SESSION V. MASS LOSS – *Chair: Lindsey F. Smith*

Lindsey Smith

OBSERVATIONS OF WOLF-RAYET MASS LOSS

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ABSTRACT. Current knowledge of the stellar winds and mass loss rates for WR stars is reviewed. Recent IR spectroscopy and reassessments of UV resonance line P Cygni profiles have led to revisions of terminal velocities, with $v_\infty \simeq 0.75 \times$ previous estimates. Radio and IR ($10_{\mu m}$) free-free emission for well-established thermal sources, coupled with recent considerations of the wind ionisation balance and chemistry, leads to WR mass loss rates lying in the range $10^{-5} - 10^{-4}$ $M_\odot$ yr^{-1}. This scale is confirmed by independent analyses of optical polarisation modulation in WR+O binaries. No significant differences are apparent between the mean mass loss rates of: (a) single and binary WR stars; (b) WN and WC stars, and (c) the WN and WC subclasses. The overall mean WR mass loss rate is $\sim 5 \times 10^{-5}$ $M_\odot$ yr^{-1}. Although WR radiative luminosities are uncertain, there may be a rough scaling of $\dot{M}_{WR}$ with L_*, with a spread of up to an order of magnitude at a given L_*. WR winds have the highest momenta of the hot luminous stars, with values of $\dot{M} v_\infty c/L_*$ in the range 1–30 (WN7,8 and WC9 stars may lie near the lower bound). An additional mechanism to radiation pressure may be required to initiate the high WR mass loss, although thereafter the winds may be radiatively accelerated. Intrinsic variability in optical light, polarisation and emission lines, and in UV P Cygni profiles, indicate significant instability in the WR winds. For extragalactic WR stars in the Local Group, optical line strengths and widths do not suggest substantial differences in wind velocities and mass loss rates of subtypes compared to galactic counterparts.

1. Introduction

It is well established that the predominant emission line spectrum of the WR stars is a direct reflection of their high levels of mass loss (Abbott & Conti 1987). Characterising their stellar winds and mass loss rates as a function of subtype is thus important in developing a quantitative understanding of their physical and chemical properties and evolutionary status from both observational and theoretical standpoints. This paper reviews progress in observational studies of WR mass loss and stellar winds, emphasising recent work over the past five years or so. I shall not dwell much on the theory of WR mass loss – this will be covered in the next review, by Cassinelli (these proceedings). Excellent comprehensive reviews of earlier work in this field have been given by Barlow (1982) and in the exemplary paper by Abbott *et al.* (1986).

2. Radio and IR continuum data

Abbott *et al.* (1986, hereafter ABCT) provide the most extensive set of 4.9 GHz radio observations of WR stars from their own data and earlier work by Hogg (1982, 1985), Dickel *et al.* (1980), Florkowski (1982) and Becker & White (1985). In their sample 22 stars have measured 4.9 GHz fluxes, whilst upper limits were obtained for a further 13 stars. ABCT also present radio observations at 14.9 GHz for 6 stars based on their data and that of Hogg (1982). The radio flux is presumed to arise from free-free emission in the outermost regions of the WR winds, where the wind velocity has reached its terminal value, v_∞. In spherical symmetry, the formula developed by Wright & Barlow (1975) may then be used to deduce the rate of mass loss, *viz.*:

$$\dot{M} = 0.095 v_\infty \left(\frac{S_\nu^{0.75} D^{1.5}}{(g\nu)^{0.5}} \right) \left(\frac{\mu}{Z\gamma^{0.5}} \right) \qquad M_\odot \text{yr}^{-1}$$

where S_ν is the radio flux in Jy at frequency ν in Hz; v_∞ in km s^{-1}; D is the distance in kpc; g is the gaunt factor; μ, Z and γ are respectively the mean molecular weight, r.m.s. ionic charge and mean number of electrons per ion. With X_i, M_i and Z_i as the fractional abundance, molecular weight and ionic charge of species i, then:

$$\mu = \frac{\sum X_i M_i}{\sum X_i}; \quad Z = \frac{\left(\sum X_i Z_i^2 \right)^{0.5}}{\sum X_i}; \quad \gamma = \frac{\sum X_i Z_i}{\sum X_i}$$

In the radio region, the free-free spectrum is predicted to have a distribution $S_\nu \propto \nu^\alpha$, with $\alpha = 0.6$, (the departure in α from a value of 2/3 reflects the frequency dependence of the gaunt factor). ABCT considered three methods to test the validity of interpreting the radio data as thermal, free-free emission: (i) interferometric observations of the visibility function compared to predictions of thermal wind models, (ii) consideration of the observed radio or radio–IR spectral index, and (iii) comparison of the observed radio flux with that predicted from the observed optical recombination line emission measure.

Hogg (1985) has used the VLA to resolve the radio emission of γ Velorum at 1.49 GHz, 4.9 GHz and 14.9 GHz (see Fig 1), confirming a thermal origin consistent with spherical outflow. The frequency dependence of the visibility functions requires an electron density decrease more rapid than r^{-2} for wind distances greater than 3×10^{15} cm which is commensurate with helium (the dominant electron source) beginning to recombine. A mass loss rate of $8.6 \pm 1.0 \times 10^{-5}$ M$_\odot$ yr^{-1} and electron temperature of 5600 ± 500 K provided the best fit to the multifrequency radio interferometric data.

Five of the six stars listed by ABCT with 4.9 and 14.9 GHz radio data (but generally too faint to determine visibility functions) show a radio spectral indedx of $\alpha \sim 0.6$, confirming their emission to be thermal (the sixth star, WR 125, has a measured index of -0.5 and is prescribed as definitely non-thermal in nature). For γ Velorum they confirm the result from Purton *et al.* (1982) who deduced $\alpha = 0.58 \pm 0.17$ from data at 5.0, 6.2, 8.1, and 14.5 GHz.

Williams *et al.* (1990) present observations between 1.25μm and 1100 μm of γ Velorum, combined with the radio measurements by Hogg (1982) at 4.9 GHz and by Jones (1985) at 0.843 GHz to examine the spectral distribution of the wind emission (Fig 2). They find $\alpha = 0.69 \pm 0.02$ between the 1100 μm and radio wavelengths, which is consistent with plausible variations of temperature and ionisation in the wind.

Barlow, Smith & Willis (1981, hereafter BSW) present infrared 10μm fluxes for 21 galactic WR stars corrected for the underlying photospheric contribution to estimate the excess wind emission at this wavelength. The 10 μm excess emission data from BSW for 12

Fig 1: Radio emission of γ Vel resolved with the VLA (from Hogg 1985)

Fig 2: The optical–IR–mm–radio emission of γ Vel (from Williams et al. 1990).
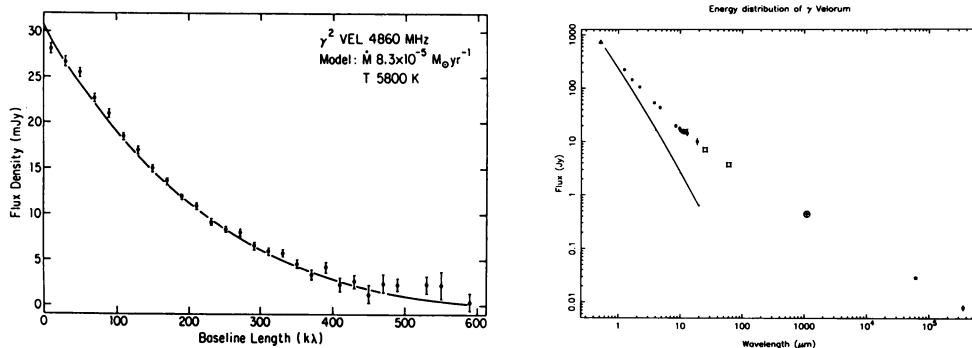
stars with measured 4.9 GHz radio fluxes give IR–radio spectral indices in the tight range of 0.66 – 0.82 (see Table 1). HD 193576 exhibits a 10μm–4.9 GHz index of 0.53 — identical to that expected for a constant velocity isothermal flow at both wavelengths. The mean value (HD 193576 omitted) of $\alpha = 0.75 \pm 0.04$ is similar to the mm–radio spectral index determined by Williams *et al.* for γ Velorum (a confirmed thermal source), suggesting that such IR-radio indices also indicate thermal emission (with the difference from 0.53 reflecting changing temperature and/or ionisation conditions in the IR and radio emitting regions).

Table 1 lists the 4.9 GHz fluxes for stars which ABCT have confirmed as thermal emitters using one or more of the above considerations, together with the 10μm data from BSW, including stars with IR but no radio measurements. For such cases, the radio flux can be predicted using the 10μm–radio index of 0.75 (BSW). In § 5, these data are combined with reassessments of wind terminal velocities, chemistry and ionisation balance to update the mass loss rate scale for WR stars.

3. Terminal velocities and v(r)

Until recently (as for analyses of OB mass loss), v_∞ has been taken as the maximum edge velocity of the P Cygni absorption components in the UV resonance lines (e.g. Willis 1982), or deduced from the maximum velocity inferred from the widths of optical emission lines (e.g. for WN stars from Conti Leep & Perry 1983, or for WC stars from Torres, Conti & Massey 1986 who extrapolate the emission line width vs. excitation potential correlations to zero E.P. to predict v_∞). ABCT used these approaches to derive values of v_∞ for the stars in their radio sample noting the good agreement between the optical results and the edge velocities of the UV P Cygni line profiles for stars in common. These approaches in effect estimate the *maximum* velocities which can be associated with any individual WR stellar wind material, v_{max}, which are listed in Table 1. Several recent papers have questioned whether these values of v_{max} are to be identified with the true terminal velocity of the wind associated with the bulk material flow, and suggested lower values of v_∞.

Williams & Eenens (1989) measured the P Cygni absorption velocities in the He I 2.058 μm line in 8 WR stars finding values ~ 0.7 of the terminal velocities deduced from the

Fig 3: The CIV λ1550 P Cyg profile in HD 165763 (from PBH)

Fig 4: v_∞ vs. WR subtype – filled symbols = v_{black} (PBH); open symbols = 0.74 v_{max}
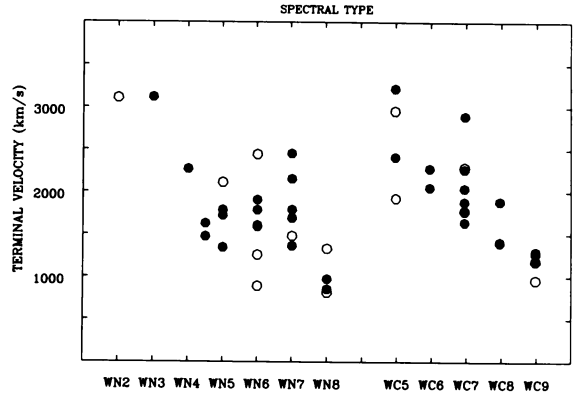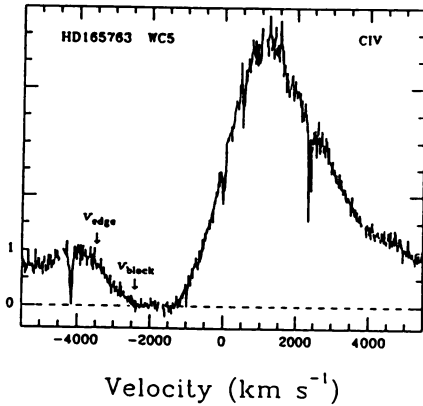
vmax methods discussed above. They argue that this HeI line is formed in the outermost regions of the WR winds and thus provides more suitable measurements of v_∞. Barlow, Roche & Aitken (1988) in their analysis of 12-13 μm spectra of γ Velorum, measured a terminal velocity from the [Ne II] 12.8 μm forbidden line of 1520 km s^{-1}, considerably lower than the value of ~ 2000 km s^{-1} deduced previously from the UV P Cygni profiles. The [Ne II] line exhibits a rectangular profile as expected for an optically thin line formed at large radii and constant velocity, and the typical density for its formation of 5×10^5 cm^{-3} suggesting an emission region radius of $\sim 1300 R_*$. The HeI 2.058 μm line in γ Velorum shows a P Cygni central absorption at ~ 1500 km s^{-1}, in accord with the [Ne II] data suggesting that the measurements given by Williams and Eenens (1989) do indeed reflect the true WR wind terminal velocities.

Recently, Prinja, Barlow & Howarth (1990, hereafter PBH) have reassessed inferences on v_∞ from UV P Cygni absorption profile measurements of both OB and WR spectra. They point out (as others have in the past) that the UV resonance line P Cygni saturated profiles generally show extended regions of zero residual intensity (up to some maximum velocity, v_{black}) and additional (non-black) absorption extending to higher velocities up to the maximum value observed, v_{edge} (Fig 3). The observed profiles differ significantly from those expected in Sobolev models of P Cygni line formation with monotonic velocity laws, where zero residual intensity is only reached at v_∞ and the profile should then rise immediately to the continuum. These differences are now generally explained in terms of non-monotonic wind velocity laws and shocks in the winds induced by instabilities in the flows (Lucy 1982, 1983, Owocki, Castor and Rybicki 1988), with $v_{edge} - v_{black}$ a measure of the velocity amplitude of the shocks. PBH argue that v_{black} is a more meaningful measurement of v_∞ and present values for 35 WR stars with available high resolution IUE spectra, finding a mean ratio of $v_\infty/v_{edge} = 0.76 \pm 0.12$. A subset of their data is given in Table 1. For 15 stars in common with the data of PBH and ABCT the mean ratio of $v_{black}/v_{max} = 0.74 \pm 0.08$, and I have adopted this scaling factor for those stars with radio data but no v_{black} measurement to estimate appropriate values of v_∞ in deducing mass loss rates (see below).

Fig 4 plots these revised values of v_∞ vs. spectral type for both galactic WN and WC stars. For the WC stars there is a clear trend of increasing v_∞ with earlier subtype, in keeping with the well known correlation of optical line width with subclass (see Torres *et al.* 1986). For the WN stars, no clear trend is apparent, although the WN8 stars exhibit

low velocity winds, whilst the very earliest types (WN2,3) have the largest values. Most WN subtypes can show a large range of wind velocities.

Little is known directly about the velocity laws, v(r), of WR winds. Cherepaschuk *et al.* (1984) have modelled the IR-UV eclipse data of V444 Cyg to empirically determine the velocity law of the WN5 component wind. Their result is reasonably well fitted with the usual parameterised law of $v(r) = v_\infty(1 - r_*/r)^\beta$ with $\beta \sim 1$. This law has generally been adopted in detailed model atmosphere analyses of WR spectra by Schmutz *et al.* (1988) and Hillier (1987, 1989) who are able to reproduce the observed emission line profiles fairly well. For OB stars, Friend & Abbott (1986) and Pauldrach *et al.* (1986) include the effects of rotation and finite disk of the star and conclude that a value $\beta \sim 0.8$ in the above velocity law provides the best fit to observational data. Thus it may be that the WR winds, like those for OB stars, are accelerated through radiation pressure, although the very high levels of WR mass loss may require an additional mechanism(s) (see below).

4. Ionisation structure

Detailed modelling of the atmospheres of WN and WC stars by Hillier (1987, 1989) characterises the ionisation structure of their winds, showing that even for high core temperature models (e.g. with $T_{eff} = 60,000$ K) the wind electron temperature can be low (e.g. 20000 K at $Ne \sim 10^{11}$ and ~ 9000 K at $N_e \sim 10^9$) giving values of T_e in the radio emitting region comparable to that deduced by Hogg (1985) for γ Velorum. The ionisation stratification in the Hillier models is compatable with observed correlations of optical line width vs. ionisation potential (e.g. Kuhi 1973). Willis (1982) argued that when the UV resonance and low excitation lines were included with optical measurements, line widths correlated better with excitation potential (E.P.) than with I.P., questioning such an ionisation stratification. As discussed by Hillier (1989) this discrepancy may now be understood, since the UV lines, with their increased opacity, may be tapping lower density, higher velocity material associated with shocked gas in the wind, and should not necessarily be considered together with the optical lines.

In the Wright & Barlow formulation the factor 'C' = $(\mu/(Z\gamma^{0.5})$ depends upon the chemistry and ionisation balance presumed for the radio-emitting regions, and recent considerations of this parameter have led to revisions in $\dot{M}$.

ABCT assumed only H and He ions contributed towards the C-factor, and for WN stars estimated the H^+/He^{++} ratio using the Pickering decrement measurements of Conti, Leep & Perry (1983) and the He^+/He^{++} ratio from measured values of the emission measures of optical He I and He II lines. For WC stars the H/He ratio was presumed to be zero, and the He ionisation balance again inferred from the optical He I and He II emission measures. For most stars He^{++} was taken as the dominant ion in the radio region. However, Schmutz, Hamann & Wessolowski (1989) conclude that He^+ is the dominant ion for the great majority of WN and WC subclasses (only three WN2 and WN3 stars in their sample have He^{++} dominant) leading to an upward revision to mass loss rates deduced from the radio data. Van der Hucht, Cassinelli & Williams (1986) for WC stars included the effects of high C-abundances inferred from evolutionary models together with calculated ionisation equilibria in simplified model atmospheres, to propose an upward revision to the mass loss rates of ABCT of about a factor of 2 for WCE stars and by about a factor of 2–3 for WCL stars.

The present view is that He^+ is the dominant helium ion in the radio emitting regions for both WN and WC stars. For WNE stars, with H^+/He^{++} generally $\leq 0.2 - 0.3$ by number (Conti, Leep & Perry 1983), the effect of H on the C-value is negligible, and thus for the radio-emitting regions we can adopt $\mu = 4.0$, $Z = 1.0$ and $\gamma = 1.0$, *viz* $C = 4.0$. For WN7 and WN8 stars the H-contribution is non-negligible in its effect on μ, which can

Star	WR	Spec type	Radio	IR	M_v	D	'C'	V_{max}	V_{black}	$\log \dot{M}$	$\log L_v$	$\dot{M}v_\infty c/L_v$	L_w	L_w/L_v
HD 4004	1	WN5	0.5	0.47	-4.6	2.63	4.0	2850		-4.09	5.54	24.29	11.28	0.085
HD 6327	2	WN2	<0.2		-2.3	2.51	1.4	4200	1720	<-4.71	4.62	72.02	5.92	0.371
HD 50896	6	WN5	1.0	0.90	-4.8	1.56	4.0	2650	1790	-4.29	5.62	10.44	4.78	0.030
HD 92740	22	WN7+abs		0.48	-6.5	2.63	2.8	2600	2155	-4.21	6.30	2.73	6.22	0.008
HD 93131	24	WN7+abs		0.38	-6.4	2.63	2.8	2800	2455	-4.21	6.26	3.64	9.11	0.013
HD 93162	25	WN7+abs		0.35	-6.2	2.63	2.8	2900	1365	-4.18	6.18	5.34	12.67	0.022
HD 151932	78	WN7	1.4	0.96	-6.7	2.00	2.7	2150		-4.29	6.38	1.44	3.01	0.003
LSS 4064	87	WN7	<0.4		-6.4	2.88	2.6	2000		<-4.44	6.26	1.44	2.46	0.003
LSS 4065	89	WN7	0.6		-7.1	2.88	2.9	2000		-4.44	6.54	1.14	3.71	0.003
HD 165688	110	WN6	1.0	0.81	-5.3	1.89	4.0	3300		-4.02	5.82	17.51	17.94	0.071
MR 87	115	WN6	0.4		-5.0	2.19	4.0	1200		-4.66	5.70	1.92	0.54	0.003
BAC 209	124	WN8		0.11	-6.7	5.98	2.9	1800		-4.27	6.38	1.46	2.97	0.003
AS 374	130	WN8	<0.2	0.38	-6.7	4.75	2.4	1100		<-4.64	6.38	0.38	0.47	0.001
HD 190918	133	WN4.5+O9Ib	<0.3	0.25	-4.3	2.09	4.0	1750	1625	<-4.52	5.42	9.28	2.53	0.025
HD 191765	134	WN6	0.8	0.70	-5.3	2.09	4.0	2300	1905	-4.13	5.82	10.60	8.51	0.034
HD 192163	136	WN6	1.6	1.05	-5.7	1.82	4.0	2000	1605	-4.07	5.98	7.11	6.96	0.019
HD 193077	138	WN6 +abs	0.6	0.29	-4.8	1.82	4.0	1700	1345	-4.46	5.62	5.48	1.96	0.012
HD 193576	139	WN5 + O6	0.3	0.33	-3.9	1.74	4.0	2500	1785	-4.60	5.26	12.30	2.55	0.037
HD 193928	141	WN6	0.6		-5.3	1.82	4.0	1700		-4.49	5.82	2.99	1.58	0.006
HD 68273	11	WC8+O9I	29.0	14.36	-5.0	0.45	4.0	2000	1415	-4.09	5.70	11.38	5.15	0.027
HD 155270	79	WC7+O5-8	0.9	0.86	-5.0	2.00	4.0	3300	2270	-4.04	5.70	20.28	14.73	0.077
MR 66	81	WC9	0.3		-4.8	1.75	4.0	1300		-4.86	5.62	1.56	0.40	0.002
HD 156327	86	WC7 +O7-9	0.5		-4.8	1.95	4.0	2400		-4.36	5.62	9.15	4.30	0.027
HD 156385	90	WC7	<0.3		-4.8	1.97	4.0	3000	2045	<-4.46	5.62	8.49	4.62	0.029
HD 157504	93	WC7 +abs	0.9		-5.6	1.74	4.0	3100		-4.13	5.94	9.57	12.14	0.036
MR 74	95	WC9	<0.4		-5.1	1.91	4.0	1300		<-4.71	5.74	1.67	0.56	0.003
HD 164270	103	WC9	<0.2		-4.8	2.54	4.0	1400	1190	<-4.66	5.62	3.10	0.98	0.006
MR 80	104	WC9	<0.4		-4.5	1.58	4.0	1600		-4.75	5.50	3.31	0.79	0.006
HD 165763	111	WC5	0.3		-3.8	1.58	4.0	3550	2415	-4.53	5.22	21.36	5.46	0.086
HD 168206	113	WC8 +O8-91V	<0.4	0.39	-4.6	2.00	4.0	2900	1890	<-4.39	5.54	11.06	4.63	0.035
HD 169010	114	WC5	<0.3		-3.6	2.19	4.0	2600		<-4.42	5.14	26.31	4.44	0.084
MR 90	121	WC9	<0.3		-4.8	2.06	4.0	1300		<-4.76	5.62	1.99	0.51	0.003
HD 192103	135	WC8	0.6	0.35	-4.7	2.09	4.0	1900	1405	-4.35	5.58	8.07	2.75	0.019
HD 192641	137	WC7 + OB	0.4		-5.0	1.82	4.0	2700	1885	-4.45	5.70	6.61	3.99	0.021
HD 193793	140	WC7 + O4-5	1.5		-4.8	1.34	4.0	3000	2900	-4.03	5.62	32.02	24.71	0.155
HD 195177	143	WC5	<0.4		-3.7	0.82	4.0	4000		<-4.77	5.18	16.14	4.59	0.079
MR 111	145	WN7 + WC4	1.0	0.31	-6.5	1.82	4.0	1500		-4.38	6.30	1.13	1.59	0.002

Table 1: Notes

Radio is the 4.886 Ghz flux in mJy (from Abbott et al. 1986): IR is the 10μm excess emission in Jy from BSW81
M_v's from van der Hucht et al. (1988) except binary values from Smith & Maeder (1989) – D is distance in kpc, from van der Hucht et al. (1988):
V_{max} in km/s from Abbott et al. (1986): V_{black} in km/s from PBH90 – $\log \dot{M}$ in $M_\odot$ yr^{-1}
L. in units of $L_\odot$ assumes B.C. = -4.5 (Smith & Maeder 1989) – $L_w = \frac{1}{2}\dot{M}v_\infty^2$ is in units of 10^{37} erg s^{-1}.

Fig 5: revised M̊ vs. subtype – filled and open symbols are single and binary stars respectively
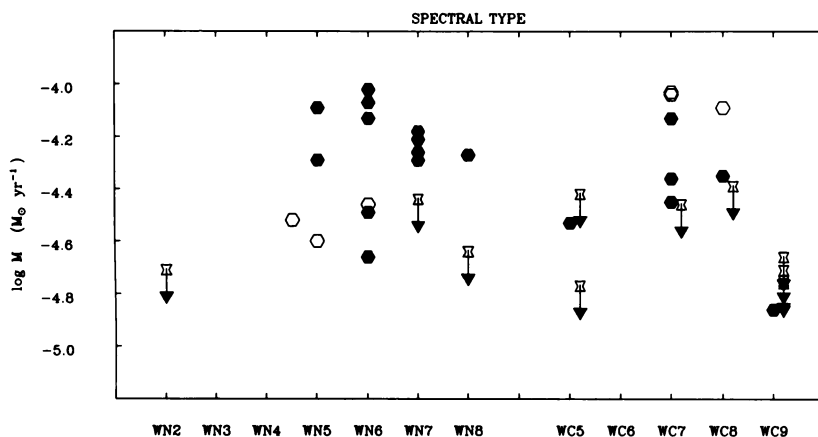
vary from 2.44 – 2.92, $Z = \gamma = 1.0$, and thus C lies in the range 2.44 – 2.92, depending on the H-content given by Conti, Leep & Perry (1983). (N.B. if He^{++} were the dominant He ion in the radio region, the corresponding C-values would be: 1.41 (WNE) and 1.29 – 1.39 (WNL)). For WC stars, the most recent estimates of the C/He ratios have been given by Smith & Hummer (1988) from analyses of near-infared recombination lines. They find C/He = 0.3 for WC6–9 stars; = 0.5 for WC5 stars and = 0.7 for WC4 stars. With He^+ as the dominant He ion in the radio region, (Smith & Hummer confirm this in general), then the C-value depends only on the presumed carbon ionisation balance. Adopting C^{2+} as dominant leads to C-values of ~ 4 for all WC subclasses (increases in μ from 5.85 (WC6-9) to 7.30 (WC4) are compensated by corresponding increases in Z and γ). (N.B. for He^{++} dominant, C-values would be ~ 2). The C-values adopted herein, based on the above discussion are also listed in Table 1.

5. Radio mass loss rates

Table 1 presents revised mass loss rates for galactic WR stars, confirmed as thermal sources, taking into account revisions to the C-factors and v_{∞} since the work of ABCT, discussed above. Distances are taken from van der Hucht *et al.* (1988). Mass loss rates have been calculated using the radio 4.9 GHz fluxes or upper limits, or (for stars with no radio observations) by predicting 4.9 GHz fluxes by scaling the excess $10\mu m$ data using a spectral index of 0.75. The terminal velocity is taken as v_{black} from PBH or as $0.74 \times v_{max}$.

The WR mass loss rates lie in the range $10^{-5} - 10^{-4}$ $M_{\odot}$ yr^{-1}, and are plotted as a function of WN and WC subtype in Fig 5. The overall mean value (excluding upper limits) is 5.3 ± 2.3 x 10^{-5} $M_{\odot}$ yr^{-1}, with no significance difference between this value and the means for (a) single or binary stars, (b) WN or WC stars. (c) WNE or WNL, (d) WCE or WCL stars. The apparently similarity in $\dot{M}$ between WN and WC stars, and between WCE and WCL stars is open to uncertainty, given the assumptions about the carbon ionisation balance in the radio-emitting regions. ABCT, BSW and van der Hucht *et al.* (1986) have argued that $\dot{M}$ for WC stars may be systematically larger (by $\sim$ x 2) than for WN stars.

6. Mass loss rates – other methods

Other independent methods of deriving mass loss rates for WR stars are generally based on studies of WR+O binary systems. For V444 Cyg, Khaliullin *et al.* (1984) have measured the period change of the system (using data over 1902–1983) to be $\dot{P} = 0.22 \pm 0.04$ sec yr^{-1}, which modelled in terms of a spherically symmetric outflow beyond the system leads to a mass loss rate determination of $\dot{M} = 1.1 \times 10^{-5}$ M$_\odot$ y^{-1}.

St-Louis *et al.* (1988) have studied the phase-dependent variation in optical linear polarisation for 10 WR+O systems, which they interpret in terms of scattering of the companion star light off free-electrons in the WR wind to derive a new, independent method of calculating WR mass loss rates in such systems. The polarisation data also yields values for the individual orbit inclinations and thus stellar masses. Their results, shown in Fig 6, give values of $\dot{M}$ in the range $10^{-4} - 10^{-5}$ M$_\odot$ y^{-1}, comparable in scale to that derived from the radio-IR data.

In the case of both WN+O and WC+O binaries, strong phase-dependent variability is also a common property in the ultraviolet — even for systems which show no optical eclipses. Pronounced line profile changes in the UV resonance and low-excitation lines are seen interpreted in terms of selective line-eclipses of the O-star light as it shines through the WR wind (Willis & Wilson 1976, Koenigsberger & Auer 1985). Such eclipse effects in the CIII] λ1909 line in γ Velorum (Willis *et al.* 1979), and in CV Serpentis (Howarth *et al.* 1982) have been modelled to yield mass loss rates for the WC8 components in these two systems of 9×10^{-5}, and 7×10^{-5} M$_\odot$ y^{-1} respectively.

Additionally, the detailed model atmosphere analyses of the helium line spectra of 30 galactic WR stars by Schmutz *et al.* (1989) provide estimates of mass loss rates for individual stars, yielding values in the range $10^{-5.3} - 10^{-3.9}$ M$_\odot$ yr^{-1}, in excellent agreement with results from the radio data.

## 7. $\dot{M}$: L relations & the wind momentum problem

It is now well established that for OB stars $\dot{M} \propto L^{1.6}$ (ABCT, Howarth & Prinja 1989), and that this observed relation agrees well with predictions of radiation pressure mass loss theory. Attempts to ascertain a corresponding scaling for WR stars are plagued by uncertainties in the luminosities to be applied, given that the values for T_{eff} and bolometric corrections are very uncertain for this stellar class.

ABCT found for five WR+O double-lined systems a tentative relation between WR mass loss rate and mass of the form $\dot{M} \sim 7 \times 10^{-8} (M/M_\odot)^{2.3}$ M$_\odot$ yr^{-1}, which, together with the Maeder (1983) WR mass–luminosity relation ($\log(L/L_\odot) = 3.8 + 1.5\log(M/M_\odot)$) implies $\dot{M} \sim 7 \times 10^{-14} (L/L_\odot)^{1.6}$ (similar in slope to that for OB stars). They further deduced a rough relation between $\dot{M}$ and the quantity $M_v - <M_v>$ (the difference for an individual WR star between its measured M_v determined from cluster membership and the average value for its spectral type), providing additional support to the assertion of a WR mass loss rate – luminosity relation.

Smith & Maeder (1989) used new data on galactic WR stellar masses and values of M_v, to show (Fig 7) that for both WN and WC stars in WR+O binary systems, a reasonably well-defined relation exists in M_v vs. M_{WR}, which has the same slope as that predicted theoretically for stellar evolution models for He-burning stars with initial masses between 120 and 40 M$_\odot$, from Maeder & Meynet (1987) ($\log(L/L_\odot) = 4.02 + 1.34\log(M/M_\odot)$). This comparison yielded a B.C. of -4.5 mag., which they suggest can be applied to all WR subclasses. Applying this B.C. for stars with known M_v and mass loss

Fig 6: $\dot{M}$ vs. M_{WR} from polarisation studies of WR+O systems (from St-Louis et al. 1988)

Fig 7: M_v vs. M_{WR} for WR binaries from Smith & Maeder (1989) implying a B.C. = -4.5 mag when compared to the evolutionary models of Maeder & Meynet (1987).
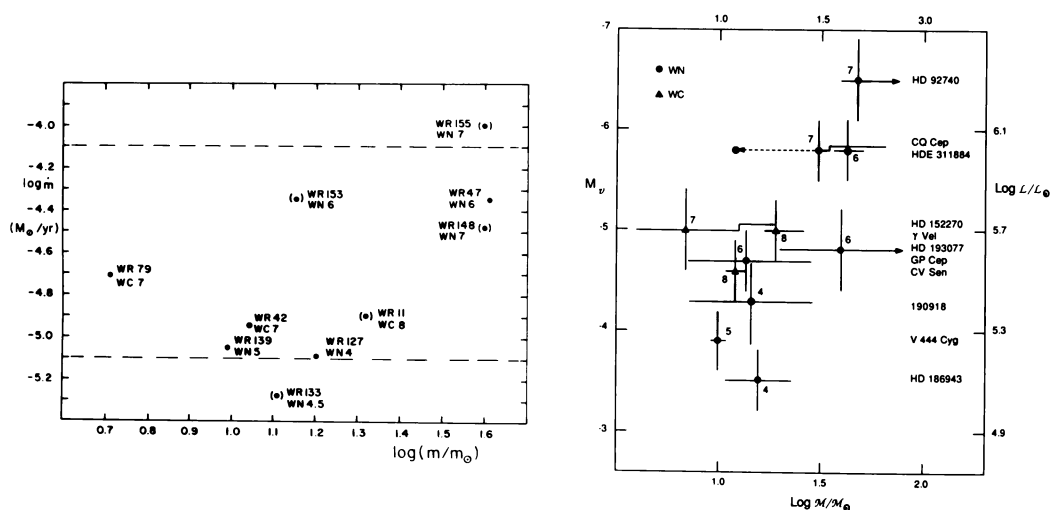
rates from radio and/or IR data from ABCT and BSW, they deduce a rough scaling of $\dot{M} \propto L^{0.7}$, with a spread in $\dot{M}$ for any given L of an order of magnitude (see Fig 8). The slope is considerably lower than the value of 1.6 deduced by ABCT. The revised values of $\dot{M}$ given in Table 1, plotted against L, would not alter their conclusions. The results from St-Louis et al. (1988) (see Fig 6) indicate a rough scaling with $\dot{M} \propto M_{WR}^{0.8-1.3}$, comparable to the Smith & Maeder (1989) conclusions. At present therefore, available data would suggest a rough scaling of WR mass loss with radiative luminosity: $\dot{M}(WR) \propto L^{\sim 1}$, shallower than for OB stars, and with a spread of up to an order of magnitude.

For WR stars characterising the ratio of the momentum in the wind to the single scattering radition pressure limit, viz. $\dot{M}v_\infty$ c/L_*, again suffers from uncertainties in L_*. Adopting a single B.C. = −4.5 mag for WR stars from Smith & Maeder (1989) results in the values of L_* given in Table 1, which can probably be taken as upper limits to the radiative luminosities. The resulting momentum ratios, given in Table 1, show values in the range ~ 1–30, with a trend for lower values for late-type WN and WC9 stars: mean values are: 2.2 (WN7,8), 10.3 (WNE), 13.5 (WC5–8) and 2.3 (WC9). These values are larger than appropriate for OB stars which typically have values $\gtrsim$ 1. Adopting lower B.C's and L_*'s proposed by BSW and Schmutz et al. (1989) will only exacerbate this problem, since then values of the momentum ratio would rise up to 50 or so. The results indicate a mechanism other than radiation pressure may be needed to initiate the WR mass loss, unless multiple scattering is extremely effective. Abbott (1982) concluded that chemical composition effects alone could not enhance the radiative driving for WN stars, and only by $\leq$ × 3 for WC stars, whilst attempts so far to include multiple scattering have led to gains of $\leq$ × 5 (e.g. Friend & Castor 1983). Smith & Maeder (1989) propose that (in addition to radiation pressure effects) an increase in mass loss rate might be promoted by mechanical instability due to the ϵ-mechanism whose effect will be enhanced with changing mass and μ within the star. The expectation is thus that for WN7 and WN8 stars, which generally show appreciable atmospheric hydrogen, radiation pressure

Fig 8: $\dot{M}$ vs. L_{WR} from Smith & Maeder (1989) assuming B.C. = -4.5 mag.
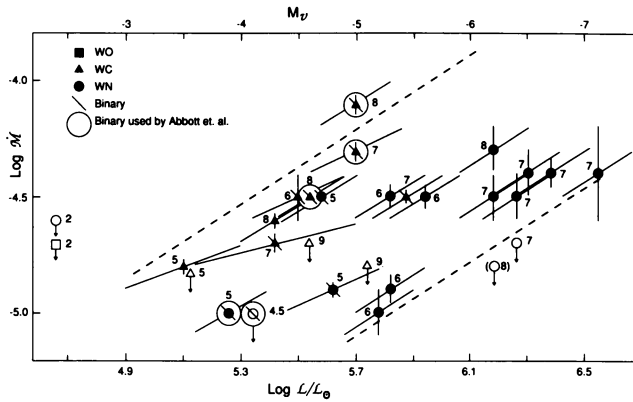
is probably the major driving mechanism. As the last of the hydrogen is removed, the instability mechanism is activated, and the mass loss rate enhanced. Alternatively, Poe, Friend & Cassinelli (1989) have developed an axisymmetric model for WR winds involving a slow-dense equatorial flow and a fast, radiation-driven wind at higher latitudes, with high rotation ($\sim$ 85 percent maximum) and substantial, open magnetic fields ($\sim$ 1500G) needed to accommodate the observed radio data and high wind speeds. The theory of WR winds and mass loss will be addressed further by Cassinelli (these proceedings).

Whatever mechanism(s) is driving the WR mass loss it is clear that these stars are a major source of mechanical energy input (and chemical enrichment) into the interstellar medium. Using the results for WR stars within 3 kpc of the Sun, this topic has been discussed by ABCT and updated by van der Hucht *et al.* (1986) who give the following inputs to the ISM: wind mass flux = 1.6×10^{-4} $\dot{M}$ yr^{-1} kpc^{-2}, wind momentum $(\dot{M}v_{\infty})$ = 2.3×10^{30} g cm s^{-2} kpc^{-2}: and wind energy input = 3.2×10^{38} erg s^{-1} kpc^{-2}, noting that whilst for WR+OBA stars, the former supply only $\sim$ 8 % of the input radiative luminosity, they supply $\sim$ 70 % of the mechanical mass, momentum and energy input. The effects of these inputs will be discussed elsewhere at this meeting.

8. WR wind instability

In addition to variability that can clearly be ascribed to phase-dependent effects in WR+O binary systems, it is becoming increasingly clear that the stellar winds of WR stars are intrinsically variable. Single WR stars often show optical continuum light variability at the level of $\sigma_{\nu} \sim$ 0.003–0.03 mag. (Lamontagne & Moffat 1987), as well as continuum polarisation varaibility at a level of $\sigma_{p} \sim$ 0.01–0.15% (Robert *et al.* 1988). High precision optical spectroscopy in the He II $\lambda5411$ line of HD 191765 (WN6) presented by Moffat *et al.* (1988) reveal time-dependent structure (emission bumps) in the emission profile, which appear to accelerate outward along with the ambient wind on a time-scale of hours. Moffat *et al.* (1988) interpret these data in terms of rapid ejections of material condensations ('blobs').

In the ultraviolet, IUE spectroscopy has provided strong evidence for intrinsic WR line profile variability particularly evident in the P Cygni absorption components. Results for HD 50896 (WN5) indicate a variability timescale of $\sim$ 1 day (Willis *et al.* 1989, St-Louis

et al. 1990), with a similar timescale for HD 192163 (WN6) (St-Louis *et al.* 1989). For HD 96548 (WN8) a longer timescale of UV variability of ∼ several days seems present (Smith *et al.* 1986). Both the UV and optical data indicate that the amplitude of this short-timescale variability can alter with epoch – for instance long term photometric monitoring of HD 50896 shows extended periods of relative 'inactivity', with abrupt changes to higher levels of variation (van der Hucht *et al.* 1990). Similarly, IUE monitoring has shown that HD 50896 can undergo periods of stability in its UV line profiles (Willis *et al.* 1989).

Whether or not radiation pressure is *the* mechanism initiating the higher levels of WR mass loss, it is likely that radiation pressure dominates the acceleration in their winds. It is now recognised that the radiation-driven winds of OB stars are highly unstable and develop strong reverse shocks (Owocki, Castor & Rybicki 1989) which may provide a natural explanation for their observed X-ray emission, extended blackness in the absorption components of UV resonance line P Cygni profiles, and the occurence and variability in discrete absorption components seen in these lines (Howarth & Prinja 1989). The WR UV P Cygni profiles also show extended regions of blackness; the X-ray emission from WR stars is (generally) comparable to that of OB stars (Pollock 1987), and therefore the WR winds may also be permeated by strong shocks, with the intrinsic WR wind variability caused by the same mechanism that generate the wind instabilities in the OB stars, with a greater amplitude reflecting enhanced WR wind densities.

9. WR mass loss in other galaxies

OB stars in the LMC and SMC show significantly lower stellar wind terminal velocities, and (possibly) lower mass loss rates from studies of their UV resonance line P Cygni profiles (e.g. Prinja 1987, Garmany & Fitzpatrick 1988), which is broadly in line with expectations of radiation pressure-driven wind models for lower metallicity environments. Whilst no attempts have been made to actually determine mass loss rates for WR stars in the MCs, its appears from the overall nature of their optical and UV spectra that there may be no significant differences in $\dot{M}$ and v_∞ with galactic counterparts. Estimates of v_∞ for LMC stars, both from IUE P Cygni profile data and optical line widths, agree with galactic values of corresponding subtypes (Abbott & Conti 1987). Smith *et al.* (1990) find a tight correlation between the ratio of the widths of $\lambda5808/\lambda4650$ and the $\lambda5808$ line width itself which is the same for both LMC and galactic WC stars.

The strength of the optical emission line spectrum may be taken as indicative of the mass loss rate (*cf* the optical emission measure *vs.* radio flux correlation from ABCT). Conti & Massey (1989) find that the line strengths of leading optical WN and WC emission lines are very similar in the LMC and the Galaxy, whilst Conti, Massey & Garmany (1990) suggest that the optical helium and nitrogen lines in the WNE stars in the SMC may be systematically weaker in strength (but not in velocity width) than galactic counterparts, although here the very small number of stars and binary companion effects may be playing a role. Further afield, Massey *et al.* (1987) find that WN and WC stars in M33 show similar optical line strength *vs.* line width correlations as found for galactic counterparts, whilst the few WR stars in M31 studied show poorer agrement. On balance, available UV and optical data do not point to gross mass loss or wind velocity differences between extragalactic and galactic WR stars *of the same subtypes*. What is striking, of course, is the substantial differences between the total WR populations and subtype occurence in the different galactic environments. If differing global galaxy metallicity is playing a role with regard to WR stars, its effect is possibly more pronounced in the WR precursor phase, than in significantly modifying the mass loss and winds of WR stars once they have formed.

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DISCUSSION

Smith, Lindsey: As co-author of the quoted low power of $\dot{M}$ dependence on M(or L), I should point out that the other author, Maeder, is now using $\dot{M} \propto M^{2.5}$ (suggested by Langer) with spectacular success. Also remembering that Langer suggests a higher rate for WC than WN, it looks like the stars, as they evolve zig-zag across the observed band in the $\dot{M}$-L diagram.

Willis: I am aware that the stellar evolutionists are employing a steeper $\dot{M}$ *vs.* M relation than implied by your work and that from the polarization results. My remit was to concentrate on observational results, which at the present do not necessarily support the theoretical viewpoint directly. I cannot help that, but there may still be considerable uncertainties in both M_{WR} and L rather than in mass loss rate, which is masking the true observational picture.

Conti: Why do we not find a single $\dot{M}$-L relation for WR stars? After all, there is one for O stars. The stellar structure people predict a $\dot{M}$-mass relation. We believe W-R winds are radiatively driven. Could one instead assume there is a unique (displaced from the O star one due to chemistry) $\dot{M}$-L relation for WR stars and use this to infer the WR stars L (and $B.C.$) since the $\dot{M}$ seems well known?

Willis: Again, the recent results in the literature based on observations of mass loss rate, L and $\dot{M}_{WR}$, do not point to a well-defined $\dot{M}$-L relation for WR stars, nor one with the same slope as for OB stars. Whilst radiation pressure is undoubtedly going to be important in WR winds, it may not be the only mechanism driving their mass loss. In that event a simple relation with L may not necessarily be expected. On the other hand, I agree it would be interesting to see the implications of assuming a relation that you propose on the inferred L and $\dot{M}_{WR}$.

Sreenivasan: Questioning observations is supposed to be in bad taste. You say that mass loss rates are uncorrelated with spectral type but Langer says he finds good agreement with observations if he uses a mass loss rate $\propto M^{2.3-2.5}$. This is confusing. Is it still in bad taste to question the observations and/or the interpretations? (From a theoretical point of view, radiatively driven winds give mass loss rates proportional to a power of luminosity and there definitely are other sources/mechanisms of mass loss in WR stars.).

Willis: I think the observations (radio, IR, polarization and UV data) are in pretty good shape, but the interpretation is still subject to some uncertainty. For instance modelling the radio emission does require a knowledge of the ionization balance (and chemistry) in the radio region, which at least for WC stars is not too well known. Factors of two or so uncertainty cannot be ruled out, say between WCE and WCL stars. As for other mechanisms driving WR winds, I can fortunately defer that aspect to Joe Cassinelli in the next review talk!

Pakull: You mentioned bolometric corrections of about -4 to -4.5.
Willis: -4.5.
Pakull: I will tell you tomorrow that there are some WR stars, namely WN, very early ones, which have bolometric corrections of about -7. These are very very hot stars which also ionize large $HeIII$ regions around them and in these stars you also have of course in a radio-emitting region He completely ionized. And this may be a reason why you find for the WN2 stars very low $\dot{M}$ whereas this is only because the He is completely ionized also in the radio-emitting region.
Willis: As far as the bolometric correction is concerned, I was attempting to illustrate the mass loss rate momentum problem by picking a luminosity which I felt was probably an

upper limit. I took the Smith-Maeder results, partly because I knew Lindsey Smith was chairing this session. For the bulk of the stars, the Schmutz values alone already raise the momentum question. So, it was an attempt to summarize the lower level of the problem, if a problem it is, and of course we have the bolometric correction problem... If you have -7, which I have not come across before I might add, that is going to ease it considerably. But, -7 will not apply to the bulk of the WR subclasses quite demonstratively, it is not going to affect the momentum ratio problem in general.

Schmutz: First thing we did after analyzing 30 stars, was looking at the mass loss rate and the luminosity and at the moment we consider our models to be good within 1 magnitude for the bolometric corrections, as absolute. But by doing so, comparing stars which have been analyzed by the same methods, you actually have problably the same systematic errors for all. So, your trend would show up much easier, and there simply is no trend of mass loss rate with luminosity. I do not believe there is any.

Moffat: A more recent compilation of polarization data of WR+O binaries in the Galaxy and the Magellanic Clouds (*cf.* poster at this meeting) show that $\dot{M}_{WR}$ and M_{WR} correlate rather well with spectral subclass for WN and WC sequences, with $\dot{M}_{WR}$ and M_{WR}. Possibly the radio $\dot{M}$'s are inflicted with large scatter due to uncertainties in the distances which are not needed for the polarization $\dot{M}$'s.

Willis: This is an interesting and important result that we need to consider. I am impressed with the utilization of polarization variability in constraining mass loss rates and relations with M_{WR} and subtype.

Smith, Lindsey: A thing that should be pointed out is that the success of the models using Langer's mass loss rate $\propto M^{2.5}$ is pretty impressive, as I am sure we will hear more about in the future.

Underhill: Just to remind you again about V444 Cyg. Fourty years of photo-electric observations saw a very distinct rate of period change. Rate of period change is supposed to be connected with a rather simple formula to rate of mass loss from the system, from one star as I should say, actually both stars got winds. The momentum rate of mass loss you can get from your observed rate of period change is $6 \times 10^{-6} M_{\odot} yr^{-1}$. I think that it is a more fundamental way of estimating rate of mass loss than using the radio flux and saying that it is free-free in a spherical distribution. The fact that you got an index of 0.6 to 0.7 only means that, if it is free-free, you are observing a body of gas with a density gradient in it. It does not tell you that it is a sphere going out. That radio flux could have three sources.

Willis: I might add actually, that the $10\mu - 6cm$ spectral index for V444 Cyg is 0.52, which is almost exactly what you would expect (0.53) for a constant velocity isothermal flow between the IR and radio region. V444 Cyg is the only star in our (BSW, 1981) 10μ sample that does this.

There seems to be some discrepancy between the actual period change, between Cherepashchuk and yourself, that does not worry me too much, actually. Essentially, the radio data agree with the polarization measurements in sofar as both interpretations give a mass loss rate of about 10^{-5}. That would agree with the Cherepashchuk period change. It is a factor or two larger than your measurement of period change of $0.08 \ s \cdot yr^{-1}$.

Underhill: (???)

Willis: What I am trying to say is that the mass loss rate inferred from these other analyses is at the lower bound of the range that one gets from the WR stars as a bunch and frankly I never get worked up about factors of two; factors of ten yes, but not factors of two.

Vanbeveren (to Underhill): You contineously repeat your $\dot{P}/P$ argument. However, according to me, you are not consistent with your own WR model. One can derive $\dot{M}$ from

$\dot{P}$/P if the $\dot{M}$ is spherically symmetric by using an easy formula. However, when you have a large accretion disc around the WR star (as you propose) then this easy relation between $\dot{P}$/P and $\dot{M}$ disappears.

Willis: I should point again out that Underhill's measurement of $\dot{P}$/P for V444 Cyg is a factor or two lower than the measurement of Khaliullin *et al.* (1984). The latter would give very good agreement with the radio mass loss rate. The question of who is right about the period change is something for these authors to sort out, but I am not particularly concerned about a factor of two in this game. Moreover, as we know, the mass loss rate for V444 Cyg is amongst the lowest for the WR stars, and the momentum problem is still there for most objects in this class.

Schmutz: I would like to point out that V444 Cyg is not a typical WN5 WR star. "Normal" strong lined WN5 stars have different line profiles. The most important difference is that weak high ionization lines of V444 Cyg are very narrow, *e.g.* $NV\lambda4940$, in contrast to the broad profiles of strong-lined single WN5 stars. This difference is not due to different v_∞ since the v_∞'s are similar. The narrow lines of V444 Cyg indicate therefore that we see down to low wind velocities whereas we do not see slow moving material in "normal" WN5 stars. Therefore V444 Cyg has not a typical velocity law which is in line with its mass loss rate that is at the lower limit of the observed rates.

Willis: I agree with you that the mass loss rate of the WN5 component in V444 Cyg (as deduced from the period change and the radio data) lies at the lower bound for WR stars, $\sim 1 \times 10^{-5} M_\odot yr^{-1}$, and as such we can probably "see" further into its wind down to low velocity parts. The reason for quoting the Cherepashchuk *et al.* (1984) velocity law for V444 Cyg was that, as far as I know, it is the only one which has been observed somewhat directly. On another topic, I concentrated on using the $B.C. = -4.5$ mag from Smith & Maeder (1989), rather than your rather lower values (generally around $B.C. = -3$ mag), partly because I wanted to emphasise effectively the *lower* limits to the momentum problem, and partly because I knew Lyndsey Smith would be chairing this session, and it seemed a wise and prudent thing to do!

Cherepashchuk: Perhaps one could try to take into account the cloud ragged structure of the WR wind. If the WR wind in the infrared and the radio region is cloudy and ragged we can obtain the same radio and IR flux for a lesser value of $\dot{M}$. It may help us to eliminate some discrepancies between $\dot{M}$ values obtained from IR and radio data and those obtained from period change in binary systems.

Schulte-Ladbeck: I just want to remind ourselves that we have heard yesterday and today that there are large-scale inhomogeneities in WR star winds: blobs, shocks, cloudlets, disk, and different effects seem to prevail in different stars. While we all agree that radiation pressure is the first order effect, would you not expect to find a large scatter in the $\dot{M}$-L relation for this very reason?

Willis: I have emphasised the new observations of intrinsic variability in WR stellar winds, both from optical and UV data. It may be that much of this can potentially be related to radiatively-induced instabilities in the winds of the kind that Owocki has talked about. On the other hand, other effects may well be operating and contributing to the $\dot{M}$-L scatter.