

SESSION 1

THE WOLF-RAYET PHENOMENON

Chairmen: P.PISMIS and H.NUSSBAUMER

Introductory speaker: P.S.CONTI

1. W.SCHMUTZ: The effective temperatures of early WR stars.
2. B.HIDAYAT, K.SUPELLI and K.A. VAN DER HUUCHT: The galactic distribution of WR stars.
3. E.M.LEEP: Line strengths in WN stars.
4. A.B.UNDERHILL: Hot mantles, moderate photospheres for WR stars.
5. C. DE LOORE, P.HELLINGS and H.J.G.L.M.LAMERS: Corrections for hydrostatic atmospheric models; radii and effective temperatures of WR stars.
6. D.G.TURNER: Preliminary results of a new study of the intrinsic properties of WR stars.
7. D.R.FLORKOWSKI: Radio observations of HD 193793
8. C.STERKEN and C. DE LOORE: Near infrared photometry of Southern galactic WR stars.
9. P.M.WILLIAMS: Infrared (1.4 - 4.1 μm) spectra of WR stars.
10. D.G.HUMMER, M.J.BARLOW and P.J.STOREY: The infrared recombination line spectra of WR stars.

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I. INTRODUCTION

I have been asked to review in broad terms the concept of Wolf-Rayet (W-R) phenomena, that is, to outline what we currently know about the properties of stars showing such phenomena and to indicate the directions in which future work is leading. I thought I would begin by listing the characteristics of W-R spectra to which probably all the participants at this Symposium will be able to agree. These can readily be adapted from Thomas (1968) who discussed them at the Boulder W-R Symposium. The characteristics of W-R spectra are as follows:

(1) They are primarily an emission line spectrum superimposed on a "hot" continuous spectrum.

(2) P Cygni absorption components are observed for some lines in some stars; a fact not realized in 1968 was that a very few W-R stars have intrinsic absorption lines (e.g. The Balmer series in HD 92740 -- Niemela (1973)).

(3) The emission lines represent a wide range of excitation and ionization. This level is often higher than indicated by simple modeling of the continuous spectrum.

(4) The emission lines are broad, corresponding to widths of hundreds to thousands of kilometers per second; widths often differ among various ions in the same star.

(5) The W-R stars can be divided into two subtypes: These are the WN types, in which the ions of nitrogen dominate, and the WC types, in which the ions of carbon (and oxygen) dominate. Both sub-types have

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strong lines of helium; in a few cases, hydrogen lines, in emission, are also observed (Underhill 1968).

The above statements are the defining characteristics of the W-R spectral phenomena. There should be, among us all, agreement with these facts because they come to us directly from the spectroscopic observations. It thus seems to me that one could now infer that we are dealing, fundamentally, with an optically thick stellar wind. The ionization conditions, the velocity law, and the density, and probably the composition, may differ drastically from object to object.

I should now like to add the following specific remarks. Many of the WN subtypes do contain some carbon (Underhill 1968). This is primarily seen in the C IV lines, both in the optical at $\lambda\lambda 5801, 5812$, and in the UV, where the resonance doublet at $\lambda 1550$ is generally observed (Smith 1973b; Willis and Wilson 1978; Garmany and Conti 1982). It should be realized that the strongest C III lines, $\lambda 4650$ and $\lambda 5696$, are not generally observed in WN stars. If those lines are seen, then invariably the object is given a mixed classification (i.e. WN+WC). I shall return to this point later on. The WC subtypes contain little or no nitrogen. The only evidence for nitrogen ions in the optical is possible weak blends of N III ions on otherwise very strong carbon features (which might even be due to other carbon ions) according to Underhill (1959) and Bappu (1973). In UV, N IV and N V lines may be weakly present but blends make the identification a little uncertain (Willis 1980). As Smith (1973a) has remarked, the predominant ions are well developed in each subtype.

The above observations suggest that the apparent composition anomalies are related to stellar evolution (Smith 1973a; Paczynski 1973). This was recognized almost from the very beginning when nuclear physics reactions were first realized to occur in stars. I feel it would be suitable to quote from Gamow (1943): "It is well known that Wolf-Rayet stars can be divided into two groups: the WC group with strong carbon emission lines, and the WN group [with strong nitrogen lines] It seems that, whereas the observed intensity ratio of C and N lines [may] not necessarily correspond to the actual abundance ratio, the change of this ratio from star to star indicates a real difference in chemical composition..." My point here is that even for a nonspectroscopist, such as Gamow, the difference between the WN and WC subtypes is so overwhelming, and so similar to what is expected from products of nuclear reactions in stars, the most natural conclusion is that it is related to stellar evolution. We still are not certain of the actual values of the elemental composition but for me the conclusions are straightforward:

WN subtypes result from the evolution of stars in which the CNO equilibrium products are observed on the stellar surface (in the wind). These include enhanced helium and nitrogen, and diminished carbon and oxygen (compared to "normal"). WC subtypes result from the appearance of products of helium burning in which carbon and oxygen are enhanced at the expense of helium and nitrogen. Furthermore, we will see discussion at this symposium (Barlow and Hummer 1982) of a related subtype, the WO subtypes, in which the oxygen is enhanced at the expense of carbon, an extreme of continued helium burning reactions. It is also true that among central stars of planetary nebulae there exist objects with W-R spectra. Certainly, we can all accede to the proposition that central stars of planetary nebulae are highly evolved objects; it is almost certainly a result of their particular evolution that their spectra are carbon and oxygen rich.

The claim has been made that the difference between the WN and WC subtypes can be understood purely in terms of ionization and excitation and structural differences among them. This has always been difficult to support because of the similarity in the N III and C III ionization levels (to the next stage) and the wide disparity in the observed spectra. Such claims also have no basis in physics and are completely ad hoc; no attempts have ever been made to model stellar winds in which either the nitrogen ions or the carbon ions can be made to dominate with solar (normal) composition. I seriously doubt if it can be done. I will take it as given, therefore, that the subtypes represent fundamentally different compositions, suggesting that they result from the consequences of stellar evolution.

Wolf-Rayet phenomena occur to a wide variety of objects: They are seen in Population I stars of subtypes WN, WC and WO; they are found among the nuclei of planetary nebulae, in which WC and WO subtypes are observed; finally, they are found among the luminous exciting stars of giant H II regions, in which WN subtypes (only?) are observed (Conti and Massey 1981). The masses and luminosities cover a large range: $1 M_{\odot} \sim M_{W-R} \gtrsim ? 100 M_{\odot}$; $10^4 L_{\odot} \gtrsim L_{W-R} \lesssim 10^8 L_{\odot}$. The effective temperatures are not well known but are probably in the range of $2-5 \times 10^4$ °K. In any case, the W-R phenomena occur only in objects on the far left of the HR diagram.

The general themes of W-R phenomena are included in the organization of this symposium as you can see from the program. I would like to consider for my contribution the following specific problems: the absolute visual magnitudes (M_V); the heterogeneity of WN spectra; the existence of transition type spectra and compositions; the mass loss rates; the existence of very luminous and possibly very massive W-R

stars; a brief overview of our current understanding of the theoretical aspects of stellar evolution and stellar winds; and the various scenarios that have been proposed to understand W-R stars.

II. ABSOLUTE VISUAL MAGNITUDES OF W-R STARS

M_V can be obtained from stars in which m_V are measured and for which reddening can be estimated. Well established distances are also necessary. The first two quantities have been estimated from broad band UBV colors and/or from intermediate band uvby or similar indices (Smith 1968a,b) for many stars in our galaxy and in the Large Magellanic Cloud (LMC). Recently, Massey (1981) has begun an extensive observing project to measure the stellar continua directly, with absolute spectroscopy and sufficient resolution to avoid, and also to measure, the emission lines. He finds, from preliminary data, the previous m_V may have been in error by up to 0.5 magnitudes in some WC stars because the emission line contribution has been estimated from "average" properties at each subtype. Smaller discrepancies are occasionally found among the WN subtypes but even so he finds that the intrinsic colors are not yet well established for many stars. If the intrinsic colors are not well known then estimates of the reddening and the unreddened magnitudes are similarly uncertain. A far bigger problem in dealing with M_V however is introduced by the estimates of the distances. These can be found for those W-R stars that are in well-studied clusters, or associations, only.

In view of the problems with the reddening, and the desire to retain a homogeneous sample of data, I have decided to restrict my discussion to the M_V of WN stars in the LMC. Here the interstellar reddening is small, the measures are all made by Smith (1968b) on her system and the distance to the Cloud is well known. There is, however, still a problem with possible close visual companions to W-R stars at the distance of the LMC. These have been considered very carefully by Prévot-Burnichon et al. (1981) who obtained well exposed plates of the LMC and examined the W-R stars for separable close companions and elongated images. The M_V form the basis for Figure 1, which gives the individual values for WN stars in the LMC, along with some other objects I will discuss shortly. The spectral types are from the Prévot-Burnichon paper, supplemented in some cases by my own examination of image tube slit spectra, following the precepts in the Sixth Wolf-Rayet Catalogue (van der Hucht et al. 1981). An examination of Figure 1 suggests the following inferences:

(1) Stars with absorption lines are usually brighter at a given subtype. This is consistent with a binary nature for these objects

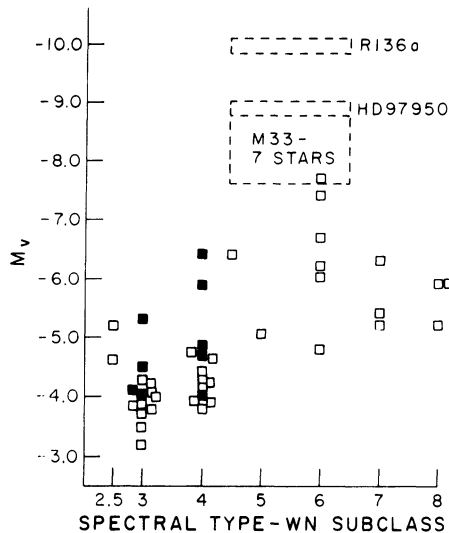


Figure 1. Spectral type- M_V relationship for WN stars. Filled boxes: stars in LMC showing absorption lines; open boxes: stars in LMC without absorption lines and presumably single. The dashed areas show the approximate locations of the superluminous WN stars in M33, R136a in the 30 Doradus region and HD 97950 in NGC 3603. Among the apparently single stars, there is a wide dispersion in M_V at a given subtype.

but does not prove it (Massey 1981). Note that there are relatively few such WN binaries.

(2) Among the apparently single stars: there is a relatively small but real dispersion at M_V among the earlier types but there is a relatively large dispersion in M_V among the later types.

(3) Some very luminous stars of WN type, with $M_V \lesssim -7$, are known. These include R136a among the 30 Doradus complex (Cassinelli, Mathis and Savage 1981) HD 97950 in NGC 3603 (Walborn 1973) and at least seven WN objects in M33 (Conti and Massey 1981). The exact M_V of these WN stars are not well established but it seems clear that they are, indeed, very luminous.

(4) The WN stars do not form a heterogeneous grouping in M_V properties even among the same WN subtypes. Whatever the origin of the stellar wind that produces W-R like spectra, it can occur to objects with substantially different M_V and (presumably) luminosity. There is no one-to-one relationship between the spectrum and the luminosity, except that the highest ionization objects have the faintest M_V and, perhaps the smallest dispersion in their values. Aside from the early types, the spectrum by itself is not a good predictor of M_V .

I have not plotted the WC stars, partly for reasons having to do with the current uncertainties about the m_V , and reddening but also because the few data that are available (Smith 1968b) suggest these objects have similar M_V , at about -4.5 , over most subtypes. The WC 9 stars, on the basis of one object in the galaxy found in a cluster, seem to be a little brighter, perhaps with $M_V \sim -5.5$ (van der Hucht, Thé and Bakker 1980). Many WC stars in the LMC are apparently brighter than M_V of -4.5 but invariably they also have an absorption spectrum present, as if from a brighter companion. It is a curious fact that the single WC stars appear to have less dispersion in their M_V than do the single WN stars.

III. HETEROGENEITY OF W-R SPECTRA

As part of a detailed study of the spectra of numerous galactic and Magellanic Cloud W-R stars, Leep, Perry and I have measured strengths of a number of emission lines. The nitrogen ions will be discussed later in this session (Leep 1982). Here I will show the He II lines. Figure 2 gives the equivalent widths (in $\log W-mA$) for a number of WN stars in our galaxy and in the LMC. It can be seen that those stars with absorption lines generally have weaker emission, as if the strengths have been diluted by the presence of a companion. Leaving these objects aside, there is still considerable dispersion in the He II line strengths among the WN stars, even at the same subtype. This suggests that there is not a standard WN line strength, but rather a range of values among each subtype. The uncertainties in the measures are of the order of 0.1 in the \log (3σ is a factor two).

The He II lines increase in strength by about a factor four from the latest to the earliest WN subtypes. This is comparable to the dispersion in values in each subtype. The $\lambda 4686$ He II line in some WN stars reaches a total equivalent width of 400 \AA , but in several stars is no stronger than about 10 \AA . This line is also appreciably stronger than the $\lambda 4200$ He II line of the Pickering series.

The Galactic and LMC line strengths appear similar among the different subtypes, except those of $\lambda 4200$ for the WN7 stars. The evidence suggests that the galactic WN7 objects have weaker $\lambda 4200$ lines than other adjacent subtypes, and are also weaker than the LMC WN7 stars. The WN7 stars in general have weaker nitrogen lines than the WN6 and WN8 subtypes (Leep 1982) and may represent a somewhat different W-R structure than the remaining WN stars.

The most important conclusion from these studies is that the WN subtypes demonstrate a very heterogeneous mixture of line strengths.

The collection of data on the line strengths in WC stars is still under way but preliminary results suggest that they show somewhat more homogeneity than those of the WN stars illustrated here. There is

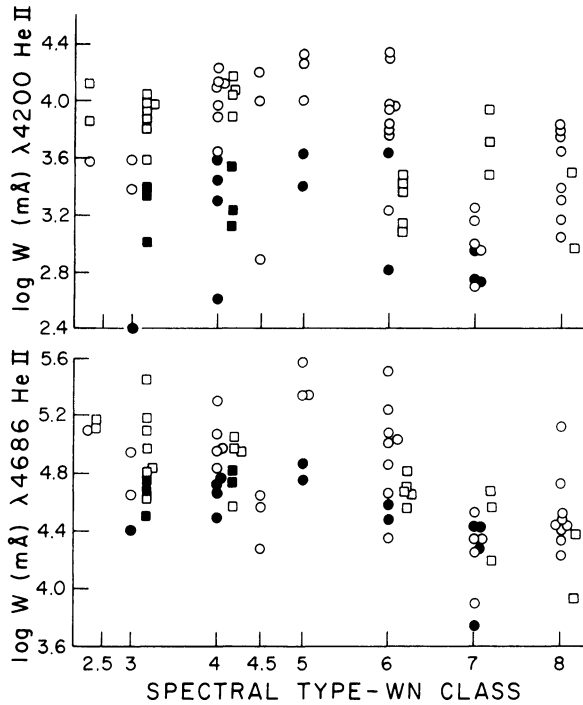


Figure 2. Emission line strengths in WN stars, showing the lines $\lambda 4200$ (upper) and $\lambda 4686$ (lower) of the He II ion. The circular symbols represent the values for stars in the galaxy; boxes stars in the LMC. The filled symbols represents the values for stars with absorption lines; the open symbol stars without absorption lines and presumably single. Among the former group, the lines are usually weak, as if the continuum has been diluted from a companion; among the latter group there is a considerable dispersion in the line strengths, even at a given subtype.

also, as I have noted, less dispersion in the M_V . An examination of the line strengths in the WN stars compared to their M_V does not indicate any convincing relationship.

IV. TRANSITION WOLF-RAYET SPECTRA

I would now like to discuss what can be inferred from the existence of stars with spectroscopic properties intermediate between Of and WN types, and between WN and WC subtypes.

The Of/WN objects in Carina were first noted by Walborn (1974). It was later suggested that these objects formed an evolutionary

sequence (Conti 1976), because of the similarities of M_V and the presence of hydrogen. I would like to stress that the difficulty in classifying such objects may often not be so much the fault of the classification system but rather that one is dealing with stars which have only slightly different properties. In addition to the objects in Carina that were the subject of the Liège Symposium, a montage of WN/O3 stars from a recent paper of Walborn (1982) is instructive: The star $-67^\circ 22$ in the LMC is another intermediate case with both WN and Of properties. In his paper, Walborn notes the difficulties in classifying this star since both broad emission lines and a Balmer series in absorption are visible. In addition, a narrow 4057 N IV line is seen in this star and the others. I will describe later in this Symposium (Conti 1982) other new cases similar to $-67^\circ 22$.

The spectra of the Carina WN stars, and analogous object $-67^\circ 22$, can be understood simply in terms of the degree of emission line strength compared to Of stars. These objects are otherwise morphologically similar, in having an absorption spectrum, hydrogen present and comparable M_V ; the Of/WN differences can be understood as those of stellar wind density alone. If there are only differences in stellar wind strength among Of stars and some of the stars of the WN sequence, does it follow that they are in different evolutionary states? Is there any necessity to conclude that the former are core hydrogen burning and the latter helium burning? Are the former all single stars while the latter are all post Roche lobe overflow? I think not... .

This gradual merging of the classification of the most extreme Of stars with the least extreme WN objects suggests to me that there is a close relationship in their properties. One can infer that the evolution from one type to the other is gradual and not dramatic. Stellar wind mass loss, or chemical mixing, can explain such behavior; Roche lobe overflow scenarios cannot.

Let me now turn to the existence of stars with both WN and WC characteristics. As I have already noted, most WN stars show the presence of the C IV lines at $\lambda\lambda 5801, 5812$ and the resonance doublet at 1550 \AA . We have preliminary measures of the optical lines for a small sample of WN stars. There is a dispersion in the strengths of these lines in most stars similar to what is found for the He II lines and the nitrogen ions. A very few stars stand out in having extremely strong C IV lines in the yellow spectral regions. Particularly noteworthy is HDE 269485, which also has a strong $\lambda 1550$ C IV resonance doublet (Garmany and Conti 1982).

In addition to these stars, for which the classification is WN, there are other objects in which the C III $\lambda 4650$ lines are present. Primarily for historical reasons (classification was done initially in the blue spectral region) objects showing nitrogen ions and C III lines were given a mixed classification, WN + WC, as if two stars were present. If two stars are present, then the binary nature of the

spectrum should be revealed by periodic velocity variations. You will hear later in this Symposium the evidence for binary nature of HD 62910 (Niemela 1982). Roche-lobe overflow scenarios predict that WN + WC binaries might exist.

Leaving the case of HD 62910 for later, I wish to turn to MR 111, which also shows a WN + WC spectrum. Figure 3 illustrates this spectrum, which Massey and I obtained with the IIDS at KPNO last fall. This heavily reddened object shows an early WN spectrum together with the strong C III blend at $\lambda\lambda 4650$. It has been suggested by Pesch, Hiltner and Brandt (1960) that it is a binary with a period near 21 days. According to recent unpublished information from Massey, who has obtained a number of spectrograms of this object, the spectrum is variable and the emission lines all move in phase with one another. Thus the object, while a binary, has carbon and nitrogen ions present in one star. Hence in at least this case, the WR spectrum itself is of both the nitrogen and carbon sequences. There are three (out of 159 stars) of mixed classification in the WR Catalogue (van der Hucht et al. 1981). The statistics of intrinsic nitrogen-carbon types are not well established, however, because one or two of the others might be a double-lined binary. Furthermore, the number of stars showing enhanced C IV lines (but not C III) is not established. It is also not clear with the data currently in hand, whether or not there is a continuum of carbon strengths in WN stars, or whether there is a sharp dividing line between those WN stars with strong carbon and those with only "normal" C IV strength. This topic requires more quantitative work.

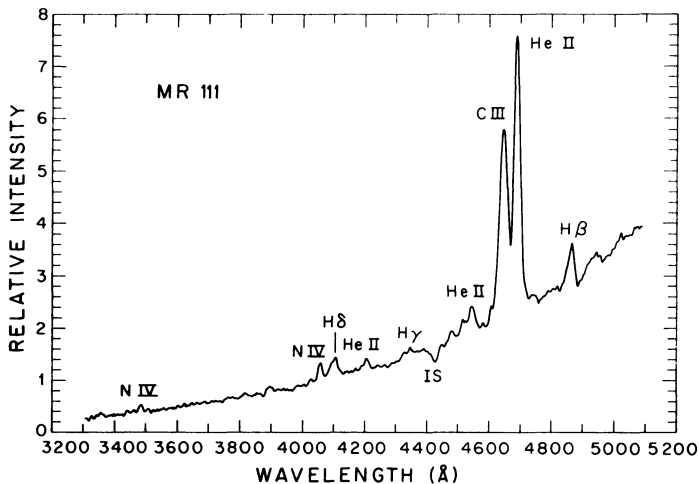


Figure 3. Spectrophotometry of MR 111, a star classified as WN + WC on the basis of the C III lines at $\lambda\lambda 4650$ being present in an otherwise WN type spectrum. According to Massey (1981) all emission lines move in phase in this spectroscopic binary, hence arise in the same object.

It is clear, however, that most WN stars, while showing C IV, do not show C III. A few stars seem to have enhanced carbon, either in the form of very strong C IV lines, or with C III present at $\lambda 4650$. The existence of such transition nitrogen-carbon stars suggests an evolutionary connection between WN and WC types, although it does not prove it. One would like to imagine that as the CNO cycle begins to end, the helium burning will begin. Then the carbon should begin to manifest itself in the composition of the star. However, the currently envisaged scenarios do not permit this to happen gradually. There should be a sharp demarcation between nitrogen and carbon rich atmospheres in W-R objects, as there is in the existence of the two separate WN and WC sequences.

V. MASS LOSS RATES

I have previously summarized some of the problems that go into determining stellar mass loss rates (Conti 1981) and wish to present here only the most recent data for early type stars. These results are summarized in Figure 4. Most values for the O and Of type stars come from the analysis of the UV spectrum by Garmany *et al.* (1981); Much of the data from the radio regions comes from VLA observations by Abbott, Biegging and Churchwell (1981); the work on the W-R stars is also from VLA data (Abbott, Biegging, and Churchwell, 1982) or IR observations by Barlow, Smith and Willis (1981). The O and Of stars follow a relationship between the mass loss rate \dot{M} and luminosity consistent with the predictions of the radiatively driven wind theory of Castor, Abbott and Klein (1975). The W-R stars seem to have rates which do not follow such a relationship but cluster near a value of $\dot{M} \approx 2 \times 10^{-5}$, regardless of spectral type. I have only plotted the "classical" W-R stars: the central stars of planetaries have smaller rates; the luminous "exciting" stars may have larger ones.

For the O and Of stars, the \dot{M} of the luminous stars, of order 5×10^{-6} or greater, would seem to be large enough to affect the subsequent evolution of the object itself. The most luminous stars have rates which will drastically affect the evolution, as a substantial fraction of the initial mass will be removed. The rates of W-R stars themselves are also large enough to affect their own evolution.

A most curious and ironic inference from Figure 4 is that the W-R stars, with substantially divergent spectra, show a small dispersion in their \dot{M} . This is to be contrasted with their wide dispersion in mass, luminosities, and emission line strengths, in addition to the obvious disparities between the WN and WC subtypes and their respective ionization sequences. An important issue, presently unresolved,

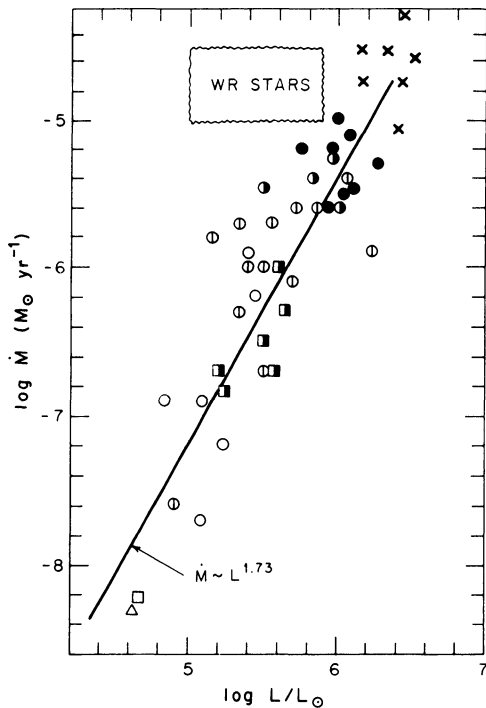


Figure 4. Values of mass loss rate \dot{M} vs. luminosity for O and Of type stars with well determined distances. The values for the ordinate come from various sources (see text) as follows: circular or box symbols -- UV analyses; x symbols -- radio continuum detection. The dashed line encloses the approximate location of the W-R stars from IR and radio data. The straight line is a least-squares linear fit to the O and Of star UV data (alone).

is whether or not the winds in W-R stars are radiatively driven (Barlow et al. 1981). Note that some O and Of stars have \dot{M} similar to those of W-R objects; the wind structures must therefore be different.

VI. VERY LUMINOUS W-R OBJECTS

One of the most exciting announcements in the last year has been that of Cassinelli et al. (1981) who argue that the central exciting object of the 30 Doradus complex, R136a, is a single star with a mass of $3000 M_{\odot}$ and a luminosity of $10^8 L_{\odot}$. I will not duplicate their discussion here, and I do not necessarily endorse all their numbers. However, it seems highly probable to me that this object, which has a W-R spectrum, is somewhat more massive than the previous canonical limit of "stable stars" of $100 M_{\odot}$ and is considerably more luminous

than any other previously known star. A morphologically similar object is found in the center of the galactic giant H II region NGC 3603. This star, HD 97950, has been discussed and compared to R136a by Walborn (1973) who calls attention to the similarities of the spectra. Additionally, Conti and Massey (1981) have found analogous objects as the central exciting stars of a number of the giant H II regions of the nearby spiral galaxy M33. The spectra of these objects, while W-R like and of WN type, are not easily classifiable on the Smith system (see also D'Odorico and Rosa 1981). The M_v of these exciting stars, if they are single, are invariably brighter than -7^m , the previous upper limit for WN stars (e.g. Smith 1968b).

Spectra of the exciting stars in M33 are shown in the Conti and Massey (1981) paper. A question unanswered at the present time is whether or not the exciting stars in M33 are single, as we believe, or multiple, as argued by D'Odorico and Rosa (1981). The resolution of ground based telescopes is insufficient to answer this question; speckle photometry is probably not good enough to observe the faint objects in M33 and we must await the Space Telescope for final answers to this question. By analogy with R136a, however, which does have speckle information and resolves to a single object, a case can be made that the exciting stars in M33 are likewise similar.

I propose to refer to these central exciting stars as "super-massive" W-R stars. I think it very likely that they are, like R136a, more massive than $100 M_{\odot}$ and their W-R like nature is due to the strong stellar winds which are partly the result of their high mass, giving them an "unstable" character, and partly due to their high luminosities. It is likely that they are still burning hydrogen in their cores, and hence are "main sequence" stars. It is not impossible that such massive stars evolve quasi-homologously (Maeder 1980), thereby bringing CNO equilibrium products to the surfaces.

VII. THEORETICAL ASPECTS OF STELLAR STRUCTURE, STELLAR ATMOSPHERES AND STELLAR WINDS — O AND W-R STARS

Details of the work in this very active field are provided later in this Symposium (Chiosi 1982). The mass and composition of a stellar model, and their rates of change, can lead, in principle, to predicted luminosities and temperatures of stars. These may be compared with the observational quantities. Similarly, the observed masses and chemical compositions may be compared with the input of the theoretical models. An interplay of theory and observation is necessary for the comparison.

Evolution of stars with mass loss has been greatly aided by the work of the Brussels group (de Loore 1981), Chiosi and his associates (Chiosi 1981) and by Dearborn and Blake (1979) and Stothers and Chin (1979). These practitioners give predicted luminosities and effective

temperatures of evolving massive stars with various parametrizations of the mass loss rates. An important common result is that mass loss tends to lengthen the main sequence burning lifetime because the stars become somewhat less luminous; they also reach lower effective temperatures while core hydrogen burning.

The luminosities and temperatures of W-R stars are not well known primarily because the latter parameter is not established. It is not clear that the ionization sequences in the WN and WC subtypes are related to effective temperature; neither do we know what the actual values of the effective temperature are for these sequences. It is not even certain that two stars of the same ionization subtype necessarily have the same effective temperature. We can be sure that some W-R stars do have luminosities that are too bright for their masses (e.g. Paczynski 1973) but the actual values for all but a handful of stars are not well known. It seems to be premature, therefore, able to argue for, or against, an evolutionary scenario, on the basis of the "position" of a W-R star in the HR diagram. On the other hand, the relevant quantities for O stars, and possibly even for Of stars, are probably well enough established that observed H-R diagrams and a comparison with the theory is both useful and meaningful for them.

An observer's view of the theory of stellar winds, stellar atmospheres and stellar structure in O and W-R stars is illustrated in Figure 5. I believe this figure and its caption are self-explanatory. Seriously, though, I would like to stress that although considerable effort has gone into the theory, much more work is needed. It is hoped that observers will be able to provide better luminosities, effective temperatures, masses and compositions, in the coming years.

VIII. EVOLUTIONARY SCENARIOS

There are basically five different scenarios that have been proposed to account to for W-R stars. These have been nicely summarized by Maeder (1981, 1982) who draws attention to the fact that they may all play a role, depending on the circumstances of initial mass, composition, and binary nature. These are:

a) Binary mass exchange/loss: First popularized by Paczynski (1973) this scenario must play a role in those systems that are close binaries (de Loore 1981).

b) Mass loss during the core hydrogen burning stage: Conti (1976) drew attention to the close morphological similarity between certain WN objects and the Of stars, suggesting an evolutionary connection. This scenario has received considerable recent attention with the acquisition of mass loss rates in many O type stars; those numbers seem to be significant by themselves only for the most luminous and most massive stars.

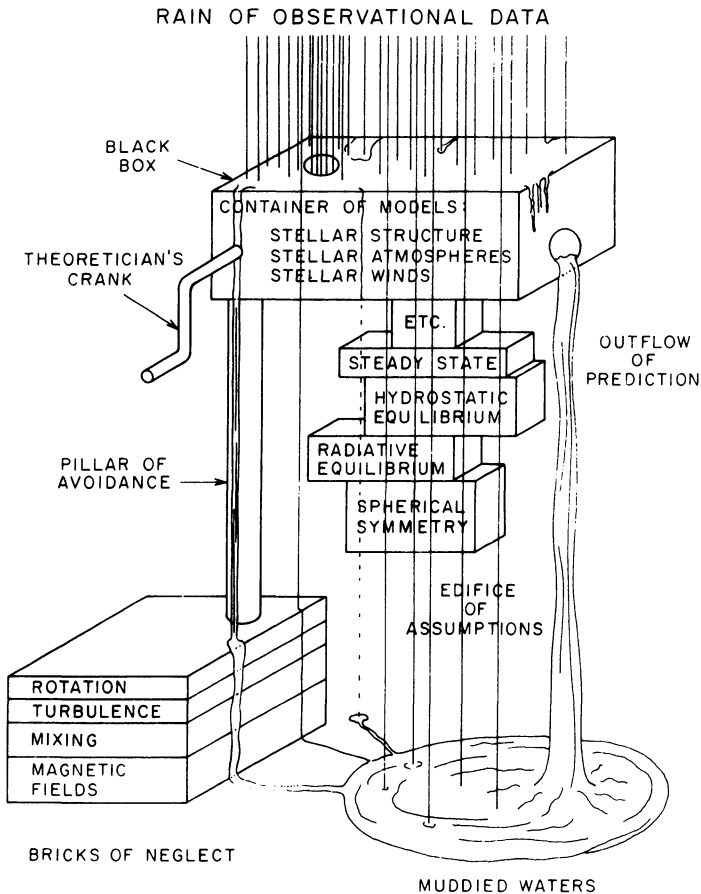


Figure 5. An observer's view of stellar theory: the central feature is a black box in which the models are contained. This is driven by a theoretician's crank, which is turned rapidly or slowly, depending on the computer budget. The black box is held up by the edifice of assumptions of steady state, hydrostatic equilibrium, radiative equilibrium and spherical symmetry, among others, and by the pillar of avoidance of difficulties, such as the neglect of rotation, turbulence, mixing (until very recently) and magnetic fields. The input to the models in the black box is a rain of observational data, which falls onto the box. Notice that only a fraction of this rain of data ever enters the black box as its top is covered and only a small hole admits the information; most of the rain flows off the container to the ground where it mixes with the outflow of prediction from the end of the black box and muddies the waters.

c) Post red supergiant evolution: Noted by Chiosi, Nasi and Sreenivasan (1978) as a viable possibility, this scenario may be important for certain kinds of W-R stars. The recent direct detection of a dust shell surrounding the WC9 star MR 80 by IR speckle ($5\mu\text{m}$) photometry (Dyke, Simon and Wolstencroft 1981) may be an important observational connection (see also Hidayat, Supelli and van der Hucht 1981).

d) Chemical mixing: This has been discussed thoroughly by Maeder (1981) who suggests several physical processes that may occur. These are undoubtedly important and perhaps in symbiotic combination with mass loss may dominate the statistics of W-R stars.

e) Basic stellar instability: The vibrational instability of massive stars has been discussed by Appenzeller (1970). This concept may now be revived for the most massive stars that are observed as the exciting stars of the giant H II regions (Conti and Massey 1981).

The various scenarios discussed here will require further study, of course, but I suspect that together and in combination they will probably be able to explain the evolutionary status of all the objects showing W-R spectra. In the words of a recent political figure "let many flowers bloom."

I must now sound a cautionary note: while we can understand that some objects have W-R spectra because of strong stellar winds, we do not understand the origin of the wind itself. It may certainly be due, at least partially, to radiation pressure. Is there some other physical aspect, not yet considered, that is necessary to understand these winds?

The applicability of the various scenarios to W-R stars suggests that it is a natural consequence of the evolution of massive stars; objects showing such extremes of mass loss may then be thought of as being in a normal ending phase of their natural life, to be finished all too briefly within a few hundred thousand years. The consequences of the death of W-R star may be interesting in its own right. Do they "go out" with a "bang" or with a "whimper?"

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DISCUSSION

Underhill: Hydrogen can be detected only when the electron temperature is low enough and the density is appropriate that hydrogen recombines at a rapid enough rate and in a large enough volume that an observable amount of energy is radiated in the Balmer lines. For several reasons I strongly suspect that the mantles of Wolf-Rayet stars are inhomogeneous. It is quite conceivable that two stars may have volumes producing similar amounts of N III, N IV and N V lines but different amounts of the Balmer lines of hydrogen, because the energies required to obtain detectable emission in H I, N III, N IV and N V are quite different. It is not justified to think that all the spectral lines of interest come from the same volume of gas.

Conti: My answer to this is that the line widths are similar, suggesting that the volumes are similar and the analysis does follow correctly. Nature would have to be very capricious to arrange stellar winds in a manner such that lines of similar width did not come from similar volumes.

Underhill: There is one thing that everyone should be absolutely clear about and that is this. On the one hand one has model stars based on the theory of stellar evolution. The starting parameters are mass, composition, and outflow according to some prescribed algorithm for the

rate of mass loss. The energy is transmitted from the centre of the star to the surface in such a manner that radiative equilibrium occurs. The output results are series of values of T_{eff} and $\log g$ or luminosity as a function of time. On the other hand one has observed stars which present a spectrum of emission and absorption lines. To substantiate any scenario about how the model stars may be linked one to one to real stars one has to make use of the theory of stellar spectra to link properties of real stars to those of the model stars. Between 1961 and 1981 17 papers have been written showing how different types of line profile result from inflow and outflow, accelerating or decelerating atmospheres, and temperature increasing outward, decreasing outward, or remaining constant. None of the model atmospheres based on outflow and radiative equilibrium (properties of the model stars which are to be identified with real stars) produces line profiles like those seen in Wolf-Rayet stars. It is a pointless exercise to make scenarios based on such a hypothetical relationship. The theory of stellar atmospheres indicates that both energy and momentum from a non-radiative source must be put into the outer layers or mantle of a star if a Wolf-Rayet spectrum is to result. When model stars doing this have been made, then, perhaps, we will be able to link model stars to real Wolf-Rayet stars. I have published attempts in this direction; they indicate that 9 Wolf-Rayet stars are like B0 stars.

Conti: I believe that emission lines can be produced in an extended envelope in a straightforward manner. A recombination spectrum may indeed need energy input and I will agree this is not yet understood for WR (or O-type !) stars. However, this does not mean one cannot estimate such wind parameters as density, ionization state and composition. One does not have to understand the entire computer hardware to be able to use the software.

Cassinelli: In regard to Anne's explanation of the weakness of H emission. We now have X-ray observations of WR stars and if the gas were hot enough to make H lines weak the X-ray emission would be larger than that observed.

Niemela: I would like to remark that the WNL and WNE binaries should not be taken together as a group because they show different mass ratio behaviour.

Pismis: Is there a relationship between the terminal velocity of the wind and the type of WR either in WN or in WC stars ? I thought there was none some years ago. How is the situation at present ?

Conti: I think that such a relationship is suggested for WC stars such that earlier WC stars have higher velocities. I don't think such a relation holds for WN types.

Underhill: I have results for a few IUE spectra of WR stars. There are not enough values for statistical accuracy, but for what its worth, the v_{∞} values of WC and WN stars cover the same range. The values are smaller than what is found for O3 and O4 stars; they are typical of early-B or late-O supergiants.

Moffat: Spectral heterogeneity is based partly on scatter in line strengths. Surely line ratios must be more homogeneous. What are the considered limits you would give for a given spectral class ?

Conti: Ms. Leep will discuss this later. Basically, there is some overlap among nitrogen ion line ratios between adjacent WN types. One might think that the ionization conditions alone among WN stars are, by themselves, insufficient to give the observed types.

Heap: You imply the major distinction between WR stars and Of stars is the density of their winds. Do you have any evidence concerning the characteristics of the winds ? In particular, do the winds of WR stars and Of stars have the same velocity law ?

Conti: Probably the velocity laws differ since some Of stars have rates similar to WR stars, yet the spectra are different.

Niemela: If WC stars were post red supergiants, would you expect to see red supergiants in those open clusters where you see WC stars ?

Conti: The suggestion is that the WC9-WC8.5 stars are the result of post red supergiant evolution. My understanding of the post red supergiant scenario is that it is so short so as not to be observed directly.

Houziaux: I have a comment and a question: (a) Your talk assumes as a basic parameter the spectral(sub)-type. However this spectral type is based on a narrow wavelength range. I think that if classification is to be of any use, it should include the whole spectrum from X-ray to radio radiation, as well as the spectral energy distribution in the continuum. (b) Does the heterogeneity of the spectral characteristics (line intensities, line intensity ratios) not depend on the fact that the parameter is the spectral type ? If you took another characteristic more physically related to the stars (like L^* , T_{eff} , \dot{M}) would this heterogeneity be reduced ?

Conti: My reaction to your first comment is that it is an excellent point. However, the UV spectra we have seen also suggest a large heterogeneity. The radio and IR free-free detections suggest a larger homogeneity. The X-ray detections are nearly all upper limits, so the spectra are indeed heterogeneous.

As to the second point, the scanty mass information also shows dispersion: Massey has discussed the fact that stars of similar WN type can have very different masses. The effective temperatures are not yet well known. It would not surprise me if it turned out that stars with similar subtype were found to have different effective temperatures.

Barlow: One detects the presence of hydrogen in its ionized form by means of its recombination spectrum. If one appeals to very high temperatures to lower the recombination rate and thus the detectability of ionized hydrogen, one should bear in mind that the recombination rate of doubly ionized helium has the same temperature dependence and thus the relative line intensities of hydrogen and helium will not change with increasing temperature once helium is fully ionized.

Conti: That nicely confirms my feeling that the observed H/He ratio is not very model dependent.

Firmani: What is the minimum mass you would estimate for Pop I WR stars ?

Conti: According to binary star work the minimum (Pop I) mass is between 5-8 M_{\odot} .

Vanbeveren: Does there exist a lower limit for the hydrogen abundance in order to be detectable ?

Conti: The lower detection limit of H/He by number for WN stars is estimated to be 0.1. No good estimates exist for WC stars.

Smith(L.F.): You based the case that single Of stars evolve into WN stars on the existence of numbers of intermediate types. Yet, as I understand present mass exchange models, the abundance of the surface after RLOF is H/He = 1/1 by number ($X \sim 0.2$). There is a significant time before continued mass loss produces a full fledged WN star. I expected you to base your argument on whether or not some WNE stars have more hydrogen than $X \sim 0.2$.

Conti: I believe that full fledged WN stars, eg. HD 92740, may have a normal, or near normal, H/He ratios. The actual numbers for the early stars are uncertain. The presence of the Balmer series in a few early WN stars does indicate that its absence in others is not an ionization effect.