cygni from a detailed analysis of light curves in the wavelength range between 2460Å to 3.5 µm. The result is extremely interesting: At the stellar core, defined by $\tau_{Th} = 2/3$, which has the radius $R^* = 2.9\ R_\odot$, the electron temperature is extremely high, i.e. between 80000K to 100000K, and the outflow velocity is $v^* \approx 400$ km/s. (Note that although CEK state $\tau_{Th} = 1$ at $R^* = 2.9\ R_\odot$, integration of their derived electron density gives $\tau_{Th} = 0.63$.) The atmosphere extends over several stellar radii and the temperature drops to values between 40000K and 20000K in the intermediate to outer layers, which explains the relatively low temperatures normally attributed to WN5-stars. CEK obtain the velocity field via the equation of continuity, using the empirically-determined density stratification and the well-observed mass-loss rate of the WN5-component (1.2×10^{-5} $M_\odot$/yr, Khaliullin, 1974, Kornilov and Cherepashchuk, 1979, $1.3\ 10^{-5}$ $M_\odot$/yr, Bieging et al., 1982, $1.8\ 10^{-5} M_\odot$/yr, Barlow et al.). The terminal velocity obtained by CEK is consistent with the value 2500 ± 400 km/sec obtained by Eaton et al. (1982) from low-resolution IUE observations.

This observational determination of photospheric radius and temperature is unique for WR-stars. We can thus check whether the theory of radiation driven winds reproduces the observed stellar wind structure, with the newly-determined parameters, by means of calculations using an improved theory for the radiatively-driven winds. These calculations

---

* Staff Member, Quantum Physics Division, National Bureau of Standards; Permanent address, JILA, University of Colorado and NBS, Boulder, Colorado, 80309

1985A&A...148L...1P

are summarized in section 2. The comparison with the empirical model of CEK is given in section 3, which is followed by a short discussion of the consequences for the determination and interpretation of WR-star parameters.

2. The Stellar Wind Calculations

We have under development two independent complementary codes for radiatively-driven stellar wind calculations. The first (Pauldrach, 1985) is based on an improved version of the method of Castor et al. (1975, hereinafter CAK), while the second (Puls, 1985) involves a simultaneous solution of the equations of radiative transfer and gas dynamics. Our version of the CAK method contains two important modifications:

i) We use the improved force multiplier given by Abbott (1982a):

$$M_1(t) = k\, t^{-\alpha} \left(\frac{n_E}{W} \right)^{\delta} , \qquad (1)$$

where $t = \sigma_E \rho\, v_{th} \left(\frac{dv}{dr} \right)^{-1}$ is the depth parameter, W the dilution factor, n_E the electron density (the latter taken in units of $10^{11}\mathrm{cm}^{-3}$ in eq. (1)). k, α, δ are parameters suggested by Abbott to fit his tabulated force multipliers. As Abbott's data are tabulated only up to T_{eff} = 50000K, whereas the temperature found by CEK for the inner atmosphere of V444 Cygni (at R_{Th} = 2/3) is about 90000K, we could use only the force multiplier quoted at the hot boundary of Abbott's table 2. (These values are represented well by α = 0.68, k = 0.137, δ = 0.07). But since the T_{eff}-dependence of $M_1(t)$ over 50000K ≥ T_{eff} ≥ 10000K is rather weak, this approximation is probably not too severe. More important is the use of Abbott's approximation for the ionization equilibrium, in which collisions are neglected and the continuous radiation field is that of an optically thin atmosphere and changes by dilution only. While this is reasonable for OB-star winds, it must be scrutinized for the dense extended winds of WR-stars. Moreover, in the calculation of $M_1(t)$ each line receives pure continuum radiation unaffected by other lines. In the case of ζ Puppis, Abbott and Lucy (1985) have shown that this assumption overestimates the mass-loss rate by a factor of 2. Since we do not aim at a perfect fit of the observations, but rather examine whether radiation driven wind theory can explain the basic observational features, we feel that $M_1(t)$ is adequate for a description of the situation. This is supported by a variety of experiments in which the force-multiplier parameters are varied in a reasonable way to estimate roughly the influence of more complete physics. In the most extreme cases $\dot{M}$ and v_∞ changed by a factor of two and 20%, respectively. In view of the other theoretical and observational uncertainties this is not alarming.

ii) A significant improvement is the consideration of the finite angular size of the radiating stellar core in the calculation of the line force. This is done by a correction factor to eq. (1), yielding

$$M_2(t(r,v,v')) =$$
$$M_1(t) \left(2/(1-\mu_c^2) \right) \int_{\mu_c}^{1} \left[\left(\frac{dv}{dr} \right)^{-1} \left((1-\mu^2) \frac{v}{r} + \frac{dv}{dr} \mu^2 \right) \right]^{\alpha} \mu d\mu ; \quad (2)$$

μ_c is the cosine of the angle of the stellar core (see also eq. (49) and (50) of CAK). As we found for normal OB-stars (to be published, see also Pauldrach, 1985), the use of $M_2(t)$ changes the wind dynamics significantly, increasing v_∞ drastically (a factor of two), and removing much of the discrepancy between the observed and theoretical values of the ratio v_∞/v_{esc} (see Abbott, 1982a).

One of the basic assumptions in the CAK formalism is the evaluation of the line force in the Sobolev approximation neglecting continuum radiative transfer. In the case of V444 Cygni, with its optically-thick supersonically- expanding photosphere, this assumption can be checked by the complementary algorithm. For a given density and velocity stratification the radiative force is calculated line-by-line by solving the equation of radiative transfer in the comoving frame, thus avoiding the Sobolev approximation and the question of the force multiplier. The effects of continuous opacity are included fully in calculating the radiation field, but the force of radiation on the gas through continuous true absorption, which should be small, is not yet included. As we are not yet able to treat Abbott's complete line list, we use instead a sample of strong, intermediate and weak lines located at three parts of the spectrum (shortward of, longward of and at the Planck-maximum), which are weighted such that the total strength of the line force corresponds to Abbot's force multiplier in the outer layers, where the continuum is already optically thin. Thus we treat the behaviour of the line force in deeper layers correctly and are able to investigate the effects of thermalization of line photons and of the Sobolev approximation in the subsonic region.

With this line force the normal (Euler) equations of motion for the stellar wind are solved yielding new density and velocity structures. Then a new line force is computed and the process is iterated to convergence. Our modified CAK algorithm provides the starting approximation.

The temperature stratification is calculated using the spherical grey approximation of Lucy (1971), as the wind dynamics are not sensitive to the temperature structure. The continuous opacities, sound velocity, and electron density are those of a pure doubly-ionized helium atmosphere (see CEK). Abbott (1982a) shows that the line force does not change significantly when a solar composition atmosphere is replaced by CNO burned material.

Table I

Input and Derived Model Parameters

Model	$T_{eff}(R^*)$	$10^{-5}L/L_\odot$	k	δ	$R^*/R_\odot$	$10^{-5}\dot{M}$ $(M_\odot/yr)$	v_∞ (km/sec)	v^* (km/sec)	$10^{-11}\rho^*$ (gm/cm^3)	Γ_e	$\dot{M}v_\infty C/L$
1	91000	5.22	0.137	0.07	2.60	1.30	2050	543	3.8	.792	2.52
2	91317	5.29	0.137	0.07	2.70	1.39	1950	590	3.4	.803	2.34
3	92000	5.45	0.137	0.07	3.00	1.58	1800	712	2.55	.828	2.57
4	92000	5.45	0.177	0.02	2.55	1.27	2140	506	4.1	.828	2.35
5	92500	5.57	0.177	0.02	2.70	1.40	1980	595	3.3	.846	2.39
6	93000	5.69	0.177	0.02	3.00	1.59	1906	690	2.6	.864	2.6
CEK	80-100000	3.1-7.6	-	-	2.90	1.2-1.4	20-2500	400	3.1($R=3R_\odot$)		5.5-1.5

The parameters which enter into our calculation (besides the parametrization of $M_2(t)$) are stellar mass M, luminosity L and radius R_i at the inner boundary of the photosphere, which is defined by $\tau_{Th} = 10$. Following CEK we have chosen $M = 10\,M_\odot$ and $L \simeq 5 * 10^5\,L_\odot$ as typical parameters (see Table 1), and use as the inner radius the value $R_i = 2.0\,R_\odot$, which corresponds to an effective temperature at $R=R^*$ of approximately 90000K.

3. Results and Comparison with Observation

In view of the uncertainty in the values of the stellar parameters and line force multiplier just mentioned, we have computed a variety of models with parameter values close to those discussed above to assess their sensitivity to such uncertainties. We then compare the photospheric radius R* and the mass loss rate $\dot{M}$, along with the run of velocity and density, with the values obtained from observations and from the CEK model. Particular attention is given to R*, for which CEK obtain 2.9 $R_\odot$. The input parameters of selected models are given in Table 1, along with the values of R*, $\dot{M}$, v_∞, $v^*=v(R^*)$, $\rho^*=\rho(R^*)$, and $\Gamma_e = \sigma_e CL/4\pi GMc$, where $C = (1+\eta Y)/(1+4Y)$, $\eta \equiv$ number of free electrons per He nucleus and $Y = n(He)/n(H)$.

Models 1-3 are computed with force multiplier parameters corresponding to the high temperature end of Abbott's (1982a) data, while for Models 4-6 the parameters have been modified to simulate roughly the effect of multiple scattering in the outer layers. By lowering ad hoc the parameter δ we reduce the decrease of $M_2(t)$ towards outermost layers, thus simulating the gain of radiative momentum due to multiple scattering at larger velocities. (The parameter k is renormalized to give the same $M_2(t)$ in the photosphere). For all models, $\alpha = 0.68$.

The results in Table 1 are obtained from our improved CAK theory. They agree well with the results of our complementary self-consistent solution; differences in the velocity and density stratification are at the 10% level.

This good agreement is caused by the rather large Γ_e, which for V444 Cygni is close to unity. Consequently, in the photosphere a large part of radiative momentum arises from electron scattering. As the contribution of the line force in this region is only 10% to 30% of the contribution of electron scattering, differences as large as a factor two in the radiative line force between the two algorithms are here not important. Thus the values of $\dot{M}$ and v_∞ do not depend strongly on the parameter values adopted for $M_2(t)$, as mentioned in section 2.

The large value of Γ_e also explains the strongly extended photosphere. As demonstrated in Table 1 the degree of extension depends strongly on Γ_e: Increasing Γ_e by roughly 3% results in an increase of R* by approximately 11%. If Γ_e becomes smaller than 0.7, then the sonic point lies clearly outside the photosphere and R* is close to the radius of the inner boundary R_i.

The run of velocity and total density with R/R* for Model 2 is shown in Figure 1; the agreement with CEK's values is satisfactory. This case is typical of all of our models with $\Gamma_e \geq 0.7$, which yield an extended photosphere with supersonic flow speeds. The critical and sonic points, labelled C and S in Figure 1, are well below the level of the photosphere, which is indicated by the broken line.

These are not the ultimate models of V444 Cygni, and further work on this object is in hand. Our goal has been to demonstrate that the basic observational features of perhaps the best observed WR star can be reproduced by an improved radiatively-driven wind theory, with correctly determined stellar parameters.

4. Discussion

By demonstrating the internal consistency of the semi-empirical model of CEK, we support their conclusion that the effective temperatures and luminosities of Wolf-Rayet stars are much larger than commonly accepted. Moreover, our results provide strong evidence that the theory of radiatively-driven stellar winds can explain the properties of Wolf-Rayet atmospheres. The physical reason is that the high temperature of the stellar core found by CEK puts the object close to the Eddington limit. It is, of course, obvious to speculate that the same might hold for other WR-objects. This would mean that the commonly

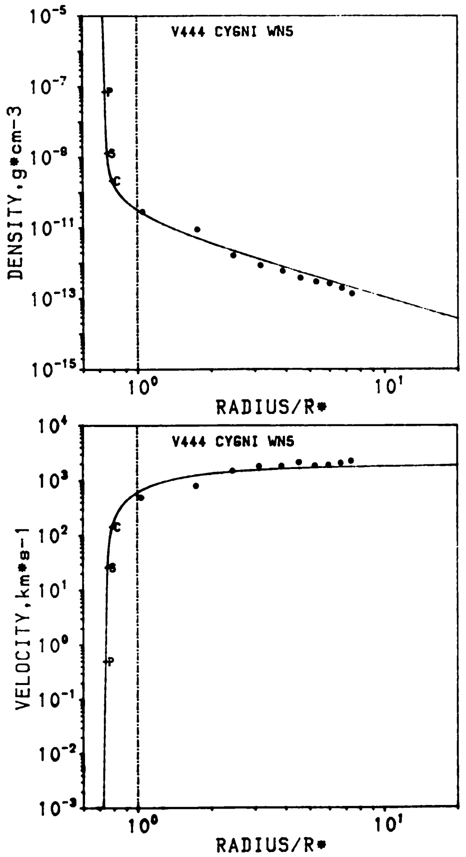

Figure I: The density and flow speed vs. R/R*, where R* is the radius at which τ_{Th}=0.63, for Model 2. The dots are CEK's values, and the points labelled C, S and P are, respectively, the critical point, the sonic point and the location of τ_{Th}=10.

accepted values of T_{eff} and/or L for the WN spectral types are too small. It is well known that in extended photospheres not only the determination but even the definition of both quantities is difficult. Energy distribution methods on the basis of plane-parallel models must lead to drastic underestimates of stellar temperatures in this case. Evidence for the high temperatures of Wolf-Rayet stars has already been advanced by Hillier (1983), who has constructed semi-empirical models of the WN5 star HD 50896, which reproduce both the continuum spectrum and the HeI and HeII line profiles. He concludes that the effective temperature (at R=3 $R_{\odot}$ where τ_{Th}=4.0) must be larger than 50000K.

On the other hand, the large value of Γ_e found by Cherepashchuk et al. and used here implies values of L/M substantially larger than found in the evolutionary theory of helium core-burning stars (we are indebted to Dr. L.B. Lucy for stressing this point). The discrepancy is considerably smaller for helium shell burning; for example a calculation by Maeder (1981) for a 30 $M_{\odot}$ star evolving to 10 $M_{\odot}$ by mass loss, yields $L/L_{\odot}$ = $3.0*10^{5}$ for a helium shell-burning phase, which is smaller than the luminosities appearing in Table 1 by factors of only 1.74 to 1.90. In view of the highly uncertain evolutionary status of Wolf-Rayet stars, we believe radiatively-driven models worthy of further serious consideration despite this unresolved problem.

Acknowledgements

D. Hummer is grateful for a "Senior U.S. Scientist Award" from the von-Humboldt-Stiftung. We are indebted to Drs. D.C. Abbott, A.G. Hearn and L.B. Lucy for helpful remarks.

References

Abbott, D.C.: 1982a, Astrophys.J. 259, 282
Abbott, D.C.: 1982b, in "Wolf-Rayet-Stars: Observations, Physics, Evolution", ed. de Loore and Willis, p. 295
Abbott, D.C., Hummer, D.G.: 1985, Astrophys. J., in press
Abbott, D.C., Lucy, L.B.: 1985, Astrophys.J. 288, 679
Barlow, M.J., Smith, L.J., Willis, A.J.: 1981, Monthly Not. Roy. Astron. Soc. 196, 101
Bieging, J.H., Abbott, D.C., Churchwell, E.B.: 1982, Astrophys.J. 263, 207
Cassinelli, J.P.: 1982, in "Wolf-Rayet-Stars: Observations, Physics, Evolution", ed. de Loore and Willis, p. 173
Castor, J.I., Abbott, D.C., Klein, R.I.: 1975, Astrophys.J. 195, 157
Cherepashchuk, A.M., Eaton, J.A., Khaliullin, K.F.: 1984, Astrophys.J. 281, 774
Eaton, J.A., Cherepashchuk, A.M., Khaliullin, Kh.F.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research", ed. Y Kondo (NASA CP-2238), p. 542
Hillier, D.J.: 1983, The Extended Atmosphere of the WN Star HD 50896, Thesis, Australian National University, Canberra
Lucy, L.B.: 1971, Astrophys.J. 163, 95
Lucy, L.B., Solomon, P.M.: 1970, Astrophys.J. 159, 879
Maeder, A.: 1981, Astron. Astrophys. 102, 410
Khaliullin, K.F.: 1974, Soviet Astr. AJ 18, 229
Kornilov, V.G., Cherepashchuk, A.M.: 1979, Pisma Astr. Zu. 5, 398
Pauldrach, A.: 1985, Dynamik von radiativ getriebenen stellaren Winden, Diplomarbeit, Ludwig-Maximilians-Universität München
Puls, J.: 1985, Strahlungstransport in sphärisch symmetrisch expandierenden Atmosphären heißer Sterne, Diplomarbeit, Ludwig-Maximilians-Universität München