II. EVOLUTION OF MASSIVE STARS

EVOLUTION AND MODELS

BASIC OBSERVATIONAL CONSTRAINTS ON THE EVOLUTION OF MASSIVE STARS

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ABSTRACT

The sources of information and uncertainties in the intrinsic stellar parameters of luminosity, effective temperature, mass, composition and mass loss rates are discussed. These are used to compare the observed positions of massive stars in the Hertzsprung-Russell Diagram (HRD) with evolutionary tracks. The current status of this effort is briefly reviewed. A short summary of the kinematic properties of massive stars is made. A preliminary but fairly extensive discussion of the distributions and numbers of O-type and Wolf-Rayet stars in the galaxy and other members of the local group is then given.

I. INTRODUCTION

I have been asked to review the basic observational features of "massive stars." I shall take as a lower mass limit a value $M \gtrsim 10\ M_\odot$ as an arbitrary dividing line between these stars and those of "intermediate" or "low" mass discussed elsewhere in this symposium. This corresponds to a lower luminosity limit $L \gtrsim 10^{3.5}\ L_\odot$. This mass is roughly the lower mass limit for supernova progenitors; similarly it is near the upper limit of mass for stars with an asymptotic giant branch. In spectral-type terms, "massive stars" include the O to B3 main sequence, and luminous supergiants of all spectral types.

From work over the past decade or so, we know that for most of these massive stars, mass loss in the form of stellar winds plays an important, in some cases, even dominant, role in their evolution (Conti and McCray 1980). The Wolf-Rayet (W-R) stars, and other luminous hot variable stars, such as η Car, P Cyg, R71, R122, the S Doradus stars and the Hubble-Sandage variables, are clearly related to massive stars and undoubtedly represent advanced evolutionary stages (e.g. Maeder 1984). I shall refer to the non W-R or "other," hot stars as "luminous blue variables," or LBV, in my talk. LBV are thus nicely contrasted with LPV, long-period variables, which are luminous red supergiants.

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W-R stars come in two types, WN and WC. Subtypes, based mostly on line ratios also are identified: WN subtypes range from WN2 to WN9; WC subtypes from WC4 to WC9. In both cases, the higher ionization stages have smaller numbers analogous to MK subtypes. Unlike MK types, these W-R subtypes may not be an effective temperature sequence.

As is well known, the intrinsic properties of a star which most clearly define its evolutionary state are the mass and composition (throughout). Recently, we have needed to include mass loss, $\dot{M}$, as an input to stellar evolution. The angular momentum and magnetic fields may also play a role but I will not discuss them here. The observable quantities, in addition to M,$\dot{M}$ and composition are luminosity, L, and effective temperature, here T.

The interplay among these parameters, both observationally and theoretically, forms the current drama for stellar evolution. The theoreticians write the script; the observers provide the stage set and costumes. We are the actors in this play, which is going onward amongst continual script and set revisions, role exchanges, and general commotion. The audience is, for the most part, members of the astronomical community, who provide applause at important junctures; granting agencies provide the critical financial backing. Drama critics, better known as paper referees, provide comments on the actors and their roles. Unlike real-life productions, actors and critics frequently play both roles at once. I do not know whether or not our stellar evolution play is a comedy or a tragedy, but I do know, as a participant, that it is fun!

II. INTRINSIC PARAMETERS

A. Luminosities

Stellar distances are intimately related to the determinations of luminosity. Massive stars, which are quite rare, are not close enough to the Sun to have measurable parallaxes. Cluster and association membership with distances provided by the B-type stars (Walborn 1972; Conti and Alschuler 1971) provides the spectroscopic calibration for nearly all O-type stars. A recent compilation is given by Conti, Garmany, de Loore and Vanbeveren (1983). These authors also discuss the M_V calibration of W-R stars, based mostly upon membership in the Large Magellanic Cloud. These M_V magnitudes ultimately depend on cluster fitting methods extending back to the Hyades and the absolute values depend on that distance. The LBV are even more rare than W-R stars but their luminous properties (e.g. Humphreys and Davidson 1979) make them readily visible at large distances and hence they were among the first objects detected in nearby galaxies (see also Lamers, de Groot and Cassatella 1983; Wolf, Appenzeller and Cassatella 1980; Wolf, Appenzeller and Stahl 1981). Surprisingly, the distance scale for local group galaxies such as M33 seems to be uncertain to a factor two (Sandage and Carlson 1983) so moduli for many LBV are not well determined. P Cyg and η Car can reasonably be assigned to associations in their vicinity; some LBV are known in the Magellanic Clouds.

In addition to distances, one needs apparent magnitudes, m_V, and colors to determine the interstellar reddening of distant stars. These observables are reasonably well in hand for massive stars, particularly with the recent absolute spectrophotometry of W-R stars by Massey (1983). With M_V determined, it is then necessary to estimate the bolometric correction, e.g., which can be quite large for hot stars in which most of the radiation is emitted below visible wavelengths. This determination depends critically on the T and the stellar model, which is not well known in some cases. My estimate of the current status of the uncertainty on luminosity as deduced from the spectrum is as follows:

	M_V	log L	No. of Stars
MK types	$\pm 0\overset{m}{.}5$	±0.3	$\sim 10^3$
W-R	$\pm 1\overset{m}{.}0$	±0.5	$\sim 10^2$
LBV	$\pm 1\overset{m}{.}2$	±0.5	~ 10

B. Effective Temperatures

Basically, three independent measures have been used to determine T: the absorption line spectrum; the overall continuum, and the Zanstra procedure. These cannot always be used together: the latter depends on the detection of the H II region surrounding the star and an estimate of the radiation escaping below 912 Å. All methods are very model dependent, and the models, particularly for W-R stars, are not well determined.

For O stars, and LBV with absorption lines, the spectroscopic method has been heavily utilized. The non-LTE models of Auer and Mihalas (1972) were utilized by Conti (1973) in determining a temperature scale for O stars. These were recently revised downward for the (mostly) Of stars of highest temperatures by Kudritzki, Simon and Hamann (1983) and Simon, Jonas, Kudritzki and Rahe (1983) by use of lower gravity models. Isolated estimates of individual temperatures of LBV have been made by, e.g., Lamers et al. (1983), Wolf et al. (1980, 1981). For W-R stars which generally do not show absorption lines, spectroscopic methods give only constraints of the ionization temperatures from the emission lines in the wind. These are typically a few $\times 10^4$ to 10^5 K.

Considerable recent work on continua of massive stars has been published by Underhill (1980, 1981). Among O stars, she finds little correlation between temperatures found by fitting plane parallel models to the observed ultraviolet data and those from spectra. Among W-R stars the temperatures are in the range 20,000-40,000 K. These efforts have recently been criticized by Garmany, Massey and Conti (1984). These authors make use of absolute spectrophotometry from 1200 Å - 7000 Å to find the observed continua of a number of W-R stars. They point out that Underhill's adoption of a standard reddening law, or more exactly a UV extinction law for all parts of the galaxy leads to inconsistent results. Massa, Savage and Fitzpatrick (1983) have presented similar arguments based upon a different sample of stars. I conclude that, at least for now, intrinsic continua of hot stars in the far UV cannot readily be determined until the extinction is established independently. Hence model continua fitting cannot be trusted since most radiation is emitted in this region or below 912 Å.

My estimate of the current status of the uncertainties of effective temperature are as follows:

	T	No. of Stars
MK types	±10%	~100
WR	±50%	~10
LBV	±50%	A few

C. Masses

For this important parameter, one must depend on binary systems. In particular, direct mass estimates can come only for double-lined spectroscopic binaries (there are no suitable visual binary candidates) which are also eclipsing, so that the inclination can be found. The spectroscopic analysis provides the velocity amplitude while a separate photometric analysis provides the period, orbital eccentricity and inclination.

Catalogues of O-type stars (Cruz-Gonzales et al. 1974) and of W-R stars (van der Hucht, Conti, Lundstrom and Stenholm 1981) provide much of the background material on binary systems. Reviews of the masses determined have been provided by Popper (1980) and Massey (1982). There is little direct information on masses of LBV since none are known to be double-lined eclipsing systems.

Indirect information on stellar masses comes from the location of the stars in a Hertzsprung-Russell diagram and evolutionary scenarios. These are good to perhaps a factor two. My estimate of the current status of uncertainties in the mass is as follows:

	Masses	No. of Stars
MK types	±30%	~10
WR	±50%	~10
LBV	Factor 2	A few

D. Composition

This parameter is obtained from the spectrum; a good atmospheric model is absolutely essential. With the advent of UV spectroscopy, particularly the IUE satellite, the important information on resonance lines of carbon, nitrogen and silicon ions is now becoming available. With the exception of the analysis of the B stars τ Sco (Hunger 1955) and γ Peg (Aller and Jugaku 1959) many years ago, detailed studies of massive main sequence stars have generally not been done. Coarse analysis of many O-type stars (Conti 1973) suggests compositions which are solar to a factor two. A small subset of OB stars has strong lines of nitrogen or carbon (e.g. Walborn 1970) suggesting abundance anomalies. The O4f star ζ Pup appears to be slightly helium rich according to a modern analysis of Kudritzki et al. (1983). The important issue of possible nitrogen enhancement in this star is not yet settled.

Among W-R stars the available information indicates helium and nitrogen enhancement among WN stars and helium, carbon and oxygen enhancements among WC stars (Smith and Willis 1983; Willis 1982; Nugis 1982; Conti, Leep and Perry 1983). The anomalies are consistent with what would be expected from observing the products of H-burning in CNO equilibrium (WN stars) and He-burning (WC stars). We are thus observing the "cores" of highly evolved massive stars.

There has been little work to date on the compositions of LBV specifically, although the analysis of Luud (1967) on P Cygni should be noted.

The largest uncertainties in all these composition analyses is the stellar models. These are reasonably good for OB and Of stars but not too reliable for W-R stars and LBV. The recent analysis of the ejecta of η Car by Davidson, Walborn and Gull (1982) is very important. The material which left the star in the last century has a density state which can best be described by the physical relationships of interstellar material, rather than stellar atmospheres. They find large N/C ratios, similar to highly processed material. In this one LBV object, we see evidence for a highly evolved stage.

My estimate of the current status of the compositions of massive stars is as follows:

	Composition	Uncertainties	No. of Stars
MK types	"Normal"	Factor 2	~10
WN	CNO Equilibrium	Factor 2	~10
WC	He Burn Products	Factor 2	~10
LBV	?	Factor 2	A few

E. Mass Loss Rates

There has been considerable progress on this topic in the past few years. I provided a review recently (Conti 1981), but additional efforts over the past few years have given us many new numbers. In particular, Abbott, Bieging and Churchwell (1982) have provided $\dot{M}$ for 21 W-R stars using free-free emission measures and Garmany, Olson, Conti, and Van Steenberg (1981) and Garmany and Conti (1984) have given mass loss estimates for 50 O stars based on UV spectra. Other data have been provided by Olson and Castor (1981).

My estimate of the current status concerning $\dot{M}$ is as follows:

	$\dot{M}$ ($M_\odot$ yr^{-1})	Uncertainties	No. of Stars
MK Types	$\lesssim 10^{-7}$ to a few $\times$ 10^{-5}	Factor 2	$\gtrsim 50$
W-R	Few $\times 10^{-5}$	Factor 2	~20
LBV	Few $\times$ 10^{-5} to 10^{-7}	Factor 2	A few

III. LOCATION OF MASSIVE STARS IN THE HRD

It will be recalled that Humphreys (1978) and Humphreys and Davidson (1979) provided the first modern compilation and discussion of the location of luminous stars of the galaxy and Large Magellanic Cloud in the HRD. The central features of those figures were:

1) The existence of luminous blue supergiants with inferred masses $\gtrsim 60$ $M_\odot$ and

2) the absence of similarly luminous (and massive) red supergiants with M_{BOL} brighter than $-9^{m}\!.8$.

3) The presence of considerable numbers of hot supergiants redward of the termination of hydrogen core burning tracks, compared to those stars still burning hydrogen.

This latter has been described as "main sequence widening" by Stothers and Chin (1977); Chiosi, Nasi and Sreenivasan (1978); Cloutman and Whitaker (1980); Bressan, Bertelli and Chiosi (1981). Meylan and Maeder (1982) noticed a similar effect in an analysis of young cluster magnitude diagrams.

I should like to present a comparison of stars of the galaxy, LMC and SMC with a current theoretical HRD of Maeder (1983). Similar diagrams will be shown by Humphreys (1984) later in this symposium based on a different sample of stars. My data for the galaxy are limited to those stars within 2.5 kpc of the Sun. Garmany, Conti and Chiosi (1982) showed that counts of O stars were reasonably complete to this distance; I assume this is also the case for the later-type supergiants. A volume limited sample has an advantage in comparing populations in different parts of the HRD.

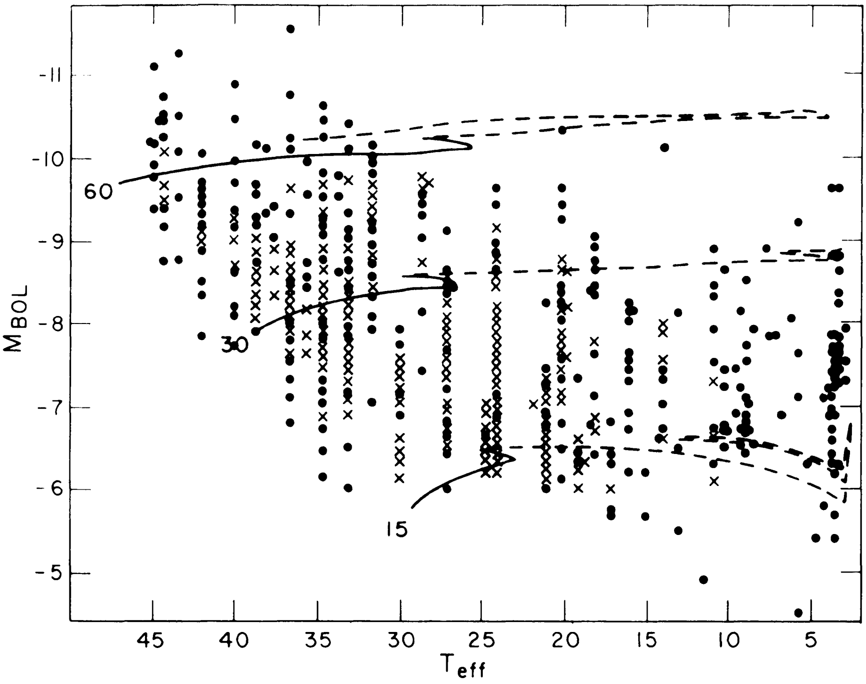

Fig. 1. Observational/theoretical HRD for luminous stars in our galaxy to 2.5 kpc from the Sun. The filled circles are single stars; the crosses represent more than one star at that position, often up to ten or so. The evolutionary tracks are those of Maeder (1983).

The central features of the Humphreys-Davidson HRD are illuminated: Luminous blue supergiants with inferred masses to ~120 $M_\odot$, the absence of comparable initial mass red supergiants, and still a strong effect of main sequence widening. These tracks incorporate mass loss and mixing but even so too many stars exist to the right of the termination of core HB. This is most clearly indicated for the 30 $M_\odot$ track: that for 60 $M_\odot$ may be wide enough. Other evolution tracks have been calculated by Doom (1982). Like the Maeder (1983) tracks, they all fail to traverse far enough to lower temperatures to explain the large numbers of B and A supergiants, even though various prescriptions of mass loss and mixing are incorporated. Completeness of the sample is probably not a problem above 30 $M_\odot$; it may begin to be an issue below there so we cannot draw conclusions about the 15 $M_\odot$ tracks.

The absence of luminous red supergiants above some mass limit, here ~50 $M_\odot$, is almost certainly related to the appearance of W-R stars as the core helium burning counterparts. Maeder (1982) has suggested various channels for production of W-R stars from their O-type predecessors. I shall return to this issue later.

In Fig. 2, I show an incomplete HRD for stars of the LMC. Photometry of hot stars is insufficient to indicate their temperatures so we have plotted only those O-stars with classification spectra. Garmany, Massey and I have a major classification project under way to remedy the incompleteness of this figure for the hot stars. I will just use this figure to indicate that the same problem with the tracks exists here!

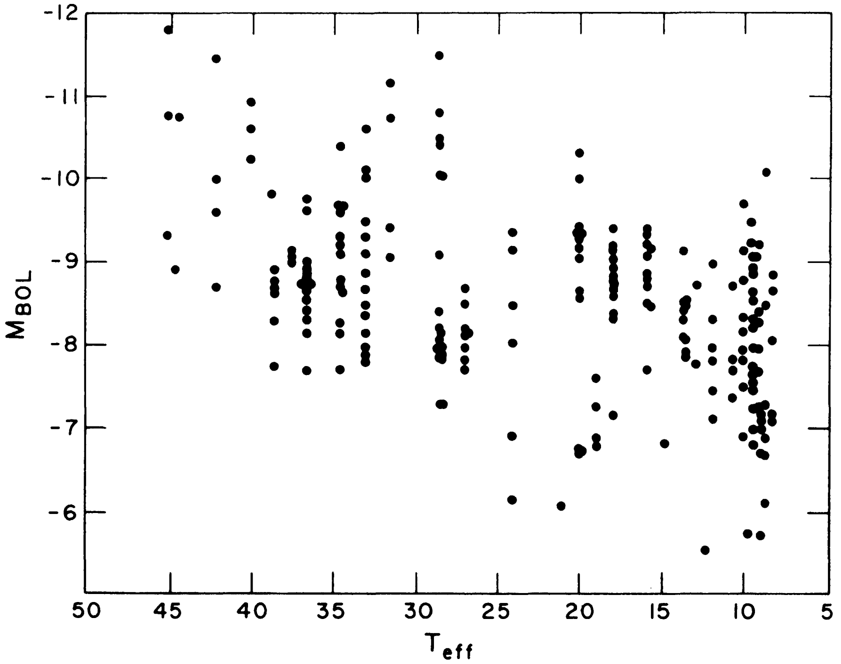

Fig. 2. Observational/theoretical HRD for luminous stars in the LMC. Only those hot stars with photometry and classification spectra are plotted. Symbols as in Fig. 1. Sample is not complete, see text.

Too many stars are to the right of the core hydrogen burning termination point. In particular, there is a group of middle B type supergiants (between 15,000-10,000 K and M_{BOL} near -9^m) which have few counterparts in the galaxy. Humphreys (1984) believes this grouping to be a selection effect, but I am not so sure.

In Fig. 3, I show an incomplete HRD for stars of the SMC. As for the LMC, only those O-type stars with spectral classifications have been plotted. Along with Garmany, Humphreys and Massey, we have a major classification program under way for the hot stars of the SMC. Again, too many stars exist to the right of the core hydrogen burning tracks. Perhaps this statement will need to be modified when the classifications are complete but I doubt it, given the number of candidate O stars, of order one hundred.

In summary, I have demonstrated that the current evolutionary tracks which incorporate mass loss and mixing do not yet sufficiently account for the "main sequence widening" of the solar vicinity, or Magellanic Clouds. Some physical ingredient(s) are not yet included in the models. Stars more massive than ~50 $M_\odot$, with these tracks, do not become red supergiants, or exist there only a very short time.

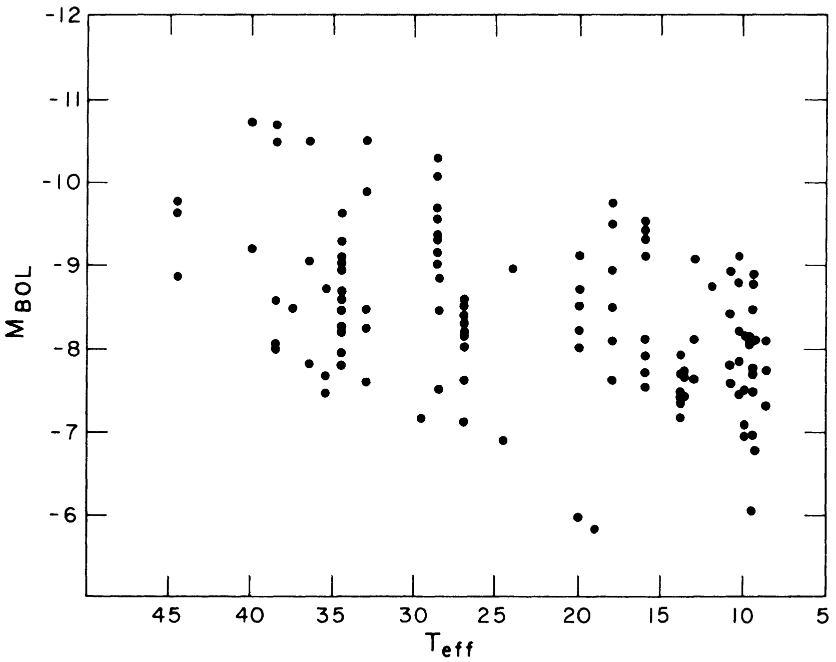

Fig. 3. Observational/theoretical HRD for luminous stars in the SMC. Only those hot stars with photometry and classification spectra are plotted. Symbols as in Fig. 1. Sample is not complete, see text.

IV. EXTRINSIC PARAMETERS

A. Kinematics

Radial velocities are provided in various catalogues for O stars (Cruz-Gonzalez et al. 1974) and W-R stars (van der Hucht et al. 1981). The latter are not well determined, being based upon measures of broad emission lines, often differing from ion to ion. In some spectroscopic binaries, γ velocities from the O components may give good estimates of real kinematic radial velocities. Recently, Torres and Conti (1984) attempted to derive meaningful radial velocities of some narrow lined WC9 stars. The results were not too satisfying, having fairly large uncertainties. There is no catalogue of properties of LBV but scattered data are found in the literature.

My estimate of the uncertainties in radial velocity measures are as follows:

	Uncertainties	No. of Stars
MK Types	~10 km s^{-1}	Few 100
W-R	30-40 km s^{-1}	~20
LBV	10 km s^{-1}	A few

Scattered proper motion data exist in the literature but as most stars are well beyond 1 kpc these numbers do not provide much independent kinematic data aside from proving or disproving cluster membership.

B. Binary Fraction

Some 40% of the MK stars, at least along the main sequence, are binaries (Abt and Levy 1978; Garmany, Conti and Massey 1980). This is similar to the fraction of W-R type binaries (Massey 1982), at least those with massive companions. There is an entire scenario of massive binary evolution which suggests some W-R systems will be found with neutron star companions. Moffat (1982a) sums up the evidence for the existence of these objects. Although at one time W-R systems were all supposed to be binaries (e.g. Paczynski 1973), more recent arguments (e.g. Vanbeveren and Conti 1980; Massey 1982) suggests this is not the case in some systems. Among LBV, P Cyg has been suspected of being a binary (e.g. De Groot 1969) but the case has not been proven. While the binary nature of some massive stars clearly will affect their subsequent evolution, the physical importance of mass loss and mixing in these objects also plays a key role.

There has been little systematic study of duplicity for stars outside our galaxy but Moffat (1982b) has begun such an effort for W-R stars in the Magellanic Clouds.

C. Galactic Distribution of Massive Stars

Garmany, Conti and Chiosi (1982) have studied the longitude distribution of a nearly complete sample of O stars to 3 kpc. In Fig. 4, I show their distribution, projected onto the plane of the galaxy. The field star distances are derived from the O spectral type calibration: the cluster stars are at distances given by the B star calibration.

Three "spiral arms" are seen: Scorpio-Sagittarius-Carina interior to the Sun; the Cygnus arm near ℓ = 90°; and the Perseus-Auriga arm outwards. These features are ill defined and certainly cannot delineate a "spiral" nature by themselves. We presume them to be so by reference to the appearance of other neighboring galaxies. The large "width" of the arms is perhaps surprising but one wonders whether or not this is caused by the individual stellar distance uncertainties.

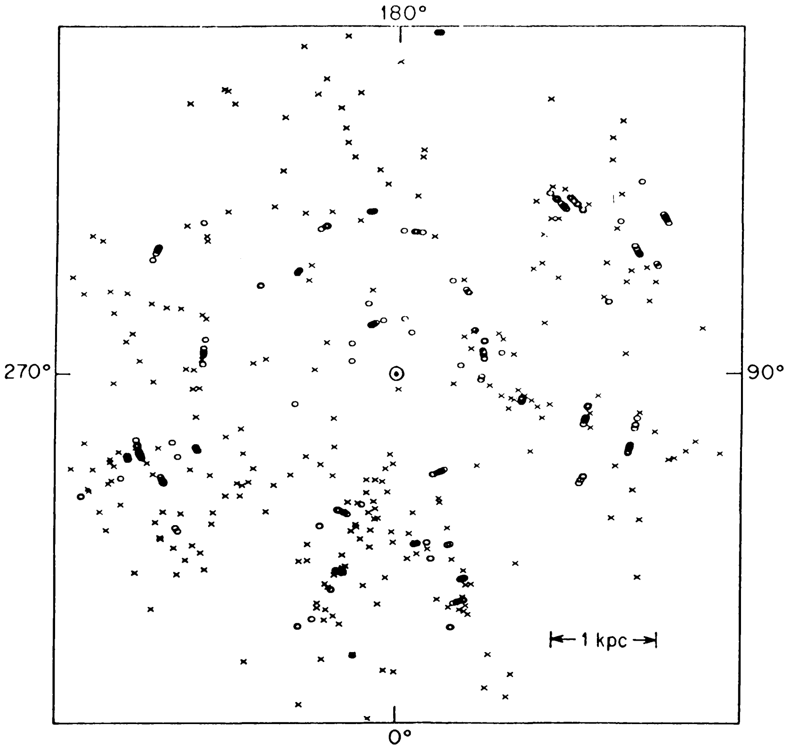

Fig. 4. O stars within 3 kpc of the Sun, projected onto the plane of the galaxy. Open circles are cluster members; crosses are field stars (adapted from Garmany, Conti and Chiosi 1982).

I will return to this issue later. The "arms" in Fig. 4 are about as well defined as any other stellar features (e.g. Cepheids).

In Fig. 5, I show the galactic distribution of W-R stars, from the work of Conti, Garmany, de Loore and Vanbeveren (1983). These distances are based upon the W-R spectral type distribution of these authors and are more uncertain than that for O stars. We see some features like that of Fig. 4 (stars in the inner and solar arms) but few outward from the Sun. The complete absence of stars in the anti-center has been known for some time (e.g. Roberts 1962).

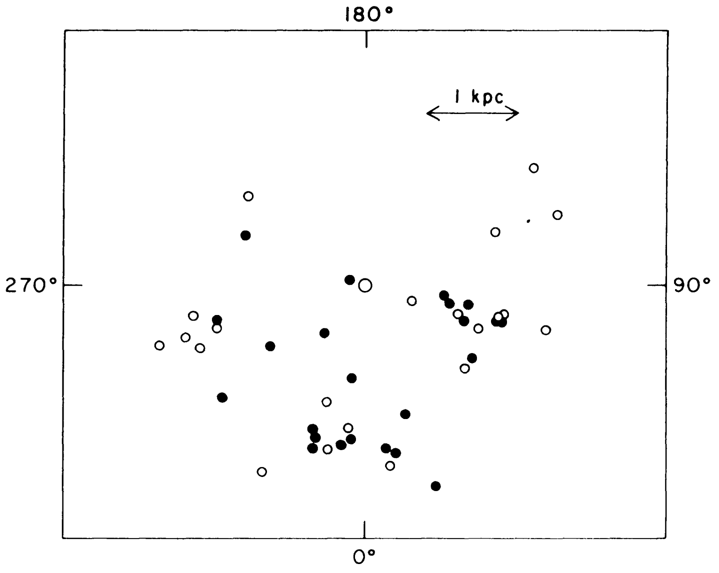

Fig. 5. W-R stars within 2.5 kpc, projected onto the plane of the galaxy (adapted from Conti, Garmany, de Loore and Vanbeveren 1983). WN stars are o; WC types have ● symbols.

There is clearly a gradient in the W-R star distribution outward from the galactic center which is not obviously present in the overall O-star distribution. It has been suggested that this is due to different evolutionary histories of the progenitor stars in terms of their initial chemical composition (e.g. Smith 1973; Maeder 1981). However, as Conti, Garmany, de Loore and Vanbeveren note, another factor may be important. These authors divided the O stars of Fig. 4 into two mass ranges, those between 20-40 $M_\odot$ and those above 40 $M_\odot$. The division was somewhat arbitrary initially, in that models of this mass value are published. Figures 6 and 7, adapted from their paper, show these two mass distributions.

We see that the lower mass O stars (Fig. 6) do not show much of a gradient with galactocentric distance, while such a gradient is present in the massive O star distribution (Fig. 7). Garmany et al.

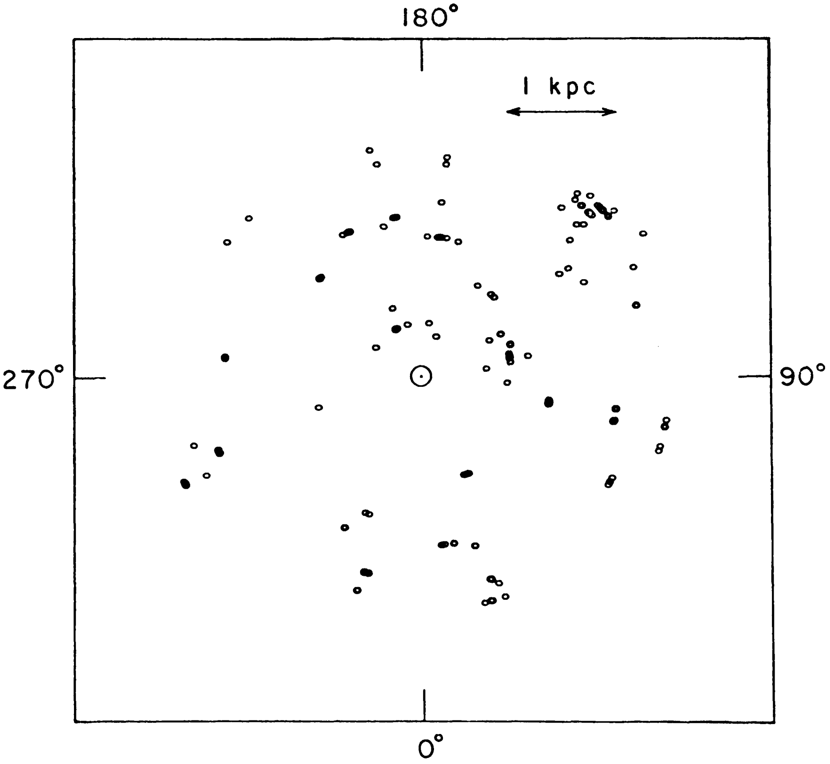

Fig. 6. Galactic distribution of O stars within 2.5 kpc with initial masses between 20-40 $M_\odot$ (from Conti, Garmany, de Loore and Vanbeveren 1983).

(1982) and Conti, Garmany, de Loore and Vanbeveren (1983) suggested that the observed difference in the O star mass population -- a difference in the slope of the massive end of the initial mass function (IMF) — could be a major contributor to the W-R star gradient. A natural consequence would then be that W-R stars are mostly descendant from massive O stars, and not from all O stars.

In retrospect, I regret that in Conti, Garmany, de Loore and Vanbeveren, we did not sufficiently stress that the 40 $M_\odot$ dividing line was not absolute: Plots of 35 $M_\odot$ and 45 $M_\odot$ analogous to Fig. 7 were not very different from one another in the appearance of the gradient. A 30 $M_\odot$ did show less of a galactocentric gradient. I believe that it is safe to conclude that most W-R stars appear to be related to the most massive O stars, the lower limit being near 40 $M_\odot$ but not as small as 30 $M_\odot$. Of course, exceptions (e.g. binary condition) may allow lower initial mass stars to become W-R. Also, this sample is near the Sun where the chemical gradient is small (factor two across the sample). As Maeder (1981) has stressed, the initial composition, if very different,

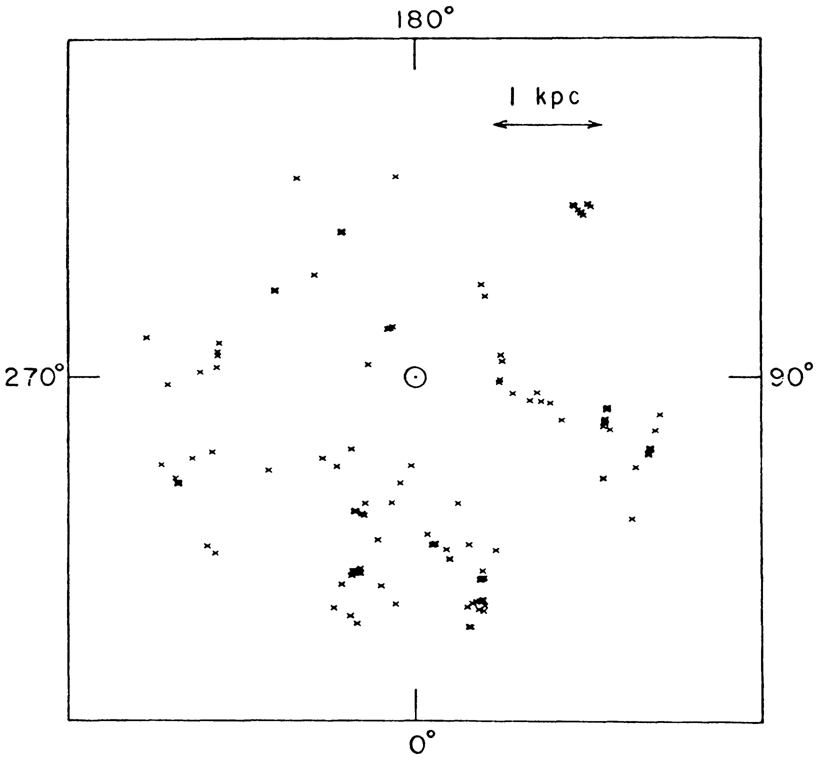

Fig. 7. Galactic distribution of O stars within 2.5 kpc, with initial masses greater than 40 M$_\odot$ (from Conti, Garmany, de Loore and Vanbeveren 1983).

may also have an important function. In this regard, the massive star population of, say, the SMC, with a "metal" composition perhaps 20% of the Sun, may give us useful evidence.

In Fig. 5, I have plotted the galactic WN and WC stars with different symbols. A careful perusal will indicate that these objects do not have quite the same galactic distribution: there are relatively more WC vis-à-vis WN stars toward the galactic center and conversely toward the anti-center. Of course, with such a small sample, statistics are uncertain and I do not expect skeptics to be persuaded by this figure. I will return to the variation in the WN/WC ratio later.

D. Distribution of Massive Stars in the Magellanic Clouds

There has been no comparable study of a complete sample of O stars in the Magellanic Clouds although a number of us are at work on this problem. A nearly complete sample of W-R stars is available for the Clouds: Breysacher (1981) lists 100 stars for the LMC and Azzopardi and Breysacher (1979) list eight stars for the SMC. While the distribution in these galaxies of the WN + WC types has not been studied, it is known from these listings that the WN/WC ratio is about 4 for the LMC and 7 for the SMC. Furthermore, whereas nearly all WN and WC subtypes are present in the solar vicinity sample, and nearly all WN subtypes in the LMC, only early WC subtypes are found there. Also in the SMC the seven WN stars are of early subtype, as is the lone known WC star. What are we to make of this? Frankly, whereas one might devise evolutionary scenarios that produce early or late WN or WC, these are purely speculative since we have not linked the subtypes to either an effective temperature scale, or to a mass or to a luminosity scale. The curious distribution and presence and/or absence of WN and WC subtypes is going to give us information on massive star evolution eventually.

E. Distribution of Massive Stars in Local Group Galaxies

The landmark survey of bright supergiants in M33 (Humphreys and Sandage 1980 -- HS) will be a starting point for every modern study of luminous stellar populations. Spectral types exist for only a handful of the M33 stars and the photometry is very incomplete, so we are unable to discuss individual stellar distributions. HS did assign association boundaries to obvious groupings of bright blue stars. Their paper clearly shows the spiral arm distribution of the luminous stellar population. LBV are, of course, also known in M33.

What of the W-R stars in this galaxy? Phil Massey (mostly) and I have been studying candidate W-R objects found from survey plates taken "on-line (λ4686 Å)/off-line" with narrow band filters. With data already in the literature we have discussed a sample of 80 W-R stars in M33 (Massey and Conti 1983). This number is, at most, 50% incomplete and better data may become available this fall. Even so, the distribution of WN and WC stars within this galaxy is interesting: the WN/WC ratio changes with galactocentric distance within M33, with increasing values away from the center analogous to the sketchy information available for our galaxy (Fig. 5). The subtype distribution is also curious: Nearly all WN stars are of early subtype, as are all the identified WC stars. This is unlike the galaxy, or the Magellanic Clouds. What are these subtype distributions telling us? We don't know yet, but surely they are somehow related to initial masses, or initial compositions, or combinations of these parameters or possibly others.

A few W-R stars are known in the small irregular galaxies NGC 6822 and IC 1613 (Westerlund et al. 1983; D'Odorico and Rosa 1982). A survey of the massive spiral M31 (Shara and Moffatt 1982) revealed some 21 W-R stars. It seems hard to believe this sample is complete, as claimed by these authors, but I must confess my surprise at the smallness of the "total," given the mass of M31 compared to, say, M33. Unless Moffat and Shara are incomplete by a factor 100, the apparently small W-R population of M31 suggests an exceedingly small number of massive stars in this galaxy.

The distribution of W-R stars in M33 is indicated in Fig. 8, adapted from Massey and Conti (1983). The spiral arm structure is a little difficult to make out! A careful examination of this figure reveals that most W-R stars are in arms, but not all arms have W-R stars! In particular, the arm going NE, ending at NGC 604 has no W-R stars (or candidates). We do not understand this yet. I should also draw your attention to the "width" of the arms, like that in Figs. 4-7. By stellar appearance, we would conclude that our galaxy, in the solar vicinity, is much like M33 in type.

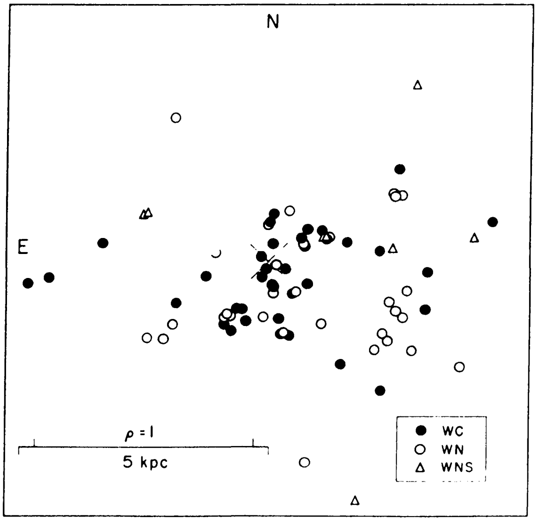

Fig. 8. Distribution of known W-R stars in M33, projected on the plane of the galaxy which has been tilted to remove the inclination (from Massey and Conti 1983).

V. SUMMARY AND CONCLUSIONS

Massive stars are important stellar constituents of our galaxy and other spiral and irregular types. They provide the supernova progenitors, most of the ionizing radiation and greatly modify their environments by their stellar winds. Their light dominates the spiral arm structure. The evolution of massive stars, discussed in detail later in this symposium by Maeder, is a very exciting topic. The general outlines are understood to involve luminous blue supergiants, LBV, and W-R subtypes, in order of increasing evolution. The details are still controversial but their resolution will help in our understanding of how spiral galaxies evolve. W-R stars and their subtype distributions may provide clues to the progenitor initial masses and/or compositions. Luminous stars are among the first objects individually studied outside our own galaxy. They can just barely be investigated spectroscopically in galaxies outside the local group. Problems of the distance scale perhaps can be addressed with these objects.

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DISCUSSION

Iben: You have established a galactic gradient in both the O-star and the WR-star distributions, but it does not then follow that all WR progenitors must be O-stars. Here are other galactic gradients such as those in average "metallicity" and in the WC/WN ratio. If, for example, one were to assume that the average mass loss rate from massive stars decreases with decreasing metallicity one can immediately account for both the WR and the WC/WN gradients. This interpretation is reinforced by the evidence that all of the WR-stars in the SMC (whose metallicity is down by about a factor of 4 from that of the Sun) may be binaries, suggesting that when Z (and $\dot{M}$) is too small, one needs the help of Roche-lobe overflow to expose highly processed layers. The gradient in the frequency of WR-stars is larger than that of O-stars because O-stars can of course become WR-stars, but as their frequency decreases, obviously this source of WR-stars decreases, leaving only less massive stars (with smaller $\dot{M}$'s) and binaries.

de Loore: 1. According to our computations for massive single stars (mass loss, overshooting modelling Humphreys' diagram, or by adopting Roxburgh's criterion, see Doom) the initial mass producing the most luminous red supergiant is 33 $M_\odot$.
2. On one hand I am coresponsible for the lower limit determination of WR-stars (Conti et al, Ap.J., 1983), on the other hand we made new computations for massive close binaries, especially for the accreting components. Comparison of these accreting models with observations allows to determine the inclination, hence to determine the mass of the O-component, and hence also the WR mass. This reveals that the masses of WR binaries (determined for 8 systems) are in the range 7-10 $M_\odot$, and the initial masses of the initial primaries can then be as low as 15-20 $M_\odot$.

Maeder: The WR-star excess you find depends clearly on the limit of 40 $M_\odot$ for initial stellar masses leading to the WR-stars you have chosen. When looking at the data from a quantitative point of view one can check that the galactic gradient of WR-stars is steeper than the gradient of O-stars for any lower mass limit one may choose. In my opinion, the best way of gathering information on the lower initial mass for WR formation is to look at clusters and associations containing WR stars. H. Schild has done so and obtained a value around 20 $M_\odot$.
Now, regarding another point, don't you think that, in view of the strong dependence of the predicted number of WR-stars on metallicity Z, even a very small dependence of mass loss rates $\dot{M}$ on Z (well inside the data scatter) would be helpful to account for the gradient of WR stars?

Conti: I agree that the observed galactocentric gradient is steeper for WR-stars than for O-stars of any other lower mass limit, thus suggesting that other parameters, such as the initial metal content, may play a role. On the other hand, the observed numbers of WR-stars are not large and small number statistics may affect this result.
As to the second issue, concerning the small differences in metal content affecting $\dot{M}$: I agree this is possible. On the other hand, we have shown (Garmany and Conti, 1984, Ap.J. in press) that among stars of the same cluster, thus presumably of the same metal content, there is quite a wide disparity in observed $\dot{M}$ (for a given luminosity). This scatter presumably is due to other factors affecting $\dot{M}$ - such factors may dominate metal abundance effects.

McCarthy: You list 101 WR-stars in Large Magellanic Cloud. Can you tell us if WN-stars predominate toward the center while WC-stars abound toward the outer regions? What can you say of the distribution of these stars in the Large Cloud?

Conti: We haven't had a chance to look at this yet, being busy with M33, but it sounds like a fine idea.

McCarthy: A comparison of these early-types and their distribution should be most interesting. I suggest a comparison between the 30 Doradus region and the area designated by Shapley as constellation III.

Cox: I have two questions. What about the Underhill very blue edge of the main sequence? For the red side, for these upper main sequence stars, there is a core helium and H-shell burning region just merged to the core hydrogen burning. Why do you then not count this region, which is also long lived, as part of the main sequence band when you compare with the observed HRD distribution? Both these questions bear on the accuracy of stellar opacity values.

Conti: The first question concerns the effective temperature scale of the hottest main sequence O-stars. Underhill found the earliest types were

not hotter than ~40000°K. I am sorry she is not here to take issue with my response but I will say I don't think her result is correct: she included no O3-stars among the earliest types and she fitted dereddened continua to plane parallel models. We have recently argued that a standard reddening law cannot be applied to determine ultra-violet extinction. Furthermore, the models do not match the continua over wavelength ranges from the UV to the IR, better physics is needed.
The second question bears on the issue of counting stars to the right of the present evolution tracks core hydrogen burning point. As I have argued, there are too many stars rightwards of the CHB point to be considered post-CHB. Thus the tracks must be extended to cooler temperatures. The problem might be helped by opacity but as I understand it, this arises other problems. There is still some missing physics - perhaps increasing again turbulent diffusion will help.

Renzini: When superficially looking at HR diagrams for massive stars I've been always confused by the apparent virtual absence of stars close to the ZAMS. Could you comment on that?

Conti: I have noticed this too. It seems to be a clumping of stars a little away from the current ZAMS. Part of the problem may be the necessary quantization of M_v at various temperatures, since for many galactic stars we get both the luminosity and the temperature from the spectrum. Perhaps some ZAMS stars are still hidden in dense clouds. Our study of the Magellanic Clouds, when complete, will help this since we will obtain the M_v from the m_v directly.

Tayler: You commented on a shortage of stars close to the zero age main sequence. Presumably the uncertainties of 10 percent in T_{eff} and ½ magnitude in luminosity means that the ZAMS is not the lower envelope. In addition, 40 percent binarity will move stars away from ZAMS. Do you think that a significant number of young massive stars could still be obscured in clouds?

Conti: My personal belief is very few are hidden, at least within 2.5 kpc from the sun. Infra-red workers I have questioned feel few have been missed. The IRAS satellite will have the data to answer this question.

de Groot: I want to help Peter Conti with his statistics: As far as proper motions are concerned P Cygni's has been determined at least twice; in 1967 and rather recently. There also is a binary among the LBV, because the Heidelberg people (Wolf, Zickgraf) have found that R81 in the LMC which is exactly like P Cygni has a lightcurve like an eclipsing binary. This latter may mean I can also give you a mass for an LBV, once the radial velocity curve has been determined and the system analysed more completely.

Janes: Is it possible that there is a significant population of stars that have not yet reached the zero age main sequence?

Conti: I don't think so. Scaling arguments suggest pre-main sequence lifetimes are at most 1 % of the MS lifetime. Thus a few stars in our sample, or not yet found, could be pre-main sequence.

Richer: Could you amplify your remarks concerning uncertainty in the distance modulus to M33?

Conti: Actually, I'd rather not get into this controversy, but for what it's worth, the distance to M33 is uncertain by a factor two. Sandage now assigns a somewhat further distance based upon his analysis of Cepheids. Madore finds a distance somewhat closer based upon IR photometry. The mean WR magnitudes, compared to galactic stars, tend to favour the smaller distance but I would be hesitant to use this to settle the matter.

Humphreys: You mentioned a problem with the relative numbers of Wolf-Rayet stars in the LMC and M33. What happens if the distance to M33 is doubled?

Conti: I think we would still be relatively complete in our M33 survey for WR candidates. The mean magnitudes would be brighter, though.