13. — ON THE RELATIONSHIP BETWEEN OF AND WR STARS

by

PETER S. CONTI (*)

Joint Institute for Laboratory Astrophysics
University of Colorado and National Bureau of Standards
Boulder, Colorado 80302, U.S.A.

ABSTRACT

Of, WR, and P Cygni types are spectral classifications assigned to several different very hot and luminous stars with emission lines. They manifest what can be recognized as a similar physical phenomenon: stellar winds. Of stars appear to be otherwise normal O stars with temperatures and/or luminosities high enough that an expanding envelope which produces the observed emission lines is formed surrounding the star. WR stars are highly evolved objects with a much denser envelope, lower mass, and differences in composition from normal O stars caused by mass loss and mixing within the star. P Cygni stars are also highly evolved objects with envelopes less dense than WR stars, but much more extended. Some Of stars are also called P Cygni stars, and conversely. The former objects have winds which are accelerating outward, in some cases modified by rotation; the latter objects, generally cooler, have decelerating winds. The mass loss rate of single Of stars from their stellar winds may be sufficient to produce what we would identify as a single WR star. Of stars in binary systems may evolve to WR stars in binary systems. P Cygni stars represent a very heterogeneous sample of objects, not all of which have had an identical history.

INTRODUCTION

I have been asked in this review to discuss what we presently know about the physical properties of the so-called Of, WR, and P Cygni type stars. These terms are labels attached to those stars that fit certain rather arbitrary spectral classification parameters. The term Of was introduced by Plaskett and Pearce [1] to denote O type stars with emission present at λ 4634, 40 NH III and λ 4686 He II. WR stars are very hot stars with broad wide emission lines of the ions of helium, carbon, nitrogen, and oxygen which were first noted spectroscopically by Wolf and Rayet [2]. P Cygni types are assigned to stars showing line profiles having a violet shifted absorption and a more or less central emission (e.g. Beals [3]).

I cannot completely review the entire field of Of, WR, and P Cygni stars, although I will cover in some detail the Of stars on which I have worked quite a bit myself. Two fairly recent Symposia have treated the WR stars [4], [5] in considerable depth, and the interested reader can refer to these volumes. There has not lately been a summary of the P Cygni stars, although the article by de Groot [6] is useful and a recent paper by Kuan and Kuhi [7], to which I refer later, is quite important.

(*) Also Departments of Astogeophysics and Physics and Astrophysics.
In §II I shall discuss some more modern descriptions of these classes of stars and pay particular attention to the nomenclature which underlie the spectral classification. In particular, it should be realized that the term "P Cygni" refers to a very heterogeneous mixture of stars, with rather different physical and evolutionary properties among themselves. In §III I shall show some sample spectra of Of, WR, and P Cyg stars, and discuss the recent methods we are using to study the spectra of Of stars. Section IV will review what we know of the parameters of luminosity, temperature, and mass of these stars, particularly the Of stars, for which we have now perhaps the best information. An important recent advance in our understanding of these objects has been the realization that mass loss may be fundamentally important. With this in mind, in the last section, V, I shall describe an evolutionary scenario which will, I believe, tie together very nicely the relationship between the Of and WR stars.

II. NOMENCLATURE

a) Of stars.

Of stars are basically O type stars; that is they show absorption lines typical of the O classification scheme. That classification is from O3 to O9.5 the O3 stars being the hottest. The type is dependent primarily on the line ratio of He I \( \lambda 4471 \) to He II \( \lambda 4541 \) and so represents an ionization sequence. Conti and Alschuler [8] and Walborn [9] have listed the spectral types for a large sample of O type stars based primarily upon this line ratio.

Since the original paper on Of stars [1] there has been a gradual evolution of what is classified as an Of star. Examination of the literature reveals that the term Of has been applied to stars showing N III emission even though \( \lambda 4686 \) He II was in absorption, whereas the initial definition required both lines to be in emission. For example a large compilation of coudé spectra of northern O type stars [4] used this kind of classification. Walborn [9], using cassegrain dispersion, studied a somewhat larger sample of O stars in both hemispheres and introduced a spectral notation of O((f)) to denote stars with N III emission but He II absorption; O((f)) for stars with N III emission and He II weak or missing; and Of for both stars showing both groups of lines in emission. It appeared from these studies that the N III lines were found in emission exclusively in the hottest and brightest O type stars, and furthermore all stars in this restricted region of the HR diagram showed N III emission.

The physical basis underlying the N III emission phenomenon has only been understood recently. Bowen [19] proposed that these same N III lines were in emission in planetary nebulae because of a fluorescence mechanism involving the \( \text{Lz} \) He II \( \lambda 303 \) transition with an intermediate \( 3d \, ^2 \Pi \) O III line at the same wavelength. The resultant \( 3s \, ^2 \Pi \) O III cascade to the ground level is in turn coincident with the \( 3d \, ^2 \Delta \) N III transition from the ground state. This way of overpopulating the \( 3d \) level leads to the N III emission lines \( 3d \rightarrow 3p \). This particular process certainly operates in planetary nebulae but has always been a problem to understand in O stars since the O III \( 3d \rightarrow 3p \rightarrow 3s \) transitions should also be in emission and they are not [11].

On the other hand, Swings [12] made the suggestion that for O stars the \( 3d \) N III level is pumped by "continuum radiation". Mihalas, Hummer, and Conti [13] have calculated the theoretical behavior of the ensemble of pertinent N III lines in the O stars, and made a comparison to the observed line strengths. Basically, the \( 3d \)
levels of N III are filled by dielectronic recombination from an autoionizing N IV level. Due to a peculiar arrangement of transition probabilities in the downward transitions from 3p, including some «two electron» jumps, the 3d level remains overpopulated and the 3p level underpopulated. (The detailed theoretical calculations are given by Mihalas and Hummer [14]). All that is necessary for the N III emission mechanism to operate in O stars is sufficient N IV population.

Mihalas et al. [13] point out that the N III emission can occur in a «plane parallel» atmosphere, although they will be stronger if formed in an envelope. For this reason, they refer to N III emission lines as «intrinsic». By contrast, the λ 4686 He II line can be in emission only in an envelope [15], [16] which I will call an «extrinsic» emission line. Physically, the O((f)) stars, although they have N III emission lines, do not necessarily have envelopes, whereas the Of stars, with λ 4686 emission, must have them.

Conti and Leep [17] have discussed the measured line strengths of a large number of O stars, with particular attention to the N III and λ 4686 He II lines, and the Hz line. They find a definite correlation between the presence of λ 4686 emission and Hz emission, except that the latter line can be found in emission in somewhat cooler stars than those showing λ 4686. Conti and Leep feel that Hz also is indicative of an envelope, a point made theoretically by Mihalas [14]. There is a tendency for the most luminous stars to have either Hz or both of these lines in emission which physically means that luminosity and the phenomenon of an envelope are correlated. In fact, all O stars brighter than Mv ~ -6 seem to have envelopes.

For the rest of this paper, the term Of star will then be used to denote generally those O stars with envelopes (even though some may show only Hz emission).

Other emission lines are seen in many O and Of type stars. For example, λ 5696 C III line is found in all luminous O type stars from about type O6 to O9.5 [18], and is probably «intrinsic». The λ 4648, 4650 C III lines appear in many (all?) luminous O stars from types O3 to O7 and also may be «intrinsic». A few other lines, such as λλ 4089, 4116 Si IV and λ 4057 N IV occur in the very hottest stars. Walborn [19] has pointed out that the ubiquitous appearance of the latter line in the very hottest and most luminous O stars suggests that it too is «intrinsic».

All of these lines discussed so far are seen in emission in various WR stars, although invariably of much greater strength. In a few Of stars, other hydrogen lines, or He I lines, are found in emission, a point to which I shall return below.

b) WR stars.

These are very hot stars with broad strong emission lines of the ions of helium and carbon and oxygen, the so called WC subtype, or with nitrogen, the so called WN subtypes. There appears to be some disagreement in the literature as to whether or not the WC types contain any nitrogen, or the WN types either oxygen or carbon but this need not concern us here. With few exceptions, the WR stars do not show photospheric absorption lines; In some WR stars, some emission lines have violet shifted P Cygni absorption components, but in all cases the emission lines certainly dominate the spectrum. Kubi and others [20], [21] have noted the lack of appreciable hydrogen in most WR stars, suggesting that the H/He ratio is low. The few exceptions to this will be noted below. There are numerical subtypes to the WR classes, WN3-WN8 and WC5-WC9, analogous to the O stars. These are based upon various line ratios of the CNO ions [22], [23].
c) P Cygni stars.

This is a very inhomogeneous group of stars. The label appears to have been applied to any stars showing characteristic P Cygni profiles. As such then, many WR and some Of stars would be considered to be P Cygni types and have occasionally been referred to as such in the literature. P Cygni itself is a B type supergiant with many lines with the characteristic profiles, and may not even be very representative of the class [6]. A number of B and A supergiants show P Cygni profiles at Hx [24] although they are not invariably referred to as P Cygni stars (occasionally they are called z Cygni stars after the bright supergiant). The s Ae and Be stars also often show P Cygni profiles [35] as do the T Tauri stars [36] although they are mostly classified with their own peculiar labels.

Although it is probably too late to make such a terminology effective, the term P Cygni star should probably be avoided completely and the word P Cygni type used instead, or better still the term P Cygni phenomenon. Stars showing the P Cygni phenomenon are stars with an outflowing wind, as may be deduced directly from the line profile. In any case, all three groups of stars are representative of Population I objects, with the exception of those WR and Of stars which are nuclei of planetary nebulae and which are discussed elsewhere in this Symposium [37]. I also will discuss briefly only those stars showing the P Cygni phenomenon which are hot and will not consider the types of middle B and later.

d) Physical basis.

All the types of stars we are considering have winds and envelopes surrounding them. We can write the equation of continuity as:

$$4\pi \rho(r)v(r)r^2 = \frac{dM}{dt}$$

(1)

where the density $\rho$ and (outward) velocity $v$ are functions of the radial distance and the right hand side of the equation represents the mass loss rate in appropriate units. We must essentially appeal to the observed spectrum of the star to be able to estimate the variables on the left hand side of equation (1). The predicted appearance of a spectral line can be symbolically written in the form:

$$I_v(r) = \Lambda_r [S_v(r')]$$

(2)

$$S_v(r) = S_v(r) [\rho(r), T(r), I_v(r), \text{etc.}]$$

(3)

where $I_v(r)$ is the specific intensity, $\Lambda_r$ denotes an integration over space, and $S_v(r)$ is the line source function. It is no trivial matter to evaluate the right hand side of equation (3) in order to solve for $S_v(r)$ but considerable work is going forward on this fundamental problem at JILA and elsewhere. I have written these equations this way because I want to specify precisely the terminology to be used.

Envelope. — A region surrounding the star which produces the emission. The common usage of the word has had an implication that $\partial T/\partial r < 0$. The use of the phrase "extended envelope" is probably redundant.

Corona. — An envelope in which $\partial T/\partial r > 0$. There has usually been a "solar" implication in the use of this word for stars, but Rogerson [28] will discuss this point elsewhere in this Symposium.

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Wind. — Motion of material in an envelope such that \( v(r) > 0 \). This is generally believed to be driven by line radiation pressure in the far UV region \([29], [30]\). Thomas, however, will offer an alternative explanation elsewhere in this Symposium \([31]\).

Atmosphere. — This is a term used to describe the region where the stellar absorption lines are formed. The term extended atmosphere should be used only if the absorption lines are formed in an extended region.

Continuum. — The region where the continuum radiation originates, and the source of the values chosen for luminosity, effective temperature, and radius. The term extended continuum should be used only if this region is extended.

Shell. — As envelopes are generally considered to have \( \frac{dP}{dr} < 0 \), I would like to propose that the term shell be reserved for envelopes in which \( \frac{dP}{dr} > 0 \). In particular, if the density is discontinuous anywhere the term shell should be used.

In the literature the terms have often been used interchangeably which I feel is very confusing.

Elementary stellar atmosphere theory implies that the region over which the continuum is formed is interior to the stellar atmosphere; similarly, the atmosphere is interior to the envelope. We see that in principle stars can have envelopes without extended atmospheres; and extended atmospheres without extended continua; however, if a star has a demonstrably extended continuum it certainly has an extended atmosphere. It may also turn out that all stars with envelopes have extended atmospheres or continua by physical necessity \([32]\).

It is a well known fact that WR stars have envelopes. It is likely that their atmospheres or continua are extended \([33]\). By our spectroscopic definitions here, Of stars have envelopes and may have extended atmospheres and continua. The various measures of the bright Of star \( \zeta \) Pup suggests that an extended continuum is very possible \([32], [34], [35], [36]\).

As far as other Of stars are concerned Hayes \([37]\) has detected intrinsic variable linear polarization in the (UBV) B band in four Of stars. Two of the four are known spectroscopic binaries and the variable polarization may be caused by material in between or surrounding the system. The two other Of stars are single. The variable polarization then implies not only an extended continuum but one which is either non-spherically symmetric, or time variable, or both. Hayes did not find any variable polarization in several O((f)) stars; but this does not necessarily say anything about the continuum in these stars.

Kuan and Kushi \([38]\) have measured spectral energy distributions in a small but diversified group of O and Of stars. They conclude that the shape of the energy distributions for both O and Of stars is consistent with extended continuum models but not with plane-parallel models. Kuan and Kushi’s result, if confirmed, is of profound importance for construction of modern model atmospheres and stellar wind models of all O type stars.

III. INFORMATION FROM SPECTRA

This section will be concerned primarily with the optical spectrum of Of and WR stars. Morton \([39]\) elsewhere in this Symposium will discuss the far UV spectrum of a number of O and Of stars.

For the past few years I have been acquiring a substantial number of coudé
spectra of O and Of type stars to study line profiles. These typically have dispersions of 18A/mm in the blue and little less in the red region of the spectrum, and have been obtained at the Kitt Peak, Cerro Tololo, Palomar and Mauna Kea Observatories. These spectra are microphotometered and the density information written onto magnetic tape. The numerical information is filtered, intensities computed and after a continuum choice made semi-automatically, selected line profiles derived [40]. The profiles are on microfilm which can then be copied with a film reader and traced onto graph paper as needed.

The sample line profiles I wish to show here are preliminary versions of work on the earliest type O stars by Frost and myself. They are preliminary to the extent that a few plates we have of the stars to be discussed are not yet traced. I will also include a few of those spectra that occasionally do not quite come out nicely on the first pass through the computer. One uncertainty in the line profiles which we are unable to resolve with our «normal» microphotometer is the zero point of the velocity scale for a given line; occasionally an arbitrary shift of 50-100 km s⁻¹ is needed to bring one line on a plate into agreement with lines from other plates. With a PDS microphotometer this presumably would not be a problem. The «zero» velocity is the average of several photospheric absorption lines.

Figure 1 shows four helium absorption lines in the typical early Of star ζ Pup. The lines are rather broad due mostly to the high rotation of the star. We are presently working on better values for «rotational» velocities in O type stars, although if we take our spectra of the classical standard stars of Slettebak [41] and compare their similarly derived profiles with those shown here, we would estimate a «V sin i» of 210 km s⁻¹ for ζ Pup. Another result obtained from Figure 1 is the lack of appreciable variation in these line profiles. These profiles have been taken both from Kitt Peak and Cerro Tololo at different dispersions and different times over the course of hours to days or months. The few percent variation from plate to plate is the residual noise in the spectrograms. One line profile of λ 5411 is noisier than the others; this is a spectrogram that was somewhat underexposed but I included it here so one could get a feeling for the uncertainties in our reduction procedure.

Figure 2 shows the λ 4686 He II line profile in four early Of stars of nearly identical spectral type. The star HD 93129 is an O3 star, the others are O4. There is no convincing evidence for line variation greater than 5% of the continuum in any of these stars. This is rather surprising considering the results obtained Brucato [42]. For ζ Pup he found differences in equivalent width of 50% in time scales of minutes between successive spectra. Variations that large seem to be excluded by these observations, some of which are taken a few minutes apart for ζ Pup. I have no ready explanation for this difference in results although I can point out that the dispersion used here is better than available to Brucato. One spectrogram of ζ Pup does appear to show a weaker λ 4686 than the others but this may only be noise in the system, a point still under investigation.

The stars HD 190429 and HD 15570 have more or less symmetric λ 4686 line profiles. The profile in HD 93129 is definitely asymmetrical, having a pronounced violet wing. The profile of ζ Pup is closer to being symmetric but has an absorption feature more or less at the photospheric velocity. The envelopes producing the line profiles in these latter two stars appear not to be simply uniformly expanding and spherically symmetric. The overall line widths in all four stars are ~ 10³ km s⁻¹.
Fig. 1. — Filtered, normalized helium line profiles in ζ Pup. The data are taken from coudé-dispersion spectra at several observatories. There is no convincing evidence of line variations.
Fig. 2. — Filtered, normalized λ 4686 He II line profiles in four early Of stars. In HD 93129 A and ζ Pup, the profiles are not symmetrical, although they are in HD 190429 and HD 15570. There is no convincing evidence of line variations in these stars.
Fig. 3. — Filtered, normalized Hα line profiles for the stars of Figure 2. The asymmetrical shapes are similar to the λ 4686 profiles of Figure 2. There is no convincing evidence of line variations in these stars. (The one different profile in ζ Pup is a plate fault — see text.)
Figure 3 shows some H\alpha line profiles for the same stars as in Figure 2. The absorption feature at — 1600 km s\(^{-1}\) is the \(\lambda 6527\) line of He II. A nebular emission feature is found near the center of the profile in HD 93129. One of the line profiles in \(\zeta\) Pup appears to have an extended red wing. After this slide was made we discovered that the plate had a flaw at exactly this point on the spectrum so the wing is not real. Several of the spectra of H\alpha in HD 190429 appear to have a different noise frequency. These spectra were obtained at the Mauna Kea Observatory at almost twice the dispersion of the other plates but were filtered with the same filter. They are included in this underfiltered form for illustrative purposes.

There appears little evidence for line profile variations in the three stars with multiple exposures. The line profiles in HD 190429 and HD 15570 are more or less symmetrical; those of HD 93129 and \(\zeta\) Pup are asymmetrical and have a similar appearing shape as the \(\lambda 4686\) line in these stars. However, the absorption feature at H\alpha in \(\zeta\) Pup is quite a bit stronger than the corresponding feature in \(\lambda 4686\). The overall similarity in the \(\lambda 4686\) and H\alpha line profiles suggests these lines are formed in similar regions of the stellar envelopes, a point also made by Conti and Leep \cite{17} in their discussions of equivalent widths. The overall line widths of H\alpha in these stars is \(\sim 10^3\) km s\(^{-1}\).

The line profiles of the stars shown here are typical of the Of types. There are a non-negligible number of other O stars with profiles substantially like these. A very preliminary comparison of these emission line profiles with those calculated by Castor et al. \cite{30} suggests mass loss rates of the order of \(10^{-5} \odot\) per year, a number which is significant on an evolutionary time scale for the star. A substantial mass loss rate may have profound implications for the surrounding interstellar medium \cite{43}.

The far UV lines also give mass loss rates of order \(10^{-5}\) solar masses per year \cite{39}, although both kinds of spectroscopic results are to a certain extent model dependent. The final numbers must await completion of physically self-consistent envelope models with the dynamics fully accounted for.

It may be possible to estimate mass loss rates in Of stars by IR and radio measures. At least some Of stars show excess emission in the IR which can be attributed to free-free transitions an ionized halo extending to relatively large distances from the star. \cite{44} The theoretical arguments relating the emission to the mass loss rate and other parameters have been given by Wright and Barlow \cite{45} and Panagia and Felli \cite{46}. This kind of observation is less model dependent than the spectroscopic method but does require very accurate photometry and sensitive instrumentation.

I should like to turn now the WR stars and their spectroscopic similarities to (and differences from) the Of stars. Figure 4 shows a montage of five spectra, two O((f)) stars, two Of stars and one WR star. These were taken at classification dispersion by Walborn \cite{47} and (coincidentally) show two of the same stars I have discussed earlier. I have coudé spectra of all of these objects, but line profiles analogous to those of Figures 1-3 are not yet fully reduced. However, the points I wish to make can be seen by inspection.

The difference between the O((f)) of Of stars is, of course the presence of \(\lambda 4686\) emission in the latter objects. Additionally, the NV lines at \(\lambda\lambda 4604, 4620\) come into prominence in these earliest Of stars. This cannot be entirely a temperature effect, as the stars are all of about the same O spectra type. Our coudé spectrograms of these stars indicate the NV absorption seen in the two Of stars is violet shifted and weak emission is present. In the WR star, the NV lines are fully developed F Cygni profiles.
Fig. 5. - Montage of Cassegrain-dispersion spectra of some + transition + WR stars, and near the immediate and to the right of the upper panel from the top to bottom panels, as discussed in the text.

Fig. 4. - Montage of Cassegrain-dispersion spectra of some + transition + WR stars, and near the immediate and to the right of the upper panel from the top to bottom panels, as discussed in the text.
The great strength of the $\lambda$ 4686 He II emission line in the WR star is one of the primary criteria for its classification. One notices that the qualitative difference from the Of star is primarily in this line strength; the line width is larger but not markedly so. Another distinction of the WR star is that the Balmer-Pickering series lines have P Cygni profiles. The $\lambda$ 4059 N IV emission is present in the Of stars but stronger in the WR star.

Is there any essential difference between the Of stars and the WR star? I think if one did not have any preconceptions about the nature of a WR star, then examination of the spectra shown here would indicate only a difference in degree: the WR star has a more extensive envelope than the Of stars (see also Walborn [47]). I should point out, however, that this particular WR star is not typical of all WR objects, although it does represent a subtype WN7 quite well.

Let us now look at another montage of spectra, six (southern) WN stars, plus the O3f star HD 93129. These were also taken by Walborn [48] at classification dispersion. The WR stars are arranged from top to bottom in an order which ranges from less typical members to more and more typical members of the entire WR class. The spectral type and temperature differences illustrated [48] need not concern us here. The emission lines are stronger in the bottom spectra and many more lines are visible. A few P Cygni absorption lines visible in the Balmer-Pickering series in the upper WR spectra are less prominent in the lower spectra where the emission profile dominates. A few strong P Cygni absorption components, particularly $\lambda$ 4026, and $\lambda$ 4471 He I are strong in the lower spectra. One has the impression that the sequence is arranged in an order of increasing dominance by the envelope, going from the upper to the lower spectra. Is there any difference in kind between the WR stars pictured in Figure 5, or can they all be explained as differences in the envelope surrounding each star? I personally feel there is a difference only in degree.

I want to mention again the comparison of the WN stars shown here to the O3f star HD 93129. The latter has absorption lines which are not P Cygni type, and the envelope giving rise to the emission lines is apparently not as extensive as in the WR stars. But I believe the spectroscopic differences, at least, can all be explained by the physical conditions in the envelope.

Before going on I would like to review a few other well known properties of WR stars mostly taken from the very nice summary papers of Kuhf [29] and Paczynski [21]. Most WR stars appear to be binaries, but whether or not they all are binaries is unsettled. The companions identified so far are all OB stars. Orbital solutions of the double line systems yield mass estimates. The WR stars invariably have masses near $10_6$, with the companion star more massive as expected from its spectral type. The absolute magnitude of most WR types is $M_V \sim 4$ to $-5$, but the WN7 types seem to be near $-6$. There seems to be little evidence of hydrogen in most WR spectra based on photoelectric measure of the Pickering series emission lines, and it is estimated that $H/He \lesssim 0.1$. The two WR series, WN and WC, seem to differ in composition from one another. It appears that the WN stars have more N, and the WC stars more C and O, than the other class.

The most favored model for the evolutionary status of WR stars is the "peeled onion skin" proposal of Paczynski [21]. The presence of most WR stars in binary systems suggests that Roche lobe overflows and considerable mass exchange to the companion has been important. One imagines the outer portions of the WR stars being continually peeled off as the star evolves. This mass transfer process eventually reaches a layer in the star where nuclear processing has occurred. The WN stars are
those in which the peeling has gone down to the CNO cycle core; the WC stars have evolved further to the "triple alpha" core where carbon has been produced. In this commonly accepted picture the WR stars are considered to be highly evolved objects which are in a stage of very rapid evolution. The spectrum can probably all be explained by a correct choice of the envelope parameters: density, velocity, temperature, and composition. We will return again to this picture in the last section to offer one fundamental modification.

Before leaving the topic of the composition of WR stars, I would like to briefly comment on it. There is still some controversy whether or not the WN and WC stars have anomalous compositions. Concerning this point the recent IR work of Gertz and Hackwell [49] may be important. They find that there is an excess emission surrounding several WC9 stars which can be understood only as halo of hot dust. The composition of this dust presumably is graphite and its presence suggests that such excess carbon is present in the envelopes of these stars. It is significant that such excess IR radiation is not seen in WN stars, except in those cases where it arises from free-free emission. Further observations and discussion of these points is given by Cohen, Barlow and Kuhi [50].

I will now offer a few brief remarks on the P Cygni phenomenon. A very important paper by Kuan and Kuhi [?] has shown, from a study of some line profiles that \( dv/dr < 0 \) for P Cygni itself and that this probably is true for all similar-appearing later-type stars as well. Kuan and Kuhi also argue that there is a relationship between the momentum flux and the IR emission spectrum in those stars. They find that

![Diagram](image)

Fig. 6. — Observed (solid line) and computed (dashed line) profile of H\( \alpha \) in P Cygni (from figures 6a of Kuan and Kuhi [?]). This line is formed in an envelope with a decelerating outward flow.

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low momentum flux favors the presence of dust in the envelope whereas high momentum flux favors free-free emission. Although the envelope is decelerating in P Cygni itself, there is still mass loss from the system.

Kuan and Kubi [7] also discuss the mass loss rates in P Cygni and the later type stars with similar profiles, and find values of the order of $10^{-6} \odot$ per year. An example of a P Cygni profile is that of Hz shown in Figure 6. The observed curve is the solid line; the dashed curve is a computed profile with a decelerating envelope. The very intense but relatively narrow emission line shown in Figure 6 is indicative of a decelerating envelope; the broad emission lines shown in Figures 2 and 3 are indicative of an accelerating envelope.

Kuan and Kubi [7] admit they are unable to specify the driving mechanism for the outflowing material in P Cygni and similar stars. It appears that the mechanism is more of an ejection near the photosphere, then a gradual deceleration under the influence of gravity. However, in Of and WR stars, the material continues to accelerate up to some terminal velocity given by the line radiation force [36]. It appears that the physical mechanisms are sufficiently different in the two cases that the stars are not comparable. In particular, the evolutionary status of Of and WR stars may well be drastically different from P Cygni (and stars similar to it).

IV. STELLAR PARAMETERS

I shall now discuss only the Of and WR stars because the stellar parameters are much less well known for P Cygni and later-type stars of similar spectrum. Some of the material for O and Of stars is found in more detail in a review paper by Conti [51].

The temperature scale for O and Of stars can be derived by several methods, all of which give, more or less, the same results. The method that is probably the most dependable, and which has been applied to the largest number of stars, is essentially a determination of an ionization equilibrium. This is based on the non-LTE plane parallel models of Auer and Mihalas [52] and their predictions of He I and He II line strengths. In particular, Conti [36] has measured equivalent widths of $\lambda$ 4471 and $\lambda$ 4542 in a large number of O stars and used the line ratio to determine a temperature. This in turn gives a temperature scale for each spectral type [8]. It is necessary to be able to estimate the gravity of the O stars independently otherwise a wrong assignment of temperature will result. The numbers quoted by Conti [51] for O stars are probably good to 5%, although those for Of stars are, of necessity, less certain. This is because the gravities are less well known, and the applicability of the plane-parallel models somewhat questionable.

Another method to obtain the effective temperature is by analysis of the Zanstra mechanism [53]. This method can be used for O stars in which the emission measure of a surrounding H II region can be found by Hz or radio continuum measurements. The resultant temperature scale, based on a dozen or so stars, is similar to that derived by the Auer-Mihalas ionization equilibrium models [36]. This Zanstra method is somewhat insensitive to the stellar models if line blanketing is unimportant. Unfortunately, no bona-fide Of stars have been studied by this procedure, either because there are multiple stars in the nebulae, or for other reasons (possibly related to the points raised by Castor, McCray and Weaver [43]).

Another method for temperature determination is essentially one of a conti-
nuum fitting to model predictions. This is difficult because of the presence of interstellar reddening, but has been done by Morrison [54]. She made very careful measurements in the Strömgren $uwy$ photometric system of a large number of O and Of stars. The derived temperatures for O stars are similar to those of Conti [36]. The Of stars are somewhat cooler and do not fit consistently the plane-parallel model predictions, as might be expected.

For one Of star, $\zeta$ Pup, a novel temperature determination has been derived by a completely different method. This involves measuring a «radius» by interferometric techniques [55] and solving for the temperature, given the luminosity. This method for $\zeta$ Pup gives a temperature near 30,000° K while, the ionization equilibrium implies one near 50,000° K. The unacceptably large discrepancy probably results from the effects of an extended continuum. By far, the greatest effect the extended continuum occurs in the derivation of a temperature from the interferometric measures; there is probably a small effect on the ionization equilibrium method incurred in using a plane-parallel model [38], [34]. The «real» effective temperature of $\zeta$ Pup is probably near 50,000° K than 30,000° K.

The effective temperatures of WR stars are not very well known. Equilibrium considerations of the observed high ionization states would suggest temperatures from 30,000° K to 70,000° K. On the other hand, measures of the continuum radiation yields values nearer 20,000° K for many WR stars [52]. Whether these great differences in inferred temperatures can be explained merely by extended envelope models is uncertain. It may also be the case that the ionization equilibrium is strongly affected by heating effects in the envelope. Morton [53] has applied the Zanstra method to (a very few) WR stars. The range of temperatures derived by him is between the two values mentioned above.

Luminosity estimates for both the Of and WR stars are reasonably reliable. Conti and Aitchison [8] discussed the $M_V$ of a substantial number of O and Of stars in associations which have distances determined independently of the O stars themselves. Walborn [58], by an analogous procedure, also gives a luminosity scale for O stars. Both methods are in essential agreement, and values are given by Conti [51].

The $M_V$ of Wolf-Rayet stars is also obtainable by membership in clusters and associations [57] and the Large Magellanic Cloud [58]. The values are conveniently tabulated by Smith [59].

Another basic parameter of stars is the bolometric correction. The most useful tabulation of this number is given by Morton [55]. His results are derived from LTE plane-parallel models. It appears that the LTE assumption is completely inadequate for O stars but this fortunately makes little difference for the bolometric correction [52]. The influence of the extended continua on this problem is not well known. Line blanketing effects may be important. It is possible that if the wind is being driven by radiation pressure of the far UV lines, some photons will be removed completely. This may be regarded as essentially a blanketing correction; up to half of the photons could be removed [30]. On the other hand, a wind might only scatter photons, given no change in the B.C. The kinetic energy in the wind, in even the most extreme Of stars, is a negligible fraction of the luminosity and does not affect the bolometric correction.

Putting together all the values of L and $T_{\text{eff}}$ discussed previously, I can now show an HR diagram for O, Of, and WR stars. The values for the O and Of stars are tabulated in Conti and Burnichon [60] where an analogous diagram is given. The result is Figure 7, and it contains the essential thrust of this review paper. The theo-
retical mass tracks for O stars are taken from Stothers [61], with interpolation between his values for age-zero and end-point-of-main-sequence-evolution at four values of stellar mass. A number of stars seem to be appreciably above the 60 solar mass track. There is excellent agreement between the theoretical ZAMS and the observed lower boundary to O stars, at least up to masses of 60 $M_\odot$ [60].

Fig. 7. — Hertzsprung-Russell Diagram of O stars (open circles), Of stars (filled circles), WR stars (dashed box) and $\alpha$ transition $\tau$ WR stars ($\pi$ WN7 Box $\pi$). The location of P Cygni is shown by the letter P, and the components of BD + 40$^\circ$4220, by the X's. This diagram is adapted from Conti and Burnichon [49]. One may infer that O stars have masses up to $\sim$ 120 $M_\odot$, but one should not infer the masses of Of stars, as mass loss is probably important. This point is underscored by the result that the masses of the Of components of BD + 40$^\circ$4220 are 47 — 72 $M_\odot$ for the primary and 11 — 17 $M_\odot$ for the secondary.

How accurate are the masses which one would estimate from the positions of stars in this diagram? Unfortunately, there are not too many masses derived for O-type binary systems; but inspection of spectroscopic binary catalogues, such as Batten's [62], indicate consistency for masses of main sequence stars and those derived from Figure 7. This has been discussed also by Hutchings [83]. What will be needed to settle the question is study of additional spectroscopic binary O-type systems.

The filled circles in Figure 7 are Of stars, the larger symbols being stars with substantial emission at He II $\lambda$ 4026 and/or Hz such as shown in Figures 2 and 3.
These stars have mass loss rates of the order of $10^{-5} \, M_\odot$/year. The smaller filled symbols also are losing mass, but probably at rates near $10^{-6} \, M_\odot$/year, as least as deduced from the visible spectrum. We do not observe mass loss, in the visible region, from those stars in Figure 7 shown as open circles, but Morton [59] finds appreciable mass loss rates from far UV observations for a number of them.

Nearly all O stars with $M_{bol}$ brighter than $\sim 9.5$ show appreciable mass loss rates based on their visible spectrum. This luminosity limit is lowered by a factor of two, at least, if the far UV spectrum is considered [64]. The luminosity limit for appreciable mass loss for B type supergiants is also a factor two fainter than that shown in Figure 7 according to Hz emission measures by Rosendhal [24]. This might only mean that he can discern mass loss rates which are smaller than those of the O stars (presumably because of more sensitive spectral criteria), or that B stars can lose mass more efficiently. There is a suggestion of a lower luminosity limit for mass loss at lower temperatures from Figure 7. Rosendhal points out that the luminosity limit for mass loss rises in the later B and A type supergiants.

Given the substantial mass loss rates derived for the O star, one should not estimate masses for these stars from their positions in Figure 7. Evolution of O stars with substantial mass loss rates has yet been calculated, and the position of evolved stars in this diagram cannot be derived accurately. Although several O stars have masses near the 120 $M_\odot$ track, their masses may well be substantially below this value. However, main sequence stars probably do exist with masses between 60 and 120 $M_\odot$.

I have represented the position of the (majority) of WR stars by a large dashed box in Figure 7. The so-called WN7 stars are in a smaller box at a substantially higher L, as has been derived by Smith [59] and others. A better description for these WN7 stars might be to use the term «transition» WR star for reasons I will come to shortly. They are all classified WN7 subtypes by some investigators [22], [29] but not others [18]. In fact, four of these «WN7» types are illustrated in Figure 5 (the top four WR spectra).

I have already alluded to the high luminosity of the WN7 subtypes, derived from membership in associations with known distances. At least one of these stars, HD 92740, is a spectroscopic binary [63]. However, the higher Pickering-Balmer series absorption lines and the emission lines are in phase and there is no spectroscopic evidence of the secondary. The spectrum of HD 92740 shown in Figure 5 is then of the WR star alone, without an O component. This result is crucially important to the interpretation of these transition objects because it implies there are both WR emission lines and O type absorption lines in the same star. The binary nature is not crucial to the spectrum.

An important question then is the status of the other three stars in Figure 5 with spectra similar to HD 92740, namely HD 93162, HD 93131, and HD 151932. Niemelä, Walborn and I have acquired a substantial number of spectra of these objects in hopes of being able to determine whether or not they are binaries and composite. From inspection of Figure 5 it is clear that all four stars have appreciable hydrogen in their spectrum, for there is a Pickering-Balmer series alternation of line strength. This is unlike the majority of WR stars where little, if any evidence, of hydrogen exists [21]. The other two WR stars in Figure 5 show evidence of hydrogen, even though the absorption spectrum is less well marked. However, $M_V$ are not available for these stars.
V. EVOLUTIONARY SCENARIO

Now that I have discussed all the important data known at present pertaining to the Of and WR stars, I would like to propose a unifying hypothesis which relates the two groups of objects. The most important point to make is that a mass loss rate $\sim 10^{-5} \, M_\odot$ per year is significant on an evolutionary time scale for an O star. If a substantial fraction of massive O stars lose mass at this rate, what would be the outcome?

An important question to raise now is whether or not all the Of stars are binaries or whether some are single. Certainly not all have been studied carefully and some (e.g. HD 15570) appear to be double. However, there are good indications that $\zeta$ Pup, a prototype Of star, is single. For my purposes here, this observation is sufficient for what I want to say.

Let us ask what would be the eventual evolutionary status of a single Of star such as $\zeta$ Pup? The mass loss rate may be sufficient that appreciable mass will be removed before the star leaves the hydrogen-burning state. Then the evolved core would be reached, or material could mix from the core to the surface, before the star leaves the main sequence. I want to suggest that the resultant spectrum might be indistinguishable from that of a single WR star. If single Of stars can lose mass sufficiently fast for this to happen, then a binary nature is not a necessary condition for a WR star, although it may be sufficient. It is unfortunate that we cannot find directly the masses of single stars. I would suggest, though, that the mass of $\zeta$ Pup could be considerably less than would be inferred from its luminosity and temperature, and its position between the 60 $M_\odot$ and 120 $M_\odot$ tracks of Figure 7.

Consider now an Of star in a binary system. The mass loss rate may be helped by the presence of the other star in the sense that the effective gravity is lowered somewhere in the envelope by the Roche lobe. However (and this is where I would want to modify Paczynski's picture), I think the wind will be sufficiently strong that mass exchange will not occur but rather mass will be lost from the system. It turns out, in fact, that the mass exchange is not all that crucial to Paczynski's WR star evolution, provided that the binary status helps and does not hinder mass loss from the initially more-massive, and first-evolving, star.

In our picture then, Of stars become Of stars if they are sufficiently massive and luminous that a substantial wind begins to blow. If the driving mechanism stays the same, the mass loss rate will increase as the stellar mass decreases. The envelope becomes more and more prominent as the mass loss rate increases. The transition WR stars shown in Figure 5 are those objects in which some hydrogen remains, the luminosity is high, and yet the envelope has already developed sufficiently that the star is classified as WR. This picture suggests that as further mass loss occurs for these stars, the H/He ratio will decrease, the envelope will become more extensive, and the luminosity will drop to that of the classical WR stars. It would be nice to find a correlation between the H/He ratio and the luminosity of these objects (a topic which is under study).

What of an immediate progenitor to the transition cases of Figure 5? One would predict a larger H/He ratio, a less extensive envelope but still appreciable mass loss, a high luminosity, and an undermassive Of star. In fact, such an Of binary system exists. Bohannan and Conti have derived a new spectroscopic orbit of the double-line binary BD + 40°4220 (V729 Cygni). This eclipsing system has had photometry by Hall. Although unable to solve for the radii using the Russell
method owing to complications with the light curve, Hall was able to set inclination limits of 60°-90°. Bohannan and Conti derived masses of \(47-72 M_\odot\) for the primary star, and \(11-17 M_\odot\) for the secondary from the orbit. Both stars are Of types but the secondary has by far the stronger emission lines. Further, both stars are of about the same spectral type and equally luminous, with \(M_V \sim -7.1\) from membership in the Cyg OB2 association. The location of these stars in the HR diagram is roughly given by the Xs in Figure 7, the secondary being the hotter star.

Bohannan and Conti [67] point out that the secondary has a mass near that of a WR star, but the spectrum is that of an Of star. It is, in fact, a highly luminous star which has lost a good deal of mass but is not yet so evolved as to be a WR star. These authors also note that the present mass loss rate of material from the secondary is substantial, and that the appearance of Hz and He I \(\lambda 10830\) suggests this material is being lost from the system. They suggest the secondary is on its way to becoming a WR star. Our understanding of the evolutionary status of BD +40°4220 has led to the proposed scenario for Of and WR stars described here.

It is not immediately apparent how one ends up with two kinds of WR star, WN and WC. Paczynski [21] has suggested that the WC are more evolved than WN, a possibility I endorse. Another possibility is that they result from initially different mass stars in which the core is broached while hydrogen burning is still going on (WN stars), or after helium burning has commenced (WC stars). In our picture, the binary nature and separation plays a lesser role than the self-induced mass loss rate of the evolving star. Theoretical calculations of the evolution of massive stars with substantial mass loss rates might be of interest in this connection.

To summarize: the mass loss rate in single Of stars (example \(\zeta\) Pup) may be sufficient to produce single WR stars. The mass loss rate in binary Of stars must be sufficient to produce binary WR stars because we have an example (BD +40°4220) of a luminous Of star which clearly has lost a good deal of mass, and is still doing so. The evolution of BD +40°4220 must be to a WR transition star (example: the WN7 stars in Figure 5) in a relatively short time-scale. These transition WR stars may, in turn, continue to lose mass, and alter the surface H/He ratio until stars with all the classical WR properties are reached. Future possible evolution of the WR binaries, which is exciting but does not concern us here, has been sketched by v. d. Heuvel [59].

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