AN EXPLANATION OF THE RADIO FLUX MYSTERY OF HD 192163 AND EMPIRICAL MODELS FOR WN STARS

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The radio flux value of the star HD 192163 (WN6) measured by Dickel et al. (1980) imposes strong restrictions on the possible mass outflow region models of this star.

The observed radio flux remains less than the constant velocity outflow model prediction both in the case of a homogeneous ionization structure and in the case when the most abundant element helium is doubly ionized in the effective IR emission region, and singly ionized in the radio emission region. Dickel et al. (1980) and also Barlow et al. (1980) suggested that the wind terminal velocity has not been reached in the IR emission region. But when taking into account the line spectrum data, it appears that the wind velocity must be comparatively close to the star already nearly constant. So it is necessary to search for some other explanation. In our study we found that at reasonable values of density, electron and core (star) temperatures it is possible that helium becomes neutral at a comparatively large distance from the star and then the radio flux is mainly due to the f-f radiation of H^+ and N^+. In the case of such an ionization structure there are no restrictions on the outflow velocity being already constant close to the star. Therefore it is now possible to explain the radio and IR fluxes as well as the line spectrum data of HD 192163. Such an ionization structure may be realized if the optical depth in the first series continuum of He I is considerably greater than unity ($\tau_\nu(1^1S\ \mathrm{HeI}) >> 1$). This can be concluded from the following example. Let us use the 3-level atomic model (2 bound levels + continuum state). If collisional ionization can be neglected, then the ionization state for the $\tau_1 >> 1$, $\tau_2 << 1$ case can be determined from the system

$$N_2 W \int_{\nu_2}^{\infty} \frac{c\,\rho_\nu^{*}\,\alpha_\nu}{h\nu}\,d\nu = N_e N^+ A_{c2} ,$$

$$N_2 \left[(A_{21} + B_{21} W \rho_\nu^{*})\beta_{12} + N_e C_{21}\right] = N_1 (W \rho_\nu^{*} B_{12} \beta_{12} + N_e C_{12}) .$$

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Table 1. The parameters of WN stars

	HD 187282 (WN4)	HD 50896 (WN5)	HD 192163 (WN6)	HD 151932 (WN7)	MR 119 (WN8)
E_{B-V}	$0.26^{(1)}$	$0.12^{(2)}$	$0.55^{(3)}$	$0.45^{(4)}$	$1.31^{(5)}$
$r(\text{kpc})^{(6)}$	5.17	1.46	1.96	2.36	4.68
v_∞(km/s)	1000	1500	1500	1000	700
$v_\infty/v_o{}^{(7)}$	5	3	3	3	4
$T_\star$(K)	50000	60000	50000	45000	40000
T_e^{I}(K)	100000	100000	60000	60000	60000
T_e^{II}(K)	30000	36000	30000	27000	24000
$R_o(R_\odot)$	3.98	3.66	8.49	14.4	16.2
$N(\text{He})_{2R_o}$ (cm^{-3})	$2.12.10^{11}$	$1.18.10^{12}$	$6.19.10^{11}$	$2.04.10^{11}$	$1.29.10^{11}$
He/H	3÷4	3÷4	3÷4	3÷4	≃ 0.77
N/He	≃ 0.02	≃ 0.01	≃ 0.01	≃ 0.005	≃ 0.002
$\dot{M}(M_\odot/\text{yr})$	$1.00.10^{-5}$	$6.84.10^{-5}$	$1.93.10^{-4}$	$1.23.10^{-4}$	$8.14.10^{-5}$
$\dot{M}/\dot{M}_1{}^{(8)}$	5.55	32.4	35.3	7.86	4.65

Sources for E_{B-V}: (1) - the mean of the data obtained from the $(b-v)_o$ scale and from the paper by van der Hucht et al. (1979); (2) - Holm and Cassinelli (1977); (3) - Paper I by the author; (4) - Nussbaumer's estimation (quoted by Barlow et al. (1980); (5) - E_{B-V} has been found from the $(b-v)_o$ scale. We adopted the value $(b-v)_o = -0.21$ which has been derived by assuming that the E_{B-V} values given by van der Hucht et al. (1979) for the stars HD 86161 and HD 96548 have been overestimated by 0.13 as for HD 151932.

(6) - r was estimated from the scaling rule $r = \max\{r(M_V), r(E_{B-V})\}$ as in Paper I.

(7) - v_∞ and v_o were estimated from the positions of the minima of the violet-displaced absorption components.

(8) - $\dot{M}_1 = L/c\, v_\infty$, L was found from the formula $L = 4\pi^2 R_o^2 \sigma T_\star^4$.

Assuming that $N^+/N >> 1$ near the star and adopting $\beta_{12} = 1$, we shall get that at some distance from the star $N_eN^+/N_1 \propto R^{-4}$ if the first term on the right hand side of the second equation is the dominant and $N^+/N_1 \propto R^{-2}$ if the second term is the dominant. Therefore at $\tau_1 >> 1$ the ionization stage must become one step lower ($N_1/N^+ >> 1$) at some distance from the star.

In our study the matter flow is assumed to reach a constant velocity regime at the distance $R_1 \lesssim 2\ R_o$ where R_o is the radius of the core. The core is assumed to radiate as a black-body at a temperature T_*. For the inner ($R_o \leq R < R_1$) and outer ($R \geq R_1$) zones of the envelope we shall use the mean values of the electron temperature (T_e^I and T_e^{II}). The methods of calculation of the model continuum fluxes and of the line intensities are given in our preprint (1981)(hereafter called Paper I). The essence of our approach is to study continuum fluxes in the two asymptotic spectral regions: in the "optically thin envelope" region where the total flux is the sum of the core and optically thin envelope fluxes and in the IR and radio regions where the flux is due only to the radiation of the outer regions of the mass outflow envelope ($R > R_1$). For the line spectrum study we also chose the "asymptotic regions". In the case of the He II, H I and He I lines we used higher members of the Pickering, Balmer and $n^3D-2^3P^o$ series for which the coefficients $\overline{b_k\beta_{ik}}$ (b_k: Menzel coefficient and β_{ik}: escape probability coefficient) are nearly equal to unity. In the case of nitrogen ions certain subordinate series lines were used (NV λ 4945, NIV λ 6219, NIII λ 4379). For these transitions β_{ik} ought to be close to unity. The theoretical intensities of these lines in dependence on T_e were estimated in Paper I.

For HD 192163 we carried out the same sort of model-fitting study as in Paper I. Only this time for the determination of the ionization structure we used the 3-level atomic model treatment (Formula (7) in Paper I) for all important He, H and N ions and atoms and we also accounted for the absorption of stellar radiation caused by N ions. With these changes we obtained the best fit with the observed data of HD 192163 at the value $R_1 \simeq 2\ R_o$ and at the parameters presented in Table 1. At these parameters $\tau_\nu(1^1S\ \mathrm{HeI})$ becomes markedly greater than unity near $R \simeq 20\ R_o$ and the number of neutral helium atoms begins to dominate over the number of singly ionized helium atoms near 1000 R_o. When we assume that in the radio emission region T_e is the same as in the IR emission region (T_e = 30000 K), then the model-predicted radio flux at 5 GHz is ≃ 2mJy. However, far from the star the electron temperature must somewhat decrease. Assuming that beginning from $R \simeq 500\ R_o$ T_e becomes equal to 20000 K, we shall get that f_ν (5 GHz) ≃ 1.2 mJy. The observed value is 1.6 ± 0.2 mJy. Thus our model explains the radio flux "paradox" of HD 192163 as an effect of the special ionization structure. It must be said that the fulfilment of the condition $\tau_\nu(1^1S\ \mathrm{HeI}) >> 1$ seems to be necessary also for explaining the observed low ionization level in the ring nebula NGC 6888 surrounding HD 192163 (for details see Paper I).

We performed the same sort of analysis also for some other WN stars. For all the stars studied we adopted that $v \simeq \text{const} \simeq v_\infty$ at $R \geq 2\ R_0$ and that $T_e^{II} = 0.6\ T_*$ as in the case of HD 192163. The equivalent widths of the emission lines for these stars were taken from the 1974 version of the unpublished Atlas of Wolf-Rayet Line Profiles by L.F. Smith and L.V. Kuhi. The main parameters established for the stars studied are presented in Table 1. It must be pointed out that in the case of the other WN stars studied $\tau_\nu(1\ S^1\text{HeI})$ does not become much greater than unity and therefore far from the star helium remains in the singly ionized state. The ratio of N/He is within the limits $0.002 \lesssim N(N)/N(He) \lesssim 0.02$. The factor of uncertainty of our estimates is probably about 2-3 times. The ratio of N(H)/N(He) is nearly equal to 3 for the stars of earlier types than WN8, whereas in the case of the WN8 star MR119 $N(H)/N(He) \simeq 1.3$. For all the WN stars the parameter $\dot{M}/\dot{M}_1 > 1$. This conclusion is in agreement with the results of Barlow et al. (1980). It can also be concluded from our study that $T_e > T_*$ in the inner part of the envelope ($R_0 \leq R < 2\ R_0$).

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DISCUSSION

Moffat: I wonder if the radii of WNL stars currently being considered ($\sim 35R_\odot$ by Underhill; $\sim 15R_\odot$ by you) are not on the large side and thus the T_{eff}'s too low. Analysis of the double-wave, relatively large amplitude light curve of the shortest known period, 1.6d, WR binary CQ Cep (WN7) has recently been carried out (Leung, Moffat and Seggewiss, 1982) The radius of the WN7 component turns out to be '$10R_0$ and does not depend sensitivitely on the mass ratio or actual T_{eff} assumed in the light curve analysis. Admittedly, this star is very close, even in over-contact, but one should look at other eclipsing binaries where such interactive effects are less severe. Unfortunately such systems are very rare.

Nugis: The parameters of the WR binaries may differ greatly from those of single WR stars.