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STUDIES OF LUMINOUS STARS IN NEARBY GALAXIES. III. COMMENTS ON THE EVOLUTION OF THE MOST MASSIVE STARS IN THE MILKY WAY AND THE LARGE MAGELLANIC CLOUD

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ABSTRACT

An empirical comparison of the observed H-R diagrams for the supergiants in our region of the Galaxy and the Large Magellanic Cloud reveals comparable distributions of spectral types and luminosities in the two galaxies. Supergiants of similar spectral types have the same luminosities, except for the A-type stars, where selection effects may be important. These results suggest that the same basic physical processes govern the evolution of the most massive stars in the two galaxies.

Variations in the blue-to-red supergiant ratio with galactocentric distance and with luminosity involve chemical composition gradients and varying rates of mass loss. Since the relative numbers of the most luminous stars are more sensitive to mass loss, the B/R ratio from the less luminous supergiants may be a better indicator of galactic abundance gradients.

The upper luminosity boundary for both the galactic and the LMC supergiants is characterized by (1) decreasing luminosity with decreasing temperature for the hottest stars and (2) an upper limit to the luminosities near $M_{\rm bol} \approx -9.5$ to -10 mag for stars cooler than 15,000 K. We suggest that the observed luminosity limits are due primarily to the effects of large mass loss on the evolution of the most massive stars. The examples of η Car and P Cyg suggest that mass-loss rates can be very rapid and unsteady—higher on the average than presently observed for most of the hot supergiants. The evolution of stars greater than 60 $\mathfrak{M}_\odot$ to cooler temperatures is consequently limited by instabilities and the accompanying high mass loss. An initial mass near 50–60 $\mathfrak{M}_\odot$ may be an empirical upper limit to the mass at which a star can evolve to the region of the M supergiants and probably accounts for the observed upper bound to the luminosities of the cooler supergiants.

Subject headings: galaxies: Magellanic Clouds — galaxies: Milky Way — galaxies: stellar content — stars: evolution — stars: massive — stars: supergiants

I. INTRODUCTION

The H-R diagrams of the supergiants in our region of the Milky Way and in the LMC, shown in Papers I and II (Humphreys 1978*a*, 1979), are remarkably similar. Although several authors have suggested a difference in the evolutionary histories and chemical compositions between the LMC and our Galaxy, the comparison in this paper implies that the basic physics governing the evolution of the most massive stars is the same, resulting in very similar supergiant populations.

In this paper we discuss the similarities and differences between the supergiants in the two galaxies in more detail. The H-R diagrams, the distribution of luminosities and spectral types, and the blue-to-red supergiant ratio are discussed in the following sections, and in the final section, the important role of mass loss on the evolution of the most massive stars and the apperance of the H-R diagrams is demonstrated.

II. A COMPARISON OF THE H-R DIAGRAMS

The H-R diagrams (M_V versus spectral type, and $M_{\rm bol}$ versus $\log T_e$), for the Milky Way and the LMC supergiants are reproduced from Papers I and II in Figures 1 through 4. The position of the zero-age main sequence (ZAMS) is indicated in each figure, and the evolutionary tracks for massive stars with mass loss from Chiosi, Nasi, and Sreenivasan (1978) are shown on the $M_{\rm bol}$ versus $\log T_e$ diagrams. These provide reference points for estimating the approximate initial masses of stars of different spectral types and luminosities. Known peculiar stars, binaries, and Wolf-Rayet stars have not been included on the H-R diagrams.

It is clear from comparison of the H-R diagrams that the supergiant populations in both galaxies have similar distributions of luminosities and spectral types. When making any comparison of this type, possible incompleteness of the data and the effects of observational selection must be considered. For example, the galactic supergiants were required to be members of

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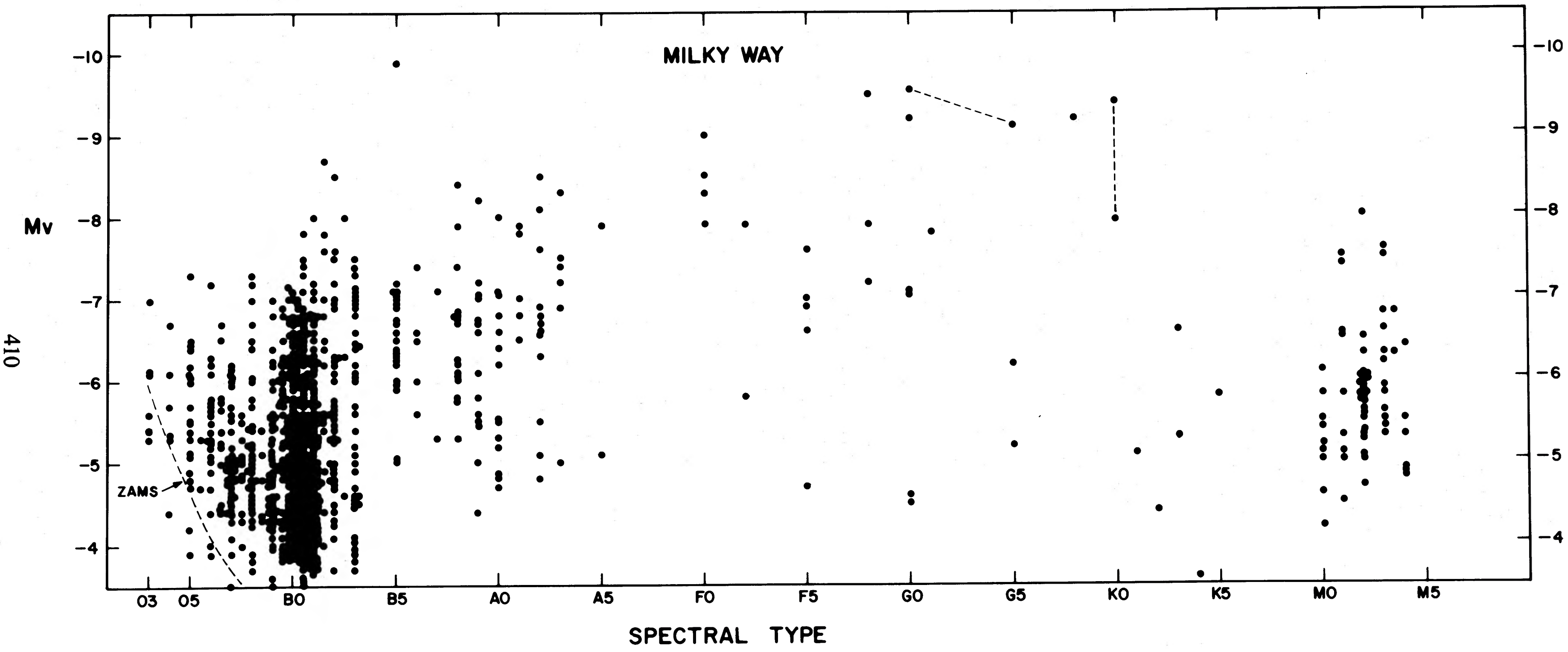

FIG. 1.—The observed H-R diagram, M_v versus spectral type for the galactic supergiants

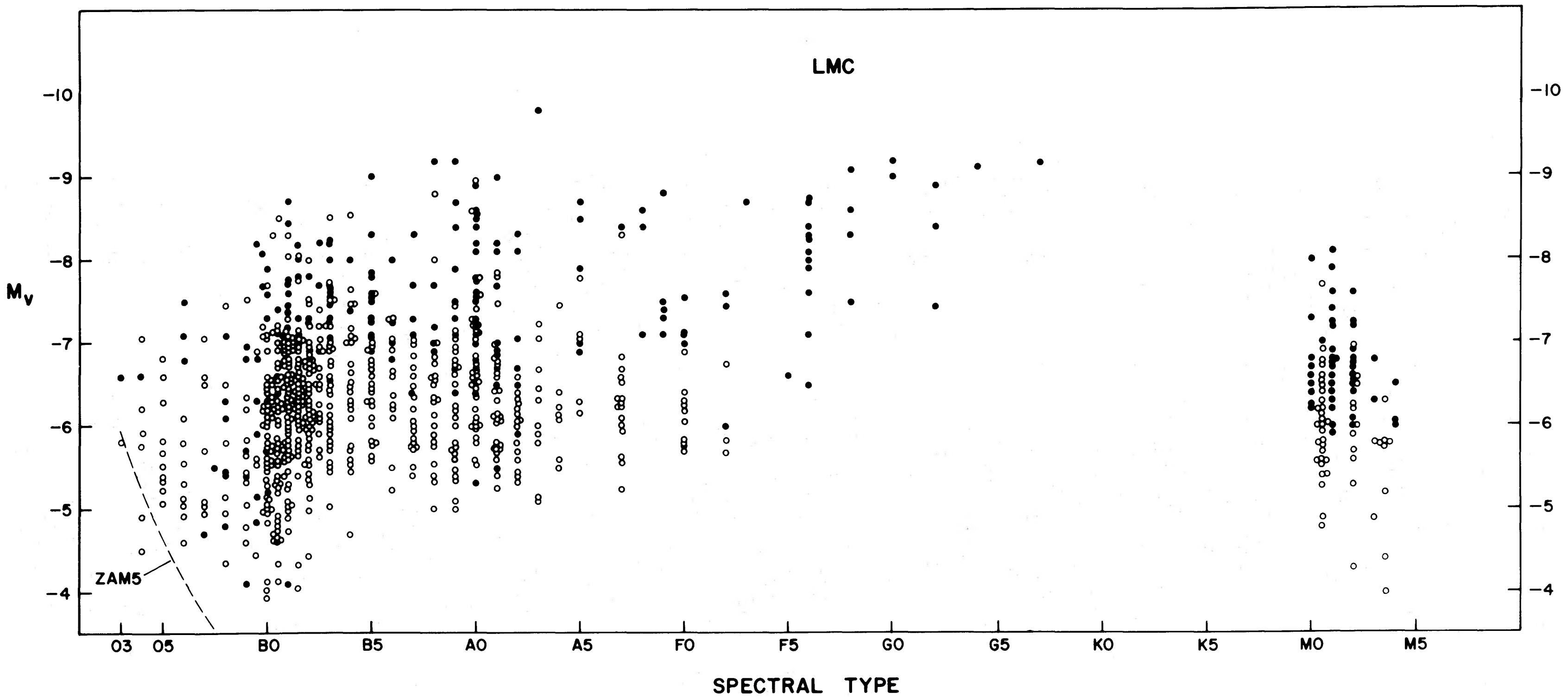

FIG. 2.—Same as Fig. 1 for the LMC supergiants

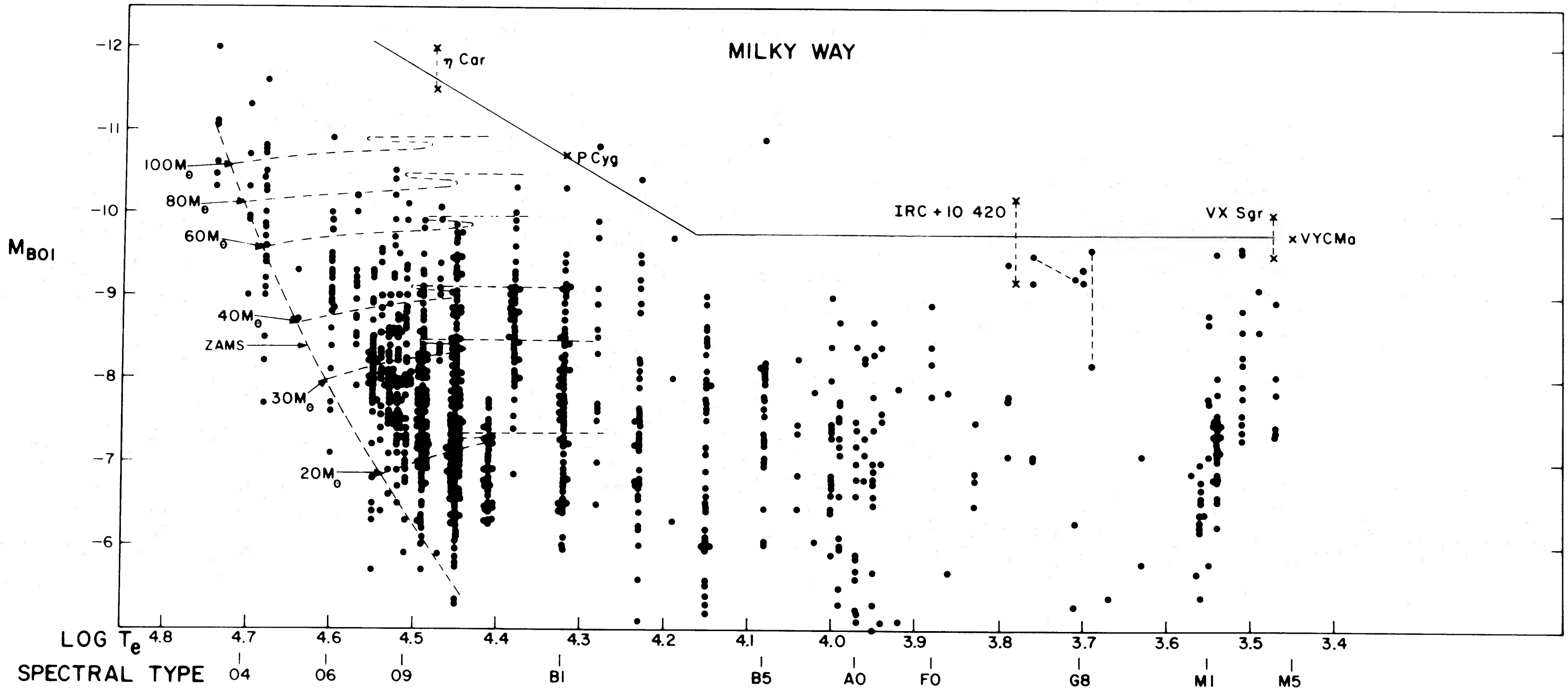

FIG. 3.—The "theoretical" H-R diagram, M_{bol} versus log T_e, for the galactic supergiants. The position of the ZAMS and evolutionary tracks with mass loss are shown. The solid line defines the approximate upper boundary of the supergiant luminosities. The positions of two peculiar stars, η Car and P Cyg, and three supergiant infrared sources are also indicated.

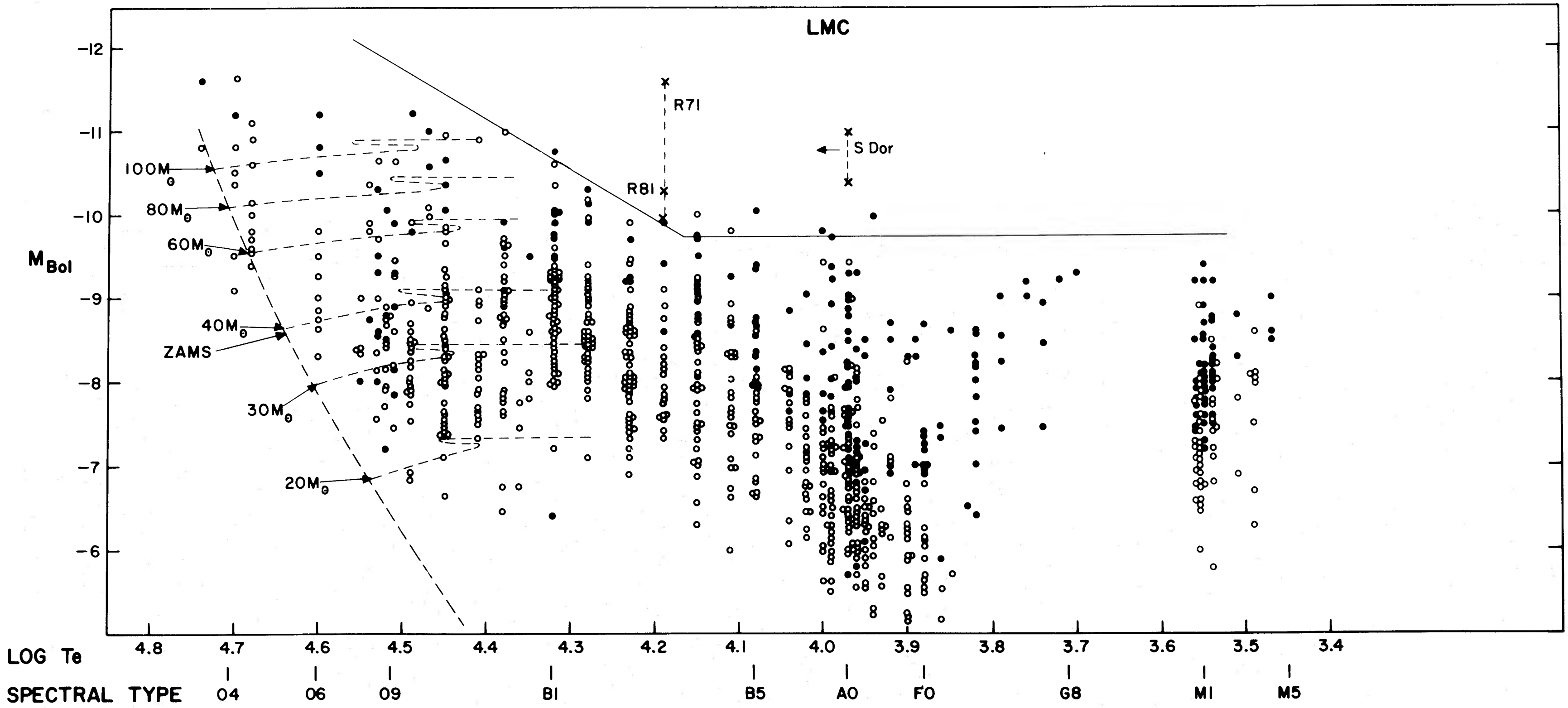

FIG. 4.—Same as Fig. 3 for the LMC supergiants. The positions of S Dor and two other peculiar stars are indicated.

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known associations and clusters (see Paper I), which may introduce some bias in the stellar distribution on these H-R diagrams. Similarly, in the H-R diagrams for the LMC there is a lack of early-type stars at the lower luminosities ($M_{\rm bol} > -7.5$ mag). As mentioned in Paper II, there are few stars in the LMC whose actual MK spectral types are known, particularly at the lower luminosities. To produce a more complete and representative diagram, additional early-type stars were added whose spectral types have been inferred from published two-color photometry. These stars are shown as open circles in Figures 2 and 4.

A simple inspection of the "theoretical" H-R diagrams, $M_{\rm bol}$ versus log T_e, reveals several important features in common: (1) a group of intrinsically very luminous hot stars (O and early B-type) with $M_{\rm bol}$ between -10 mag and -12 mag, (2) a lack of supergiants of later spectral type at these high luminosities, and (3) an apparent upper envelope to the luminosities of the later-type supergiants at about $M_{\rm bol} = -9.5$ to -10 mag beginning at approximately spectral type B3 or B5 (12,000–14,000 K) and extending across the diagram to the M stars.

A solid line has been drawn on the $M_{\rm bol}$ versus log T_e diagram for the galactic supergiants (Fig. 3) which is essentially an "eyeball fit" to the apparent upper envelope of the supergiant luminosities. It illustrates the decreasing luminosity with decreasing temperature for the hottest supergiants and the upper luminosity limit for most of the cooler supergiants. This same line has been transferred to the LMC diagram (Fig. 4), and we see that it also defines the upper envelope to the LMC supergiant luminosities quite well. Hutchings (1976), considering a smaller sample of stars, also noted essentially the same tendency for the hottest supergiants, a luminosity envelope that decreased with lower temperature.

One noticeable difference between the LMC and Milky Way is the greater relative number of high-luminosity late B and early A-type stars in the Large Cloud. It is not clear if this is a significant difference, or if it might be due to observational selection in our Galaxy. These A-type supergiants are visually very luminous ($M_v \approx -8$ to -9 mag) and consequently would be very distant in our Galaxy. Since the galactic stars in these figures are members of known associations and clusters and are therefore relatively nearby ($r \leq 3$ kpc), it is possible that many of the brightest A-type supergiants have been overlooked for these H-R diagrams. By comparison with the LMC there also appears to be a scarcity in the Galaxy diagram of the less luminous ($M_{\rm bol} \approx -5$ to -7.5 mag) supergiants between spectral types B5 and F0. This is also probably due to selection, since by restricting the population to OB associations, we select in favor of the hottest stars and against the more evolved and older supergiants which may not be in now recognizable associations.

Overall, the comparison of the H-R diagrams reveals a similar supergiant population in the Milky Way and the Large Magellanic Cloud.

III. A COMPARISON OF THE LUMINOSITIES AND SPECTRAL TYPES

The bolometric and visual luminosities of the brightest galactic and LMC supergiants in the different spectral type groups are compared in Tables 1 and 2, respectively. The number of stars at each magnitude are also given in parentheses. The data in these two tables give a somewhat more quantitative confirmation of the visual comparison of the H-R diagrams discussed in the previous section. In general, both the bolometric and visual luminosities are comparable for the brightest stars of similar spectral types. The only exceptions are the A-type stars which are systematically more luminous in the LMC. As mentioned previously, this difference may be largely due to observational selection in the Galaxy. The luminosity comparisons are remarkably good for the O, B, FGK, and M spectral-type groups.

TABLE 1

COMPARISON OF THE MOST LUMINOUS STARS AT DIFFERENT SPECTRAL TYPES

Milky Way ($M_{\rm bol}$)	LMC ($M_{\rm bol}$)
A. O-Type Stars (O3–O9), $M_{\rm bol} \leq -11.0$ mag	
−12.0 (1)	−11.6 (1)
−11.6 (1)	−11.2 (2)
−11.3 (1)	
−11.1 (2)	
B. B-Type Stars (O9.5–B7), $M_{\rm bol} \leq -10.0$	
−10.9 (1)	−11.2 (1)
−10.8 (1)	−11.0 (2)
−10.4 (1)	−10.8 (1)
−10.3 (1)	−10.7 (1)
−10.0 (3)	−10.6 (1)
	−10.4 (1)
	−10.3 (1)
	−10.1 (3)
	−10.0 (2)
C. A-Type Stars (B8–A8)	
$M_{\rm bol} \leq -8.5$ mag	$M_{\rm bol} \leq -9.0$ mag
−9.6 (1)	−10.1 (1)
−8.7 (1)	−9.7 (1)
−8.6 (1)	−9.4 (1)
	−9.3 (2)
	−9.2 (1)
	−9.0 (2)
D. F, G, K-Type Stars (F0–K4), $M_{\rm bol} \leq -9.0$	
−9.6 (1)	−9.3 (1)
−9.4 (2)	−9.2 (2)
−9.3 (1)	−9.0 (2)
−9.2 (1)	
E. M-Type Stars (K5–M4), $M_{\rm bol} \leq -9.0$	
−9.6 (1)	−9.4 (1)
−9.5 (2)	−9.2 (3)
−9.1 (1)	−9.0 (1)

TABLE 2

Comparison of the Visually Brightest Stars at Different Spectral Types

Milky Way (M_v)	LMC (M_v)
A. O-Type Stars (O3–O9), $M_v \le -7.0$ mag	
−7.3 (2)	−7.5 (1)
−7.2 (2)	−7.1 (2)
−7.0 (3)	−7.0 (1)
B. B-Type Stars (O9.5–B7), $M_v \le -8.5$ mag	
−9.9 (1)	−9.0 (1)
−8.7 (1)	−8.7 (1)
−8.5 (1)	−8.5 (1)
C. A-Type Stars (B8–A8)	
$M_v \le -8.0$ mag:	$M_v \le -8.5$ mag:
−8.4 (2)	−9.8 (1)
−8.3 (1)	−9.2 (2)
−8.2 (1)	−9.0 (1)
−8.1 (1)	−8.9 (1)
−8.0 (1)	−8. 7(2)
...	−8.6 (3)
...	−8.5 (2)
D. F, G, K-Type Stars (F0–K4), $M_v \le -9.0$ mag	
−9.5 (1)	−9.2 (1)
−9.4 (1)	−9.1 (3)
−9.2 (3)	−9.0 (1)
−9.0 (1)	
E. M-Type Stars (K5–M4), $M_v \le -7.5$ mag	
−8.0 (1)	−8.1 (1)
−7.6 (1)	−8.0 (1)
−7.5 (2)	−7.9 (1)
...	−7.6 (2)

The absolute visual magnitude comparison in Table 2 is especially important for evaluating the usefulness of the brightest stars as extragalactic distance indicators. The importance of the brightest red stars as distance indicators has already been emphasized in Papers I and II. The brightest M supergiants in both galaxies have maximum visual luminosities near −8 mag; although it is probably more correct, on the basis of the H-R diagrams, to say that there is a rather tight upper limit to the bolometric luminosities of all late-type supergiants near $M_{\text{bol}} \approx -9.5$ mag which for the M supergiants results in a maximum M_v near −8 mag. Unfortunately, the visually brighter ($M_v \approx -9.5$ mag), F, G, and K-type supergiants are not useful as distance indicators, because they cannot be separated from foreground stars with similar colors.

In each galaxy the visually brightest star is an early-type supergiant with very similar visual luminosities. In our region of the Galaxy this star is Cyg OB2 no. 12 (B5 Ia^+) with $M_v = -9.9$. mag, and in the LMC it is HD 33579 (A3 Ia–0) with $M_v = -9.8$ mag. Combining the data in Table 2 for the B and A-type supergiants, one sees that although the brightest stars are the same, the second and third brightest stars differ by about half a magnitude between the two galaxies. Excluding the brightest star in each galaxy, the brightest blue supergiants in the Milky Way occur at $M_v \approx -8.5$ mag, while in the LMC they are found 0.5 mag brighter at −9.0 mag. Sandage and Tammann (1974) showed that the visual luminosity of the brightest blue supergiants depends upon the luminosity of the parent galaxy. Since the Milky Way is more luminous than the LMC, we should expect more luminous blue supergiants in our Galaxy. As mentioned in the previous section, there is probably observational selection against the inclusion of the visually brightest blue stars in the galactic H-R diagrams, and, of course, we do not see all of our Galaxy. The population of galactic supergiants discussed in this paper is restricted to a relatively small section centered on our Sun. More luminous early-type supergiants may exist.

IV. A COMPARISON OF THE BLUE-TO-RED SUPERGIANT RATIO

Two different blue-to-red supergiant ratios are discussed in the astronomical literature. One refers to variations in B/R with galactocentric distance and is a relatively straightforward ratio of the number of blue-to-red stars at different distances in a galaxy, presumably complete to some limiting magnitude (i.e., absolute visual luminosity). A B/R gradient, in which the ratio of blue-to-red supergiants decreases with increasing galactocentric distance, has been reported for the Milky Way supergiants by Hartwick (1970) and by Humphreys (Paper I) and observed in M33 by Walker (1964). These B/R gradients are thought to be due to metallicity variations across the disks of spirals (van den Bergh 1968).

The other B/R ratio is determined as a function of luminosity. This B/R ratio may be an important indicator for checking evolutionary models, since the relative numbers of stars populating different parts of the H-R diagram (blue versus red) may serve as a measure of evolutionary time scales, although there are uncertainties due to incompleteness of the data. It has been known for some time that the B/R ratio decreases with decreasing luminosity (Stothers 1969; Humphreys 1970). Indeed, it is clear from Figures 3 and 4 for both the Milky Way and the LMC that the ratio of blue-to-red stars is larger at the higher luminosities.

In Paper I it was suggested that the two different B/R ratios have separate causes, although the cause of one may affect the appearance of the other. When the data are divided by spiral arm, the B/R ratio for each luminosity interval is larger for the Sgr-Car arm, nearer the galactic center, than for the more distant Perseus arm (see Table 3). While the B/R variation with luminosity is similar in both spiral arms, the actual B/R ratios also reflect the dependence on galactocentric distance.

The B/R dependence on luminosity is shown in Table 3 for the supergiants in the Galaxy and the LMC. The B/R ratios for the galactic stars are from

TABLE 3

B/R DEPENDENCE ON LUMINOSITY FOR THE MILKY WAY AND LMC SUPERGIANTS

<table>
<tr><th>Luminosity Interval M_{bol} (mag.)</th><th>Mass Range ($\mathfrak{M}_\odot$)</th><th colspan="2">All Stars within 3 kpc of the Sun B/R</th><th colspan="2">Sgr-Car Arm B/R</th><th colspan="2">Perseus Arm B/R</th><th colspan="2">LMC B/R</th></tr>
<tr><td>≤ −11.5</td><td>100 (?)</td><td>...</td><td></td><td>...</td><td></td><td>...</td><td></td><td>...</td><td></td></tr>
<tr><td>−11.5 to −10.5</td><td>100</td><td>...</td><td></td><td>...</td><td></td><td>...</td><td></td><td>...</td><td></td></tr>
<tr><td>−10.5 to −9.5</td><td>60–80</td><td>24</td><td rowspan="2">23</td><td>...</td><td rowspan="2">>40</td><td>...</td><td rowspan="2">20</td><td>...</td><td rowspan="2">14</td></tr>
<tr><td>−9.5 to −8.5</td><td>40–60</td><td>23</td><td>...</td><td>16</td><td>11</td></tr>
<tr><td>−8.5 to −7.5</td><td>25–40</td><td>14</td><td rowspan="2">10</td><td>15</td><td rowspan="2">9</td><td>13</td><td rowspan="2">7</td><td>5</td><td rowspan="2">5</td></tr>
<tr><td>−7.5 to −6.5</td><td>20–25</td><td>8</td><td>6</td><td>5</td><td>5</td></tr>
<tr><td>−6.5 to −5.5</td><td>15</td><td>9</td><td></td><td>16</td><td></td><td>4</td><td></td><td>incomplete data</td><td></td></tr>
<tr><td>Mean B/R ($M_{bol} \leq -6.5$)</td><td></td><td>12.4</td><td></td><td>16.5</td><td></td><td>8.1</td><td></td><td>7.1</td><td></td></tr>
</table>

Table 7 in Paper I, and from the data in Figure 4 for the LMC supergiants. It is obvious that although the actual numbers are different, the same trend occurs in both galaxies; the B/R ratio decreases with decreasing luminosity. As mentioned above, the B/R dependence on luminosity reflects the variation with galactocentric distance. For the LMC supergiants the B/R ratios for each luminosity interval are lower than in either Milky Way region, Sgr-Car or Perseus. Since it is known that the abundances of the heavier elements are lower in the LMC, this is additional evidence that the B/R variation with distance is due to a composition gradient. One can speculate that there may be a continuous abundance gradient from the galactic center to the Magellanic Clouds, but the data in Table 3 only suggest that the characteristics of the LMC supergiants are more like those of the luminous stars in the outer parts of our Galaxy than those nearer the center.

The available evidence strongly suggests that the B/R variation with galactocentric distance is due to a composition gradient. (An unpublished comparison of the observed B/R gradient in M33 with the O/H abundance from the H II regions confirms this interpretation.) If the B/R variation with luminosity can be largely attributed to mass loss, then the data in Table 3 can be adequately explained by the interaction of the two effects, mass loss and an abundance gradient, on the evolution of the most massive stars. In the next section, we shall propose that the evolution of the most massive stars (> 50–60 $\mathfrak{M}_\odot$) is primarily determined by mass loss. For example, stars with initial masses greater than 60 $M_\odot$ probably do not ever become M supergiants because of large mass loss. This accounts for the very large B/R ratios at luminosities greater than $M_{bol} \approx -8.5$ to -9.5 mag. Beginning at approximately this luminosity interval, the less luminous hot stars do evolve across the H-R diagram to become M supergiants. The B/R ratio is then smaller at the lower luminosities where mass loss plays a less important role. Other effects, such as neutrino losses in the later stages (Stothers 1969; 1972), may also become more important.

Within each luminosity interval, the B/R dependence on galactocentric distance is attributed to the composition gradient, but it is also apparent from Table 3 that the B/R gradient is dependent on the luminosity interval used. At the lower luminosities ($M_{bol} \geq -8.5$ mag), where the effects of mass loss are probably less important, the evidence for a gradient in B/R is less strong. It is probable that the chemical abundance and the mass-loss rates are interrelated, so that where the heavy elements are more abundant, the mass-loss rates are higher and the B/R ratio is correspondingly larger, particularly for the most luminous stars.

If the ratio of blue-to-red stars is used to determine an abundance gradient in a galaxy, the results may depend strongly on the brightness of the stars being used. For a very distant galaxy, only the most luminous stars would be resolved, and one might conclude that a very steep abundance gradient exists where actually one is also observing the effects of mass loss on the B/R ratio. The B/R gradient derived from the less luminous supergiants is probably a better indicator of the abundance gradient.

V. DISCUSSION—EVOLUTION AND MASS LOSS

It has become apparent in recent years that significant mass loss occurs in both the blue and red supergiants and may have a major effect on the evolution of the most massive stars (Hutchings 1976; Conti 1976; de Loore, De Grève, and Lamers 1977; Chiosi, Nasi, and Sreenivasan 1978; Dearborn *et al.* 1978). Mass loss will therefore play an important role in our attempt to explain the basic appearance of the "theoretical" H-R diagrams, particularly the upper luminosity boundary, for the galactic and LMC supergiants. The two most outstanding features are (1) decreasing luminosity with decreasing temperature for the hottest stars and (2) an apparent upper limit to the luminosities near $M_{bol} \approx -9.5$ to -10 mag for supergiants later than spectral type B5.

In Figures 3 and 4 we have shown the initial phases (core H burning to shell H burning) from the recent evolutionary tracks with mass loss by Chiosi *et al.* Their models have been calculated for three different mass loss rates, and their intermediate set ($\alpha = 0.83$) has been used here. These tracks provide an estimate of the initial masses of the stars discussed in this paper.

Chiosi *et al.* emphasize, with these models, that although a star may begin with 60 $\mathfrak{M}_\odot$, for example, by the time it reaches the core H-exhaustion phase ($\log T_e = 4.48$), its mass will have decreased to perhaps 45 $\mathfrak{M}_\odot$, and mass loss still continues along the remainder of the evolutionary track. These tracks suggest that the later-type supergiants near the upper luminosity boundary ($M_{\text{bol}} \approx -9.5$ mag) have initial masses near 50–60 $\mathfrak{M}_\odot$, although by the time they become M supergiants their masses are probably more like 25–30 $\mathfrak{M}_\odot$.

From these H-R diagrams it is apparent that the evolution of stars with initial masses greater than 60 $\mathfrak{M}_\odot$ are of special interest. The observational data show that these very massive stars have few if any cooler counterparts, supergiants later than early B-type, and that their upper luminosity boundary decreases with decreasing temperature. It is particularly interesting to note that in both the Milky Way and the LMC, there are several stars that lie above the 100 $\mathfrak{M}_\odot$ track. Either these stars are superluminous for their masses or had initial masses much greater than 100 $\mathfrak{M}_\odot$.

One possible and rather straightforward explanation for the features of the H-R diagrams is rapid evolution in the later stages (postcore H exhaustion) which removes the cooler stars. The evolutionary tracks by Chiosi *et al.* for stars greater than 20 $\mathfrak{M}_\odot$ do not even extend to the region of the M supergiants, but instead terminate at warmer temperatures ($\log T_e \approx 3.9$–3.8) with core He burning. The time scales in shell H burning and core He burning are very short compared with the earlier stages. These results may support the rapid evolution suggestion; however, rapid evolution alone cannot account for the observations, the fairly tight luminosity limit near $M_{\text{bol}} = -9.5$ mag (initial mass ~ 50–60 $\mathfrak{M}_\odot$) for the cooler supergiants, and why the apparent luminosity boundary for the hottest stars crosses the tracks well into the computed shell H-burning phase. De Loore *et al.* also tried to explain the observed upper luminosity limit for the hot supergiants reported by Hutchings (1976) and concluded that it cannot be explained by a speeding up of the evolution in the shell H-burning phase.

In a series of papers Stothers (1969, 1972) suggested that neutrino processes in the later phases also speed up the evolution of the most luminous M supergiants, rapidly removing them from this region of the H-R diagram. This process was offered as a possible explanation for the B/R variation with luminosity (Stothers 1969; Humphreys 1970). However, these conservative evolutionary tracks (without mass loss) calculated by Stothers and his collaborators do not provide an explanation for the rather tight upper luminosity limit that applies not just to the M stars, but to all the supergiants from late B-type to M, nor for the upper luminosity limit of the hotter supergiants.

Eta Car and related objects shown in Figure 3 and 4, such as P Cyg, and S Dor in the LMC, may provide the clues to understanding both the upper luminosity dependence on temperature for the hot supergiants and the luminosity boundary for the cooler supergiants. Eta Car, one of the most luminous known stars, is especially interesting and suggestive. From infrared observations of its surrounding dust shell (Gehrz *et al.* 1973), we know that this object has $M_{\text{bol}} \approx -12$ mag, and there are two different ways of estimating that the star's effective temperature is near 30,000 K (see Davidson 1971 and references therein). From independent arguments involving the observed hydrogen and [Fe II] emission lines, one can estimate the effective total reddening $E_{B-V} \approx 1.1$ mag. After correction for this reddening, the observed visual wavelength continuum has a Rayleigh-Jeans slope; so we can infer the presence of a central star with a fairly well-defined, hot surface. Supposing that the emission lines originate largely in a compact H II region within the dust shell, and comparing the line intensities with the visual continuum, we can use a Zanstra-style argument to estimate $T_e \approx 30{,}000$ K (or perhaps 35,000 K). It is also possible to use the total luminosity in conjunction with the visual brightness to obtain practically the same result. Thus η Car appears to be more luminous than P Cyg and slightly hotter (see Fig. 3). These two stars exemplify the maximum feasible luminosities for $T_e \approx 20{,}000$ to 35,000 K. P Cyg must be flirting with catastrophe (it pulsates and has an extremely strong stellar wind, 3.5×10^{-4} $M_\odot$ yr^{-1} according to Hutchings 1976 or 3×10^{-5} $M_\odot$ yr^{-1} according to van Blerkom 1978), while η Car has actually been observed to undergo a catastrophe.

The halo of inhomogeneous, dusty gas around η Car was ejected from the central star in several explosive events during the past two centuries, circa 1890, 1840, and earlier (Ringuelet 1958; Walborn, Blanco, and Thackeray 1978). The observed emission lines, which are produced within this halo, further indicate that the mass loss is unsteady. To see this, consider the most plausible origins for these lines: (1) in a continuous stellar wind, (2) in a compact photoionized region in the "halo," and (3) in largely un-ionized gas, where radiative excitation may produce lines of Fe II and [Fe II]. If most of the line emission originates in (1) it should be characteristic of electron densities above 10^8 cm^{-3}, but the observed forbidden lines ([Fe II], [N II], [S II]) indicate densities between 10^5 and 10^8 cm^{-3}. Regions (2) and (3) are probably the most important. Much of the hydrogen emission must be recombination radiation from region (2), and the central object probably has a starlike spectrum capable of causing photoionization, so the continuous wind cannot be *extremely* strong. This is important because it means that the average mass-loss rate of η Car has lately been dominated by catastrophic events.

Both from the emission lines and from the thickness of the dusty shell (see Davidson and Ruiz 1975), it appears that the halo of η Car has a mass of the order of 0.1 $\mathfrak{M}_\odot$ or more, ejected during the past two centuries. At this rate ($\approx 10^{-3}$ $\mathfrak{M}_\odot$ yr^{-1}) the star would be greatly diminished within 10^5 yr. Admittedly, the *average* rate, over long periods of time, may be less;

TABLE 4

LATE-TYPE SUPERGIANTS WITH LARGE INFRARED EXCESS RADIATION

Star	Sp. Type	T_e (K)	log T_e	M_{bol} (mag)	Distance (kpc)	Remark
IRC +10420..........	F8–G0 Ia	6000	3.78	-9.2 to -10.2	~4–6	
VX Sgr..............	M4e Ia–M8	2950	3.47	-9.5 to -10	~1.6	Sgr OB1
VY CMa.............	M5e Ia	2800	3.45	-9.5	~1.5	NGC 2362

but if so, why is η Car so unstable now, and how will it recover from its instability? Note that there are only a few other stars of comparable mass in the vicinity of η Car—assuming that η Car has a mass commensurate with its luminosity.

It is not certain that the mass loss of a star like η Car is driven only by radiation pressure. It is not even certain that it is not on the main sequence! A very massive main-sequence star should pulsate for interior reasons (see Schwarzschild and Härm 1959), and the resulting pulsations should cause ejection of material. Appenzeller (1970) proposed that this can lead to the formation of an extended opaque envelope, and as Davidson (1971) remarked, the "effective temperature" of η Car may refer to such an envelope. Hoyle, Solomon, and Woolf (1973) later enlarged upon this idea. If this is correct, then one must ask why the O3 stars are so different from η Car. The observed high temperatures in hot stellar winds suggest that simple radiative acceleration is not the only cause of such winds (Cassinelli, Olson, and Stalio 1978 and references therein). The case of η Car further suggests that mass loss is very rapid and unsteady above a certain luminosity, for $T_e \approx 30{,}000$ K.

One idea that might explain the lack of very high luminosity later-type supergiants ($T_e < 15{,}000$ K, $M_{\text{bol}} \leq -10$ mag) is that discussed by Hoyle, Solomon, and Woolf (1973). They suggest that since the most massive stars ($>60\,\mathfrak{M}_\odot$) are pulsationally unstable on the main sequence as mentioned above, they may lose enough mass to become surrounded by circumstellar dust and would then be observed in the infrared. If this idea is correct, evolved cooler counterparts of the most luminous blue stars may exist in the infrared, and η Car may be an example of a star that could be the hot predecessor of such an object. What will become of η Car as the central star continues to evolve? Do cooler counterparts of η Car and related objects exist?

To investigate this question three well-known infrared sources with large circumstellar dust shells and optical spectra like very luminous late-type supergiants were examined—IRC+10420 (Humphreys *et al.* 1973), VX Sgr (Humphreys and Lockwood 1972; Humphreys 1974), and VY CMa (Herbig 1969; Humphreys 1975*a*). The observational data are summarized in Table 4. The distances to all three are uncertain to some extent, but the best available estimates yield luminosities also near $M_{\text{bol}} \approx -9.5$ to -10 mag (see Fig. 3). Apparently these three stars do not qualify as the superluminous cool descendents of the most massive hot stars. If such objects exist among known infrared sources, they have not yet been recognized as supergiants.

Several stars in the LMC with properties similar to η Car and P Cyg have also been added to Figure 4. The observational parameters for all of these stars are summarized in Table 5. Except for η Car, the effective temperatures have been derived from the observed spectral types, and the appropriate bolometric corrections were applied to determine the luminosities. As mentioned above, these effective temperatures may only apply to an extended envelope or shell, and the central star may actually be hotter. The A-type spectrum observed for S Dor probably does arise from a shell, and the central star is much warmer. Its unreddened position on the two-color diagram (Humphreys 1978*b*) certainly suggests a hotter object.

A number of very luminous blue variables, spectroscopically similar to η Car and P Cyg, have now been recognized in other nearby galaxies (Humphreys 1975*b*, 1978*b*). As a class these stars are known as the S Dor-type variables and include the Hubble-Sandage

TABLE 5

PECULIAR EMISSION LINE STARS OF HIGH LUMINOSITY

Star	Sp. Type	T_e (K)	log T_e	M_{bol} (mag)	Distance (kpc)	Remark
η Car........................	pec	30000	4.48	-11.5 to -12	≈2.5	Carina nebula
P Cyg.........................	Bleq	21000	4.32	-10.7	1.8	Cyg OB1
S Dor.........................	Aeq	9400	3.97	-10.4 (-11 max)	52.5	LMC
R71..........................	B2.5 Iep	15500	4.19	-9.9 (-11.6 max)	52.5	LMC (HD 269006)
R81..........................	B2.5 Ieq	15500	4.19	-10.3	52.5	LMC (HD 269128)

variables in M31 and M33. Infrared radiation has been detected from four of these stars, and two show evidence for circumstellar dust shells (Humphreys and Warner 1978). Var A in M33 (Hubble and Sandage 1953), one of the stars with a circumstellar shell, and Var 12 in NGC 2403 (Tammann and Sandage 1968) have light curves remarkably like that of η Car, and all of these stars show evidence for large pulsational instability. The recognition of several of these stars in different galaxies is part of the increasing evidence that the phenomena observed in η Car and P Cyg may be much more prevalent among the massive stars than previously believed.

It has already been mentioned that main-sequence stars above 60 $\mathfrak{M}_\odot$ are pulsationally unstable in their interiors. This is very close to the initial mass (50–60 $\mathfrak{M}_\odot$) corresponding to the observed luminosity boundary near $M_{\rm bol} \approx -9.5$ to -10 mag. Stars with initial masses greater than 60 $\mathfrak{M}_\odot$ very likely cannot evolve to the region of the cooler supergiants because of the instabilities and the accompanying large mass loss discussed for η Car and P Cyg. The dependence of the luminosity limit of the hottest stars on temperature is evidence that the stability or catastrophe limit is mass related.

We are suggesting that the observed luminosity boundary (decreasing luminosity with decreasing temperature) for the hottest supergiants in our Galaxy and the Large Cloud is due to instabilities in these supermassive stars resulting in rapid mass loss which prevents further evolution to cooler temperatures. This mass loss may be unsteady and much greater, at times, than the rates favored by most authors. It is probably induced by radiation pressure in the atmospheres, or pulsational instability in the interiors, or both. The luminosity limit for the cooler supergiants ($T_e < 15{,}000$ K) probably involves the upper limit to the initial mass (40–60 $\mathfrak{M}_\odot$) at which a star can evolve across the H-R diagram to the red supergiants in a stable way. A few stars somewhat above this mass limit (Cyg OB2 no. 12 may be an example, B5 Ia$^+$, $M_{\rm bol} \approx -10.9$ mag) may evolve slightly beyond the observed luminosity boundary for the hottest stars, but the time scales are very short and the evolutionary tracks loop back to the hot star region before reaching the later-type supergiants (Chiosi *et al.*). Many of the hot stars above 60 $\mathfrak{M}_\odot$ may become Wolf-Rayet stars, subtype WN7 (Conti 1976), if the mass loss is sufficient to bring the processed nuclear material to the surface. For the most part the post-main-sequence evolution of the most massive stars may be limited by near-catastrophic mass loss.

In their efforts to explain the hot star luminosity boundary, de Loore *et al.* suggested that their evolutionary tracks would reverse and the stars would evolve to the left, to the helium main sequence, if the mass-loss rates were higher than observed. They require average rates greater than $10^{-5}\,\mathfrak{M}_\odot\,{\rm yr}^{-1}$. We have suggested that most stars greater than 60 $\mathfrak{M}_\odot$ will pass through phases of large stellar winds (P Cyg, $3.5 \times 10^{-4}\,\mathfrak{M}_\odot\,{\rm yr}^{-1}$) and/or catastrophic ejections (η Car, $\approx 10^{-3}\,\mathfrak{M}_\odot\,{\rm yr}^{-1}$) with probable periods of hundreds to thousands of years. We have only been observing these stars in detail for at most a few tens of years, so the average mass-loss rates could occasionally be much higher than are currently observed—more than sufficient to produce the effect mentioned by de Loore *et al.* In a recent review, Conti (1978) also remarked that single massive stars evolving to the Wolf-Rayet stage might undergo an episode of increased mass loss to eject the remaining hydrogen envelope.

These strong stellar winds and large mass-loss rates, accompanied by a reversal of the evolutionary tracks, are very likely the physical causes of the observed upper luminosity boundary for the galactic and LMC supergiants.

VI. SUMMARY AND CONCLUSIONS

This empirical comparison of the H-R diagrams for the Galactic and LMC supergiants shows two similar physical processes govern the evolution of the most massive stars in the two galaxies. The distribution of spectral types and luminosities are comparable in the H-R diagrams for the two galaxies. The luminosity comparisons in Tables 1 and 2 show that the stars of similar spectral types have the same luminosities, except for the A-type stars, where selection effects may be important.

The variations in the blue-to-red supergiant ratio with galactocentric distance and with luminosity, presented in Table 3, can be understood as a combination of a chemical composition gradient with distance and the effects of mass loss, particularly on the most luminous stars. The evidence for a B/R gradient with galactocentric distance is less strong when restricted to the less luminous ($M_{\rm bol} \geq -8.5$ mag) supergiants. Since the B/R variation with luminosity may be due largely to mass loss, especially at the highest luminosities ($M_{\rm bol} \leq -9.5$), the blue-to-red ratio is probably a better indicator of composition gradients when restricted to the less luminous supergiants.

The upper boundary of the supergiant luminosities in both the Milky Way and the LMC H-R diagrams can be attributed primarily to the fundamental role of mass loss on the evolution of the most massive stars. Above an initial mass of 60 $\mathfrak{M}_\odot$, stellar evolution to the right on the H-R diagram is limited by instabilities and the accompanying large-scale mass loss. It is very likely that the mass-loss rates are higher on the average than we currently observe for many of these stars. The hot supergiants in the upper left part of the "theoretical" H-R diagrams are presently undergoing or will eventually undergo periods of large stellar winds or even catastrophic mass loss like P Cyg or η Car, respectively, although the degree of these phenomena are probably mass dependent.

The observed upper bound to the luminosities of the cooler supergiants ($T_e < 15{,}000$ K) at $M_{\rm bol} \approx -9.5$ to -10 mag very likely corresponds to the upper limit to the mass ($\approx$50–60 $\mathfrak{M}_\odot$) at which a star can evolve across the H-R diagram to become an M supergiant. This provides a physical explanation for the upper limit to the luminosities of the cool supergiants which for the M supergiants translates into a visual luminosity near $M_v \approx -8$ mag.

There are several stars in both our Galaxy and the LMC which lie above the $100\,\mathfrak{M}_\odot$ track, implying initial masses much greater than $100\,\mathfrak{M}_\odot$. Of course these stars might be superluminous for their masses, but the origin and evolution of these potentially supermassive stars certainly pose some interesting theoretical problems.

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