# ON THE PROPERTIES OF WOLF-RAYET STARS AND THEIR MASS LOSS

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ABSTRACT - From consideration of the observed properties of the envelopes produced by mass loss in WR stars we find that:
a) The velocity at the optical photosphere is in the range 200-800 km $s^{-1}$.
b) The effective photospheric radius for the continuous radiation capable to ionize helium twice ($\lambda$ < 228 Å) is typically 5 to 15 times the optical photospheric radius.
c) The radiation temperature in the Lyman continuum ($\lambda$ < 912 Å) is around $5 \times 10^4$K. Therefore, most of the stellar radiation is emitted in the far UV and the total luminosity is considerably higher than currently estimated.
d) Multiple scattering ($N \simeq 20$) of radiation in the interval 228-504 Å can provide most of the momentum needed to accelerate the wind up to the observed terminal velocities.

## 1. PHOTOSPHERIC RADIUS AND INITIAL WIND VELOCITY

Wolf-Rayet stars are known to lose mass at high rates, typically $\dot{M} \simeq 3 \times 10^{-5}$ $M_\odot$ $yr^{-1}$(e.g. Barlow et al., 1981; Abbott et al., 1982; Panagia et al., 1982). As a consequence, the wind is so optically thick at all wavelengths that the photosphere itself (i.e. the layer where the optical depth is of the order of unity) is expanding at a relatively high speed. To quantify this concept we consider the case in which the velocity varies as $v = v_o\ (r/R_o)^\gamma$ with $\gamma$ in the range 0-1 (Panagia et al., 1982). Assuming also mass continuity and spherical symmetry, the optical depth can be expressed as

$$\tau = 2.9 \frac{\kappa}{\sigma} \dot{M}_{-5}\ R_{01}^{-1}\ v_{02}^{-1}\ \mu_e^{-1}\ (1+\gamma)^{-1} \tag{1}$$

where $\kappa$ is the total opacity, $\sigma$ is the opacity due to electron scattering, $\dot{M}_{-5}$ is the mass loss rate in $10^{-5}$ $M_\odot yr^{-1}$, $R_{01}$ is the optical photospheric radius in 10 $R_\odot$ and $v_{02}$ is the corresponding wind velocity in $10^2$ km $s^{-1}$. The quantity $\mu_e$ is the average atomic weight per electron (in atomic units) defined as:

*C. W. H. de Loore and A. J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, 203–207.*

$$\mu_e = \frac{\Sigma X_i\ m_i}{\Sigma X_i\ Z_i} \qquad (2)$$

with $X_i$, $m_i$, $Z_i$ being the relative abundance by number, the atomic mass and the charge of the i-th ionic species. Then, characterizing the optical photosphere as the layer where $\tau$ (electron scattering) $\sim 2/3$, equation (1) can be rewritten as

$$\dot{M}_{-5}/v_{02} = 0.23\ R_{01}\ \mu_e\ (1+\gamma) \qquad (3)$$

Hereafter we shall adopt $\gamma = 0.5$, $\dot{M}_{-5} = 3$ and $\mu_e \simeq 2$ as typical parameters for the wind and $R = 13\ R_\odot$ as the average photometric radius at optical wavelengths (Barlow et al. 1981; Panagia et al., 1982). With these values inserted into equation (3) the initial velocity turns out to be $v_o \simeq 340$ km s$^{-1}$. Considering the scatter of the possible values for the other parameters in equation (3) the expected dispersion for $v_o$ is of about a factor of 2, so that values of $v_o$ between 200 and 800 km s$^{-1}$ may be expected. This is indeed the range of initial velocities implied by both line profiles (e.g. Willis, 1980) and the shape of the continuum spectrum in the IR (Panagia et al., 1982) and in the radio (Felli and Panagia, 1981). Therefore, equation (3) can confidently be used to express the ratio $\dot{M}/v_o$ which crucially determines the volume emission measure of the wind, VEM $\propto (\dot{M}/v_o)^2$, and thus its emission.

## 2. HELIUM IONIZATION

As summarized by Barlow et al.(1981), the expanding envelope of a WR star mainly consists of helium whose ionization is high, i.e. helium is mostly in the form of $He^{++}$. On the other hand, the concentration of $He^+$ is still high enough to make the envelope optically thick shortward of 228 A, i.e. for the continuous radiation which can ionize $He^+$. Requiring the optical depth at $\lambda = 228$ Å to be $\tau(228\ A) = 2/3$ gives the condition which defines the effective photospheric radius for the $He^+$ ionizing continuum. Several $He^+$ radii computed with the parameters given in the previous section for different values of the ratio $y^{++} = He^{++}/(He^+ + He^{++})$ are given in Table 1. The gas above such a radius, being optically thin, will be ionized by the radiation emitted at this $He^+$ photospheric surface. This, being optically thick by definition, must radiate as a black body at the electron temperature of the envelope. Therefore, by equating the number of $He^+$ recombinations which occur above $R(He^+)$ with the emission at the $He^+$ photosphere one can determine the black body temperature and, thus, the electron temperature. The derived values of $T_{el}$ are displayed in the third column of Table 1. We see that all values are higher than 38000 K.

On the other hand, Klein and Castor (1978) have demonstrated that the electron temperature in the wind is, on the average, a factor of 0.83 lower than the radiation temperature, $T_{rad}$, which characterizes the far UV ($\lambda < 912$ A) emission of the star. Therefore, the appropriate values of $T_{rad}$ for WR stars (column 4 of Table 1) can simply be estimated

Table 1. Computed Properties of Wolf-Rayet Stars for $\gamma = 0.5$ and $R_o = 13\ R_\odot$

| $\frac{He^{++}}{He^{+} + He^{++}}$ | $\frac{R(He^{+})}{R_o}$ | $T_{el}$ | $T_{rad}$ | | $\log(L(\lambda_1, \lambda_2)/L_\odot$ | |
|---|---|---|---|---|---|---|
| | | $10^4$ K | $10^4$ K | 0 - 228 | 228 - 504 | 504 - 912 |
| 1.000 | 1.0 | 7.5 | 7.5 | 5.13 | 6.27 | 6.21 |
| 0.999 | 4.7 | 5.0 | 6.0 | 4.41 | 5.72 | 5.89 |
| 0.99 | 7.5 | 4.5 | 5.5 | 4.17 | 5.43 | 5.73 |
| 0.90 | 12.0 | 4.1 | 5.0 | 3.95 | 5.15 | 5.56 |
| 0.75 | 14.7 | 4.0 | 4.8 | 3.84 | 5.02 | 5.48 |
| 0.50 | 17.4 | 3.8 | 4.6 | 3.69 | 4.89 | 5.40 |

as $T_{rad} \simeq 1.21\ T_{el}$ except for the limiting case of $y^{++} = 1.0$ where $R(He^{+}) = R_o$ and the computed black-body temperature must be equal to the radiation temperature. We see that most of the $T_{rad}$ values range from 46000 to 60000 K with an upper bound of ∿75000 K for a pure $He^{++}$ envelope. It is interesting to note that comparable values of $T_{rad}$ were derived for a number of WR stars in a completely independent way, i.e. from the ionization equilibrium of the HII regions which surround them (Morton, 1979).

## 3. LYMAN CONTINUUM LUMINOSITY AND WIND ACCELERATION

The luminosity emitted in the Lyman continuum can be subdivided into three wavelengths intervals, i.e. 0 - 228 Å, 228 - 504 Å and 504 - 912 Å which are the intervals limited by the ionization edges of the $He^{+}$, $He^{o}$ and $H^{o}$, respectively. The computed values are presented in Table 1. We see that while L(0-228) hardly exceeds $3 \times 10^{4} L_{\odot}$, the luminosity in both the other two intervals is usually higher than $10^{5} L_{\odot}$. This implies that a considerable fraction of the stellar luminosity is emitted in the Lyman continuum. As an illustration, let us consider the case of $y^{++} = 0.9$ which can be taken as representative for most WR stars. From Table 1 we have $L(228\text{-}504) = 1.4 \times 10^{5} L_{\odot}$ and $L(504\text{-}912) = 3.6 \times 10^{5} L_{\odot}$ to be compared with an average value for the visual and near ultraviolet of $L(912\text{-}\infty) \simeq 1.2 \times 10^{5} L_{\odot}$ which can be derived from the compilation given by Barlow et al. (1981). Therefore, the total stellar luminosity turns out to be considerably higher than that derived from the optical and near UV data. In the particular case considered here, the total luminosity results to be $6.2 \times 10^{5} L_{\odot}$ which is a factor of 3.3 higher than the estimate of $\sim 1.9 \times 10^{5} L_{\odot}$ (corresponding to $M_V = -4.9$ and $BC = -3.6$) inferred à la Barlow et al. This fact is undoubtedly important to be taken into account for a correct estimate of the energetics of WR stars.

More importantly, with the present evaluation of the Lyman continuum radiation the momentum available to accelerate the wind results greatly increased thus solving the problem that radiation appeared to fall short of a factor of 20-30 from providing enough momentum to the wind (cf. Barlow, et al., 1981). In fact, about 1/4 of the total luminosity is radiated in the range 228-504 Å where photons can undergo a large number of multiple scatterings at opposite sides relative to the star, thus effectively multiplying the resulting wind acceleration (Panagia and Macchetto, 1981, 1982). For O-type stars the typical number of multiple scatterings is around 12 and for WR stars, owing to the higher mass loss rates, one can expect an even larger number of scatterings, say 20 or more. Therefore, following Panagia and Macchetto (1982), and adopting N = 20 in the interval 228-504 Å and an average blocking factor of 2/3 elsewhere, the momentum provided by radiation to the wind is estimated to be $4.2 \times 10^{29}$ erg $cm^{-2}$, 85% of which comes from multiple scattering. This value is practically coincident with the observed one for WR stars, i.e. $\dot{M}\, v_\infty \simeq (3 \times 10^{-5} M_{\odot} yr^{-1}) \times (2000\ km\ s^{-1}) = 3.8 \times 10^{29}$ erg $cm^{-2}$. Therefore, we can conclude that radiation is quite enough to account for the wind acceleration in WR envelopes.

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## DISCUSSION

Abbott: Does your model assume that beyond a certain radius no HeII Lyman continuum photons are created. Is this a reasonable assumption? If so, are your results sensitive to the adopted radius ?

Panagia: The calculations were made neglecting possible emission from the envelope itself. Although this assumption may somewhat overestimate the photon flux needed for the $He^+$ ionization, the order-of-magnitude argument is not going to be affected. Similarly, any reasonable change of the radius will only change the detailed values of the photon flux and the radiation temperature without affecting our conclusions.

Underhill: You have shown that a lot of energy is required to maintain the ionization of HeII seen in the mantles of WN stars and you have postulated that it comes from the radiation field of the star. It is possible that the ionization is maintained by collisions with fast-moving ( high temperature ) electrons. The electrons may have received their energy as the result of the deposition of non-radiative energy or momentum in the mantle. One possible source of energy is the flux of Alfven waves discussed by Cassinelli. One should discuss such alternatives before deciding that the effective temperature of WR stars are 60000K or so.