PARAMETERS OF WOLF-RAYET STARS

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INTRODUCTION

Wolf-Rayet (W-R) stars are objects with strong emission lines in the optical region due to a substantial stellar wind. They are found among the extreme Population I stars which are the topic of this Symposium and also this talk, and as central stars of planetary nebulae which I will not discuss here. The mass loss rates, $\dot{M}$, are typically several 10^{-5} solar masses per year. W-R stars come in two major subtypes, the WN, in which strong lines of helium and nitrogen are seen, and the WC, in which strong lines of carbon and oxygen are found, along with the helium ions. In a few WN stars hydrogen appears to be present but the spectra of W-R stars are notable for the absence of this element. Absorption lines are generally not found in W-R stars, except in some instances due to a binary companion, or a more distant companion, or as a P-Cygni profile associated with certain emission features. An absorption spectrum appears to be an intrinsic feature in a very few WN stars.

The WN stars are classified into an excitation/ionization sequence depending on the line ratios among the nitrogen ions (λλ4634, 4640 N III; λ4057 N IV; λλ4603, 4618 N V). These range from the highest to the lowest excitation, WN3, WN4,...WN9, and are similarily called "early" and "late" types by analogy with the MK classification. The WC stars are also assigned to excitation/ionization subtypes which go from WC4, WC5 ,..., WC9. These depend on the ratios of the carbon ions (λ5696 C III; λλ5801, 5812 C IV) and an oxygen ion (λ5592 O III). The basis of the subtypes is outlined by Smith (1968) with a modern updating by van der Hucht et al. (1981). The WN stars show the anomalous abundances representative of "equilibrium" CNO cycle hydrogen burned material with enhanced helium and nitrogen at the expense of hydrogen and carbon; the WC stars show the composition characteristic of helium burning material, in which carbon and oxygen are produced from the previously formed helium (e.g. Willis 1982). In both cases we are observing stars that are highly evolved and in which the products of nuclear reactions in the stellar cores are seen at the surface.

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Parameters of stars describe such intrinsic characteristics as stellar luminosities, effective temperatures, chemical composition, radii, masses, and for hot stars such as these the mass loss rates. In this talk I shall briefly touch on these topics, in particular those in which some recent new results are pertinent to current work. It is commonly held that W-R stars are the decendants of massive O-type stars in which the initial convective cores have become visible due to mass loss and mixing in the progenitor object. After discussing the distribution of W-R stars in our galaxy, I will indicate at the end of my talk the arguments for believing that W-R stars are a natural consequence of massive star evolution.

LUMINOSITIES

Ideally we wish to discuss the bolometric luminosity of a star; thus we need to know not only its M_v but also the bolometric correction. For W-R stars, the first of these features is now relatively well known; the latter parameter is not. M_v can be found for galactic W-R stars that are members of clusters and associations with well established distances. Lundström and Stenholm (1984) have recently made a detailed compilation of these values for a number of objects. Similarly, the W-R stars known in the Large Magellanic Cloud can be used as an independent calibrator. This has recently been rediscussed by Conti et al. (1983b). The basic data one needs to have are the optical photometry, so one will have the apparent magnitudes and the color of the star. One may then determine the reddening and with the distance modulus of the cluster/association (found independently from the OB stars) find the M_v directly. The calibration I will show here is still incomplete as it deals with only a small fraction of the known galactic W-R type stars. Some other W-R stars in the LMC suffer from crowding and confused photometry with nearby stars.

Figure 1a shows the M_v calibration of the galactic W-R stars, adopted from Lundström and Stenholm (1984). There is a substantial dependence of M_v on subtype, particularly for the WN classes. The earlier types are certainly fainter in M_v but whether or not they are in M_{bol} remains to be seen. Figure 1b shows the M_v for the W-R stars in the LMC. We notice immediately that not all subtypes seen in the galaxy are found in the LMC. There is a very similar M_v dependence with spectral subtype in both the galaxy and the LMC for the WN and WC stars, although the difference at WN6 is a little larger than for the other subclasses. There is also a substantial scatter at a given subtype. Table 1 gives the mean M_v-spectral type relation for the W-R stars in both the galaxy and in the LMC. The σ, or standard deviations of one measure, are also indicated in Table 1. These values, which range from 0.3 to 1.0 magnitudes, indicate what uncertainty is assigned to estimating an M_v from a single spectral type determination; this represents the current best "calibration" of M_v for spectral types of W-R stars.

The bolometric corrections (b.c.) depend critically on the effective temperatures of the stars in question. For W-R stars, these

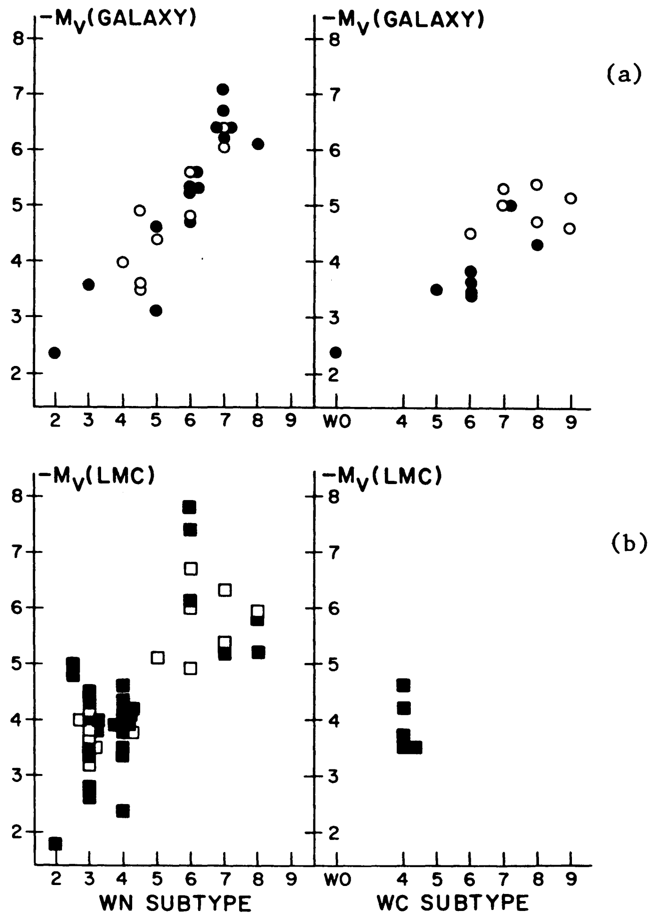

Fig. 1. Absolute visual magnitudes versus W-R subclasses for galactic stars in clusters/associations (circles) and LMC members (boxes). The filled symbols indicate stars with better photometry than the open symbols.

numbers range from 30,000-100,000°K according to the excitation/ ionization temperatures and between 20,000-40,000°K from the continuum measures (e.g. Conti and Underhill 1986). The b.c. would thus be between 3^m and 6^m. As I will describe shortly, the effective temperatures are not well known; uncertainties of a factor two still are present in the interpretation of the data. Thus there are similar questions about the luminosities of W-R stars since the b.c. will dominate the determination of the bolometric values.

Table 1. M_V-spectral type relation for W-R stars

	Galaxy			LMC			All		
	$-M_V$	σ	n	$-M_V$	σ	n	$-M_V$	σ	n
WN2	2.4	---	1	1.8	---	1	2.1	0.4	2
WN2.5		---		4.9	0.1	2	4.9	0.1	2
WN3	3.6	---	1	3.7	0.5	15	3.7	0.5	16
WN4	4.0	---	1	3.8	0.5	14	3.9	0.5	15
WN4.5	4.0	0.8	3		---		4.0	0.8	3
WN5	4.0	0.8	3	5.1	---	1	4.3	0.8	4
WN6	5.2	0.3	7	6.5	1.0	6	5.8	1.0	13
WN7	6.5	0.3	7	5.6	0.6	3	6.2	0.6	10
WN8	6.1	---	1	5.6	0.4	3	5.8	0.4	4
WC4	---	---	-	3.9	0.5	5	3.9	0.5	5
WC5	3.5	---	1		---		3.5	---	1
WC6	3.8	0.4	5		---		3.8	0.4	5
WC7	5.1	0.2	3		---		5.1	0.2	3
WC8	4.8	0.6	3		---		4.8	0.6	3
WC9	4.8	0.4	2		---		4.8	0.4	2
WO	2.4	---	1		---		2.4	---	1

EFFECTIVE TEMPERATURES

When observing the emergent continua of W-R stars we are detecting photons only from the wind, even in the optical region. This is not the usual situation since in nearly all other stars the absorption lines and the wavelength dependence of the continuum radiation give one an estimate of the surface parameters, and thus the overall structure of the star itself. The wind clearly must be related to some intrinsic stellar property but this relationship is not fully understood for W-R objects, and is only beginning to be constrained for O-type stars (Kudritzki and Hummer 1986). For models of W-R winds and atmospheres extended spherical geometry must be used, and the radiative transfer and statistical equilibrium equations must be solved in a moving atmosphere. This very difficult problem has not yet been addressed adequately although various approximations in the literature have begun to make some progress (e.g. Hillier 1983).

Most of the flux of these hot objects is found in the far UV regions, much of which is below the 912 Å Lyman limit and hence completely inaccessible to observations due to the interstellar absorption. I show in Figure 2 a cartoon which I think nicely demonstrates

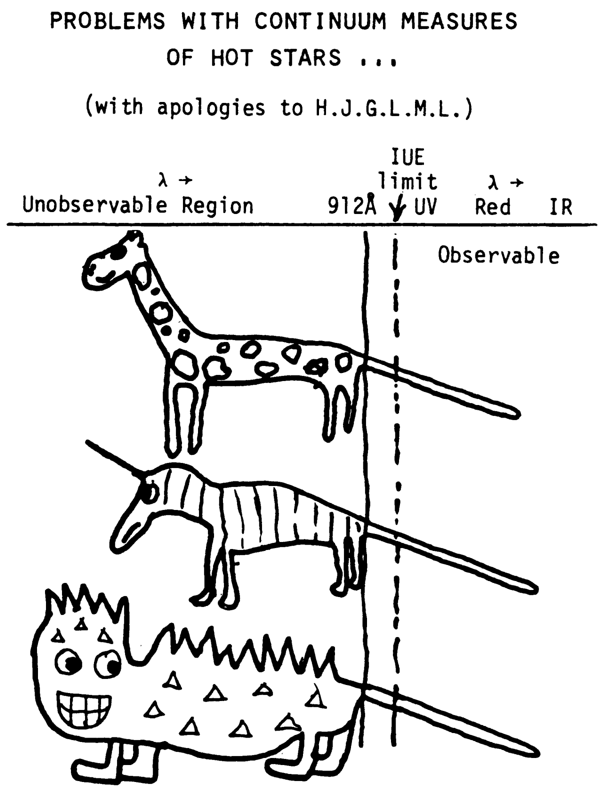

Fig. 2. Cartoon showing difficulty in discerning the nature of the "beast" existing below λ912 Å, the Lyman limit, if one only has the "tail" of the distribution to observe in the UV, optical, and IR wavelengths.

the nature of the problem with the data: we are in a situation, even with IUE observations, in which we only measure the "tail" of the distribution of energy coming from a hot star. The actual "beast" that lurks shortward of the Lyman limit is only dimly perceived through theoretical modeling of a moving atmosphere, which is an incompletely solved problem. In particular, the backscattering of photons from the wind may affect the emergent continuum of the underlying stars (Hummer 1982). This is only now being incorporated in models for O stars (Abbott and Hummer 1985), and will play a critical role for W-R stars. My caution here is to realize the models of W-R stars are very inadequate and that conclusions which rest heavily upon them are subject to considerable revision.

It should also be kept in mind that the observed data need to be corrected for the interstellar absorption. This is by no means a straightforward procedure as the extinction "law" is not universal in the UV regions (Massa et al. 1983; Garmany et al. 1984).

What then can be done about effective temperatures for W-R stars? There are a very few eclipsing binaries which do lend themselves to determinations of this quantity. Very recently a detailed discussion of the light curves of V444 Cyg = HD193576 has been carried out by Cherepashchuk et al. (1984). Using data extending over the UV to near IR regions, they find the eclipse durations are a function of wavelength (as would be expected if the opacity depends strongly on this quantity). They are thus able to model the eclipses and find a relatively small core radius for HD 193576 of some 2.9 $R_{\odot}$, implying a large effective temperature of 90,000°K for this WN5 star. Pauldrach et al. (1985) have reported an improved code for calculating radiatively driven wind models. They were able to duplicate the inferred density, radius, and velocity relationships for the V444 Cyg found empirically by Cherepashchuk et al. with their high effective temperature.

Hillier (1983) found that an effective temperature of 60,000°K fit the emission line measures of HD 50896, another WN5 star, but pointed out his data did not yield a sensitive determination of this quantity. Cherepashchuk (1982) reviews data on three other W-R eclipsing binary systems which might be used to determine radii and thus empirical effective temperatures. The relatively small core radii found suggest relatively high values for the temperature, corresponding more closely to the excitation/ionization values than to those implied by the emergent continua.

My conclusion is that at present the effective temperature scale for W-R stars is not well known. The earliest types may have values near 100,000°K and the latest near 30,000°K but the relationship with the spectral types is not at all certain. Presumably, the effective temperature will scale with the excitation/ionization sequence but I would not be completely surprised if it eventually turned out that two, say, WN5 stars ended up with different effective temperatures. I would again like to stress that the spectrum of the W-R stars is one of the wind and this may be only loosely coupled to the intrinsic parameters of the star itself.

MASSES

There is not too much new to add to the review of this problem given by Massey (1981). There are values for some dozen or so W-R binaries, either members of the eclipsing systems or those for which the spectrum of the O-type companion is estimated well enough that its mass can be found. The values for W-R stars range from some 10 to 40 $M_{\odot}$; the extremes are for two stars of the WN6 class so there is no simple dependence on spectral subtype. Although one might expect that WC stars are more evolved than WN stars, given their compositions, the former are not less massive than the latter. Thus with the data presently in hand it is not possible to conclude that all WN stars become WC, nor that all WC were once WN. Massey suggests that the WC stars might have evolved from the more massive WN type but we cannot go much beyond this at the present time, at least in my opinion.

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COMPOSITION

I have already alluded to the compositions of W-R stars. The pertinent references are Willis and Wilson (1978), Smith and Willis (1982), Nugis (1975, 1982), Conti et al. (1983a), Torres et al. (1985). These results suggest that the WN stars have greatly enhanced helium and nitrogen and little or no hydrogen present. Carbon and oxygen are found in WN stars in more or less normal abundance. In WC stars helium, carbon and oxygen are found to be in great abundance and there is no evidence for hydrogen or nitrogen. These data are qualitatively in agreement with the predictions of massive star evolution with mass loss and mixing revealing the underlying nuclear reaction core (Noels and Gabriel 1981; Maeder 1983). The quantitative agreement is a factor of a "few" but this may reflect problems in the evolution of the models or in the absolute abundance or some combination of these features.

MASS LOSS RATES

Abbott et al. (1985) have completed a detailed study of detections of thermal free-free emission from the winds of O and W-R stars. These are mostly at 6 cm wavelength and all with the VLA. This emission is proportional to the mass loss rate of the star, with practically no model dependence. The $\dot{M}$ can be found if the distance of the star is known (the uncertainty here scales as the 3/2 power) and if the terminal velocity of the wind can be obtained (typically with IUE measures). A presumption is that the terminal velocity measured a few tens of stellar radii away is unaffected out to a few hundred radii where the free-free emission is measured. In spherical flow models this should be readily satisified.

Recently it has been recognized that some of these hot luminous stars have a nonthermal component to the radio emission measures. Abbott et al. (1985) are able to show that for most W-R stars, the nonthermal contribution is small since the wavelength dependence of the flux follows a power law with exponent -0.6 they list 7 W-R stars as definite thermal emitters and another 17 as probable thermal sources, thus giving 24 stars with well-determined mass loss rates. I have appended their data in Table 2. Is there any dependence of $\dot{M}$ on the W-R subtypes? Figure 3, adapted from Abbott et al., shows there is not. The WN and WC subtypes appear to have similar $\dot{M}$ and there is no dependence on excitation class. There is a certain spread in the values of $\dot{M}$ at a given subtype, a point to which I will return shortly.

Abbott et al. (1985) have determined $\dot{M}$ for five binary systems for which reasonable mass estimates are in hand. Figure 4, adapated from their paper, shows that as far as these data are concerned, there is a relation between the $\dot{M}$ and the stellar masses, the mass loss rates being larger in the larger mass stars. One would certainly like to have more data points, but Figure 4 looks pretty convincing. Why does the $\dot{M}$ depend on the stellar mass? Abbott et al. suggest this is

Table 2. Mass Loss Rates for W-R Stars[a]

WR	Spectral type	log $\dot{M}$ ($M_\odot$ yr^{-1})	WR	Spectral type	log ($M_\odot$ yr^{-1})
142	WO2	<-4.7	2	WC9	<-4.6
111	WC5	-4.8	133	WN4.5+O9I	<-5.0
114	WC5	<-4.8	1	WN5	-4.5
143	WC5	<-5.1	6	WN5	-4.5
92	WC6+Abs	-4.5	138	WN5+Abs	-4.9
79	WC7+O6	-4.3	139	WN5+O6	-5.0
86	WC7+Abs	-4.6	110	WN6	-4.3
90	WC7	<-4.8	115	WN6	-5.0
137	WC7+Abs	-4.7	134	WN6	-4.5
11	WC8+O9I	-4.1	136	WN6	-4.5
113	WC8+O8V	-4.5	141	WN6	-4.9
135	WC8	-4.6	78	WN7	-4.4
81	WC9	-4.9	87	WN7	<-4.7
95	WC9	<-4.8	89	WN7	-4.4
103	WC9	<-4.7	130	WN8	<-4.8
104	WC9	<-4.7	145	WN/C	-4.7
121	WC9	<-4.8			

[a]From Abbott et al. 1985.

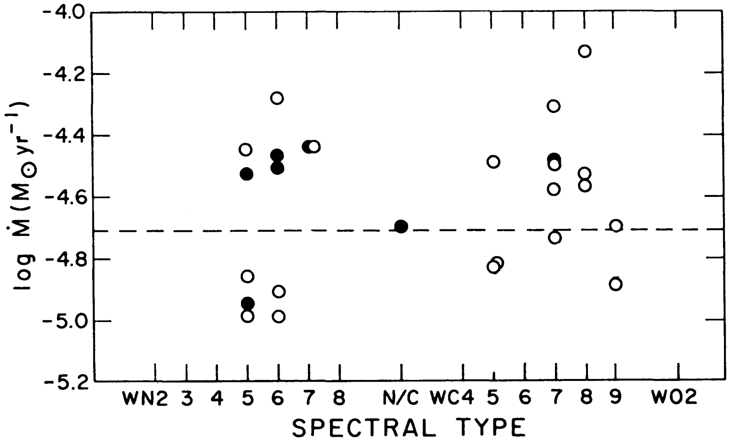

Fig. 3. Mass loss rates versus W-R subclasses (from Abbott et al. 1985). The filled symbols represent definite thermal sources; the open symbols the probable thermal sources.

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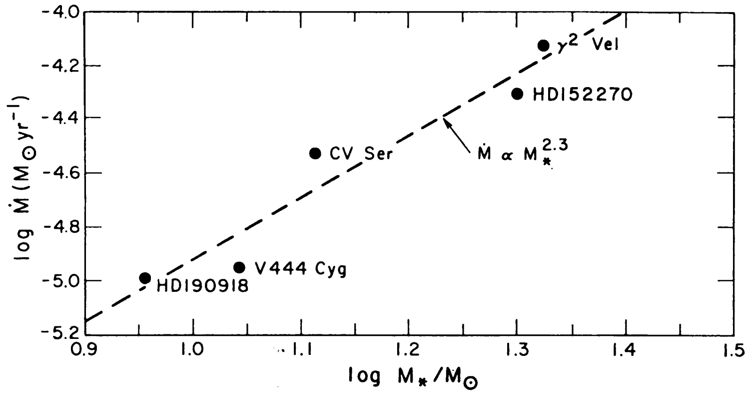

Fig. 4. Mass loss rates versus masses for five binary systems with well determined parameters (from Abbott et al. 1985).

because the more massive stars are the more luminous. As I have discussed previously, the bolometric luminosities of W-R stars are not well estimated. However, Abbott et al. were able to skirt this problem by taking advantage of an artifact. They took a mean M_V for each spectral subtype and then a deviation from the mean for each W-R star with a measured $\dot{M}$. The correlation of this artificial luminosity with $\dot{M}$ is shown in Figure 5. Here there are more data points and there is a tendency for the stars with the higher $\dot{M}$ to be brighter (in M_V within their subtypes). This is to be expected if the winds in W-R stars are radiatively driven. Figure 5 is currently the best indica

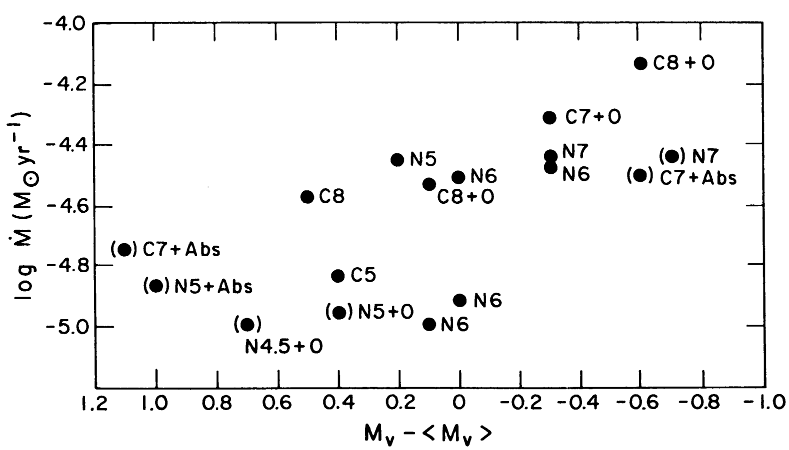

Fig. 5. Mass loss rates versus artificial luminosities (M_V minus means M_V) adapted from Abbott et al. (1985). The symbols with parentheses have less certain M_V.

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tion of mass loss rate depending on the luminosity for W-R stars. I will also recall the recent theoretical model of Pauldrach et al. (1985) in which they are able to match the wind law of V444 Cyg found by Cherepashchuk et al. (1984) with a radiatively driven wind from a core of 90,000°K effective temperature.

The substantial mass loss rates found for W-R stars by Abbott and his associates are significant on the evolution time scale for these objects. These values will peel down a considerable fraction of the remaining mass in the helium burning lifetime. As the star becomes less massive, its luminosity also may decrease and the loss may taper off. The final state of a W-R star is by no means clear, whether they just "poop out" or violently explode is an interesting question.

DISTRIBUTION OF W-R STARS IN OUR GALAXY

I should now like to address the question of where W-R stars are found in our galaxy. Garmany (1986) has given a plot of the longitude distribution of OB stars more massive than 40 $M_{\odot}$ projected onto the plane of the galaxy within 3 kpc. In Figure 6, I show the analogous distribution of W-R stars making use of the M_v calibration of Table 1 and the available photometry (e.g. van der Hucht et al. 1981). We see considerable numbers of these objects in the inner Scorpio-Saggitarius arm, and in the Cygnus-Carina arm but very few outward from the Sun in

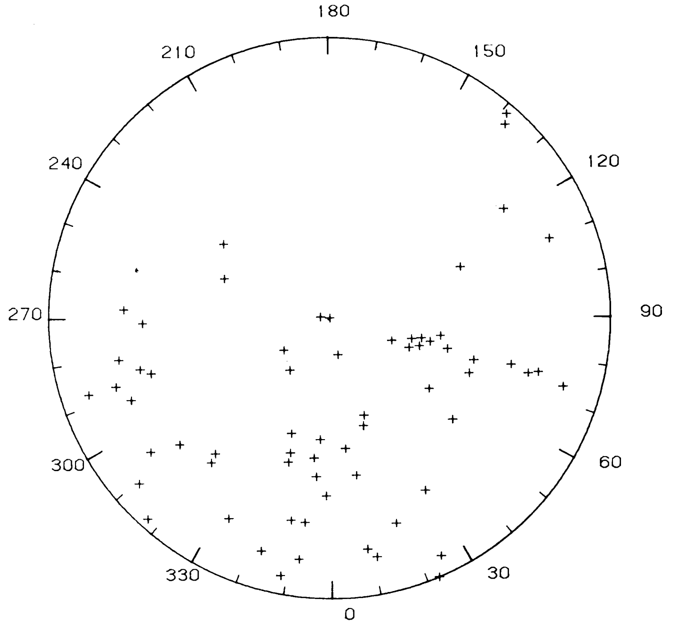

Fig. 6. W-R stars within 3 kpc, plotted on the galactic plane. This figure can be compared with that shown by Garmany (1986).

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the Perseus arm. The distribution is similar to that of the massive O stars, suggesting that the W-R stars are decendents of these objects (Conti et al. 1983b). There are 245 progenitor massive OB stars in Garmany's 3 kpc volume; this is to be compared with 63 W-R descendants in Figure 6. Thus if all stars more massive than 40 $M_{\odot}$ become W-R stars, the lifetimes are in the ratio of about 4. I will return to this issue presently.

The galactic latitude, or better, the vertical Z distribution of massive stars in our galaxy can be found from the distances and the coordinates. That for the massive OB stars within 3 kpc is given by Garmany (in this volume). The OB stars are indeed closely confined to the galactic plane as would be expected from an extreme Population I sample. The vertical extent of the extreme Population I stars seems to be some ±100 pc. A very few OB stars are found substantially further from this range and would be described as "runaway" stars. Gies (1984) has recently considered the nature of such objects and concludes they have escaped from close star-star interactions in the cores of young clusters and associations.

Figure 7 shows the galactic latitude (in terms of Z) distribution of the W-R stars within 3 kpc. These stars are similarly closely coupled to the massive O-star distribution. The vertical extent is like that of the parent population. We see two stars appreciably far from the plane, presumably decendents of the "runaway" OB stars found there. There is no need to suggest a different Z dependence for W-R stars compared to the massive OB stars, as has sometimes been done in the literature.

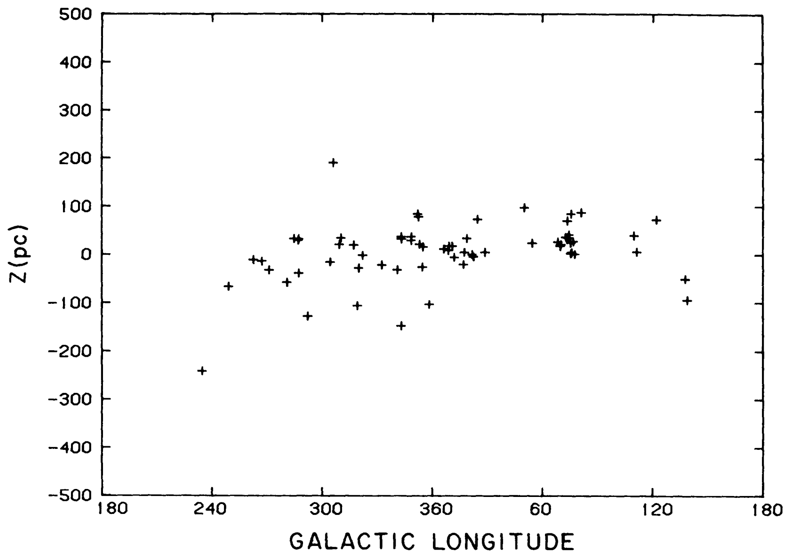

Fig. 7. W-R stars distribution in "Z" distance from galactic plane, within 3 kpc.

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CONCLUSIONS

Let me first raise some questions concerning W-R stars. We see that they all have substantial mass loss rates. Is it possible that these large values are a result of the high effective temperatures, thus very large luminosities, and the winds are driven by radiative forces? I think this is a plausible conclusion but confirmation will await further work. The wind law (that is the run of opacity and velocity with radius) in W-R stars seems to be rather "soft" compared to OB stars. By this I mean the velocity increases rather slowly with radius. What physically causes this? Here I don't really have any good suggestions except to note that the hydrogen/helium ratio, which is very low in most W-R stars may play a role in the structure of the wind. Why do different subclasses of WN and WC stars exist? Is this merely because of the different effective temperatures? Even more importantly, what is the t_{eff} scale for the WN and WC subtypes? Is there an evolutionary connection between the WN and WC subclasses; for example, do late WN evolve to early WC? Or early WN evolve to late WC? At present there is no real understanding of the W-R subtypes and their evolutionary connection.

The number ratio of massive OB stars to W-R stars in the solar vicinity, presumably a reasonably complete sample of each to 3 kpc, has the value 4. Thus if all OB stars more massive than 40 $M_\odot$ become W-R stars, the lifetime of the latter phase is some 25% of the main sequence phase. Traditionally, the helium burning lifetime of a star is some 10% of the hydrogen burning time so the observed value seems a little large. However, on the bus ride to this meeting, Maeder told me that the new rates for carbon-alpha particle reactions will lengthen the helium burning lifetime of massive stars by about a factor of two. Does this take care of the discrepancy? (As an aside, later during the Symposium both Chiosi and de Loore asserted the new rate would not affect the ratio; Maeder still concluded it did.) Possibly a few close binaries, with masses less than 40 $M_\odot$, could become W-R stars because of interactions with their companions, or perhaps, as Maeder has stressed, the metal abundance of the progenitor star will affect its ease of evolving to the W-R stage.

What evidence supports the general scenario? We see that the massive OB stars and the W-R stars share a similar galactic longitude and latitude distribution. In particular there are fewer of both objects toward the anti-center region. Humphreys et al. (1985) have pointed out that in associations in our galaxy and in M33, the W-R stars and the red supergiants are anti-correlated, that is they are not found together. Humphreys and Davidson (1979) had previously noted that in the galaxies of the Local Group, red supergiants are never found brighter than M_V brighter than -8.0 magnitude, corresponding to an initial mass between 30-50 $M_\odot$, depending on whose evolution tracks are used. It seems clear that above some initial mass, which is of the order of 40 $M_\odot$, stars do not become red supergiants when they begin to burn helium in the core. But helium burning must go on someplace, which one can readily identify with the W-R stars. We have already noted the evidence that these objects are, in fact, helium

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rich. They must also be helium burning for the most part since the mass/luminosity ratio of those in binaries indicates they are over-luminous for their mass (e.g. Paczynski 1973).

So, we see solid and consistent evidence that the W-R stars are the helium burning descendants of massive stars. We don't understand all the details of the evolution but we can begin to use these objects as probes of the luminous stellar population in other galaxies, the subject of the next talk.

This work has been supported by the National Science Foundation. I am indebted to my colleagues Drs. Garmany and Massey for their intimate involvement with much of the work reported here, to Dr. Abbott for an advance look at his newest results on the radio observations and Mike van Steenburg for construction of several of the figures.

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Discussion : CONTI.

APPENZELLER :

You mentioned the great range of mass values observed for WR stars. Can the lowest mass WR's form according to the same mechanism as the high mass ones?

CONTI :

We don't really know. Presumably higher mass W-R stars come from higher mass progenitors by mass loss and mixing processes.

MELNICK :

The most massive stars in Irr galaxies are located in giant HII regions where crowding and differential extinction exclude them from any magnitude limited survey. Thus the luminosity function of any galaxy that has giant HII regions will be severely incomplete at the high as well as the low luminosity ends. This applies both to your work on the LMC as well as to that of Freedman on M33. On the other hand, since bursts of star formation are stochastic, if you look at a galaxy that has no giant HII regions you will still find a luminosity function that has too few massive stars. That does not mean that the IMF of that galaxy is abnormal but instead that at the particular time of your observation there are no massive O stars alive! This stochastic limitation is a fundamental one and in my opinion completely precludes any effort to determine the IMF in late type galaxies.

CONTI :

I have mentioned that even with a substantial incomplete search the LMC has appreciably more O stars than would be expected compared to the SMC.

LORTET :

Should we not systematically reintroduce the subdivision into narrow (A) and broad lines (B) for WN stars and especially for WN6 stars, even if intermediate cases (A(B) or (A)B) also exist. There is increasing evidence that WNA, either in binaries or clusters, are associated with the hottest O stars (e.g. core of 30 Dor region) while WNB are associated with evolved late O and B supergiants : this is striking when reading the Schild and Maeder paper (1984, Astron. Astrophys., **136**, 237). A new example is Brey 72 in LMC which has been found to be a binary WN6 with very broad lines +B1Ia (Moffat, private communication).

CONTI :

I think the "A" and "B" designations are useful for the extreme cases but it must be remembered that line widths in WR stars show a continuous range. This is shown in studies of some 60 WN stars (Conti et al. Ap.J. 1984) and so is the case for WC stars (Torres et al. Ap.J. 1985).

GRAHAM :

Do you ever find WR stars which happen to be unusually heavily reddened?

CONTI :

It is not at all uncommon to find substantial reddening (E_{B-V}>1.0) for W-R stars within 3 Kpc.

NIEMELA :

Do you include those WN stars with H in their spectra also in the He-burning phase? Were these included in your statistics?

CONTI :

I would make a restriction for the Carina WN stars which are H-burning stars, that is 3 stars. The other WN stars with hydrogen may

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also have been counted as He burning stars in WR statistics, so maybe this is not very consistent. It would bring down the WR/O number by a few percent in the totals.

VIOTTI :

Concerning the problem of the effective temperature of WR stars, I would like to highlight the case of HD 93162 and 193793, whose high-resolution UV spectra display, according to Fitzpatrick (Ap.J. 261, L91), narrow absorption lines of FeIV and FeV probably formed in the WR photospheres. Certainly, the identification of these lines will narrow the range of possible T_{eff} in WR stars.

MAEDER :

Classically, the ratio t_{He}/t_H of the helium to hydrogen lifetimes is 10%. With the new 12C (alpha,gamma)16O cross-sections by Kettner and colleagues, this ratio is about 20% which is in agreement with the observations by Conti et al.

CONTI :

I'm pleased to hear this, since the observed WR/O ratio is also near this value.