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Mass-loss rates for 21 Wolf–Rayet stars

M. J. Barlow, L. J. Smith and A. J. Willis *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT*

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Summary. Mass-loss rates have been derived for 21 WR stars encompassing most subtypes in the WN and WC sequences, from measurements of their infrared free–free fluxes. The resultant mass-loss rates show a range of only a factor of 4. WC stars generally have larger mass-loss rates than WN stars, the mean rates being $\dot{M}(\mathrm{WC}) = 4.1 \times 10^{-5} M_\odot \mathrm{yr}^{-1}$ and $\dot{M}(\mathrm{WN}) = 2.7 \times 10^{-5} M_\odot \mathrm{yr}^{-1}$. Optical and ultraviolet data have been used to estimate bolometric luminosities for a range of WR spectral types, and it is shown that the derived mass loss rates are too large to be powered by radiation pressure. The total kinetic energy injected into the interstellar medium through mass loss during the WR phase of a massive star is estimated to be 7×10^{50} erg, comparable to that of a supernova event.

1 Introduction

The mass-loss rates of Wolf–Rayet stars are of interest both from an evolutionary point of view and from the standpoint of the physical mechanisms responsible. The radio detection of free–free emission from ionized mass outflows probably provides the most accurate method for the determination of individual mass-loss rates, but as yet few WR stars have been detected at radio frequencies; e.g. γ Vel (Seaquist 1976; Morton & Wright 1979), HD 193793 (Florkowski & Gottesman 1977; this star exhibits complex variability and is excluded from the present analysis) and HD 192163 (Dickel, Habing & Isaacman 1980). Infrared wavelengths also sample the free–free emission from these mass outflows, but from regions of higher density much closer to the star. Thus the 10 μm emission may arise from characteristic radii where the wind has not yet reached terminal velocity, with a consequent departure of the density distribution from the simple r^{-2} case appropriate for the more extended radio-emitting regions. That this in fact occurs is shown by a consideration of the spectral indices of WR stars between infrared and radio frequencies (the spectral index is α when the flux $S_\nu \propto \nu^\alpha$). For an r^{-2} density distribution $\alpha = 2/3$ is predicted (Wright & Barlow 1975; Panagia & Felli 1975), modified by the weak frequency dependence of the Gaunt factor such that $\alpha = 0.60$ should apply at radio frequencies and $\alpha = 0.53$ should apply between 10 μm and 5 GHz. The observed spectral indices of γ Vel and HD 192163 between

10 μm and 5 GHz are 0.69 and 0.75 respectively (see below), indicating a steeper density distribution than r^{-2}, analogous to the case of P Cyg discussed by Barlow & Cohen (1977). The derivation of mass loss rates for WR stars directly from their infrared fluxes thus requires a knowledge of the appropriate velocity law. Hartmann & Cassinelli (1977) have, for instance, modelled the density distribution of the infrared emitting regions around the WN5 star HD 50896, but without deriving the mass loss rate. Hackwell, Gehrz & Smith (1974) derived mass loss rates on the basis of a single density shell model. Another method suggests itself, whereby an empirically determined mean 10 μm–5 GHz spectral index is applied to observed 10 μm free–free fluxes to yield predicted 5 GHz fluxes, from which mass loss rates can be derived in the standard manner. Barlow (1979) discussed this method and derived mass loss rates for several WR stars. By making use of more recent radio and infrared data we have applied this method here to the WR stars for which 10 μm data exist.

2 Derivation of mass-loss rates

2.1 BASIC PARAMETERS

Table 1 presents the data necessary for the derivation of 10 μm free–free fluxes. It is assumed for this purpose that the observed 10 μm fluxes represent the sum of a contribution from the free–free emission of the wind, together with an underlying stellar blackbody contribution. This core–halo model may be unrealistic for WR stars since they have very large optical depths in their winds. However, since the model is applied self-consistently, both in deriving a mean spectral index for γ Vel and HD 192163, and then applying it to the other stars, significant errors should not result, especially in view of the fact that the blackbody fluxes at 10 μm are typically found to be only about 10 per cent of the free–free fluxes. Column 3 of Table 1 lists the stellar monochromatic magnitudes at 5500 Å, normalized to 0.00 mag for α Lyr, corresponding to $3.50 \times 10^{-23}\,\mathrm{W\,m^{-2}\,Hz^{-1}} \equiv 3500$ Jy (Oke & Schild 1970; Hayes & Latham 1975). The sources of these magnitudes are listed in column 7. Column 4 of Table 1 gives the colour excess E_{B-V} adopted for each star. These were obtained from the sources listed in column 8. Where values of E_{B-V} derived from the method of nulling the 2200 Å interstellar extinction feature were available, these were preferred. Preference was given in the following order: *IUE* (Nussbaumer *et al.* 1981). *ANS* (van der Hucht *et al.* 1979), optical scanner (Cohen, Barlow & Kuhi 1975) and optical filter (Smith 1968a). Column 5 of Table 1 lists the 10 μm magnitudes [10] of the various stars, on a scale where α Lyr has [10] = 0.00 mag. For the northern WR stars, 10 μm data was usually available from both Hackwell *et al.* (1974) and Cohen *et al.* (1975), and the magnitudes adopted herein take both sets of photometry into account, as well as adjacent 8.5 μm and 11.5 μm magnitudes when available. In only two cases (HD 193576 and HD 191765) did the 10 μm magnitudes from these sources differ by more than the 1 σ photometric errors and in these two cases we adopted a straight mean. Those WR stars exhibiting infrared thermal dust emission were excluded from the present analysis. The 10 μm magnitude of BAC 209 (the exciting star of M1-67 = Sh 2-80) was taken from Cohen & Barlow (1975), whilst the 10 μm photometry of those WR stars south of −30° Dec was taken from Barlow & Cohen (1981). To convert the 10 μm magnitudes to fluxes we have adopted for flux calibration purposes the $T_{\mathrm{eff}} = 9400\,\mathrm{K}$, $\log g = 3.95$, line-blanketed model of α Lyr by Kurucz (1979), which fits the observed optical and near infrared energy distributions of this star extremely well and predicts $F_\nu\,(0.55\,\mu\mathrm{m})/F_\nu\,(10\,\mu\mathrm{m}) = 94.10$, implying a 10 μm zero magnitude flux calibration of 37.2 Jy. Column 6 of Table 1 lists $F_{\mathrm{ff}}\,(10\,\mu\mathrm{m})$ – the 10 μm free–free fluxes of the programme stars. These were derived by subtracting the extrapolated visual stellar fluxes from the observed 10 μm fluxes. *IUE* observations of 13 single WN and WC stars have yielded a

Table 1. Observed parameters.

Star	Spectral type	m_{5500}	E_{B-V}	[10]	$F_{\mathrm{ff}}(10\,\mu\mathrm{m})$ (Jy)	Source for m_{5500}	Source for E_{B-V}
HD 190918	WN4 + O9I	6.79	0.38	5.2	0.25	1	2
HD 4004	WN5	10.11	0.85	4.7	0.47	1	7
HD 50896	WN5	6.86	0.00	4.0	0.90	1	5
HD 193077	WN5	7.92	0.47	5.1	0.29	1	1
HD 193576	WN5 + O6	8.00	0.67	4.9	0.33	1	1
= V444 Cyg							
MR 111	WN5/WC5			5.1	0.31		
= AS 422							
HD 165688	WN6	9.76	1.06	4.1	0.81	2	2
HD 191765	WN6	8.00	0.42	4.25	0.70	1	5
HD 192163	WN6	7.56*	0.52	3.8	1.05	1*	5
HD 92740	WN7	6.41	0.28	4.5	0.48	2	5
HD 93131	WN7	6.51	0.16	4.8	0.38	2	5
HD 93162	WN7	8.09	0.59	4.9	0.35	2	2
HD 151932	WN7	6.50	0.45	3.8	0.96	2	5
BAC 209	WN8	11.05	1.35	6.0	0.115	3	3
AS 374	WN8	12.25	1.68	4.9	0.38	4	4
HD 165763	WC5	8.11	0.16†	4.9	0.39	1	1†
MR 112	WC5			4.5	0.56		
HD 113904	WC6 + O9.5I	5.70	0.18	4.4	0.53	2	2
= θ Mus							
HD 152270	WC7 + O5	6.95	0.32	4.0	0.86	2	2
HD 68273	WC8 + O9I	1.88	0.03	0.85	14.36	6	6
= γ Vel							
HD 192103	WC8	8.33	0.38	5.0	0.35	1	5

*The observed monochromatic magnitudes for HD 192163 given in Table 2(a) of Cohen *et al.* (1975) are in fact dereddened by $E_{B-V} = 0.10$ mag, and this inadvertent dereddening carries through to their Table 3(a) where HD 192163 is dereddened by $E_{B-V} = 0.10$ mag too much.

†It was found that dereddening HD 165763 with the values of E_{B-V} derived from nulling the 2200 Å feature, e.g. 0.26 mag (Nussbaumer *et al.* 1981) or 0.33 mag (van der Hucht *et al.* 1979) resulted in energy distributions steeper than that of an infinite temperature blackbody in the UV region, whereas the values of E_{B-V} from the optical data, e.g. 0.16 mag (Cohen *et al.* 1975) and 0.17 mag (Smith 1968a) gave dereddened energy distributions which could be fitted with finite temperature blackbodies. The dust in the line of sight to HD 165763 may therefore have an anomalously strong 2200 Å feature. $E_{B-V} =$ 0.16 mag was adopted.

References (1) Cohen *et al.* (1975); (2) Smith (1968a); (3) Cohen & Barlow (1975); (4) Pyper (1966); (5) Nussbaumer *et al.* (1981); (6) Code *et al.* (1976); (7) van der Hucht *et al.* (1979).

mean best fit blackbody temperature to their continua of 25 200 ± 3700 K between 2000 and 5000 Å (Nussbaumer *et al.* 1981), so we have adopted a blackbody temperature of 25 000 K in order to extrapolate the dereddened 5500 Å magnitudes to 10 μm ($R \equiv A_V/E_{B-V} = 3.1$ was adopted). In the case of three of the stars; HD 190918, θ Mus and γ Vel, the optical energy distributions are dominated by the O9I or O9.5I companions, and in their cases we have extrapolated the dereddened stellar 5500 Å fluxes to 10 μm using the ratio $F_\nu(0.55\,\mu\mathrm{m})/F_\nu(10\,\mu\mathrm{m}) = 256.5$, given by Kurucz's (1979) line blanketed model with $T_{\mathrm{eff}} =$ 30 000 K and log g = 3.5.

The 10 μm free–free flux for γ Vel is 14.36 Jy (Table 1), which in conjunction with its 5 GHz flux of 36 mJy (Seaquist 1976) implies a 10 μm – 5 GHz spectral index of $\alpha = 0.69$. The free–free fluxes from HD 192163 of 1.05 Jy at 10 μm (Table 1) and 1.6 mJy at 5 GHz (Dickel *et al.* 1980) imply a 10 μm – 5 GHz spectral index of $\alpha = 0.75$. Finally Hogg (1980, private communication) has made radio detections of a WN5 star and a WN6 star at flux levels which imply 10 μm–5 GHz spectral indices of 0.77 and 0.79 respectively. Consequently we have adopted a mean 10 μm–5 GHz spectral index of 0.76 in order to obtain the predicted 5 GHz fluxes listed in column 3 of Table 2 (the predicted fluxes at other radio frequencies can be obtained by using a spectral index of 0.60 between 5 GHz and the relevant frequency).

The mass loss rate, $\dot{M}$, of a star emitting a flux S_ν at frequency ν can be determined using the following formula (Wright & Barlow 1975):

$$\frac{\dot{M}}{v_\infty} = \frac{0.095 \mu S_\nu^{3/4} D^{3/2}}{Z \gamma^{1/2} g^{1/2} \nu^{1/2}} M_\odot \, \mathrm{yr}^{-1}/\mathrm{km\,s}^{-1} \tag{1}$$

where S_ν is in Jy, ν is in Hz, D is the distance of the star in kpc and v_∞ is the wind terminal velocity in km s^{-1}. μ, Z and γ are respectively the mean molecular weight per ion, the rms ionic charge and the mean number of electrons per ion. Therefore if X_i, m_i and Z_i are respectively the fractional abundance, the molecular weight and the ionic charge of ion species i, we have

$$\mu = \frac{\Sigma X_i m_i}{\Sigma X_i}, \qquad Z = \frac{(\Sigma X_i Z_i^2)^{1/2}}{\Sigma X_i}, \qquad \gamma = \frac{\Sigma X_i Z_i}{\Sigma X_i}. \tag{2}$$

From Spitzer (1962) the Gaunt factor at radio frequency ν and electron temperature T_e is given by:

$$g = \frac{3^{1/2}}{\pi} \{17.22 + \ln (T_\mathrm{e}^{3/2}/\nu Z)\}. \tag{3}$$

The distances given in column 4 of Table 2 were primarily derived using the absolute magnitude calibration for WR stars given by Smith (1973; the calibration is for a mean wavelength of v = 5160 Å), together with the v magnitudes of Westerlund (1966) and Smith (1968a) and the interstellar extinctions determined from Table 1 with R = 3.1, scaled to 5160 Å using the relationships given by Smith (1968b). When independent distance estimates were available these were preferred, e.g. γ Vel (Conti & Smith 1972), θ Mus (Moffat & Seggewiss 1977), the three stars in the η Car complex – HD 92740, 93131 and 93162 – (Walborn 1973a) and HD 151932 and 152270 in Sco OB1 (Garrison & Schild 1979). The stars MR 111 (WN5, Bromage & Nandy 1973) and MR 112 (WC5) are located very close in the sky to the Cyg OB2 Association and, like the association members, undergo very heavy extinction (Reddish 1968), estimated as $A_\mathrm{V} \sim 7.5$ and 9.0 respectively. We have therefore adopted the distance to Cyg OB2 (Walborn 1973b) as appropriate for these two stars also. We have adopted the absolute magnitudes given by Smith (1968b) for HD 190918 and 193576. We have also retained the absolute magnitude given for HD 193077, on the assumption that it was a binary, by Smith (1968b). Although Massey (1980) has since shown that it may be a single star, the absolute magnitude for an ordinary WN5 star would not appear to be appropriate for an object with such an abnormal spectrum. The distance to HD 193077 is thus highly uncertain.

For WN4, 5, 6 and WC5, 6, 7 stars in our sample we have adopted $\mu = 4$, $Z = 2$ and $\gamma = 2$. This follows from the fact that their spectra indicate that $\mathrm{He}^+/\mathrm{H}^+ \gg 1$ and $\mathrm{He}^{2+}/\mathrm{He}^+ \gg 1$ (Castor & Van Blerkom 1970; Nugis 1972a, b; Rublev 1972; Smith 1973).

The helium ionization balance is more uncertain for the WN7, 8 and WC8 stars, since He I recombination lines are quite strong in their spectra. A detailed analysis of the helium spectra of these stars is obviously needed, but for present purposes we assume that the He I

Table 2. Mass loss rates.

Star	Spectral type	Predicted S_ν (5 GHz) (mJy)	D (kpc)	$\dot{M}/v_\infty$ ($M_\odot$ yr^{-1}/km s^{-1})	v_∞ (km s^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})	$\dfrac{\dot{M}}{L/v_\infty c}$	L_W ($\times 10^{37}$ erg s^{-1})	L_W/L	Source for v_∞
HD 190918	WN4 + O9I	0.34	3.16	1.10 (−8)	1700	1.9 (−5)	31	1.7	0.087	1
HD 4004	WN5	0.63	2.13	9.70 (−9)	(2600)	2.5 (−5)	27	5.4	0.12	
HD 50896	WN5	1.21	1.77	1.21 (−8)	2700	3.3 (−5)	36	7.5	0.16	2
HD 193077	WN5	0.39	2.78	1.02 (−8)	1700	1.7 (−5)	12	1.6	0.034	3
HD 193576	WN5 + O6	0.44	2.08	7.23 (−9)	2500	1.8 (−5)	19	3.6	0.077	5
MR 111 (AS 422)	WN5/WC5	0.42	1.82	5.63 (−9)	(2600)	1.5 (−5)	16	3.1	0.068	
HD 165688	WN6	1.09	1.91	1.24 (−8)	(2400)	3.0 (−5)	12	5.4	0.048	
HD 191765	WN6	0.94	2.08	1.27 (−8)	2600	3.3 (−5)	14	7.0	0.062	2
HD 192163	WN6	1.41 (1.6)*	1.36	9.98 (−9)	2250	2.3 (−5)	8.5	3.6	0.032	2
HD 92740	WN7	0.65	2.63	1.47 (−8)	2600	3.8 (−5)	11	8.1	0.048	2
HD 93131	WN7	0.51	2.63	1.23 (−8)	2800	3.4 (−5)	11	8.5	0.050	2
HD 93162	WN7	0.47	2.63	1.17 (−8)	2900	3.4 (−5)	11	9.0	0.052	4
HD 151932	WN7	1.29	2.09	1.75 (−8)	2250	3.9 (−5)	10	6.3	0.037	2
BAC 209	WN8	0.16	4.33	1.13 (−8)	(1800)	2.0 (−5)	3.8	2.1	0.011	
AS 374	WN8	0.51	4.45	2.86 (−8)	(1800)	5.1 (−5)	9.6	5.2	0.029	
HD 165763	WC5	0.52	2.63	1.16 (−8)	3700	4.3 (−5)	28	18.5	0.18	2
MR 112	WC5	0.75	1.82	8.74 (−9)	(3700)	3.2 (−5)	21	13.9	0.13	
HD 113904	WC6 +O9.5I	0.71	2.00	9.64 (−9)	(3500)	3.4 (−5)	38	13.0	0.22	
HD 152270	WC7 + O5	1.16	2.09	1.49 (−8)	3300	4.9 (−5)	53	16.9	0.29	1
HD 68273	WC8 + O9I	19 (36)*	0.46	2.95 (−8)	2000	5.9 (−5)	52	7.4	0.17	6
HD 192103	WC8	0.47	2.43	1.37 (−8)	2000	2.7 (−5)	24	3.5	0.08	2

*Values of S_ν (5 GHz) in parentheses are the *observed* 5 GHz fluxes, which are preferred for the subsequent derivation of $\dot{M}$. Sources for v_∞: (1) Kondo & McCluskey (1981); (2) Willis (1981); (3) P. S. Conti, private communication; (4) M. Pettini, private communication; (5) K. van der Hucht & F. Beeckmans, private communication; (6) this paper.

4471 Å and He II 4542 Å lines are both optically thin, so that with the recombination coefficients given by Osterbrock (1974) for $T_e = 20\,000$ K we find that $He^{2+}/He^{+} \sim 1.1$ W(He II 4542)/W(He I 4471). For the WN7 star in her sample, Smith (1973) found $He^{2+}/H^{+} = 1.0$ and W(He I 4542)/W(He I 4471) = 2.6, which using the relationships in equation (2) yields $\mu = 2.7$, $\gamma = 1.4$ and $Z = 1.5$. For the WN8 star in Smith's sample $He^{2+}/H^{+} = 1/2.3$ and W(He II 4542)/W(He I 4471) = 1.1, implying $\mu = 2.3$, $\gamma = 1.2$ and $Z = 1.3$. We adopt these respective values for the WN7 and WN8 stars in our sample. Rublev (1972) has shown that $He^{2+}/H^{+} \gg 1$ in the WC8 star HD 192103, and the high dispersion spectrum of this star presented by Bappu (1973) indicates that W(He II 4542)/W(He I 4471) ~ 1. We therefore adopt $\mu = 4$, $\gamma = 1.5$ and $Z = 1.6$ for the two WC8 stars in our sample. Massey (1980) has shown that HD 193077 (WN5) may be a single star with intrinsic hydrogen absorption lines, and thus our assumption that He^{2+} is dominant in its wind may not be correct.

With these various parameters the values of $\dot{M}/v_\infty$ listed in column 5 of Table 2 have been derived from the predicted 5 GHz fluxes using equation (1). The mass loss rates, $\dot{M}$, can then be obtained by multiplying by the appropriate terminal velocity, v_∞. These velocities are listed in column 6 of Table 2 and have been obtained from the sources listed in column 11. Following Willis (1981) most weight has been placed upon the velocities derived from the high ionization stages. A terminal velocity in parentheses indicates that no data were available for the particular star, so that a value derived from other stars of the same spectral type was used instead. The terminal velocity adopted for γ Vel is that appropriate for the WC8 component, rather than the value of 2900 km s^{-1} appropriate for the O9I component (Willis *et al.* 1979). The strong C II 1335 Å feature in γ Vel, which is not observed in O9I stars, was found by Willis *et al.* (1979) to vary in binary phase with the WC8 component and have an edge velocity of 1600 km s^{-1}. This line, the Si II 1526 Å line, and the CIII 1909 Å, 2297 Å lines, show exactly the same velocity-excitation potential dependence as found for the single WC8 star HD 192103 by Willis (1981) and so we adopt for γ Vel the terminal velocity of 2000 km s^{-1} found for HD 192103 from the higher ionization potential lines of C IV and Si IV (which in γ Vel are swamped by the O9I companion).

Column 7 of Table 2 lists the derived mass loss rates, $\dot{M}$. The mass loss rate for HD 192163 given in Table 2 agrees with that obtained by Dickel *et al.* (1980), since we have adopted their observed 5 GHz flux. Our derived mass loss rate for γ Vel is almost the same as that obtained by Morton & Wright (1979), because our adoption of $v_\infty = 2000$ km s^{-1}, instead of 2900 km s^{-1}, is almost exactly balanced by our assumption that $He^{2+}/He^{+} \sim 1$ instead of $\gg 1$.

It is necessary to make estimates of the radiative luminosities of WR stars if quantities such as the upper limit for mass loss by radiation pressure are to be obtained. We have derived the stellar luminosities given in Table 3 from an analysis of the UV and optical continuum flux distributions of a sample of 13 single WR stars using data described in detail by Nussbaumer *et al.* (1981). Each stellar luminosity estimate consisted of two components: (1) the directly observable flux longward of 1300 Å; and (2) the flux shortward of 1300 Å, estimated by extrapolating to shorter wavelengths a Planck function (normalized to 1300 Å) corresponding to the most appropriate blackbody temperature for the 1300 Å region. It is well known that the colour temperature of a WR star's continuum flux distribution increases with decreasing wavelength (Kuhi 1966) and this is interpreted as being due to the effects of a very dense extended atmosphere, such that the continuum opacity, and thus the atmospheric reprocessing of the stellar radiation field, increases with increasing wavelength. We have estimated the continuum flux at points every 50 Å in our SWP (1150–2000 Å) and LWR (1900–3100 Å) *IUE* low resolution spectra and for each SWP wavelength we have derived a blackbody temperature, T_{BB}, which would connect it to the flux at each LWR

Table 3. Radiative luminosities.

Spectral type	WN4	WN5	WN6	WN7	WN8	WC5	WC6	WC7	WC8
M_V	−3.9	−4.3	−4.8	−6.8	−6.2	−4.4	−4.4	−4.4	−4.8
T_{BB} (1300 Å)	42 000	55 000	60 000	36 000	38 000	60 000	54 000	46 000	38 000
$\log L/L_\odot$	4.71	5.08	5.47	5.65	5.68	5.44	5.18	5.18	5.05
M_{bol}	−7.00	−7.95	−8.90	−9.35	−9.45	−8.85	−8.20	−8.20	−7.85
BC	−3.10	−3.65	−4.10	−2.55	−3.25	−4.45	−3.80	−3.80	−3.05
$\log S_L$	48.23	48.78	49.20	49.01	49.12	49.18	48.86	48.77	48.47

wavelength. We were then able to inspect the trend of T_{BB} with decreasing LWR and SWP wavelength. It was found that T_{BB} was not a strong function of wavelength for the later type WR stars (WN7, 8, WC8) but that the value of T_{BB} increased with decreasing wavelength for the earlier spectral types. An estimate was made of the most appropriate blackbody temperature in the 1300 Å region, T_{BB} (1300 Å), and this was used to derive the flux shortward of 1300 Å. The values of T_{BB} (1300 Å) adopted for the various spectral types are given in Table 3. There is of course no guarantee that the stellar energy distributions will not get hotter still at shorter wavelengths, but the fact that the values of T_{BB} (1300 Å) are broadly consistent with the effective temperatures implied by the observed degrees of ionization leads us to believe that this is unlikely. In the case of the WC stars a significant fraction of the total radiative luminosity is contained in emission lines. For the WC5, 6 stars in our sample a mean flux correction factor of 1.65 was derived between 1300 and 3000 Å, whilst a mean correction factor of 1.30 was derived for the WC7, 8 stars; where this factor represents the ratio of the total stellar flux (including lines) to the stellar flux under the chosen continuum points. In deriving integrated luminosities for WC stars it was assumed that these correction factors apply over their entire spectra and so the luminosities defined by the continuum points were multiplied by the appropriate flux correction factors. In the case of the WN stars a smaller fraction of the stellar luminosity is contained in emission lines. We derive mean flux correction factors of 1.35 for the WN5, 6 stars in our sample and 1.10 for the WN4, 7, 8 stars, and applied these factors to obtain the luminosities listed in Table 3.

Table 3 lists for a range of WR spectral types: the absolute magnitude (from Smith 1973); the value of T_{BB} (1300 Å); the integrated stellar luminosity; the absolute bolometric magnitude, M_{bol}; and the bolometric correction, BC, implied by M_v and M_{bol}. The bolometric corrections are smaller than those corresponding to a blackbody temperature of T_{BB} (1300 Å) normalized to the visual flux, but larger than those corresponding to a blackbody of the same temperature normalised to the 1300 Å flux. No unique effective temperature can be associated with these bolometric corrections, since the ultraviolet and visual fluxes originate from different radii. The last column of Table 3 lists $\log S_L$, where S_L is the total number of photons capable of ionizing hydrogen (viz. $\leqslant$ 912 Å) emitted from the star per second, implied by the extrapolation of T_{BB} (1300 Å) to shorter wavelengths, where the flux correction factors discussed above have been applied.

2.2 SOURCES OF ERROR

If the full range of the 10 μm–5 GHz spectral indices for WR stars lies between 0.69 and 0.79, then our adoption of $\alpha = 0.76$ would imply a possible error of $^{+84}_{-23}$ per cent in the predicted 5 GHz fluxes and a consequent error from this source of $^{+58}_{-17}$ per cent in the derived mass loss rates. γ Vel has a significantly smaller value of α than the three WN stars detected at radio frequencies suggesting that WC stars in general might have a similarly lower value of α. If the other WC stars in Table 2 have $\alpha = 0.69$, then their derived mass loss rates would be increased by 58 per cent over the values given in Table 2.

The photometric errors associated with the $10\,\mu$m magnitudes are unlikely to be greater than ± 25 per cent, which translates into an error in $\dot{M}$ from this source of ± 20 per cent. In calculating the Gaunt factors to be used in equation (1) we have assumed an electron temperature $T_e = 40\,000$ K for the radio emitting regions around WN4, 5, 6 and WC5, 6, 7 stars and $T_e = 30\,000$ K for WN7, 8 and WC8 stars. However, the derived mass loss rates are very insensitive to the assumed values of T_e, since a change of $\pm 10\,000$ K in T_e leads to a change of only ± 2 per cent in the derived value of $\dot{M}$.

There is some uncertainty about the $\mathrm{He}^{2+}/\mathrm{He}^{+}$ ratios in the winds of WN7, 8 and WC8 stars, which affects the factor $\mu/Z\gamma^{1/2}$ in equation (1). In the unlikely event that He^{+} was completely dominant in these stars, their derived mass loss rates would have to be increased by factors of 2.6, 2.5 and 2.0 respectively; whilst if He^{2+} were dominant their $\dot{M}$s would have to be decreased by factors of 1.2, 1.3 and 1.4 respectively. Underhill (1980) has suggested that the WR stars might have 'normal' cosmic abundances. Whilst we do not adopt such abundances here, it should be pointed out that the mass loss rates which would be derived for an assumed hydrogen-rich wind ($\mu = 1.26$, $\gamma = 1.0$, $z = 1.0$) differ only by 12 per cent from those derived in Table 2 when He^{2+} is assumed to dominate.

Finally, the mean absolute magnitudes given for WR stars by Smith (1973) have an unknown dispersion, which represents another possible source of error, since the derived mass loss rates are proportional to $D^{3/2}$.

3 Discussion

The derived mass loss rates in Table 2 show a relatively small range lying between 1.5 and $6 \times 10^{-5} M_{\odot}\,\mathrm{yr}^{-1}$. There is no apparent correlation between the derived mass loss rates and the stellar radiative luminosities. The WC stars show a tendency to have slightly higher mass loss rates than the WN (the mean value of $\dot{M}$(WC) is $4.1 \times 10^{-5} M_{\odot}\,\mathrm{yr}^{-1}$ compared to the mean value of $\dot{M}$(WN) of $2.7 \times 10^{-5} M_{\odot}\,\mathrm{yr}^{-1}$). These rates are typically about a factor of 10 higher than those of luminous O-type stars.

It is useful to compare the derived mass loss rates with the upper limit for mass loss by single-scattering radiation pressure acting through continuum opacity, equal to $L/v_{\infty}c$ (Cassinelli & Castor 1973). Column 8 of Table 2 lists the ratio of the derived mass loss rate to this upper limit. The ratio is relatively insensitive to the real distance of the star, being proportional to $D^{-1/2}$. Inspection of column 8 of Table 2 shows a fairly noticeable trend for the WN stars, the ratio rising from a value typically 10 for WN7, 8 stars, to about 16 for WN5, 6 stars, with some WN5, 4 stars having even larger ratios. The anomalously low ratio for the WN8 star BAC 209, compared to the other WN7, 8 stars, may be due to the assumption of too low a terminal velocity. The adopted value of $v_{\infty} = 1800\,\mathrm{km\,s^{-1}}$ for the WN8 stars comes from an analysis of the UV spectrum of HD 96548. If the true terminal velocity of BAC 209 was $2500\,\mathrm{km\,s^{-1}}$, its value of $\dot{M}/(L/v_{\infty}c)$ would rise to the same as the other WN7, 8 stars. The WC stars show a much smaller range, with an average value for $\dot{M}/(L/v_{\infty}c)$ of about 36. These values are all much larger than the ratios of typically 0.5 found for luminous OB stars by Barlow & Cohen (1977) and appear to be too large for even multiple scattering radiation pressure to be invoked as the major mass loss driving force, since more than 40 effective backward scatterings would be required in some cases. It seems unlikely that the very large values of $\dot{M}/(L/v_{\infty}c)$ are due to an underestimate of the stellar radiative luminosities. In order to reduce the numbers in column 8 of Table 2 below unity, it would be necessary for the unobserved flux shortward of 1100 Å to be characterized by a blackbody temperature of ~ 140 000 K for the WN7 stars, ~ 200 000 K for the WN6 stars and ~ 250 000 K for some of the WN5, 4 and WC stars. Such high temperatures are completely at variance with the observed spectral excitations of these stars.

Column 9 of Table 2 lists the wind power, $L_W = \frac{1}{2}\dot{M}v_\infty^2$, and column 10 lists the ratio of L_W to the stellar radiative luminosity, L. Again there is a trend for this ratio to rise from a value of 5 per cent for late WN stars to about 9 per cent for the early WN stars, with the WC stars having a mean value of 18 per cent. A typical value for an Of star, such as ζ Pup, is 0.4 per cent. The magnitude of this ratio for the WR stars demonstrates the importance of their winds in their energy balance, and suggests that the winds must be driven by some deep-seated core mechanism.

The WN and WC stars are respectively thought to represent the early and late stages of the core helium burning phase of evolution of massive stars (Willis & Wilson 1978). There is evidence from Table 2 that the rate of mass loss and the wind kinetic power increase as a WR star evolves from WN to WC. This may represents a continuation of the trend suggested by Lamers, Paerels & de Loore (1980) and Conti & Garmany (1980), whereby evolved Of stars seem to have significantly greater rates of mass loss than main-sequence O stars of the same luminosity, and the results of the present paper showing that WR stars have much larger mass loss rates than Of stars of the same luminosity.

Chiosi, Nasi & Sreenivasan (1978) have estimated a core helium burning lifetime of 4×10^5 yr for a star of initial mass $40 M_\odot$. If we adopt mean values of $\dot{M}(\mathrm{WR}) = 3\times10^{-5} M_\odot$ yr^{-1} and $v_\infty(\mathrm{WR}) = 2500$ km s^{-1}, then during the WR phase approximately $12 M_\odot$ of mass will be ejected into the interstellar medium, with a total kinetic energy of 7×10^{50} erg. This is comparable to the initial kinetic energy estimated for supernova events and since the kinetic energy is transferred more effectively to the interstellar medium in a continuous rather than a single impulsive process (McCray & Snow 1979) the present results indicate that WR stars must be taken into account in any consideration of the overall energy balance of the interstellar medium. For example, 18 WR stars lie within the contours of the X-ray superbubble in Cygnus discovered by Cash *et al.* (1980), and 12 have distances consistent with their being physically associated with the bubble. WR stars may also have been largely responsible for the Giant and Supergiant Shells discovered in the Large Magellanic Cloud by Meaburn (1980) and for the galactic H I Supershells found by Heiles (1979).

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References

Bappu, M. K. V., 1973. In *Proc. IAU Symp. 49*, p. 59, eds Bappu, M.K.V. & Sahade, J., D. Reidel, Dordrecht, Holland.
Barlow, M. J., 1979. In *Proc. IAU Symp. 83*, p. 119, eds Conti, P. S. & de Loore, C. W. H., D. Reidel, Dordrecht, Holland.
Barlow, M. J. & Cohen, M., 1977. *Astrophys. J.*, **213**, 737.
Barlow, M. J. & Cohen, M., 1981. In preparation.
Bromage, G. E. & Nandy, K., 1973. *Nature*, **241**, 30.
Cash, W., Charles, P., Bowyer, S., Walter, F., Garmire, G. & Riegler, G., 1980. *Astrophys. J.*, **238**, L71.
Cassinelli, J. P. & Castor, J. I., 1973. *Astrophys. J.*, **179**, 189.

Castor, J. I. & Van Blerkom, D., 1970. *Astrophys. J.*, **161**, 485.

Chiosi, C., Nasi, E. & Sreenivasan, S. R., 1978. *Astr. Astrophys.*, **63**, 103.

Code, A. D., Davis, R. J., Bless, R. C. & Hanbury Brown, R., 1976. *Astrophys. J.*, **203**, 417.

Cohen, M. & Barlow, M. J., 1975. *Astrophys. Lett.*, **16**, 165.

Cohen, M., Barlow, M. J. & Kuhi, L. V., 1975. *Astr. Astrophys.*, **40**, 291.

Conti, P. S. & Garmany, C. D., 1980. *Astrophys. J.*, **238**, 190.

Conti, P. S. & Smith, L. F., 1972. *Astrophys. J.*, **172**, 623.

Dickel, H. R., Habing, H. J. & Isaacman, R., 1980. *Astrophys. J.*, **238**, L39.

Florkowski, D. R. & Gottesman, S. T., 1977. *Mon. Not. R. astr. Soc.*, **179**, 105.

Garrison, R. F. & Schild, R. E., 1979. *Astr. J.*, **84**, 1020.

Hackwell, J. A., Gehrz, R. D. & Smith, J. R., 1974. *Astrophys. J.*, **192**, 383.

Hartmann, L. & Cassinelli, J. P., 1977. *Astrophys. J.*, **215**, 155.

Hayes, D. S. & Latham, D. W., 1975. *Astrophys. J.*, **197**, 593.

Heiles, C., 1979. *Astrophys. J.*, **229**, 533.

Kondo, Y. & McCluskey, G. E., 1981. In preparation.

Kuhi, L. V., 1966. *Astrophys. J.*, **143**, 753.

Kurucz, R. L., 1979. *Astrophys. J. Suppl.*, **40**, 1.

Lamers, H. J. G. L. M., Paerels, F. B. S. & de Loore, C. W. H., 1980. *Astr. Astrophys.*, **87**, 68.

McCray, R. & Snow, T. P., 1979. *A. Rev. Astr. Astrophys.*, **17**, 213.

Massey, P., 1980. *Astrophys. J.*, **236**, 526.

Meaburn, J., 1980. *Mon. Not. R. astr. Soc.*, **192**, 365.

Moffat, A. F. J. & Seggewiss, W., 1977. *Astr. Astrophys.*, **54**, 607.

Morton, D. C. & Wright, A. E., 1979. In *Proc. IAU Symp. 83*, p. 155, eds Conti, P. S. & De Loore, C. W. H., D. Reidel, Dordrecht, Holland.

Nugis, T., 1972a. *Publs Tartu astrophys. Obs.*, **40**, 325.

Nugis, T., 1972b. *Publs Tartu astrophys. Obs.*, **40**, 355.

Nussbaumer, H., Schmutz, W., Smith, L. J. & Willis, A. J., 1981. *Astr. Astrophys.*, submitted.

Oke. J. B. & Schild, R. E., 1970. *Astrophys. J.*, **140**, 689.

Osterbrock, D. E., 1974. *Astrophysics of Gaseous Nebulae*, W. H. Freeman, San Francisco.

Panagia, N. & Felli, M., 1975. *Astr. Astrophys.*, **39**, 41.

Pyper, D. M., 1966. *Astrophys. J.*, **144**, 13.

Reddish, V. C., 1968. *Observatory*, **88**, 139.

Rublev, C. V., 1972. *Astrofiz. Issled, Izv. Spets. Astrofiz. Obs.*, **4**, 3.

Seaquist, E. R., 1976. *Astrophys. J.*, **203**, L35.

Smith, L. F., 1968a. *Mon. Not. R. astr. Soc.*, **140**, 409.

Smith, L. F., 1968b. *Mon. Not. R. astr. Soc.*, **141**, 317.

Smith, L. F., 1973. In *Proc. IAU Symp. 49*, p. 15, eds Bappu, M. K. V. & Sahade, J., D. Reidel, Dordrecht, Holland.

Spitzer, L., 1962. *Physics of Fully Ionized Gases*, 2nd edn, p. 148, Interscience, New York.

Underhill, A. B., 1980. *Astrophys. J.*, **239**, 220.

van der Hucht, K. A., Cassinelli, J. P., Wesselius, P. R. & Wu, C-C., 1979. *Astr. Astrophys. Suppl.*, **38**, 279.

Walborn, N. R. 1973a. *Astrophys. J.*, **179**, 517.

Walborn, N. R., 1973b. *Astrophys. J.*, **180**, L35.

Westerlund, B. E., 1966. *Astrophys. J.*, **145**, 724.

Willis, A. J., 1981. In *Proc. IAU Coll. No. 59*, D. Reidel, Dordrecht, Holland, in press.

Willis, A. J. & Wilson, R., 1978. *Mon. Not. R. astr. Soc.*, **183**, 559.

Willis, A. J., Wilson, R., Macchetto, F., Beeckmans, F., van der Hucht, K. A. & Stickland, D. J., 1979. In *The First Year of IUE*, Symp., p. 394 ed. Willis, A. J., University College London.

Wright, A. E. & Barlow, M. J., 1975. *Mon. Not. R. astr. Soc.*, **170**, 41.