LUMINOUS BLUE STARS: DISTRIBUTION AND NUMBERS

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I. INTRODUCTION

Because the term "luminous blue stars" is relative, let me begin by delineating what region of the H-R diagram I am considering. For the purpose of this talk, I will discuss primarily O-type stars, with $T_{eff} > 30,000$ K and $M_{bol} > -7$, but I will also mention their evolved descendants the B supergiants with $30,000 \text{ K} > T_{eff} > 10,000$ K and $M_{bol} > -8$, and their even later evolutionary form, the Wolf-Rayet (W-R) stars with $T_{eff} > 30,000$ K and uncertain M_{bol}. Although these stars are not among the visually brightest stars, they are the bolometrically most luminous as well as the hottest stars. They are also the most massive. They are an important channel in the metal enrichment in a galaxy through the action of mass loss via stellar winds and their ultimate disruption as supernovae (Maeder 1981). They also contribute in a major way to the energy balance of the interstellar medium (Abbott 1982).

If we are to understand galactic evolution in detail, it is vital that we understand stellar evolution and star formation rates. Two fundamental questions, posed by Scalo (1984) and Freedman (1985) among others, are: how does the star formation rate (SFR) vary among galaxies, and can all star forming clouds produce the initial mass function (IMF) each time? It is natural to start seeking answers to these questions at the massive end of the spectrum and to expect that variations in the SFR or the IMF will affect the entire top of the H-R diagram.

W-R stars are currently observable in many Local Group galaxies, and their distribution provides tantalizing clues (Massey, this volume). However, understanding these clues requires the total evolutionary picture for massive stars. At present, such data are only attainable for our Galaxy and the Magellanic Clouds. This talk will deal with massive stars within 3 kpc of the Sun and in the LMC and SMC. Section II will cover what observations are required to resolve these stars and the calibrations used to construct an H-R diagram. Section III deals with our current knowledge of massive stars in the solar vicinity and Sec. IV with massive stars in the Magellanic Clouds.

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II. PARAMETERS FOR MASSIVE STARS

To answer questions about massive star evolution, SFR and the IMF, we must start with a data set. Perhaps the most universally useful is a "theoretical H-R diagram," a term used by Humphreys (1983), and consisting of M_{bol} vs. T_{eff} for a volume limited sample of stars. The sample could consist in principle of a single cluster at a known distance, but because the mass function tapers off so rapidly for massive stars, a cluster invariably suffers from small number statistics. It also ignores the issue of the field O stars. Hence a number of recent studies have used a large volume of space and attempted to count all the stars within that volume and assign an M_{bol} and T_{eff} to each star.

Let us first consider problems connected with determining M_{bol} and T_{eff}. The observations generally include apparent magnitude and colors, usually V, (B-V) and (U-B), a spectral type which varies in quality from a low dispersion objective prism type to a high quality MK type, and information on cluster membership. Distances for cluster members usually rely on cluster fitting for less massive but more numerous B stars. These cluster stars have then been used to define the absolute magnitude calibration as a function of spectral type for the O and B supergiants. This calibration has been thoroughly discussed by Blaauw (1963); it has been reexamined over the years by Walborn (1972), Conti et al. (1983) and Humphreys and McElroy (1984), as more cluster stars have become available. However, it is well to remember that these basic calibrations still make use of the old distance modulus for the Hyades! The difference between the old and new Hyades distance modulus is 0.2 in M_V, but before we rush to increase the M_V calibration for O stars, it should be noted that Blaauw (1963) also discussed an independent determination of the M_V calibration from the Scorpio-Centaurus association and confirmed the results based on the (old) Hyades calibration. Until a careful reexamination of cluster fitting from the Hyades to h and χ Persei is made, we should keep in mind that the systematic uncertainty in the M_V calibration possibly exceeds 0.3 mag. The current state of M_V vs. spectral type is shown in Fig. 1.

The radical difference between an H-R diagram based on M_V rather than on M_{bol} is illustrated by Massey (1985, Fig. 3). The bolometric correction is usually computed as a function of T_{eff}. As temperature determinations are discussed by Kudritzki (this volume), I will say nothing further. Figure 2 shows bolometric correction vs. T_{eff} as recently computed by different authors.

For stars that are apparently not cluster members, distance must be computed from the relation:

$$V-M_V = 5 \log D - 5 + 3.1 \, [(B-V)-(B-V)_0)] \quad .$$

In addition to the uncertainty in the M_V calibration, this equation contains assumptions about the ratio of total to selective absorption and about the intrinsic color of the star. How well are the intrinsic colors known? As there are no nearby unreddened O stars, these numbers are based on a large degree of extrapolation (FitzGerald 1970).

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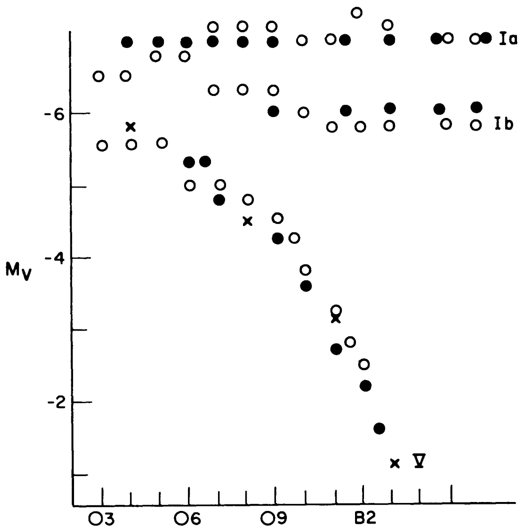

Fig. 1. The M_V-spectral type calibration by different authors. Walborn 1972 (•), Garrison 1978 (×), Humphreys and McElroy 1984 (V).

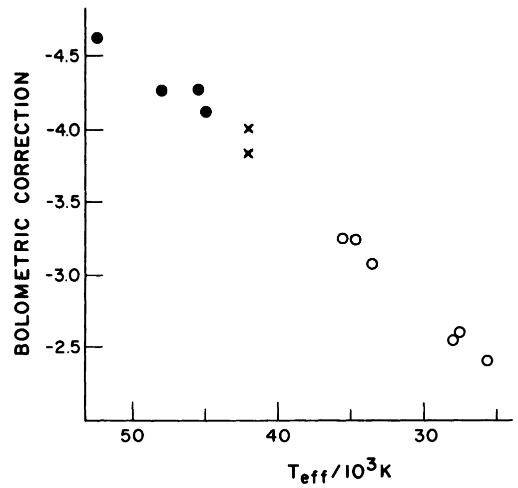

Fig. 2. Bolometric correction vs. temperature. Kudritzki et al. (1983) (•), Remie and Lamers 1982 (o), Abbott and Hummer 1985 (×).

Furthermore, as Massey (1985) has illustrated, the intrinsic UBV colors for O stars are degenerate in the sense that there is little difference between the $(U-B)_0$ or $(B-V)_0$ for an early or a late O star. Recently, Massa and Savage (1985) have found from a study of Galactic stars that none of the O stars have UV colors much bluer than normal B0 V stars. We will discuss further evidence for intrinsically redder colors for O stars in Sec. IV.

III. GALACTIC STARS

How complete are existing catalogs of massive stars? In the past 10 years there have been repeated updates of such lists: Cruz-Gonzales et al. (1974) (600 O stars), Humphreys (1978, Galactic associations), Garmany, Conti, and Chiosi (1982, 780 O-stars), Humphreys and McElroy (1984, O and B stars). Garmany et al. felt the O-star were essentially complete to 2.5 kpc from the Sun; Humphreys and McElroy felt the O and B stars were complete to 3 kpc for stars brighter than $M_{bol} = -8$. However, a complete list of stars is an elusive goal, as we have found in updating our list of O stars (Garmany 1984). We currently have a computer list of 1088 O stars, although data on some of these stars are not complete. This is a 40% increase over our list in 1982, and some of the new additions lie within 2.5 kpc of the Sun.

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The arguments for completeness within a given volume of space rely on the time-honored technique of star counts, which in the Galaxy should increase with the square of the distance if the stars are confined to the plane. That they are so situated is shown in Fig. 3, which gives the distribution in Galactic Z of the O stars in our Catalog and the luminous B stars from Humphreys and McElroy. These stars all lie in the plane of the Galaxy, but Fig. 3 also shows that the plane is warped. The midplane is negative in the third and fourth quadrant and positive in the first and second.

Now, if we examine a plot of the log (number of O and B stars) vs. distance we find that the slope of the line is just about 2 out to 3 kpc, and then becomes flat. To zero order, this suggests that our most current list of O and B stars is basically complete to 3 kpc. But should these stars follow a uniform star count relation? We are surveying a region containing three Galactic spiral arms, and the total number of O and B stars within the solar circle is significantly greater than the number outside the solar circle. Indeed, a plot of log (number stars) vs. distance for the region within the solar circle has a slope greater than 2, reflecting the interarm gap between the Sun and the Carina-Sagittarius arm. The same plot for the region outside the solar circle has a slope less than 2, which probably reflects the gap in the arms between the local arm (or spur) and the Perseus arm. See Fig. 4.

The nonuniform distribution of O and B stars is even more striking if we consider only stars that have initial masses greater than 40 $M_\odot$ (Fig. 5) according to evolutionary models. The major

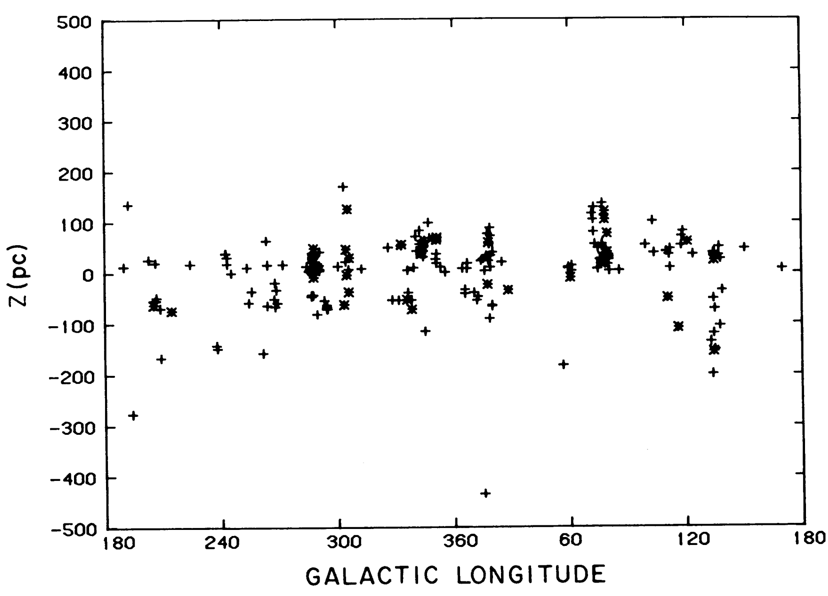

Fig. 3. The O and luminous B stars in the plane of the Galaxy.

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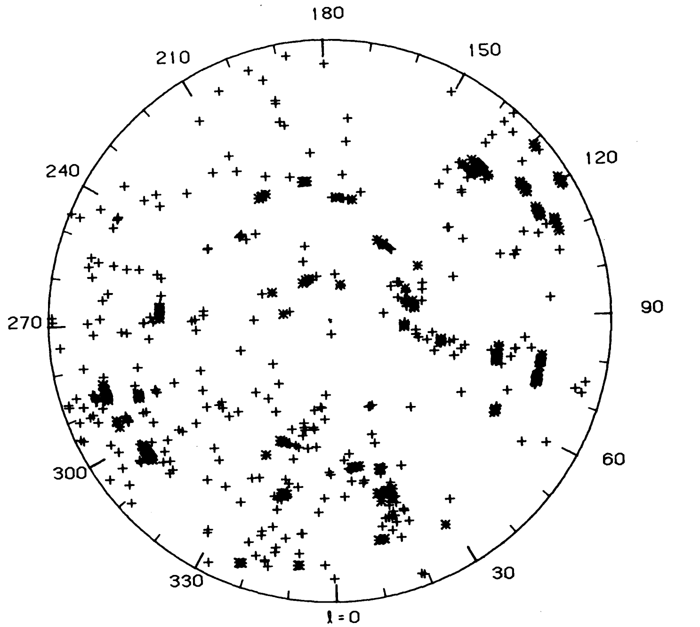

Fig. 4. The O and luminous B stars projected onto the Galactic plane within 3 kpc of the Sun.

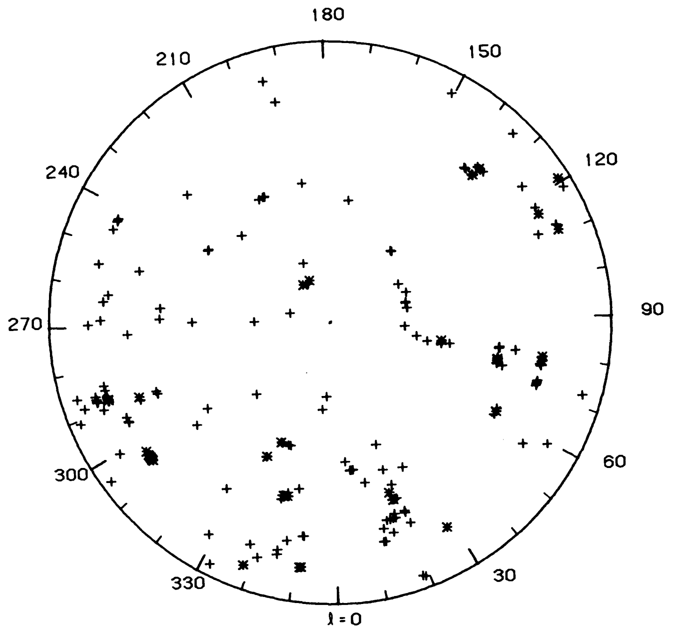

Fig. 5. Stars with initial mass greater than 40 $M_\odot$ projected onto the Galactic plane within 3 kpc of the Sun.

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spiral arms are defined, but what is more interesting, there is a very strong gradient in the space density of stars. As pointed out by Conti et al. (1983) the same gradient is observed in the distribution of W-R stars: O and B stars of 40 $M_{\odot}$ and greater, as well as W-R stars, are preferentially found in the Carina-Sagittarius arm and the Cygnus arm, but not in the Perseus arm or Orion spur. This offers further indirect evidence that W-R stars are the descendants of very massive O stars, and suggests that probing the W-R population in other galaxies will tell us about the uppermost end of the mass function. (See Conti, this volume, Fig. 6 for the distribution of W-R stars in the plane.)

The greater space density of massive stars and W-R stars within the solar circle is incontrovertible; the cause of this is subject to debate. Garmany et al. (1982) argued that the data on O stars indicated a real difference in the upper end of the initial mass function (IMF) between the inner and outer region of the Galaxy. Humphreys and McElroy (1984), using data on the O and B stars, have concluded that only the star formation rate (SFR) is different, and that differences in the slope of the IMF can be explained by missing late-type O stars in the inner region of the Galaxy. (It should be emphasized here that the region of the Galaxy under consideration extends only 3 kpc from the Sun. By comparison, surveys of giant molecular clouds (Cohen et al. 1985; Solomon et al. 1985) extend 10-15 kpc from the Sun.)

I have reexamined this issue, using our current O-star list which contains 777 stars within 3 kpc and also the Humphreys and McElroy (1984) list of B stars brighter than M_{bol} = -7 within the same distance, for a total of 1,041 stars. Table 1 shows the distribution by mass, using evolutionary tracks by Bressan et al. (1981), for these stars divided into the region interior to and exterior to the solar circle. Indeed, the ratio of stars interior to the Sun to those exterior to the Sun is 1.8 (671/370) but the ratio of stars more massive than 40 $M_{\odot}$ inward vs. outward is 3.0 (128/42). If the difference is entirely caused by missing stars in the mass range 20-40 $M_{\odot}$, then we have to conclude that all these stars have been detected outside the solar circle, but only 55% of them have been detected inside the solar

Table 1. Number of stars within 3 kpc interior and exterior to the solar circle.

Mass interval	Interior	Exterior
>100	2	0
80 - 100	4	1
60 - 80	27	5
40 - 60	95	36
30 - 40	174	80
20 - 30	369	248

circle. Why should there be such a disparity? One suggestion is that the missing stars are hidden in molecular clouds. However, opinions differ on whether giant molecular clouds might be preferentially hiding early O-type stars or late O stars.

IV. MASSIVE STARS IN THE MAGELLANIC CLOUDS

The Magellanic Clouds provide an ideal laboratory for comparison of massive stars. They are close enough to observe normal main sequence O stars, their reddening is very low, and they are far enough out of the Galactic plane that foreground contamination of blue stars is not an issue. In addition, there are a number of fascinating contrasts between the LMC and the SMC. The LMC is more massive than the SMC by a factor of 4 to 5 (Fujimoto 1979). The difference in metallicity (based on H II regions) has been studied by Dufour (1984) who finds that compared to the Galaxy, the LMC is deficient by 2-4 and the SMC by 5-20 for CNO.

The indications of massive star formation all point toward differences between the LMC and SMC. Davies _et al._ (1976) found that H II regions are richer and larger in the LMC than the SMC. Dark nebulae in the SMC are about half the size of those in the LMC (Hodge 1974). Stellar associations of blue stars are much richer in the LMC than in the SMC (Lucke 1974; Hodge 1985). Although surveys of CO are incomplete, it appears that CO clouds are much more widespread in the LMC than the SMC (Rubio, Cohen and Montani 1984). Humphreys (1983) found that luminous blue stars are deficient in the SMC compared to the LMC and the Galaxy. The W-R population is dramatically different: there are 105 known W-R stars in the LMC (Breysacher 1981; Hutchings _et al._ 1984; Conti and Garmany 1983) but only 8 in the SMC (Azzopardi and Breysacher 1979).

There have been a number of studies of the luminosity function (LF) of the luminous stars in the Clouds, which are reviewed by Freedman (1984). As the IMF can, in principle, be derived from the luminosity function, these studies should reflect the current state of the massive star population. In general, it has been found that the slope of the LF, or the IMF, is similar in the Clouds, and similar to the Galaxy (Lequeux _et al._ 1980, Humphreys and McElroy 1984, Freedman 1984). What can we conclude from these studies about the O-star population in the Clouds? The answer seems to be not very much, in large part because much of the available stellar data include only photometry (UBV) and objective prism spectroscopy. As pointed out in Sec. II, photometric determinations of spectral type carry a large uncertainty. Slit spectra are required to resolve early from late O, or early B stars.

Conti, Massey and I began a program a few years ago to obtain slit spectra at classification dispersion for candidate O stars in the Clouds. So far we have taken 175 spectra in the LMC and 134 in the SMC with the CTIO 4-meter, image tube and IIIa-J plates at a dispersion of 47 Å/mm. Our observing lists have been extracted from catalogs of early-type stars in the Clouds. In the LMC this includes

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Rousseau et al.'s (1978) catalog of 1822 stars, from which we chose candidates having objective prism classifications, many by Sanduleak (1969). In the SMC we have used the catalog by Azzopardi and Vigneau (1982) of 524 stars. Of course, some stars in these catalogs have already been classified from slit spectra by Walborn (1977), Crampton (1979), Crampton and Greasley (1982), and Humphreys (1983); our observing list does not include these stars except for comparison.

Combining our new data with published data that include both spectral types and photometry confirms our feeling that photometry is useful in choosing candidates, but cannot identify O stars unambiguously. Figure 6 is a color-color plot for LMC stars classified as O6.5 or earlier, either from published work, on our new classification. The line defining unredded class V stars (FitzGerald 1970) is also indicated, and an arrow shows the magnitude and slope of the average foreground reddening (McNamara and Feltz 1980). Examination of this figure suggests either a much steeper reddening curve applies in the LMC or the unreddened colors are too blue.

From the UV, there is evidence that the reddening law is steeper and the extinction is much higher than in the Galaxy (Nandy et al. 1981, Fitzpatrick and Savage 1984). Although the reddening law might be somewhat steeper in the optical region, it could not explain the position of the stars in Fig. 6. Figure 7 is a similar color-color plot, but contains stars classified O6.5 through O9. There is little difference in the position of these stars and the early O stars, suggesting that the intrinsic colors of O stars may be redder than generally assumed. As mentioned earlier, Massa and Savage (1985) have found from the UV that the colors of O stars are not any bluer than a normal B0 V star. (A detailed study of this matter is in preparation.)

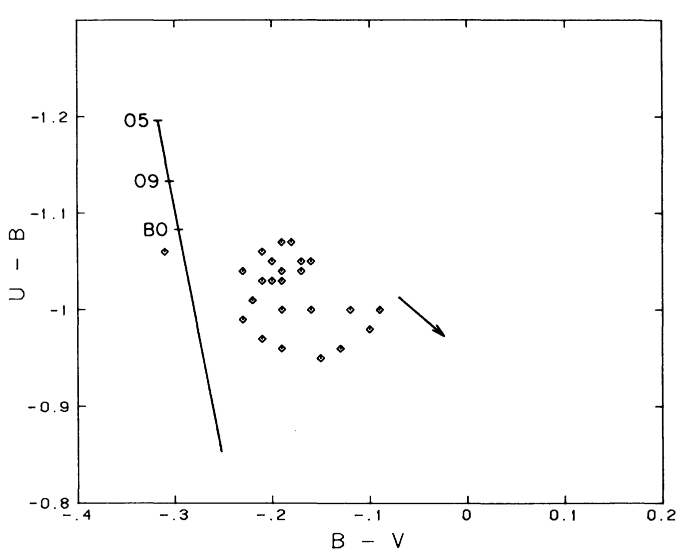

Fig. 6. Color-color plot for stars in the LMC earlier than O6.5.

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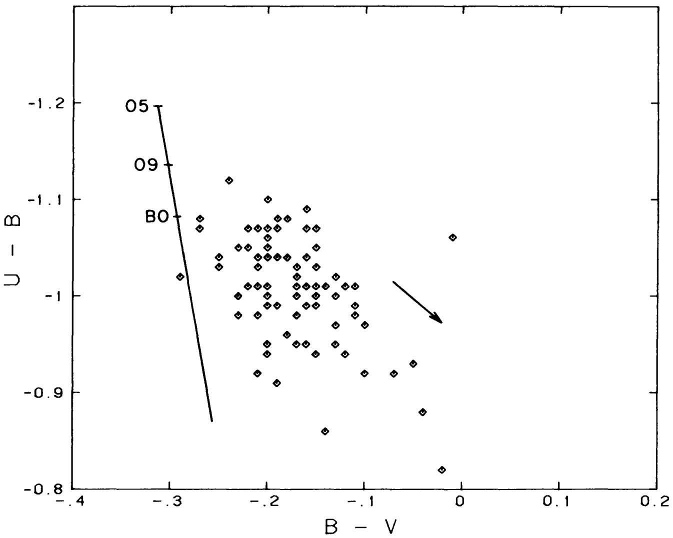

Fig. 7. Color-color plot for stars in the LMC classified as type 06.5 through 09.

How much progress has been made in identifying a major portion of the O stars in the LMC? Although we have observed most of the candidates, there are a great number of stars not catalogued by Rousseau _et al._ (1978). These include the stars in the associations studied photographically by Hodge and Lucke (1970). We have obtained spectra for 37 stars in four of these associations and discovered 29 new O stars. Eastwood and Massey have begun a program to obtain CCD frames of the Lucke-Hodge associations; this will tell us a great deal more about massive stars in the LMC. An H-R diagram of the LMC based on all available data represents mainly field O and B stars, so it is premature to compare it with the Galaxy.

Our search for massive stars in the SMC seems closer to completion than that in the LMC: not only are we dealing with a smaller galaxy, but the number of O stars is very small. Azzopardi and Vigneau (1982) estimate that at least 80% of the SMC members brighter than B = 14.3, and outside the central part of clusters or nebulae, are included in their catalog. Based on colors and objective prism classification, spectral types have been published for 75% of the candidate O stars, and unlike the LMC there do not seem to be scores of unidentified O stars in associations.

Hodge (1985) has completed a study of the associations in the SMC and finds that, compared to the LMC, bright members are scarce. Not counting the two richest clusters, NGC 346 and NGC 330, there are an average of five stars brighter than 14.2 in each association. Many of these stars already have been classified, especially the brighter ones. Thus it is now appropriate to examine the H-R diagram for massive

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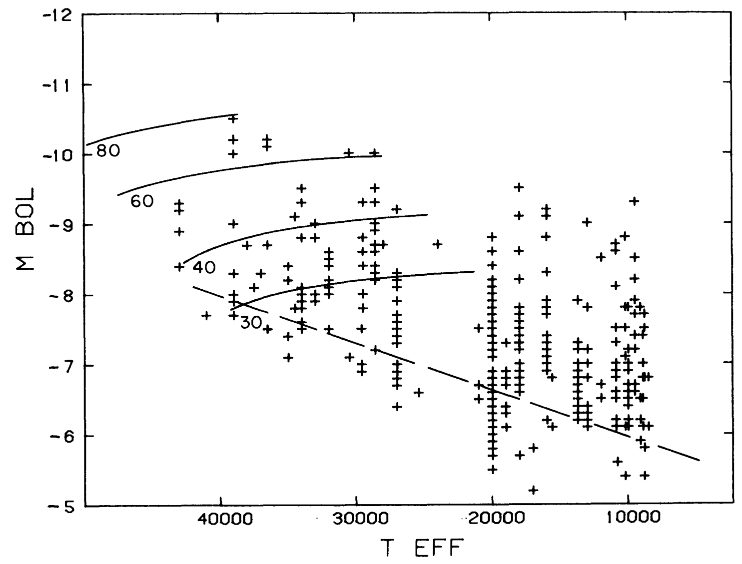

Fig. 8. The H-R diagram for stars in the SMC classified from slit spectra. The data are incomplete below the dashed line.

stars in the SMC, and expect it to be complete enough to be significant.

Figure 8 contains all stars with spectra in the SMC. Evolutionary tracks by Bressan et al. (1981) are shown, and the region where the data are incomplete is cross hatched. One thing is clear in Fig. 8: there are very few stars above 40 $M_\odot$. Recall that there are only eight stars classified as W-R in the SMC, and two of these look more like Of stars on spectra taken by P. Massey and myself. The situation in the SMC is reminiscent of the outer region of our Galaxy, and if we compute an IMF for stars above 30 $M_\odot$ in the SMC, the points lie within root N error bars of the points outside the solar circle.

At present, it appears that the SMC has produced remarkably few massive O stars in recent stellar generations, and consequently has very few W-R stars. On the other hand, the LMC is rich in W-R stars and it appears to be equally rich in massive O stars.

This work has been done in collaboration with Drs. P. Conti and P. Massey, and I gratefully acknowledge their help in preparing this paper. I especially thank Dr. Conti for presenting this paper on very short notice when illness prevented me from attending IAU Symposium #116. This research has been supported by NSF Grant AST83-12964.

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Discussion : GARMANY.

HUMPHREYS :

I have 2 comments.

1. It is well known that spiral structure diagrams for individual stars show a lot of scatter due to the uncertainties in the luminosities of individual stars. Use of associations and stars clusters cleans up the diagram considerably.

2. I agree that the number of massive stars is greater inside the solar circle but I do not think there is a significant difference in slope because of incompleteness in the counts of massive stars in our galaxy which is probably more of a problem for the inner region because it is affected more by observations from the southern hemisphere and higher extinction toward the galactic center.