OBSERVATIONS OF STELLAR WINDS IN EARLY TYPE STARS

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I. INTRODUCTION

I have been asked to review the "observations" of winds in "early-type" stars. This normally means stars of spectral type OB and those of the Wolf-Rayet (WR) class. In this paper I will concentrate on the massive population I stars of these types, and primarily the O and WR classes on which most of the recent work has been done. The early B type supergiants share many of the wind properties of the O stars but the later supergiant types, Be stars, and main sequence stars may not. Stellar winds are a ubiquitous phenomenon among these early type stars (Snow and Morton 1976). We see evidence of their winds in the resonance line P Cygni profiles in the UV region, in the emission lines of Hα and λ4686 He II in the optical spectrum, and in the free-free emission from the ionized plasma as observed in the IR and radio regions of the spectrum.

The physical parameters of a stellar wind can be conveniently grouped into four separate entities. We speak of a velocity law $v(r)$, and a density law $\rho(r)$, shown schematically in Figure 1; an ionization state law $I(r)$ and the chemical (or more correctly atomic) composition law $C(r)$, where the radius r is scaled in terms of the stellar radius R^*. We expect that the velocity law $v(r)$ attains a terminal velocity v_∞ and find in some cases this value can be measured. The density falls off more steeply than an inverse square law up to the point where the terminal velocity is reached--after which it follows r^{-2}. We expect (perhaps hope is a better word) that in all stars the $v(r)$ and $\rho(r)$ are single valued and schematically follow Figure 1. According to the radiatively driven wind theory of Castor, Abbott and Klein (1975, hereafter CAK), analytic expressions for $v(r)$ and $\rho(r)$ may be formulated. A test of a theory is how well it reproduces the observations, a point I will return to later.

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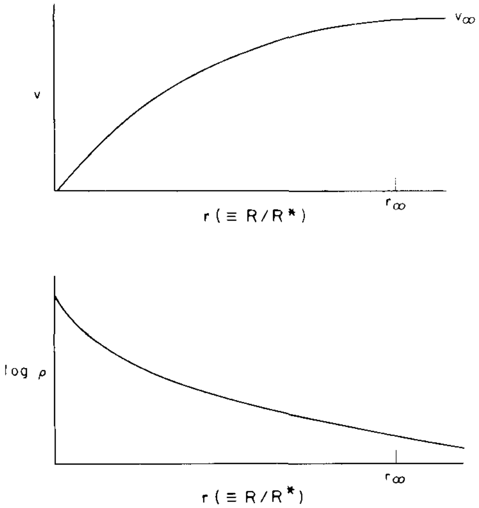

Figure 1. Schematic representations of the velocity law v(r) and density law ρ(r) of the stellar winds of early type stars.

For the ionization state, I(r), there are currently only rough estimates as to the form of the dependence upon r; it may well be different for individual ions, depending on the ionization temperature and the local density. There could well be cases where the ionization is constant throughout the wind or where it increases, or decreases, outwards. The functional form may not be single valued and cannot yet be treated analytically. We expect that the chemical composition is constant throughout the stellar wind and given the flow time for material to transit the wind, of the order of hours, it is identical to the surface values.

It would be nice to discuss all of these parameters in some depth but the usual thrust of work in the literature has been to derive the mass loss rates from the available observational data and analysis. I shall therefore restrict myself to a discussion of the derived rates, and indicate what conclusions can be drawn from them.

The mass loss rate can be written as

$$\dot{M} = 4\pi r^2 \rho(r) v(r) \qquad (1)$$

under the usual assumptions of spherical symmetry and homogeneity. I will later return to these basic assumptions which underlie all mass loss determinations in the literature. There are two spectroscopic methods and two continuum methods to determine the mass loss rates via Eq. (1). These use different ways of estimating the variables on the right-hand side of this equation.

One spectroscopic method makes use of the P Cygni profiles of resonance and metastable lines of common elements, which in early type stars are invariably found in the far ultraviolet (UV) region of the spectrum. In a few stars, emission profiles can be seen in the subordinate lines of hydrogen and helium, namely at Hα and λ4686 He II in the visible region of the spectrum. I shall refer to these two spectroscopic methods as the UV and the optical.

Since the stellar winds are highly ionized they also contain electrons. These emit free-free radiation which can be detected in some cases. The expression relating the mass loss rate to this emission was given independently by Panagia and Felli (1975) and by Wright and Barlow (1975). It can be written in the form

$$\dot{M} = \frac{0.095\ \mu}{Z\gamma^{1/2}g}\ \frac{S_\nu^{3/4}D^{3/2}v_\infty}{\nu^{1/2}} \tag{2}$$

where the mean molecular weight, μ, the mean ionic charge, Z, and the mean number of electrons per ion, γ, depend primarily on H/He ratio and the I(r). The other parameters are g, the Gaunt factor, S_ν the flux at frequency ν and the distance D. The S_ν is proportional to ν^α, where the α is referred to as the spectral index and is <1. To obtain a mass loss rate, the distance must be known, and the S_ν and v_∞ are measured. The other factors of Eq. (2) are estimated from the presumed properties of the wind. Equation (2) holds only in the case of a density law $v(r) \sim r^{-2}$, i.e. beyond a point at which the terminal velocity is reached. This free-free excesss has been detected in the infrared (IR) regions of the spectrum 1-20 μm and in the radio regime, e.g., at 6 cm. I shall distinguish between these two kinds of continuum detections as IR and radio, respectively.

Of the four methods, the UV one is currently the most sensitive and can detect the smallest mass loss rates. Work has been done primarily with the Copernicus and now IUE satellites. The optical method is basically limited to the stars that have the highest rates so that Hα or λ4686 come into emission against the background of a photospheric absorption at these wavelengths. This requires sensitive signal-to-noise detectors, which are just now becoming available. The IR method is potentially the most sensitive but is currently detector limited. Although the S_ν falls off with increasing wavelength, it does so less steeply than the continuum radiation from the star; one is always attempting to measure the excess flux against a stellar continuum background. I would expect that the newest IR telescopes, and the planned satellite ones, which can operate at submillimeter wavelengths, will be the best hope for observations of faint objects with weak winds. The most sensitive radio telescope is presently the very large array (VLA) operating at 6 cm. Its 20 cm detectors are currently being assembled. The VLA is detecting stars with winds of similar strength to those found by the current IR detectors, but with less ambiguity: The IR radiation comes from a region of the wind where the velocity law has not yet reached the terminal value. A model law must therefore be specified for the IR method, whereas the radio detection is, in principle, unambiguous according to Eq. (2). I shall now discuss each of these methods in some detail in the following section. The results will mostly be deferred to Section III.

II. METHODS TO DETERMINE THE MASS LOSS RATE DETERMINATIONS

a) UV method

Figure 2 shows an idealized P Cygni profile. It is idealized both for its sharp violet edge which may be unequivocally identified with a terminal velocity and because it is unsaturated, that is, some radiation escapes at all wavelengths. Such a profile is observed by a scattering of photons from an ion, as seen in projection against the stellar disk. Observed profiles of some lines in some stars look remarkably similar to that illustrated in Figure 2 so it seems reasonable to proceed with the theory describing such a profile.

Under the usual assumption of a Sobolev approximation (wind velocity large compared to the sound velocity -- a very reasonable assertion) a radial optical depth for scattering may be written (Olson 1980, following CAK)

$$\tau_r(r) = \frac{\pi e^2}{Mc} f\lambda_0 n_i \left(\frac{dv}{dr}\right)^{-1} \tag{3}$$

where in addition to the usual constants, f is the oscillator strength, λ_0 the rest wavelength of the transition, n_i the density (cm^{-3}) of absorbers, and dv/dr is the radial velocity gradient. The density is the unknown so one must model the τ_r in terms of the parameter $W = v/v_\infty$. The most commonly used parametrization is that of Castor and Lamers (1979) who write (3) in the form

$$\tau_r(w) = T(1+\gamma)(1-w_0)^{-1-\gamma}(1-w)^\gamma \tag{4}$$

where

$$T = \int_{w_0}^{1} \tau_r(w)dw = \frac{\pi e^2}{Mc} \frac{f\lambda_0}{v_\infty} N_i$$

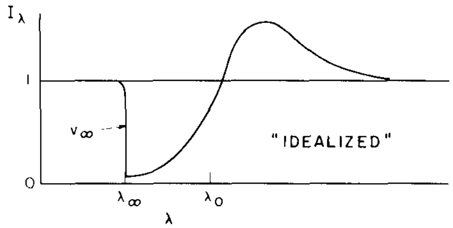

Figure 2. Idealized P Cygni profile of a resonance line formed in a stellar wind.

and N_i is the column density (cm^{-2}). One then adjusts the T and γ to fit the observed profile. Since the n_i and N_i differ for various ions in the same stellar wind, it is helpful if more than one P Cygni profile is available. Unfortunately, such is not always the case.

The mass loss rate, under the fundamental assumptions of spherical symmetry and homogeneity, can then be written in the form

$$\dot{M} = 4\pi r^2 v(r) \mu M_H \frac{n_i(r)}{g_i A} \tag{5}$$

where g_i is the fractional ionic abundance and A is the number abundance relative to hydrogen. Combining the last two terms we then can write the complete expression for a given line:

$$\dot{M} = \frac{4\pi\mu M_H}{f\lambda_0} \frac{Mc}{\pi e^2} \frac{[r^2 v(r) dv/dr]}{g_i(r) A} \tag{6}$$

Near $v = 1/2\ v_\infty$ the quantity in brackets is a very insensitive function of v(r). One estimates T and γ from the observed profile, and evaluates τ_r at $w = 1/2$. If it is then possible to specify g_i at this point the mass loss rate may be estimated. This last step is currently the weakest link in the derivation of mass loss rates from UV spectra. This is especially true because the commonly observed resonance lines of Si V, C IV, N V and O VI are not in the predominant ionization stages and large corrections to the total element abundance must be made.

Subsequent to giving this talk in Trieste, I found that G. Olson (1980) had devised a method for treating P Cygni lines in excited states by an analysis similar to that described above. The advantage of his method is that excited lines of O IV and O V are observed in some early type stars and these ionization stages dominate the total oxygen abundance. On the other hand, for such lines, an excitation temperature must be estimated, an additional complication. However, the combination of resonance and excited lines in the same star does give one additional confidence in the results. Such work is currently proceeding at JILA.

Ideally, one proceeds with such P Cygni line profile analysis with as many lines as are available. If several ions of different species are available, reasonable estimates of T and γ can be made and an iterative procedure can be followed for the ionization balance. Individual results have been reported by Gathier, Lamers and Snow (1981), Conti and Garmany (1980a,b) and others, summarized by Lamers (1981). A more detailed model, taking into account X-ray data, has been given for eight stars by Olson and Castor (1981).

A serious observational constraint is that typically only a few lines are available. In addition, in stars with relatively strong stellar winds such as Of and WR stars, the resonance lines are saturated and give no information on the mass loss rate (Castor and Lamers 1979). An example of the fitting procedure implicit in the use of Eq. (4) and the parametrization is given in Figure 3 (adopted from data of Conti and Garmany). This figure indicates a reasonable fit between the model and observed profiles (from IUE spectra). I have shown vertically two pairs of stars with similar spectral types. Each is a member of the same cluster and the M_V are known from the measured magnitudes. We see that in both cases the brighter star has the weaker C IV line. Since the stars have similar spectral types (hence ionizations) these must indicate real differences in mass loss rates. I wish to emphasize that the stars with the higher rates are the fainter in both cases. I will return to this matter in Section III when I discuss all the data.

b) Optical method

Figure 4 shows a schematic idealized profile of an optical line, say Hα. Two cases are indicated, one with a relatively weak emission in which the absorption contribution must be fully taken into account, and one with a strong emission in which the absorption can be nearly neglected. The theory underlying the derivation of the mass loss rate from the core of such a line has been outlined by Klein and Castor (1978), again following the precepts of CAK.

Like the UV method, this spectroscopic determination is sensitive to the adopted model. Klein and Castor made detailed statistical equilibrium calculations for the hydrogen and ionized helium lines. The models were basically scaled to the same v(r) relation, but had different masses and effective temperatures. The Hα equivalent width was then found to scale as the square of the mass loss rate. The largest uncertainties in this method are the adoption of a scaled v(r) relation and the predicted contribution of the absorption part of the Hα or λ4686 profiles, possibly complicated by rotation. The Sobolev approximation, and the usual assumptions of spherical symmetry and

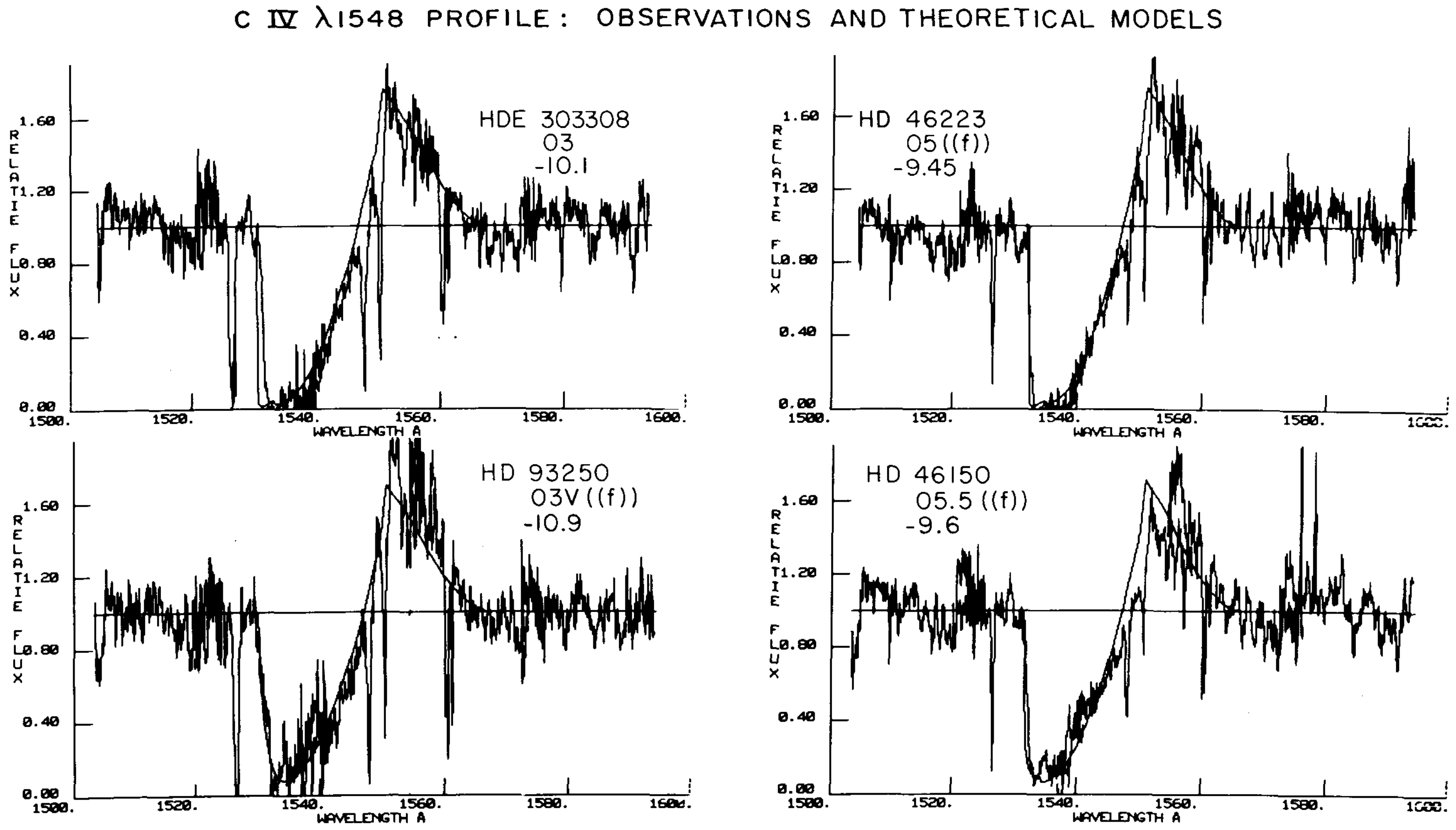

Figure 3. Observed P Cygni profiles of the C IV resonance doublet and a parametrized modeling -- adapted from Conti and Garmany (1980b). The fit is reasonably good, and the overall appearance of the lines is similar to the idealized case illustrated in Figure 2. The stars shown are of similar spectral types and in clusters where their M_V may be determined.

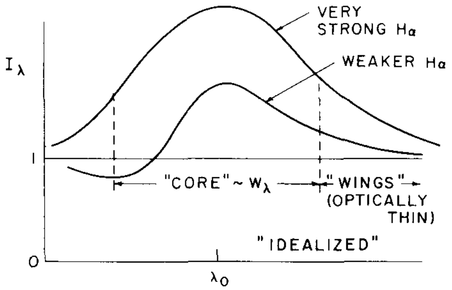

Figure 4. Idealized Hα emission profiles. Two cases, of stronger and weaker line strength, are illustrated.

homogeneity also apply. Klein and Castor derived mass loss rates for a number of stars, based on the Hα and λ4686 measures of Conti and Leep (1974).

An alternative derivation of the mass loss rate from the optical emission lines has been outlined by Olson and Ebbets (1980). This makes use of the "wings" of the line, rather than the core used by Klein and Castor (1978). Olson and Ebbets proceed by an analytic integration of the source function for Hα in the optically thin case; the fitting involves measuring the intensity as a function of distance from line center. This method needs very accurate line profiles, but has the advantage that it is not necessary to assume a velocity law _a priori_. The velocity law is instead estimated from the intensity measurements. Linear electronic detectors, such as the coude reticon used by Olson and Ebbets are now sensitive enough that 1% or better accuracy may be obtained. This new method is a powerful one to determine mass loss rates from spectroscopic observations but is basically limited to stars with the highest mass loss rates. Ten stars were discussed by Olson and Ebbets but more are amenable to this kind of treatment.

c) Infrared (IR) method

The basic relationship between the mass loss rate and the observed free-free flux is given by Eq. (2). However, for IR work, this emission comes from a region of the stellar wind where the velocity is less than the terminal velocity, hence the density falls more steeply than an inverse square law. A velocity law, v(r), must therefore be specified, _a priori_. Most of the current observational material and the details of this method are contained in the paper by Barlow and Cohen (1977), in which they discuss their data for ten luminous O type stars and other later types. Results for WR stars have been reported by Hackwell, Gehrz and Smith (1974), and by Cohen, Barlow and Kuhi (1975).

In IR work, one needs to measure an "excess" emission, that above the stellar continuum. The continuum itself must be specified, which involves knowledge of the effective temperature and the stellar model. The interstellar reddening and the total-to-selective extinction must also be known. A number of IR wavelengths need to be measured such that the free-free emission can be accurately estimated. In a few cases, notably those of late type WC stars, dust is also present in a shell surrounding the star and its thermal emission must be disentangled from the free-free radiation (Hackwell et al. 1974).

As contrasted to the spectroscopic results, the continuum methods depend on the stellar distance, as $D^{3/2}$. Other than this, the largest uncertainty in the IR mass loss determination is the adopted velocity law. Usually a CAK form of the law is adopted and all stars scaled together. The law adopted by Barlow and Cohen (1977) themselves was that for P Cygni. This was later criticized by Castor and Lamers (1979) who suggested that such a law was too "shallow" to represent most OB supergiants. A modification of their v(r) to one near that of CAK indicated mass loss rates about a factor two higher than those found by Barlow and Cohen (see, e.g. Lamers, Paerels, and de Loore 1980). Such an arbitrary scaling has usually been adopted in the subsequent analyses. The IR method also makes use of the assumptions of spherical symmetry and homogeneity.

d) Radio method

For free-free emission at cm wavelengths, the energy comes from a region of the wind where the terminal velocity has been reached. In this case, although a velocity law does not need to be specified, a terminal velocity must be known. Fortunately, the advent of the IUE satellite has made such data available for nearly all stars in which radio detections have been made. In principle, then, the radio method is the least model dependent, and should be the most accurate. Again, the results depend on the assumptions of spherical symmetry and homogeneity.

Radio telescope detections and mass loss rates have been reported by Abbott, Bieging, Churchwell and Cassinelli (1980) and Abbott, Bieging and Churchwell (1980) for OB stars, and by Seaquist (1976), Dickel, Habing and Isaacson (1980), and others, for WR stars. These results have to date been limited to the nearest stars with the largest mass loss rates. So far, nearly all the detections have been at single wavelengths, notably 6 cm for the VLA. It would be useful to observe some stars at more than one wavelength to determine that the emission follows Eq. (2), as it must if the emitting material is in a region of the wind at the terminal velocity.

A modification of the IR/radio detection method was made by Barlow, Smith and Willis (1980). They noted that the spectral indices between the 10 μm and 6 cm wavelengths for two dissimilar WR stars, were 0.69 and 0.75. They then argued that if all WR stars scaled similarly, one could use IR measurements to estimate the radio flux by using a mean α of 0.7, and thereby not need a priori knowledge of the velocity law. The terminal velocities were obtained from the IUE data. This method assumes that in the outermost parts of the wind the v(r) relation scales similarly among all WR stars. Although this has no theoretical basis as yet, it does appear to be a nice way to proceed at the current level of our understanding. Barlow et al. provided mass loss rates for 21 WR stars.

III. RESULTS

In the previous section I have listed the important sources of data for mass loss rates. Lamers, Paerels and de Loore (1980) have discussed most of these data -- with the exception of the newer UV spectroscopy of Conti and Garmany (1980a,b) and the VLA results of Abbott, Bieging, Churchwell and Cassinelli (1980) and Abbott, Bieging and Churchwell (1980). Lamers et al. adopted a scaling of all the mass loss rates to the radio detection result for ζ Pup given by Morton and Wright (1978). This is based on the belief that the radio method, being the most model independent, should be the most reliable. Lamers (1981) has further followed this precept in scaling mass loss rates to those of three O type supergiants detected with the VLA (Abbott, Bieging, Churchwell and Cassinelli 1980). There are two fundamental difficulties with this: one of practice and one of principle.

The practical problem is with the data. A subsequent VLA detection of ζ Pup was about a factor two smaller than that found by Morton and Wright (1978) necessitating a revision in the scaling for ζ Pup. Furthermore, Abbott et al. detected 9 Sgr with the VLA; these data were not used by Lamers (1981) because they were "too discrepant" with the other methods. A scaling procedure is therefore highly dependent on the selection of the data, and can change as newer data become available.

Aside from this problem, there is a more important difficulty. If one adopts a scaling law one makes the assumption that the stellar winds of the stars being considered are similar in their v(r) and ρ(r) relations, differing only in the total density, and hence in mass loss rate (the ionization differences are accounted for in the analysis). I do not believe there is any theoretical basis for such an assertion; furthermore the data are insufficient to enable us to show that it is true on an empirical basis.

In fact, the few data we do have on mass loss rates suggest that the stellar winds are not similar. In Table 1, I have given mass loss rates for a few of those O type stars for which more than one determination has been made. The only adjustment in these data is for the IR results of Barlow and Cohen (1977) which have been revised upwards by 0.3 following the theoretical arguments of Castor and Lamers (1979) that their adopted velocity law was too "shallow." We see for a few stars, ζ Pup, HD 14947 and Cyg OB2 #5 (a double-lined spectroscopic binary by the way) that the differences among the various methods are usually less than a factor two. So far, so good. But what are we to make of the results for 9 Sgr and Cyg OB2 #9 which differ by more than a factor ten? For these single stars there seems no obvious explanation for the discrepancies; certainly an arbitrary scaling would obscure the results. Portions of Table 1 suggest the possibility that perhaps some of our understanding of stellar winds is not complete.

I have mentioned already that all mass loss determinations are based on the assumptions of spherical symmetry and homogeneity. How do these affect the results? Such an answer is not simple but depends on each method. One could imagine a rotationally distorted star with a nonspherically symmetric wind, leading to very different results depending on the ratio of the axes, and the viewing angle. For the UV method the projected cross section is important but for the Hα and IR methods the total volume is important. For the radio determination, however, the wind, now being far from the star, may well have a more spherically symmetric appearance. In the case of nonhomogeneity, or clumping, the continuum methods give only upper limits and the real rates may be less. Nonhomogeneity also affects the spectroscopic methods but differently. A combination of clumping and nonspherical

Table 1
Intercomparison of Mass Loss Rates (selected O stars)

Star	Spectrum	Radio	IR*	Optical	UV
ζ Pup	O4 ef	-5.4	-5.2	-5.1	-5.2
9 Sgr	O4	-4.6			-5.6†
HD 14947	O4f		-5.3	-5.1	
Cyg OB2 #9	O5f	-3.9		-5.0	
Cyg OB2 #5	O7f	-4.7		-4.7	
ζ Ori	O9.5I	-5.6	-5.7	-5.5	-5.6‡

*Barlow and Cohen data adjusted by +0.3
†Conti and Garmany obtained -6.2.
‡Olson and Castor obtained -6.3

symmetry might lead to very different results from the various mass loss methods. It might pay to have some attention given to these problems.

In any case, the results of Table 1 suggest that for many stars we can trust the mass loss rates to a factor two; for some others, the numbers may be far off. I think one must also be very careful in drawing definitive conclusions about the effect of mass loss on stellar evolution when the rates are still uncertain by even a factor as small as two; such uncertainties can make a substantial difference in the final outcome. This uncertainty also affects the controversy between the predictions of the radiatively driven wind (CAK) and fluctuation theory of Andriesse (1979). These theories predict rather different dependences of the mass loss rate on the luminosity. Different selections of the data (e.g. Chiosi 1980, Lamers 1980, Andriesse 1980) lead to dissimilar conclusions. I suspect the data are not yet stable enough to enable us to determine this outcome, even leaving out the problem of the highly discrepant stars.

Even with these problems, there are two interesting conclusions that can be made at the present time. In Figure 5, I show my selection of the data: these show mass loss rates as a function of luminosity. These are taken from the extensive compilation of Conti and Garmany (1980b), which still is very preliminary. Most of their UV data are based on the C IV resonances line. Garmany and Olson have now added lines of other elements and some of the excited transitions of O IV and O V. These have changed some of the values for the various stars but the overall appearance of Figure 5 is unchanged and the conclusions I will draw are still tenable. The rates for the WR stars come from Barlow et al. (1980).

We see first of all in Figure 5 that there is a relationship between mass loss rate and the luminosity in the sense that for normal stars, the more luminous ones have higher rates. We also see that at any given luminosity, there is dispersion in the rate which is between a factor 10 and 100. This cannot be accounted for by any error in the analysis but must be real. To illustrate this scatter another way, recall Figure 3 in which pairs of stars with similar spectral types and known luminosities (from cluster membership), indicate also a dispersion in the C IV line strength, hence the mass loss rate, such that it cannot depend uniquely on the luminosity. We may thus conclude that a major contributor to the mass loss rate is the luminosity; but this cannot be the entire story.

Furthermore, we can note from the different symbols of Figure 5 that at the present time the various methods sample different mass

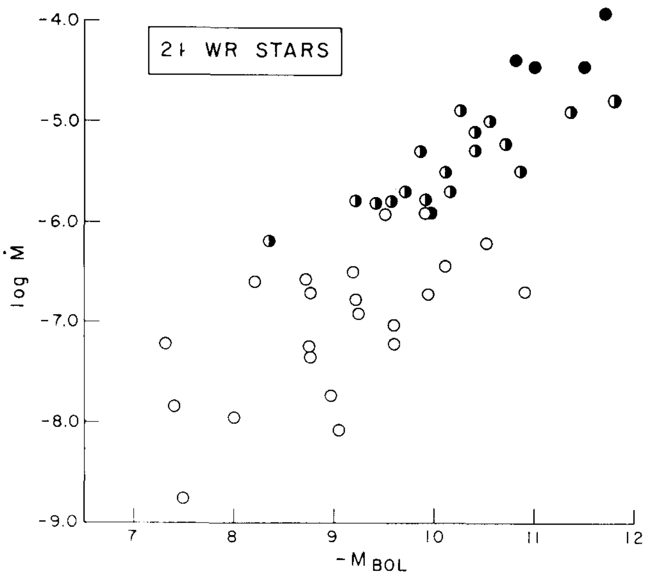

Figure 5. Mass loss rate as a function of luminosity: O -- rates determined from UV data; ◑ -- rates determined from optical and/or continuum data; ● -- rates determined from radio data (VLA) alone. Different methods sample different mass loss rates. There is some overlap in determinations for those stars indicated by half-filled symbols. Even among these, there is some unaccounted scatter -- Table 1. Leaving this problem aside, one sees that more luminous stars have higher mass loss rates in general, but there is a substantial dispersion in the relation between $\dot{M}$ and L.

loss rates. The continuum and Hα methods primarily detect the highest rates, and the UV method detects the lowest values. This is implicit in the methods and the current technology. An improvement in the IR detection capability will probably make it possible to sample stars with the weakest stellar winds.

We see that the WR stars discussed by Barlow *et al.* (1980) have very similar rates, to within a factor two of $4 \times 10^{-5}\ \dot{M}\ \mathrm{yr}^{-1}$. I find this somewhat ironic in view of the substantial spectroscopic differences among these stars. As contrasted to the normal O and O(f) stars of Figure 5, which have similar spectra but substantially different mass loss rates, the enigmatic WR stars with very dissimilar spectra have very similar rates. It must be remembered that the mass loss rates for WR stars are currently based entirely on IR measures, and not on the spectrum. The spectrum is complicated by questions of composition, let alone a correct wind model. It will be interesting to see why it is that for WR stars the spectrum does not have much to do with the IR excess. I doubt that this would have been predicted even with our current limited understanding of stellar winds.

IV. TENTATIVE CONCLUSIONS

I will discuss this in two parts: what I would consider to be our current beliefs, and what can be considered as unresolved issues. These represent my personal appraisal of the situation at the present time. Considering the rapid changes in this field of stellar astrophysics, these should only be thought of as opening a dialog.

Current beliefs about early type stars:

1. All have stellar winds. The mass loss rates range from 10^{-8} to 10^{-4} $\dot{M}$ yr^{-1}.
2. There is a tendency for $\dot{M}$ to depend on L, but there is a dispersion at a given luminosity, which is between a factor 10 and 100, which cannot be due to error in the analysis.
3. The winds are primarily driven by radiation pressure from the UV lines, but other, as yet unknown factors, may determine the density and hence the rates.
4. The stellar winds are highly ionized, more so than would be inferred from their continuum radiation temperatures. The ionization equilibrium in the winds is affected by local X-rays which have been detected by the Einstein satellite.
5. Variability in the stellar winds is a common phenomenon, occurring at about the 50% level in the density, and possibly with slight changes in the terminal velocities. This is not understood but may be related to items above.

Unresolved issues:

1. Are assumptions of spherical symmetry and homogeneity justified?
2. Do real stellar winds have single valued velocity and density laws?
3. What other physical mechanism(s) could be important in the stellar wind?
4. What is the source of the X-ray emission?
5. What is the role of rotation, "turbulence," and magnetic yields?
6. What is the source of the variability in the stellar winds? (Is a radiatively driven flow inherently unstable?)
7. To what extent does mass loss affect stellar evolution?

These are all important issues to which increasing attention will be paid in the forthcoming year. We certainly need more data on mass loss rates, but we also need more theoretical understanding. I would like to close with what I consider a current enigma, namely: O stars have similar spectra and luminosities, but very different mass loss rates. WR stars have very dissimilar spectra and lumonosities but similar mass loss rates. How can this be?

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References

Abbott, D. C., Bieging, J. A., Churchwell, E., and Cassinelli, J. P.: 1980, Astrophys. J. 238, 196.
Abbott, D. C., Bieging, J. A., and Churchwell, E.: 1980, preprint.
Andriesse, C. D.: 1979, Astrophys. Space Sci. 61, 205.
Andriesse, C. D.: 1980, Monthly Notices Roy. Astron. Soc. 192, 95.
Barlow, M. J., Smith, L. J., and Willis, A. J.: 1980, Monthly Notices Roy. Astron. Soc. (submitted).
Barlow, M. J. and Cohen, M.: 1977, Astrophys. J. 213, 737.
Castor, J. I., Abbott, D. C., and Klein, R. I.: 1975, Astrophys. J. 195, 157.
Castor, J. I., and Lamers, H. J. G. L. M.: 1979, Astrophys. J. Suppl. 39, 481.
Chiosi, C.: 1980, Astron. Astrophys. (in press).
Cohen, M., Barlow, M. J. and Kuhi, L. V.: 1975, Astron. Astrophys. 40, 291.
Conti, P. S. and Leep, E. M.: 1974, Astrophys. J. 193, 113.
Conti, P. S. and Garmany, C. D.: 1980a, Astrophys. J. 238, 190.
Conti, P. S. and Garmany, C. D.: 1980b, in Proceedings of the Symposium on the second year of the IUE (in press).
Dickel, H. R., Habing, H. J. and Isaacson, R.: 1980, Astrophys. J. Letters 238, L39.
Gathier, R., Lamers, H. J. G. L. M., and Snow, T. P.: 1980, Astrophys. J. (in press).
Hackwell, J. A., Gehrz, R. D. and Smith, J. R.: 1974, Astrophys. J. 192, 383.
Klein, R. I. and Castor, J. I.: 1978, Astrophys. J. 220, 902.
Lamers, H. J. G. L. M.: 1981, Astrophys. J. (submitted).

Lamers, H. J. G. L. M., Paerels, F. B. S., and de Loore, C.: 1980, Astron. Astrophys. 87, 68.

Morton, D. C. and Wright, A. E.: 1978, Monthly Notices Roy. Astron. Soc. 182, 47.

Olson, G.: 1980, Astrophys. J. (submitted) and private communication.

Olson, G. L. and Castor, J. I.: 1981, Astrophys. J. (submitted).

Olson, G. L. and Ebbets, D.: 1980, Astrophys. J. (submitted).

Panagia, N. and Felli, M.: 1975, Astron. Astrophys. 39, 1.

Seaquist, E. R.: 1976, Astrophys. J. Letters 203, L35.

Snow, T. P. Jr., and Morton, D. C.: 1976, Astrophys. J. Suppl. 32, 429.

Wright, A. E. and Barlow, M. J.: 1975, Monthly Notices Roy. Astron. Soc. 170, 41.

DISCUSSION

FRIEDJUNG: I wish to compare these stars with even more unusual stars like novae. I would like to know what is the ratio of kinetic energy flux to radiative flux.

CONTI: 1/10% for O stars, rising to 1% for WR's.

GOLDBERG: You first pointed out that the methods based on UV-optical observations are relatively uncertain as compared to the radio method. But then you worried about discrepancies between the two. Is not the real problem the uncertainty of the optical method?

CONTI: There is some uncertainty in the optical/UV method for determining $\dot{M}$ but not enough to account for the difference in all cases. For example, in 9 Sgr, the radio rate gives a number similar to that for "strongest" Of stars, yet there is no optical emission; similarly for most Of stars the major UV P Cygni lines are saturated but they are not in 9 Sgr. If the radio detection is not spurious we would have to conclude that some of our understanding of stellar winds is incomplete perhaps the spherical symmetry or homogeneity assumptions are not valid in all cases.

VANBEVEREN: If one determines the $\dot{M}$ from spectral analysis (UV or H_α) one assumes that the star has a solar abundance. However one only has to remove some 20% to 30% of the stellar mass in order to see layers that were originally in the convective hydrogen burning core. Computations reveal that these layers have the equilibrium CNO abundances which are very different from the solar ones. Do you think that if these layers reach the surface the $\dot{M}$ determinations may be considerably different than the values obtained with solar abundances?

CONTI: I think that O and Of stars have normal H and He, but perhaps the latter stars might have a low C/N ratio, as you indicate. This would effect Of UV rates, but often the lines are saturated anyway and not used. Certainly in WR stars we suspect anomalous composition but the published rates for those stars are based upon IR or radio emission detections.

MOFFAT: Concerning variability of stellar winds I have photoelectric data for ζ Pup obtained over a large number of nights with a small telescope which show periodic variability of the depth of the P Cygni absorption of H_α. The period derived is 5 days, the same as the period of rotation of the photosphere ($2\pi R/V_{Rot}$) derived from the broadening of the photosphere absorption lines. Thus, we have evidence for the first time of a wind perturbation corotating with the photosphere. The constraining force may be provided by a magnetic field as recently speculated theoretically by Mihalas and Conti (1980, Ap J); ζ Pup shows no radial velocity variations so this cannot be due to binary pertubation.

CONTI: This is an interesting result. I understand Landstreet has a new upper limit measure to an ordered (dipolo) field of ~100 G in ζ Pup. However, a disordered field could be present and might also give co-rotation.

PISMIS: You showed us two cases with two stars each where the stars have similar luminosities and spectra but that their mass loss rates are different. It may well be that the velocity profiles are variable within each star and that such variation is similar in the two stars but that one is observing them at different phases of their variation. As regards the variability itself this could be explained if the mass loss rate from the star is not isotropic; instead it is from regions, active spots on the star. Our previous work on the velocity field in three symmetrical nebulae has given sufficient evidence that these nebulae are essentially formed by ejection from the central stars; that ejection has not been spherically symmetrical but rather from diametrically opposite regions on a rotating star whose axis of rotation is oblique to this diameter. My suggestion is the following: if the stars have ejected mass in the past non-isotropically it is reasonable to expect that their present mass ejection (all three stars show P Cygni profiles) is taking place in the same fashion, we should then consider seriously the possible non-isotropy of stellar winds caused by the non-isotropy of the underlying mechanism.

CONTI: As to your first part, I don't believe variability can account for the observed differences. There is not a lot of data yet but subsequent IUE spectra of several stars do not indicate CIV profiles once saturated to become unsaturated, or conversely. The differences between the pairs of stars are considerable. Non-isotropy may be an important feature just out of the current formulation, as I have indicated in the text.