

SESSION 3

MASS-LOSS FROM WR STARS : OBSERVATIONS and THEORY

Chairman: L.HOUZIAUX

Introductory speakers: M.J.BARLOW  
J.P.CASSINELLI  
D.C.ABBOTT

1. P.S.THE, K.A. VAN DER HUUCHT and M.ARENS: The influence of the ratio of total to selective extinction on the determination of the mass loss rates of WR stars from IR excess measurements.
2. N.PANAGIA and M.FELLI: On the properties of the WR stars and their mass loss.
3. W.ROBBRECHT, C. DE LOORE and G.OLSEN: A hot corona model for O-stars and WR stars.
4. D.C.ABBOTT, J.H.BIEGING and E.CHURCHWELL: Radio continuum measurements of mass loss from WR stars.
5. D.E.HOGG: Radio emission from WR stars.
6. J.D.HILLIER: IR spectroscopy of WN stars.
7. N.PANAGIA, E.G.TANZI and M.TARENGHI: The near-IR properties of selected WN stars in the LMC.
8. J.M.VREUX: Near-IR observations of galactic WN stars.
9. W.M.RUMPL: Line formation in winds with enhanced equatorial mass loss rates and its application to the WR star HD 50896.

# OBSERVATIONS OF MASS LOSS FROM OB AND WOLF-RAYET STARS

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## 1. INTRODUCTION

In this review, three observationally accessible parameters of the winds of OB and Wolf-Rayet stars will be discussed:

- (1) Terminal velocities
- (2) Velocity laws
- (3) Mass loss rates

In addition, some discussion of the ionisation structure of the winds will be included. In general, only the most recent results for OB stars will be mentioned (Section 2) as a large number of reviews have appeared on this topic since IAU Symposium No. 83 on mass loss from O-type stars (Conti and de Loore, 1979); e.g. Cassinelli, Castor and Lamers (1978), Cassinelli (1979), Conti (1978, 1981), Conti and McCray (1980), Hutchings (1980) and Lamers (1981). The data on Wolf-Rayet stars will be discussed in Section 3.

## 2. OB STARS

### 2.1 Terminal velocities

Abbott (1978) used the blue absorption edge velocities of well saturated UV resonance lines as a measure of the terminal velocity for 33 stars earlier than spectral type B1. He found a correlation between terminal velocity,  $v_\infty$ , and escape velocity,  $v_{\text{esc}}$ , such that  $v_\infty \sim 3v_{\text{esc}}$ . Castor, Abbott and Klein (1975) showed that single scattering line driven radiation pressure theory predicts a velocity law of the form

$$v(R) = (\alpha/1-\alpha)^{\frac{1}{2}} v_{\text{esc}} (1 - R_*/R)^{\frac{1}{2}} \quad (1)$$

where  $R_*$  is the stellar core radius and  $v(R)$  is the velocity at radius  $R$ . Equation (1) therefore yields

$$v_\infty = (\alpha/1-\alpha)^{\frac{1}{2}} v_{\text{esc}} \quad (2)$$

$\alpha$  is a numerical constant determined by the relative proportions of

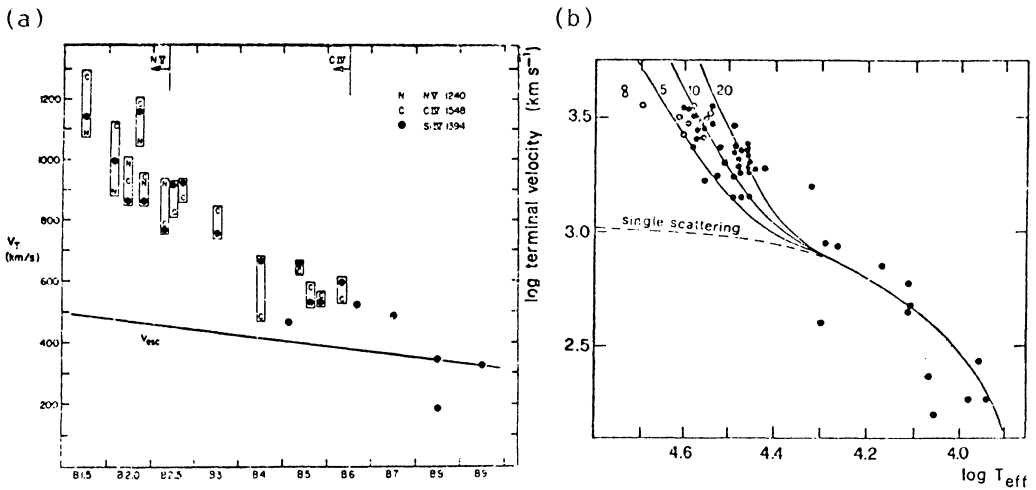


Figure 1. (a) Terminal velocities, derived from the resonance lines of NV, CIV and SiIV, versus spectral type for B supergiants between B1.5 and B9 (from Cassinelli and Abbott, 1981). (b) The dots show terminal velocities for O and B stars versus effective temperature. The solid lines show the predicted terminal velocities corresponding to the labelled number of multiple scatterings (from Panagia and Macchetto 1981).

optically thick and thin lines in a wind. If all the lines are optically thick then  $\alpha = 1.0$  and if all are optically thin then  $\alpha = 0.0$ . The observed value of  $v_{\infty}/v_{esc} \sim 3$  for O-type stars corresponds to  $\alpha = 0.9$ , i.e. to most of the driving lines being optically thick, according to the interpretation of Abbott (1978; however see below for later work by Abbott on the *predicted* value of  $\alpha$ ).

Hutchings and von Rudloff (1980) and Cassinelli and Abbott (1981) have shown that the relationship,  $v_{\infty} \sim 3v_{esc}$ , breaks down for spectral types later than about B1. Figure 1(a), from Cassinelli and Abbott, shows a fairly smooth decline in  $v_{\infty}/v_{esc}$  for supergiants after B1, reaching a value of unity at spectral type  $\sim$  B8I. The relation  $v_{\infty} \sim v_{esc}$  seems to hold between B8I and A2I, corresponding to  $\alpha \sim 0.5$ .

In order to obtain the predicted value of  $\alpha$ , ab initio, Abbott (1982 and this volume) has calculated the cumulative force due to more than one thousand lines of the 27 cosmically most abundant elements. He finds that  $\alpha \sim 0.5 - 0.6$  is predicted for the entire range of effective temperatures from  $1 \times 10^4$  K to  $5 \times 10^4$  K, implying  $v_{\infty} \sim 1.0 - 1.5 v_{esc}$  for all spectral types from A to O. Since terminal velocities as low as this are seen only for the late B and early A stars, an additional accelerating mechanism is required for the earlier spectral types.

Panagia and Macchetto (1981) have also noted the trend of increasing terminal velocity with earlier spectral type and have offered an explanation in terms of multiple scattering of photons by the wind. If the radiative acceleration of a wind is determined by single scattering

processes only, then the momentum rate would be given by  $\dot{P} = \bar{B}L/c$ , where  $\bar{B}$  is the spectrum averaged line blocking factor and  $L$  is the stellar luminosity.  $\dot{P}$  is composed of the momentum carried to infinity by the wind ( $Mv_\infty$ ) plus the force needed to support the extended envelope against gravity (Abbott, 1980). Panagia and Macchetto note that typical observed values of  $\bar{B}$  longward of the Lyman limit for OB stars are  $\sim 0.25$ . Observed mass loss rates, coupled with plausible velocity laws (Section 2.2), require values of  $\bar{B}$  which are less than 0.25 only for late B and early A type stars. Such stars therefore have terminal velocities and mass loss rates which are consistent with single scattering radiation pressure.

Panagia and Macchetto suggest multiple photon scattering as the additional source of momentum needed for the hotter stars. They list three conditions which must be satisfied for this mechanism to be efficient; (a) the driving lines must have large optical depths, (b) the lines should be closely spaced, ideally by  $\Delta\lambda \sim \lambda v/c$ , so that a backward scattered photon will encounter another line at the opposite side of the envelope, and (c) the relevant lines should be located in a region of high stellar continuum flux. These conditions are satisfied by stars hotter than about  $3 \times 10^4$  K, which have many strong lines in the region of the Lyman limit and shortwards (Abbott, 1982; Panagia and Macchetto, 1981). Figure 1(b) shows the curves of  $v_\infty$  versus  $T_{\text{eff}}$  predicted by Panagia and Macchetto for values of  $N$  (the number of scatterings per far-UV photon) between 1 and 20. Values of  $N$  between 5 and 20 seem to match the observations.

The optical depth of absorbing lines will decrease with increasing radius, whereas the probability of a photon being backscattered without being absorbed by the stellar core will increase with radius. The model of Panagia and Macchetto therefore predicts that multiple scattering will occur most efficiently at typically 2 - 4 stellar radii, i.e. the velocity law should be quite extended. Whether or not slow velocity laws are allowed observationally for all O-type stars is discussed in the next section.

Abbott (1982) has pointed out that the observed value of  $v_\infty/v_{\text{esc}}$  seems to peak at about  $T_{\text{eff}} \sim 3 \times 10^4$  K, decreasing somewhat towards higher effective temperatures (this is in addition to the more obvious drop towards cooler temperatures shown in Figure 1(a)). This can be understood in terms of multiple scattering if we assume that all stars hotter than  $T_{\text{eff}} \sim 3 \times 10^4$  K possess enough suitably spaced lines. Consider two stars in this range having the same mass and luminosity (and therefore the same mass loss rate according to the discussion in Section 2.3). The net outward velocity increment due to  $N$  multiple scatterings should be proportional to  $\sqrt{N}$ .  $N$  itself should be proportional to the product of the radiative flux and particle density at a given radius,  $R$ , times the fractional area of the rear hemisphere of sky not occulted by the stellar core.  $R$  is assumed to be greater for either star than the radius at which the initial terminal velocity ( $v_{\text{esc}}$ ) is reached. Thus

$$v_\infty \sim v_{\text{esc}} + \frac{L}{4\pi R^2} \cdot \frac{A}{v(R)R^2} \cdot \left(1 - \left(\frac{R_*}{2R}\right)^2\right) \quad (3)$$

The term in brackets approximates to unity, so we obtain

$$v_{\infty}/v_{\text{esc}} \sim 1 + B/v^{\frac{1}{2}}(R)v_{\text{esc}} \quad (4)$$

For constant  $L$  and  $M$ ;  $v_{\text{esc}} \propto R^{-\frac{1}{2}} \propto T_{\text{eff}}$ . Since  $v(R) \propto v_{\text{esc}}$ , we predict

$$v_{\infty}/v_{\text{esc}} \sim 1 + C/T_{\text{eff}}^{3/2} \quad (T_{\text{eff}} \geq 3 \times 10^4 \text{ K}) \quad (5)$$

where  $A$ ,  $B$  and  $C$  are constants. This relation appears to be consistent with the observational data presented by Abbott (1982).

### 2.2.1 Velocity laws

Castor and Lamers (1979) have computed an atlas of theoretical P Cygni profiles for resonance lines, using the Sobolev approximation and velocity laws of the form

$$v(R) = v_{\infty}(0.01 + 0.99\{1 - R_{*}/R\}^{\beta}) \quad (6)$$

with  $\beta = \frac{1}{2}$ , 1, 2 or 4.  $\beta = \frac{1}{2}$  corresponds to a very fast velocity law such as equation (1), whereas  $\beta = 4$  corresponds to a very slow velocity law, such as that of Barlow and Cohen (1977), derived by empirically fitting the IR flux distribution of P Cygni. Castor and Lamers showed that the ratio of emission to absorption in a resonance line is a sensitive function of the velocity law.

Abbott, Bohlin and Savage (1982) have analysed Copernicus observations of the NV resonance doublet in 82 stars from O4 to B2. They find that the ratio of emission to absorption equivalent width,  $W_{\text{e}}/W_{\text{a}}$ , is a factor of two smaller in main sequence stars than in supergiants. This would seem to imply that main sequence stars have a faster velocity law, since a steep velocity law will give a smaller  $W_{\text{e}}/W_{\text{a}}$  on account of core occultation effects. However, some main sequence stars have such a small ratio of  $W_{\text{e}}/W_{\text{a}}$  that values of  $\beta \sim 0.05$  would be required in the models of Castor and Lamers. This would imply enormous mass loss rates that are incompatible with other observations. Even for the supergiants, the values of  $\beta$  derived ( $\sim 0.1 - 0.2$ ) imply significantly steeper velocity laws than obtained by other methods. Abbott et al suggest that the co-moving frame calculations of Hamann (1981) provide a possible resolution of this problem. Hamann showed that a large value of the microturbulent velocity,  $v_{\text{D}}$ , causes significant changes in the computed profiles, such that the value of  $W_{\text{e}}/W_{\text{a}}$  decreases with increasing  $v_{\text{D}}$ . Values of  $v_{\text{D}}/v_{\infty} \geq 0.1$  seem to be necessary to explain the observed profiles with reasonable values of  $\beta$ , so that  $v_{\text{D}}$  must be highly supersonic and 'microturbulence' a misnomer. Figure 2 illustrates the effect on the line profile found by Hamann for various values of  $v_{\text{D}}/v_{\infty}$ , with  $\beta = \frac{1}{2}$ , compared to the result obtained for the same velocity law using the Sobolev approximation.

Hamann's results can also explain another aspect of observed P Cygni profiles that is not predicted by Sobolev calculations. Sobolev approximation results predict that the saturated absorption component of a P Cygni profile should reach zero intensity only very close to terminal velocity and should then return to unit intensity very sharply

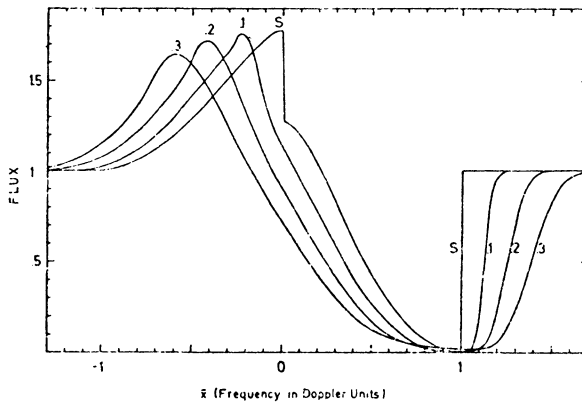


Figure 2. Emergent flux profiles, (1) calculated using the Sobolev approximation and labelled 'S', or (2) from co-moving frame calculations labelled by the parameter  $v_D/v_\infty = 0.1, 0.2$  or  $0.3$ , where  $v_D$  corresponds to the Doppler broadening velocity (from Hamann, 1981).

at terminal velocity. Observed UV resonance line profiles, on the other hand, sometimes have very extended black absorption cores that do not return sharply to unit intensity (cf. Figure 8 for an example). In the co-moving frame calculations of Hamann, shown in Figure 2, the extended absorption on either side of  $v_\infty$  arises because a photon travelling outwards can be resonantly scattered over a finite radius if the intrinsic line width is broadened, e.g. by turbulence. Lucy (1982a) has offered a similar explanation for the extended black absorption cores of UV resonance lines in terms of non-monotonic velocity fields and has proposed a physical basis for their origin, namely that the extended absorption is caused by radially spaced highly supersonic shocks in the wind. These are the shocks invoked by Lucy and White (1980) to explain the observed characteristics of the X-ray emission from early type stars.

Lamers, Gathier and Snow (1982) have discussed the presence of discrete shell absorption components in the resonance line profiles of 16 out of 26 stars with spectral types between O4 and B1. The narrow absorption features are seen at the same velocity in both components of resonance doublets and in different resonance lines of the same star. The average shell component velocity is found to be  $\sim 0.75v_\infty$ , with a width (FWHM) of  $\sim 0.19v_\infty$ . Their contribution to the total column density of a given ion ranges from 10% to 60% and their degree of ionisation is higher than the wind as a whole. An example of shell components in the wind of  $\lambda$  Ori is shown in Figure 3. Two alternative explanations for the shell components are offered by Lamers et al. The first is a two component model, one component being the normal wind material and the other consisting of shell material at fairly large radii with velocities of  $(0.65-0.85)v_\infty$ . If the two components coexist, then relative velocities of  $(0.15-0.35)v_\infty$  will occur, leading to hypersonic shocks and X-ray emission. In the context of the model of Lucy and White (1980), the 'shell components' could represent material ahead of the

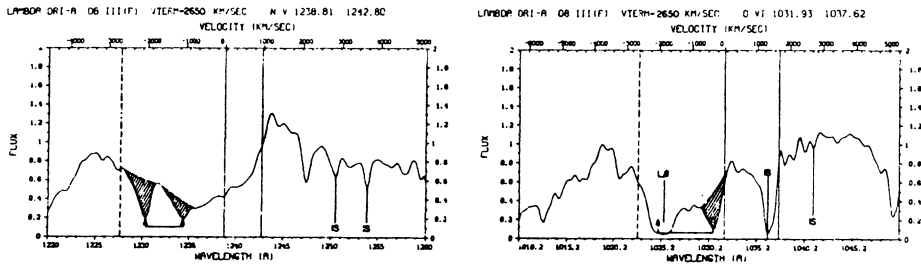


Figure 3. Narrow absorption components in the NV (left) and OVI (right) profiles of  $\lambda$  Ori. The full vertical lines indicate the rest velocity of each resonance doublet component and the dashed vertical lines indicate the terminal velocity for the short wavelength component. The arrows indicate the position of the 'shell' absorption features (shaded) in each doublet component (from Lamers, Gathier and Snow, 1982).

dense blobs produced by their postulated wind instability. Shadowing by the blobs would lead to a reduced acceleration and velocity relative to the blobs, giving rise to shocks and X-rays.

The alternative explanation for the shell components which was discussed by Lamers et al, is a plateau in the velocity law, along the lines proposed by Hamann (1980) to explain the existence of shell components in unsaturated lines in the UV spectrum of  $\zeta$  Puppis. An extended region of almost constant flow velocity will lead to a large column density and optical depth at that velocity. Figure 4 shows the velocity law derived for  $\zeta$  Puppis by Hamann (1980), along with the law proposed by Lamers et al (1982) to explain the shell components in their sample of stars. Lucy (1982b), in a development of the Lucy and White (1980) X-ray emission model, postulates a spectrum of shocks spaced throughout a wind. Lucy goes on to speculate that the monotonic velocity law predicted by classical line driven radiation pressure theory may be modified by the change in ionic abundances produced by the secondary radiation from the shocks, so as to reduce the acceleration and impose a velocity plateau which could yield the shell components seen by Lamers et al. An explanation of this nature, involving both a velocity law with a plateau and shock produced

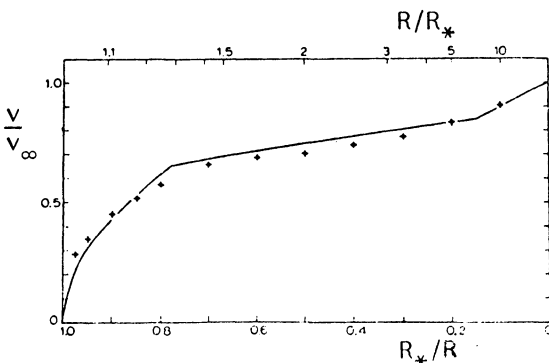


Figure 4. The normalised velocity law (solid line) required to fit the observed shell components of Lamers et al (1982) by means of a velocity plateau. The crosses indicate the velocity law used by Hamann (1980) to fit the line profiles of  $\zeta$  Puppis (figure taken from Lamers, Gathier and Snow, 1982).



turbulence throughout the wind, has the advantage that it can simultaneously explain the 'shell' components in the weaker P Cygni profiles and the extended black absorption regions in strong P Cygni profiles. The observed plateau velocities of  $\sim 0.75v_{\infty}$  are, however, too high to correspond to the transition between single scattering and multiple scattering acceleration discussed in the previous section. The lack of obvious shell components at the expected transition velocity for O-type stars of  $v_{\infty}/3$  would seem to imply that there is no significantly extended region at that velocity.

The analysis by Abbott et al (1982) of NV resonance line profiles, as discussed earlier, seems to indicate that main sequence O stars have steeper velocity laws than supergiants. A similar conclusion is reached when infrared observations of these stars are considered.  $\theta$  Sgr is an O4V((f)) star for which the radio observations of Abbott et al (1980, 1981) yield a very large mass loss rate of  $(2.5 - 4.0) \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ . Infrared observations of this star by several groups show that it has at most a very small excess at  $10 \mu\text{m}$ , implying an extremely fast velocity law if the radio mass loss rate is accepted. On the other hand, the O4If star  $\zeta$  Pup, with a mass loss rate of  $3.5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$  (Abbott et al, 1980), has an infrared excess flux distribution between 2.2 and  $10 \mu\text{m}$  which can be fitted by a relatively slow linear velocity law of the form  $v(R) \propto v_1(R/R_* - 1)$  (Castor, 1979). Van Blerkom (1979) found that such a law, combined with a rapid rise to terminal velocity at large  $R$ , could also explain the H $\alpha$  profile of  $\zeta$  Pup. Since 2-10  $\mu\text{m}$  infrared fluxes and H $\alpha$  emission are primarily sensitive to the inner high density regions of a wind, a subsequent velocity plateau at  $\sim 0.75v_{\infty}$ , followed by a final rise to  $v_{\infty}$ , can probably not be ruled out by these data. Van Blerkom (1978) was also able to obtain a good fit to the observed H $\alpha$  profile of P Cygni (B1I) by using a  $v(R) \propto R$  velocity law and a mass loss rate close to the  $(1 - 2) \times 10^{-5} M_{\odot} \text{ yr}^{-1}$  implied by radio observations.

### 2.2.2 Ionisation structure

The long controversy over the origin of those stages of ionisation seen in the winds of OB stars which are anomalously higher than expected from radiative equilibrium production by the photospheric radiation field (cf. Cassinelli et al (1978) for a review), now seems to have been resolved in favour of the Auger ionisation model of Cassinelli and Olson (1979). In this model, inner shell ionisation by X-rays of the dominant stage of ionisation,  $X^{n+}$ , of element X, produces small amounts ( $\sim 10^{-2} - 10^{-3}$  of the total abundance) of ionisation stage,  $X^{(n+m)+}$ , where  $m$  is usually 2. Einstein X-ray observations (e.g. Long and White, 1980) have vindicated this model but have shown that the X-rays cannot arise in a thin corona at the base of the wind, as envisaged by Cassinelli and Olson, but must arise instead from hot material distributed throughout the wind (Lucy and White, 1980). This is on account of the relatively soft X-ray spectra which are observed. These are inconsistent with a base coronal origin since the emergent X-rays should then have undergone significant absorption and hardening by the overlying wind material. A detailed analysis by Cassinelli et al (1981) of Einstein observations of ten OB stars shows that the observed X-ray luminosities



are sufficient to explain the anomalous ionisation stages and confirms that the X-rays must arise relatively far out in the wind itself. However, a problem may still remain in explaining the superionised stages deep within the flow ( $v \ll v_\infty$ ) because of the large attenuation which would be suffered by X-rays propagating in the inward direction.

Apart from the superionised stages, the overall ionisation balance of OB stellar winds is thought to be determined by radiative equilibrium processes, which are governed by the photospheric and diffuse emission radiation fields (e.g. Olson and Castor, 1981). Very little work has been carried out to date on the topic of whether the observed ionisation balance is a strong function of radius. For a constant velocity flow and a photospheric radiation field only, the ionisation balance should be invariant with radius, whilst for an accelerating flow the degree of ionisation should increase outwards. Lamers and Rogerson (1978) found evidence for a lower degree of ionisation at higher velocities in the wind of  $\tau$  Sco (B0V).

Abbott et al (1982) have found that the ionisation fraction of  $N^{4+}$  changes by only a factor of about 1.6 on going from spectral type O4 to B2. This constancy is extremely surprising, since three different mechanisms are thought to account for NV over this range. These are (a) radiative equilibrium production by the photospheric radiation field for spectral types earlier than O6, (b) ionisation of NIV by the diffuse radiation field for spectral types between O6 and B0 and (c) Auger ionisation of NIII for spectral types later than B0.

### 2.3 Mass loss rates

Ultraviolet spectroscopy provides the most sensitive method for the detection of mass loss effects, on account of the intrinsic strength and ease of excitation of UV resonance lines. Unfortunately, accurate mass loss rate determinations can be difficult as all the resonance lines in the accessible UV are usually either saturated, or from trace ionisation stages, leading to uncertain ionisation fraction corrections.

The Castor and Lamers (1979) atlas of theoretical P Cygni profiles was published for the purpose of allowing mass loss rates to be derived by comparison of observed resonance line profiles with those in the atlas. For a given line they define a strength parameter,  $T$ , given by

$$T = \int_{v_{\text{phot}}}^{v_\infty} \tau_{\text{rad}}(v) dv \quad (7)$$

For ground state resonance lines:

$$T = \frac{\pi e^2 f \lambda_0}{mc} \frac{N_i}{v_\infty} \quad (8)$$

where  $N_i$  is the column density of the absorbing ion. Thus  $\dot{M}$  is proportional to  $T v_\infty / q_i$ , where  $q_i$  is the ionisation fraction of the ion. If  $T$  can be determined from a profile fit, the mass loss rate can be obtained. Castor and Lamers' atlas of profiles is parametrised by:

$$\tau_{\text{rad}}(v/v_\infty) = T(1+\gamma)(1-v_{\text{phot}}/v_\infty)^{-1-\gamma}(1-v/v_\infty)^\gamma \quad (9)$$

where  $\gamma = \frac{1}{2}, 1, 2$  or  $4$  and velocity laws are of the form given by equation (6) with  $\beta = \frac{1}{2}, 1, 2$  or  $4$ . It has been shown (Olson and Castor 1981; Garmany et al, 1981) that if the absorption part of a P Cygni profile is evaluated at  $v = v_{\infty}/2$ , the dependence on the parameters  $\beta$  and  $\gamma$  largely vanishes, allowing  $\dot{M}$  and thereby  $\dot{M}$  to be obtained straightforwardly. If the profile is saturated, only a lower limit to  $\dot{M}$  can be determined.

Conti and Garmany (1980) used the Castor and Lamers atlas to analyse IUE resonance line profiles of NV, SiIV and CIV for six O-type stars on or near the main sequence. They derived much lower mass loss rates per unit luminosity than those of *evolved* O-type stars taken from other sources. However, subsequent work by the same group and by Gathier, Lamers and Snow (1981) has shown that the ionisation fractions assumed by Conti and Garmany were over-estimates, leading to values of  $\dot{M}$  which were too low.

Gathier et al have analysed Copernicus profiles of up to six different resonance lines for 25 stars between O4 and B1, making use of the Castor and Lamers atlas and normalising their derived mass loss rates to those of eight calibration stars in their sample with well determined mass loss rates from other methods. Olson and Castor (1981) have determined mass loss rates for eight OB stars by means of detailed empirical fits to Copernicus spectra of up to eight resonance lines per star and with ionisation equilibria computed to match the line strengths.

Olson (1981) has demonstrated a method of determining mass loss rates from excited state lines (e.g. NIV 1718 Å, OIV 1343 Å, OV 1371 Å) which has the advantage that it can be applied to dominant ionisation stages. Because photoexcitation determines the populations of excited state levels, there is a strong dependence of the level populations on radial distance from the star and on the absolute level of the photo-exciting flux. Olson finds that  $\dot{M} \propto T v_{\infty}^2 / F(v_i) q_i$  and provides an atlas of theoretical profiles for the determination of  $\dot{M}$ .  $F(v_i)$  is the stellar flux at the frequency of the photoexciting transition and provides the major uncertainty in this method, since it lies in the unobservable UV. As with the resonance line method, the fitting of profiles is normally done at  $v = v_{\infty}/2$ , since this minimises the dependence on the velocity law and optical depth parameters,  $\beta$  and  $\gamma$ .

Garmany et al (1981) have used both the excited state and resonance line methods to analyse IUE spectra of 31 O-type stars (chiefly on the main sequence) in clusters and associations with known distances. The two methods are complementary, since if excited state lines show wind absorption the resonance lines are usually saturated, whilst if the resonance lines are unsaturated no wind absorption can usually be seen from excited state levels. Garmany et al found that their simple analysis, when applied to the unsaturated CIV and NV resonance lines of six stars in common with the sample of Olson and Castor (1981), led to mass loss rates in excellent agreement with those obtained from the much more detailed analysis of the latter authors. In general, Garmany et al found that the mass loss rates derived from the excited state lines were too low compared to determinations by other methods or even, in some cases, compared to the lower limits implied by saturated

resonance lines. Correction factors were therefore applied to the subordinate line  $\dot{M}$  determinations, using eight calibration stars, across the spectral type range, having reliable values of  $\dot{M}$  from other techniques. A plot of Garmany et al's final mass loss rates (resonance line plus corrected subordinate line) versus luminosity is shown in Figure 5. The correlation was fitted by

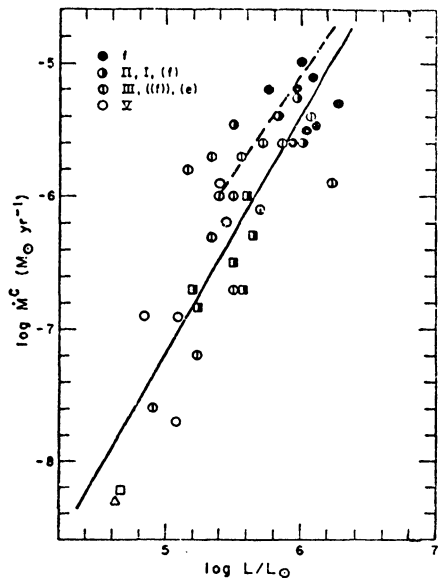
$$\dot{M} = 1.1 \times 10^{-15} (L/L_0)^{1.73} M_0 \text{ yr}^{-1} \quad (10)$$

shown as the solid line in Figure 5.

Mass loss rate determinations from optical spectroscopy have only been carried out for OB stars whose winds are strong enough to give significant populations of hydrogen or helium excited state levels, thus in general restricting the technique to supergiants. The mass loss rates derived by Klein and Castor (1978), from H $\alpha$  and HeII emission lines, assumed a  $\beta = \frac{1}{2}$  velocity law and are quite sensitive to changes in  $\beta$ . Olson and Ebbets (1981) have analysed high signal-to-noise H $\alpha$  profiles for ten supergiant OB stars. They concentrated on fitting the high velocity wings of the profiles in order to avoid the uncertainties encountered at line centres due to stellar rotation, photospheric lines and the inadequacies of the Sobolev approximation at low velocities. The mass loss rate and velocity law was adjusted for each star until a good fit was obtained. The resultant values of  $\dot{M}$  generally agreed within a factor of two with the radio rates of Abbott et al (1980) and the IR rates of Barlow and Cohen (1977).

The method of determination of mass loss rates from infrared measurements of the free-free emission has been reviewed by Barlow (1979). Since then, Tanzi, Tarengi and Panagia (1981) have obtained 1-5  $\mu\text{m}$  photometry of 70 southern OB stars and have fitted the excess free-free flux distributions of 37 of the stars with velocity laws of the form  $v = v_{\text{phot}} (R/R_*)^\gamma$ . A value of  $\gamma = 2$  was found to lead to good agreement with other  $\dot{M}$  determinations, yielding rates 30% lower than those of Abbott et al (1980; 3 stars in common) and 20% lower than those of Barlow and Cohen (1977; 7 stars in common).

Figure 5. Mass loss rates for O-type stars derived by Garmany et al (1981), versus stellar luminosity. The solid line shows the  $\dot{M} \propto L^{1.73}$  line fitted to these observations by Garmany et al. The dashed line shows the  $\dot{M} \propto L^{1.56}$  correlation found by Abbott et al (1981) from radio observations of OB stars (figure from Garmany et al, 1981).



In principle, radio flux measurements provide the most accurate method for obtaining mass loss rates. The free-free emission from a wind at radio wavelengths originates at very large radii, where the wind can confidently be expected to have reached terminal velocity. The observed radio flux  $S_\nu$  at frequency  $\nu$ , combined with the distance  $D$  to the star, uniquely determines the value of  $\dot{M}/v_\infty$ . An estimate of  $v_\infty$  then gives the mass loss rate. Radio observations of OB stars were reviewed by Barlow (1979). Subsequently, Abbott et al (1980) carried out the first VLA survey of early-type stars, yielding five new detections in addition to the previously detected stars P Cyg and  $\zeta$  Pup. Abbott et al (1981) have detected a further four stars, all in the Cyg OB2 Association. They found that the entire sample yielded a strong dependence of  $\dot{M}$  upon stellar luminosity  $L$ . Their relation, shown by the dashed line in Figure 5, was

$$\dot{M} = 3.9 \times 10^{-15} (L/L_\odot)^{1.56} M_\odot \text{ yr}^{-1} \quad (11)$$

Most radio mass loss rate determinations have been made at only one frequency so far. It would be desirable for observations at other frequencies to be made, in order to test if the  $S_\nu \propto \nu^{0.6}$  law predicted by the constant velocity model is obeyed. Long baseline interferometry of sufficient angular resolution to resolve the radio emission from winds would also be useful. Extending the formalism of Wright and Barlow (1975), it is simple to show that, for a constant velocity spherically symmetric wind, the angular radius,  $\theta_f$ , at which the surface intensity of radio emission has fallen to a fraction  $f$  of its central value is given by

$$\theta_f = \frac{12.87 S_\nu^{1/2} (\text{mJy})}{\nu (\text{GHz}) \{ \ln(1/1-f) \}^{1/3} T_e^{1/2}} \quad \text{arcsec} \quad (12)$$

$S_\nu$  is the total observed flux at frequency  $\nu$  and  $T_e$  is the wind electron temperature in Kelvin. If, after deconvolution from the telescope beam profile, the observed radial intensity distribution matches that predicted by equation (12), then the model can be considered to be confirmed and the wind electron temperature can be derived:

$$T_e = \frac{165.6 S_\nu (\text{mJy})}{\nu^2 (\text{GHz}) \theta_f^2 (\text{arcsec}) \{ \ln(1/1-f) \}^{2/3}} \quad \text{K} \quad (13)$$

Baselines somewhat larger than that of the VLA are required to resolve currently observed stellar wind radio fluxes.

Schmid-Burgk (1982) has considered the case of radio emission from arbitrarily nonspherical constant velocity stellar winds (e.g. ellipsoids, cones, radial streamers, etc.). He finds that the  $S_\nu \propto \nu^{0.6}$  law still holds in all cases and that ratios of structural scale lengths in excess of ten are needed before mass loss rates are significantly overestimated by the spherically symmetric model.

Apart from one or two badly discrepant stars such as  $\eta$  Sgr, the various methods of deriving mass loss rates agree to within a factor of 2-3 usually, which is remarkably good considering the widely different spectral regions, velocity laws and other assumptions that are utilised. Both the UV sample of Garmany et al (1981) and the radio sample of

Abbott et al (1981) show a strong dependence of  $\dot{M}$  upon stellar luminosity ( $\propto L^{1.73}$  and  $L^{1.56}$ , respectively), with no obvious separation between main sequence and evolved O stars. Abbott (1982, and this volume) has shown that the most recent development of radiation driven wind theory, with lines treated realistically, leads to the prediction  $\dot{M} \propto L^2/M_{\text{eff}}$ , where  $M_{\text{eff}}$  is the mass of a star adjusted for radiation support. For upper main sequence stars,  $L \propto M^2$ , so  $\dot{M} \propto L^{1.5}$  is predicted; whilst for stars evolving with mass loss, the dependence of  $L$  upon  $M$  decreases, leading to  $\dot{M} \propto L^{1.5-2}$ . As well as predicting the correct luminosity dependence, the absolute values of the mass loss rates predicted by Abbott are comfortably equal to the observed rates and are within the single scattering limit,  $L/v_{\infty}c$ , corresponding to the predicted terminal velocities of  $v_{\infty} \sim (1 - 1.5)v_{\text{esc}}$ . Multiple scattering must then be invoked to explain the observed terminal velocities of  $v_{\infty} \sim 3v_{\text{esc}}$  for O-type stars (and would simultaneously explain values of  $\dot{M}v_{\infty}c/L$  which are greater than unity). This scenario seems to be consistent with all the relevant observations of evolved OB stars but may encounter difficulties in the case of main sequence O-type stars. If, as seems to be the case, their mass loss rates are the same as those of evolved stars of the same luminosity (Abbott et al, 1981; Garmany et al, 1981) then they must have extremely fast velocity laws in order to be consistent with the UV and IR data (Section 2.2.1). A very fast velocity law would seem to be inconsistent with the requirement that their large terminal velocities and wind momenta are due to multiple scattering. It is to be hoped that future work will clarify this situation.

Suggestions have sometimes been made that the observed mass loss rates of early-type stars depend on parameters such as stellar radius  $R_*$ , as well as on mass and luminosity. For instance, the fluctuation theory of Andriesse (1981) predicts

$$\dot{M} \approx L^{3/2} (R_*/M)^{9/4} / G^{7/4} \quad (14)$$

Abbott et al (1981) found no obvious correlation between  $\log \dot{M}$  and  $\log(LR/M)$  for their sample of O and early B-type stars. However, the best test of a dependence of  $\dot{M}$  upon  $R_*$  should come from a comparison of late B and early A-type supergiants with O-type stars, on account of the large difference in stellar radii. To avoid systematic effects the mass loss rates of both groups of stars should be derived using the same techniques. To date, published estimates of their mass loss rates have unfortunately come from different methods (IR for the B and A supergiants, UV and radio for the O stars). However, there is reason to believe that work currently underway by several groups should resolve this question in the near future.

### 3. WOLF-RAYET STARS

#### 3.1 Terminal velocities

Willis (1981) has analysed P Cygni profiles present in IUE high dispersion spectra of 7 WN and 3 WC Wolf-Rayet stars and combined these

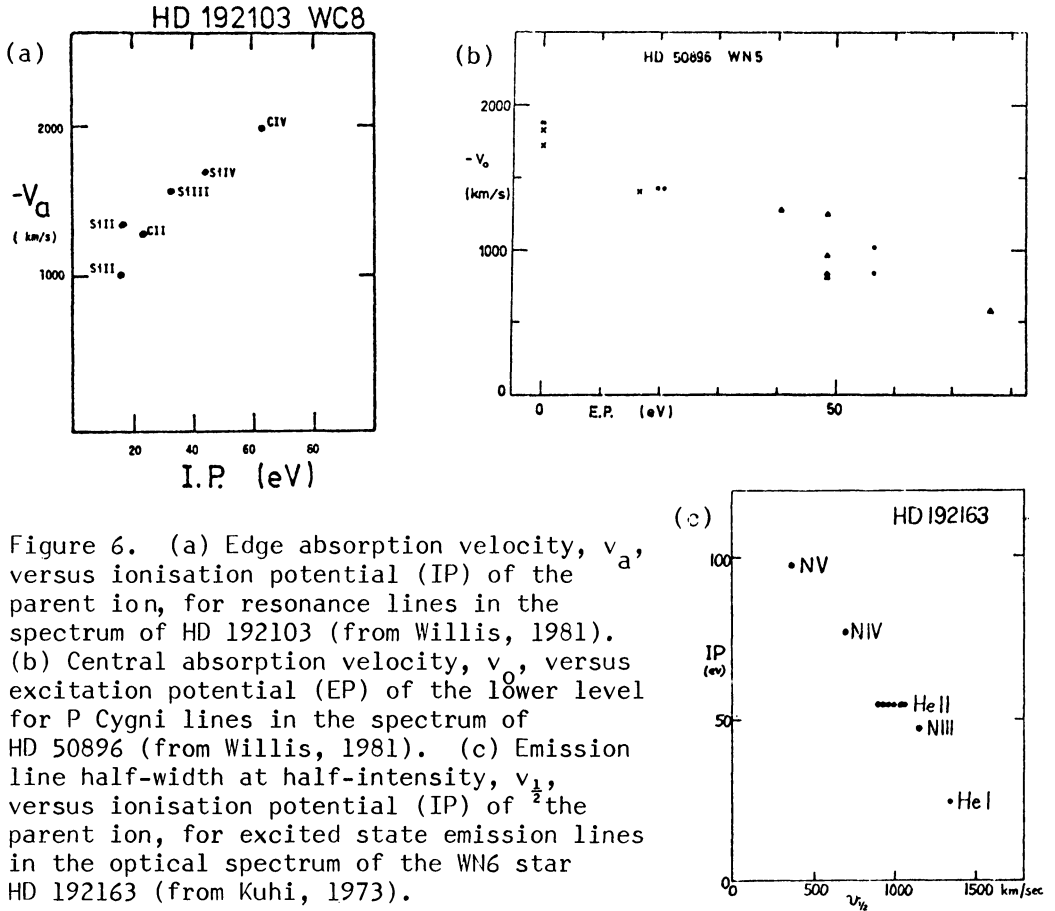


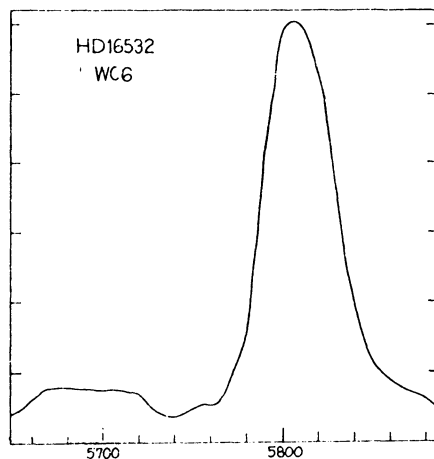
Figure 6. (a) Edge absorption velocity,  $v_a$ , versus ionisation potential (IP) of the parent ion, for resonance lines in the spectrum of HD 192103 (from Willis, 1981). (b) Central absorption velocity,  $v_o$ , versus excitation potential (EP) of the lower level for P Cygni lines in the spectrum of HD 50896 (from Willis, 1981). (c) Emission line half-width at half-intensity,  $v_{1/2}$ , versus ionisation potential (IP) of the parent ion, for excited state emission lines in the optical spectrum of the WN6 star HD 192163 (from Kuhl, 1973).

data with existing high dispersion optical data on P Cygni profiles. When plotting the blue absorption edge velocity,  $v_a$ , of resonance lines, versus the ionisation potential (IP) of the parent ion, he found strong correlations for all stars, in the sense that the highest IP lines had the highest edge velocity. Figure 6(a) illustrates the correlation for the WC8 star HD 192103.

Willis also found a correlation between  $v_o$  (the central velocity of the absorption component) and the excitation potential (EP) of the lower level of the transition. Figure 6(b) shows the correlation for the WN5 star HD 50896. Willis found that WN7 stars gave the steepest correlations, with the remainder of the WR stars giving about the same slope as HD 50896. The correlations are in the sense that lowest EP lines have the highest velocities. This can be understood in terms of either photoexcitation or collisional excitation models where radiation and particle densities, and thus the excited level populations, decrease outwards and argues that the lines arise in an accelerating region of the wind. Spherically symmetric decelerating winds would be expected to give a correlation of the opposite sense to that found, since particle densities,  $n(R) (\propto \{v(R)R^2\}^{-1})$ , and radiation densities should still



Figure 7. Photoelectric spectrum scanner profiles of CIII 5696 Å and CIV 5801,12 Å for the WC6 star HD 16532, in the form of intensity versus wavelength (from Kuhi, 1973).



decrease outwards. Willis noted that a similar  $v_0$  versus EP correlation is also found for the O4If star,  $\zeta$  Pup, but it is much steeper than that found for WR stars. As with their other properties, the WN7 stars thus seem to be intermediate between the Of and the classical WR stars, although much closer to the latter.

Kuhi (1973) reviewed a correlation between IP and emission line width shown by optical lines in WR spectra (Figure 6(c)). This correlation is of a sense opposite to that found by Willis for the UV resonance lines in Figure 6(a); higher IP lines have lower velocities. It is now clear that what in fact was being plotted by Kuhi was the correlation between EP and velocity, since optical transitions tend to be between higher and higher levels as the degree of ionisation of an element increases.

A well known spectral effect exhibited by WC stars is that the CIII 5696 Å 3d-3p emission feature becomes more and more flat-topped towards earlier spectral types, whilst the adjacent CIV 5801,12 Å 3p-3s feature is always round-topped. Kuhi (1973) has discussed the observations in detail and Figure 7 shows his data for the WC6 star HD 16532. The interpretation of the flat-topped 5696 Å CIII profile is that it originates from an optically thin region expanding at constant velocity. The transition cannot occur in the inner accelerating regions of the wind. The peaked CIV profile, on the other hand, is consistent with emission originating from the inner as well as the outer regions of an accelerating flow. Since there seem to be no obvious reasons why the source function of the CIII 3d  $^1D$  - 3p  $^1P$  transition should be suppressed in the inner regions, the conclusion must be that CIII is absent in the inner regions. Therefore the degree of ionisation of the wind must decrease outwards. HeI emission lines also become increasingly flat-topped towards earlier spectral sub-types in both the WN and WC sequences (Bappu, 1973), whereas HeII lines remain round-topped, suggesting that the  $He^{2+}/He^+$  ratios decrease outwards. Hummer, Barlow and Storey (these Proceedings), in their analysis of the infrared HeI and HeII lines in the spectrum of the WC8 component of  $\gamma$  Vel, have also found weak evidence that the  $He^{2+}/He^+$  ratio decreases outwards.

These conclusions seem to be in conflict with the UV data of Willis (1981), which show that the highest IP ions have the highest absorption edge velocities (Figure 6(a)). A possible answer to this problem may be that the highest edge velocities do not necessarily come from the highest IP ions but from ions with the highest elemental abundances and/or the highest oscillator strengths for their accessible transitions.



Thus the dominant stage of carbon might change outwards in the wind of a WC star from CIV to CIII, but as CIII has no strong currently accessible resonance lines, the CIV resonance lines would give the highest observed edge velocity, carbon being the most abundant heavy element in these stars. Similarly, in WN stars nitrogen is the dominant heavy element but, since NIII and NIV have no strong accessible resonance lines, NV could give the highest observed edge velocity even if the degree of ionisation decreased outwards (the observations of WN and WC stars indicate that although the lower stages of ionisation tend to appear at high velocities, the higher stages of ionisation do not disappear).

These complications, taken in conjunction with the problems of continuum level estimation and line blending, make the derivation of accurate terminal velocities from the UV spectra of Wolf-Rayet stars a non-trivial matter. However, another method of determining the terminal velocities of Wolf-Rayet winds is about to become available. Aitken, Roche and Allen (1982) have detected forbidden emission lines of [SIV] and [NeII] in the 8-13  $\mu\text{m}$  spectrum of the WC8 component of  $\gamma$  Vel. Their analysis shows that approximately equal amounts of emission are expected from regions of the wind with densities above and below the critical density,  $n_c$ , of these transitions ( $n_c \sim (0.6-4.0) \times 10^5 \text{ cm}^{-3}$ ). This is because the emissivities of the lines are proportional to  $n_e$  and  $n_e^2$ , respectively, above and below  $n_c$ . The critical densities correspond to very large radii (larger than or equal to the radio emitting radii) and so flat-topped, optically thin profiles should be seen when the lines are observed at higher spectral resolution. The full widths of the forbidden lines should be directly equal to twice the terminal velocities of the winds, without any ambiguity.

Willis (1981) found that there was a trend for the terminal velocity of WC stars to increase with earlier spectral sub-types, whilst the WN stars showed no noticeable trend. Typical values of  $v_\infty$  for various WR sub-types are listed in Table 1. They are in the same general range as those of O-type stars. Willis found that if the assumption was made that  $v_\infty \sim 3v_{\text{esc}}$ , as is the case for O stars, and if the stellar radii derived from luminosity and effective temperature estimates were used, the derived stellar masses showed quite good agreement with those obtained for similar sub-types in binary systems. This might indicate that radiation pressure may, after all, be of importance in driving Wolf-Rayet winds.

### 3.2 Velocity laws

To date, not a great deal of work has been carried out on the derivation of quantitative velocity laws for Wolf-Rayet stars. This is due mainly to the fact that they cannot be approximated by a simple core-halo structure, such as OB stars possess. As discussed below, electron scattering optical depths ( $\tau_e$ ) equal to unity occur in the wind itself. Due to the inherent difficulties of spectral line analysis, most studies have concentrated on the continuum.

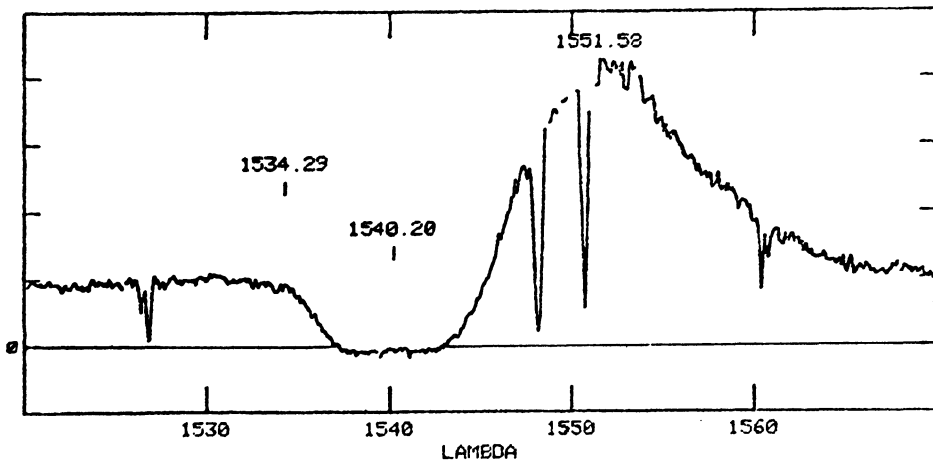
Hartmann and Cassinelli (1977) modelled the infrared free-free energy distribution of HD 50896 (WN5) with a variety of density distributions in order to obtain a best fit to the observations. This

work was subsequently extended to other Wolf-Rayet stars by van der Hucht et al (1979). For most stars it was found that a density distribution of the form,  $n(R) \propto R^{-\beta}$ , could fit the observations, with  $\beta = 10$  for  $\tau_e > 1$ ;  $\beta = 2$  for  $1 > \tau_e > 0.02$ ; and  $\beta = 10$  for  $\tau_e \lesssim 0.02$ . This corresponds to a wind with an extended constant velocity region between about 1 and 3 stellar radii, followed by a rapid rise to terminal velocity. For HD 50896 the constant velocity zone was required to extend to  $10R_*$ . Hartmann (1978) attempted to test the foregoing results by an independent method, observing the eclipsing binary system V444 Cyg (WN5 + 06) at 2.2 and 3.5  $\mu\text{m}$ . Combining his infrared data with the optical eclipse data of Cherepashchuk and Khalullin (1975), and modelling the depth of eclipse versus wavelength, he found that acceptable models gave  $1.5 \leq \beta \leq 2$  for  $0.75 \leq \tau_e \leq 1.5$ , in agreement with the results of Hartmann and Cassinelli.

At variance with the above results is the work of Cherepashchuk and Khaliullin (1975), who studied the behaviour of the eclipse of V444 Cyg using narrow band continuum filters in the optical region alone. Between 4244 and 7512  $\text{\AA}$  they found no change in the shape and depth of the eclipses and concluded that electron scattering must therefore dominate the opacity over that wavelength region. They analysed the shapes of the eclipse light curves so as to obtain the tangential electron scattering optical depths through the wind at various distances from the WN5 star. Assuming spherical symmetry, this gives the radial density distribution. They found  $n(R) \propto R^{-2.9}$ , i.e.  $v(R) \propto R^{0.9}$ ; close to being a linearly accelerating wind.

Figure 8 shows the CIV 1548,1550  $\text{\AA}$  profile of the WN5 star HD 50896. The absorption component has a very extended black region and a rounded violet edge. As discussed in Section 2.2.1, a similar effect is seen in

Figure 8. The P Cygni profile of the CIV 1548,50  $\text{\AA}$  resonance doublet in the spectrum of HD 50896 (WN5). The three wavelengths marked on the figure correspond to the edge absorption velocity,  $v_e$ , the central absorption velocity,  $v_0$ , and the peak emission velocity,  $v_p$ . The narrow absorption features are interstellar (spectrum courtesy of A.J. Willis).



the saturated UV absorption components of some Of stars and can be ascribed to the presence of 'turbulent' (Hamann, 1981) or non-monotonic (Lucy, 1982a) velocity flows. Another very noticeable feature of Figure 8 is that the emission component of the P Cygni profile is stronger than the absorption component. Therefore resonant scattering in a spherically symmetric flow cannot explain the profile. Rumpf (1980 and these Proceedings) has shown that the same situation holds for other resonance lines in the spectrum of HD 50896. One obvious explanation is that the lines do not behave as pure scattering lines, i.e. emission is excited in the wind. Rumpf investigated an alternative possibility, suggested by the fact that the spectrum of HD 50896 is intrinsically polarised, namely that the mass loss rate is enhanced in its equatorial regions. Two possible velocity laws were investigated by Rumpf: (a) a 'standard' law (equation 6) with  $\beta = \frac{1}{2}$ , and (b) a plateau velocity law of the type derived by Hartmann and Cassinelli (1977). He found that the latter could give an acceptable fit, but only if the velocity in the plateau region was about  $900 \text{ km s}^{-1}$ . The smallest absorption velocities seen in optical and UV excited state lines in the spectrum of HD 50896 are of the order of  $800 \text{ km s}^{-1}$  (Bappu, 1973; Willis, 1982).

### 3.3 Mass loss rates

There are essentially three methods for the determination of Wolf-Rayet star mass loss rates:

- (1) Analysis of the behaviour of eclipsing Wolf-Rayet binaries.
- (2) Observation of the interaction of a Wolf-Rayet wind with the interstellar medium.
- (3) Analysis of the line or continuum emission from Wolf-Rayet stars.

#### 3.3.1 Eclipsing binaries.

The analysis of the optical continuum light curve of V444 Cyg by Cherepashchuk and Khaliullin, discussed in the previous section, led to the derivation of  $n_e \sim 1.5 \times 10^{13} \text{ cm}^{-3}$  and  $R_* = 2.6R_0$  at  $\tau_e = 1$  in the WN5 component. Since their analysis implied that  $v(R) \propto e^{R^{0.9}}$ , they adopted a core velocity of  $300 \text{ km s}^{-1}$  from the assumption that the  $1500 \text{ km s}^{-1}$  half-width of HeII emission lines arose in a region  $15R_0$  across. The resulting mass loss rate for the WN5 component was  $1 \times 10^{-5} M_\odot \text{ yr}^{-1}$ .

A very simple analysis, due to Sobolev (1960), also shows that the rate of mass loss for Wolf-Rayet stars must be of this order. Sobolev assumed that emission lines with observed half-widths of  $v \sim 1000 \text{ km s}^{-1}$  originated from a layer with  $\tau_e = \frac{1}{2}$  and radius  $R_0$ , i.e.

$$\int_{R_0}^{\infty} \sigma_e n_e(R) dr = \frac{1}{2} \quad (15)$$

For a constant expansion velocity,  $v$ , one obtains  $n_e(R_0)R_0 = 5 \times 10^{23} \text{ cm}^{-2}$  and, adopting  $R_0 \sim 5.5R_\odot$  from eclipse observations of

two WR binaries, including V444 Cyg, Sobolev obtained  $\dot{M} = 10^{-5} M_{\odot} \text{ yr}^{-1}$ . This is in rather good agreement with the rates of  $(1.4-1.8) \times 10^{-5} M_{\odot} \text{ yr}^{-1}$  which are derived by the infrared and radio methods discussed in Section 3.3.3 (Barlow et al, 1981; Abbott et al, these Proceedings).

Khaliullin (1974) has analysed the O-C (observed - computed) residuals of many eclipse timings of V444 Cyg. He found a small variation of the period, which he modelled in terms of three different outflow configurations from the WN5 star. These were: I Mass exchange within the system with no variation of the orbital angular momentum. This led to a mass loss rate of  $\dot{M} = 0.37 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ . II Mass exchange with conservation of the total mass of the system and the formation of a ring around the secondary. This yielded  $\dot{M} = 1.1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ . III Isotropic outflow from the primary at a velocity exceeding the escape velocity of the system. This is the most plausible model and led to  $\dot{M} = 1.1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ .

Although  $\gamma$  Vel (WC8 + O9I) does not show eclipses in its continuum, Willis and Wilson (1976) discovered that its ultraviolet lines *do* show eclipse behaviour. Willis et al (1979) have analysed extensive ultraviolet eclipse observations of  $\gamma$  Vel. At certain phases, when the Wolf-Rayet wind is projected in front of the O star, deep absorption features are seen from ground state or low excited state lines which are normally in emission in the wind. Willis et al have analysed the CIII] 1909 Å intercombination absorption feature and derived the projected column density of  $C^{2+}$  in front of the O9I star at phases 0.41 and 0.51. From the known dimensions of the system, the mass loss rate of  $C^{2+}$  from the WC8 star was derived. Adopting a  $C^{2+}/\text{He}$  ratio of  $9 \times 10^{-3}$ , Willis et al obtained a total mass loss rate of  $1.1 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ .

### 3.3.2 Interaction of Wolf-Rayet winds with the interstellar medium

Johnson and Hogg (1965) first proposed that ring nebulae around Wolf-Rayet stars are due to ambient gas swept up by the Wolf-Rayet winds, and showed that the mass loss rate of the WR star could be deduced if the shell expansion velocity,  $v_s$ , and shell mass,  $M_s$  (or the pre-existing ISM density  $n_0$ ), were known.

Johnson and Hogg assumed that the swept-up shells were in a momentum conserving mode, the case that was also treated by Steigman et al (1975). Other treatments (Avedisova, 1972; Falle, 1975; Castor, McCray and Weaver, 1975) suggested that the shells should instead be energy conserving. Recent interferometric velocity observations of a number of wind-blown nebulae has allowed this question to be resolved. Chu et al (1982), Treffers and Chu (1982) and Chu (1982) have obtained high-resolution velocity data on five wind-blown nebulae around WR stars and have defined two parameters,  $\epsilon_s$  and  $\pi_s$ , which are respectively the ratio of the observed shell kinetic energy to the total injected wind energy and the ratio of the current shell momentum to the total injected wind momentum

$$\epsilon_s = M_s v_s^2 / \dot{M} v_{\infty}^2 t \quad (16)$$

$$\pi_s = M_s v_s / \dot{M} v_{\infty} t \quad (17)$$

$M_s$ , the mass of the shell, can be obtained from radio flux measurements, combined with an estimate of the mean nebular density, and is dominated by swept-up material. The age of the shell is given by  $t = \eta R_s / v_s$  where  $R_s$  is the radius of the shell and  $\eta = 3/5$  and  $1/2$  for energy conservation and momentum conservation, respectively. To evaluate  $\epsilon_s$  and  $\pi_s$  for each nebula, Treffers and Chu (1982) adopted values of  $\dot{M}_s$  and  $v_\infty$  from Barlow et al (1981). The typical derived value of  $\epsilon_s$  was 0.01, compared to an expected value of about 0.2 for an energy conserving shell (about 60% of the wind energy should go into heating the nebula and about 20% should be radiated away). The observed values of  $\epsilon_s$  show that energy conservation does not hold and that energy loss from the shell must be more efficient than presumed. The values of  $\pi_s$  obtained by Treffers and Chu had a mean value of about 0.5 for four of the five nebulae, consistent with the shells being in a momentum conserving phase. The fifth nebula, NGC 2359, had a much lower value of  $\pi_s$  (0.04), but its expansion velocity of  $18 \text{ km s}^{-1}$  was very low and close to a Mach number of unity, so Treffers and Chu suggested that Alfvén waves can be excited, transferring momentum to the external medium.

The above results suggest that WR mass loss rates can be determined to within a factor of two by assuming that momentum conservation holds (equation 17). It should be noted that this technique yields  $\dot{M} v_\infty$ , whereas the radio/infrared technique, discussed in the next section, determines the wind density parameter,  $\dot{M}/v_\infty$ . The fact that the estimates of  $\dot{M}$  resulting from the two methods agree to within a factor of two, indicates that the terminal velocity estimates are correct to within 40% at worst.

### 3.3.3 Mass loss rates from line or continuum emission.

Nussbaumer et al (1982) have used the Sobolev escape probability method to analyse the relative intensity of the 3-2, 4-3, 5-3 and 5-4 lines of HeII, in the spectra of six Wolf-Rayet stars. In each case, the ratio of the HeII emission region to stellar core radii was derived from the relative populations of the  $n=3$  and 4 levels; and the absolute dimension of the core was assumed to be that corresponding to the 5500 Å continuum flux and colour temperature. Finally, the ratio of the 3-2, and 4-3 lines was modelled by varying the electron temperature and  $\text{He}^{2+}$  density until a fit to the observations was obtained. The resultant densities, combined with the emitting region radii and velocities corresponding to the half-width of the HeII lines, yielded mass loss rates of  $(1.6 - 10) \times 10^{-5} M_\odot \text{ yr}^{-1}$ .

Ryl'kov (1975) has fitted the 3500-9500 Å continuous spectra of 20 WR stars with a two-component model, one component being a stellar blackbody and the other consisting of bound-free and free-free emission from a shell. An  $R^{-2}$  density distribution was assumed and  $T_{\text{eff}}$  and  $T_e$  were varied until a fit was obtained. At a core radius of  $R_* \sim 5R_\odot$ , values of  $n_e \sim (3 - 9) \times 10^{12} \text{ cm}^{-3}$  were obtained. Ryl'kov assumed a velocity of  $1000 \text{ km s}^{-1}$  at this radius giving mass loss rates with a mean value of  $5 \times 10^{-5} M_\odot \text{ yr}^{-1}$ . The adoption of lower and more plausible expansion velocities for the core region would give mass loss rates in accord with other determinations.

The relative contribution to a WR spectrum of a supposed stellar blackbody spectrum becomes increasingly small as one moves to longer and longer infrared wavelengths, until by 10  $\mu\text{m}$  free-free emission from the wind dominates totally. Hackwell, Gehrz and Smith (1974) have analysed the 2-10  $\mu\text{m}$  energy distributions of a number of WR stars in terms of a single density shell model. By identifying a change in continuum slope in the 5-10  $\mu\text{m}$  region with the transition from optically thin to optically thick free-free emission, they derived the density and dimensions of such shells ( $n \sim (0.4 - 3) \times 10^{12} \text{ cm}^{-3}$  and  $R \sim 3R_*$ , with  $R_* = 7R_0$  assumed). Adopting  $v = 1000 \text{ km s}^{-1}$ , at a radius of  $(R+R_*)/2$ , they obtained a mean mass loss rate of  $1.6 \times 10^{-5} M_0 \text{ yr}^{-1}$ .

As discussed in Section 2.3, radio flux measurements provide, in principle, an accurate means of deriving mass loss rates. Radio observations of WR stars up until 1978 are reviewed by Barlow (1979). Since then, Dickel et al (1980) have detected HD 192163 (WN6) at 5 GHz using the VLA. Elsewhere in this volume, new VLA radio observations of a number of Wolf-Rayet stars are reported by Hogg and by Abbott, Bieging and Churchwell.

Barlow, Smith and Willis (1981) have used a hybrid radio/infrared method to obtain mass loss rates for about twenty Wolf-Rayet stars. The mean 10  $\mu\text{m}$  - 5 GHz spectral index of a small number of WR stars with existing radio detections was applied to the published 10  $\mu\text{m}$  fluxes of the remaining stars, in order to predict 5 GHz fluxes. Mass loss rates were then derived from these fluxes using the constant velocity model of Wright and Barlow (1975). Barlow et al also estimated the total radiative luminosity of a range of Wolf-Rayet sub-types by adding (1) the integrated observed stellar fluxes longward of 1300  $\text{\AA}$ , to (2) the unobserved stellar fluxes shortward of 1300  $\text{\AA}$ , which were estimated by extrapolating to shorter wavelengths the continuum colour temperatures found to be appropriate at the shortest observed UV wavelengths. Table 1 presents the mean values of  $v_\infty$ ,  $\log(L/L_0)$ ,  $\dot{M}$  and  $\dot{M} v_\infty c/L$  found for each WR sub-type. The mass loss rates appear to be uncorrelated with stellar luminosity and show a very small range, which must be explained by any theory attempting to explain the magnitude of the mass loss rates. McGregor and Hyland (1981) have used a similar method with JHK infrared data to derive mass loss rates for a number of high luminosity Wolf-Rayet stars in the 30 Doradus region of the Large Magellanic Cloud. Their average mass loss rate is only a factor of two higher than that of Galactic Wolf-Rayet stars, despite the fact that their luminosities are a factor ten higher on average.

Most of the values of  $\dot{M} v_\infty c/L$  ( $=N$ ) in Table 1 seem larger than can be explained by present estimates of multiple scattering radiation pressure efficiencies, particularly those of the WC stars. However, detailed modelling is required before radiation pressure can definitely be ruled out and values of  $N \sim 10$ , such as are found for WN6-8 stars, may not be impossible. If radiation pressure is not responsible for the observed mass loss rates then it cannot be responsible for the observed terminal velocities either. Elsewhere in these Proceedings, articles by Abbott and Cassinelli discuss radiation pressure and a range of other possible mechanisms which might drive the winds of Wolf-Rayet stars.



Table 1. Mean Wolf-Rayet wind parameters.

Spectral Type	WN5	WN6	WN7	WN8	WC5	WC6	WC7	WC8
$\log(L/L_0)$	5.08	5.47	5.65	5.68	5.44	5.18	5.18	5.05
$v_\infty$ (km s <sup>-1</sup> )	2600	2400	2600	1800	3700	(3500)	3300	2000
$\dot{M}$ (10 <sup>-5</sup> M <sub>0</sub> yr <sup>-1</sup> )	2.2	2.9	3.6	3.6	3.8	3.4	4.9	4.3
$\dot{M}v_\infty c/L$	22	12	11	7	25	38	53	38

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## DISCUSSION

Carrasco: I think that it is unfair to conclude ( at present ) that there are no evolutionary effects in the relationship between the mass loss rates and stellar luminosities. We have found a correlation between different values of the ratio of terminal velocity to escape velocities and the degree of stability in a given atmosphere as measured from its departure from Eddington's stability line. Hence mass loss rates would then depend upon both effective temperature and effective gravity of the atmosphere and not upon the stellar luminosity alone. This obviously implies a relation with evolutionary stages.

Barlow: The gist of the comments in my review was that a dependence of  $\dot{M}$  on other stellar parameters besides luminosity has not yet been conclusively demonstrated observationally. It may be there and it is to be hoped that future observations will settle the question.

Underhill: Careful comparison of the profiles of lines formed in the winds of O, B and WR stars with the profiles predicted by means of the theories which you have reviewed shows many discrepancies which are greater than those which result from the use of the " narrow-line " approximation of Sobolev. Better agreement between theory and observation might be obtained by postulating a different arrangement of the material in the mantle of the star from that obtained by postulating the outflow of matter in spherical shells according to an ad hoc velocity law. These other possibilities, which include the "suspension" of gas in magnetic loops should be explored before concluding that we have a satisfactory understanding of mass loss from O, B and WR stars. Discrete components come and go and they appear at different velocities at different times. Postulating a plateau in the velocity law is an inadequate explanation for their presence.

Barlow: It would be interesting to see models such as you suggest actually calculated.

Massey: Certainly the most infamous of the WR stars which show O VI  $\lambda$  3811,3824 is the WN3 "pec" star HD 104994. Its optical spectrum looks very much like that of other WN3 stars. Why do you see O VI here? The overall envelope excitation must be similar to the other WN3's.

Barlow: For the very highest stellar temperatures one would expect almost all oxygen to be in the  $O^{6+}$  ionization stage. Due to the dependence of recombination rate on nuclear charge squared this will give rise very efficiently to O VI lines. However, if this WN3 star has an absolutely identical spectrum to other WN3 stars, apart from the presence of O VI lines, then one would presumably have to invoke a higher abundance of oxygen.