MASSIVE STAR EVOLUTION IN NEARBY GALAXIES

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In this review I will primarily be discussing the observational data relevant to understanding the process of stellar evolution in galaxies of different types. This discussion will focus on the stellar content of the nearer galaxies; those galaxies in which the brightest individual stars are resolved and can be observed.

The most luminous stars are also the most massive stars. Because of their intrinsic brightness, they are our first probes for observational studies of stellar evolution in other galaxies. The most massive stars provide our first hints that the progress of stellar evolution may have been different in a particular galaxy.

Basically we want to know if stellar evolution as we understand it for our region of the Milky Way has produced similar massive star populations in different galaxies. In the past decade we have already learned in our own galaxy that the observed HR diagram for massive stars cannot be explained adequately by conservative, non-mass loss evolution. Phenomena such as stellar winds and mass loss alter the evolution of the most massive stars and physical processes such as turbulence and mixing in the stellar interiors may ultimately control their short but often flamboyant lives.

The study of massive star evolution in other galaxies offers many advantages. In our own Milky Way our observations are limited to a small fraction of the galaxy by interstellar dust. We are uncertain how our current ideas may be influenced by incompleteness and whether massive star evolution may differ in different regions. Observations in other galaxies will eventually permit us to determine if the rate of star formation and the initial mass function for massive stars vary with location in a galaxy and with galaxy type. How is stellar evolution influenced by environmental variations such as possible chemical composition gradients in galactic disks? I will not be able to answer these questions in this review paper, but I will show that there are great similarities among the massive star populations in different galaxies and some important differences. I will try to untangle some of the

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possible causes of the observed differences such as IMF variations and chemical composition.

1. THE HR DIAGRAM

The HR diagrams (M_V vs. spectral type or M_{Bol} vs. log T_{eff}) provide an efficient overall perspective for comparison of the massive star populations in difference galaxies. The M_{Bol} vs. log T_{eff} diagram can also be compared directly with stellar models and evolutionary tracks.

The observational data for the HR diagrams include photometry and spectral types for the individual stars. Their luminosities, corrected for interstellar extinction, are then derived from the true distance modulus of the galaxy. For this paper I have used the bolometric correction-effective temperature scale from Flower (1977) with somewhat lower temperatures for the early O-type stars from Kudritzki (1981). The extensive observational data required for hundreds of stars in a galaxy means that reasonably complete or representative HR diagrams are available for the massive star populations in only three nearby galaxies: the Milky Way and the Large and Small Magellanic Clouds.

Figure 1 is the M_{Bol} vs. log T_{eff} diagram for the solar region of our galaxy. There are 2354 luminous stars in this diagram and all are members of 91 stellar associations and young clusters (see Humphreys 1978) whose distances are reasonably known. Even though the stars are essentially restricted to a region only 6 kpc across, centered on the Sun, this diagram is representative of the stellar population in the spiral arms in the outer parts of our galaxy. The most significant feature of this HR diagram for massive stars is the observed upper envelope to their luminosities. The upper luminosity boundary declines with decreasing temperature for the hottest stars, but becomes eesentially constant for the cooler stars (<10000 K) at $M_{Bol} \simeq -9.5$ to -10 mag. There are many very luminous, hot stars with $M_{Bol} = -10$ to -11 mag but they have no cooler counterparts. The evolutionary tracks are from models with mass loss from Maeder (1981, 1983).

The HR diagram for the Large Cloud (Figure 2) looks very much like that for the luminous stars in the solar region of our galaxy, revealing very similar distributions of stellar temperatures and luminosities in the two galaxies (Humphreys and Davidson 1979). The upper envelope of stellar luminosities is the same - the decreasing luminosity with decreasing temperature for the hot stars and the upper boundary for the later-type supergiants. When making any comparisons of this type, possible incompleteness of the data and the effects of observational selection must be considered. One noticeable difference between the LMC and galactić supergiants is the greater relative number of high luminosity late B and early-A type stars in the Large Cloud. This is most likely due to observational selection.

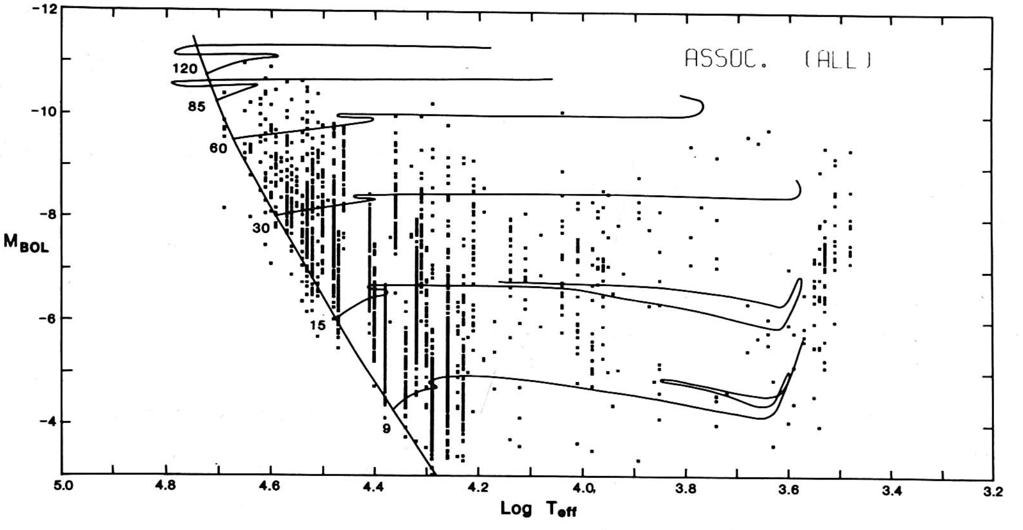

Figure 1 - The HR diagram, M_{Bol} vs. log T_{eff}, for O-type stars, supergiants, and less luminous early-type stars in 91 stellar associations and clusters in the solar region of our Galaxy.

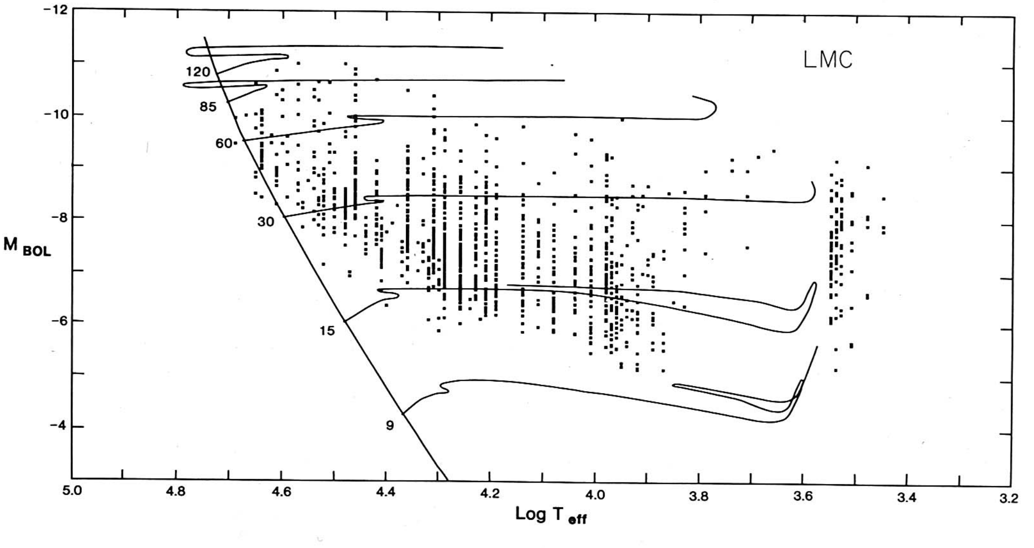

Figure 2 - The M_{Bol} vs. log T_{eff} diagram for confirmed and suspected luminous stars in the Large Magellanic Cloud.

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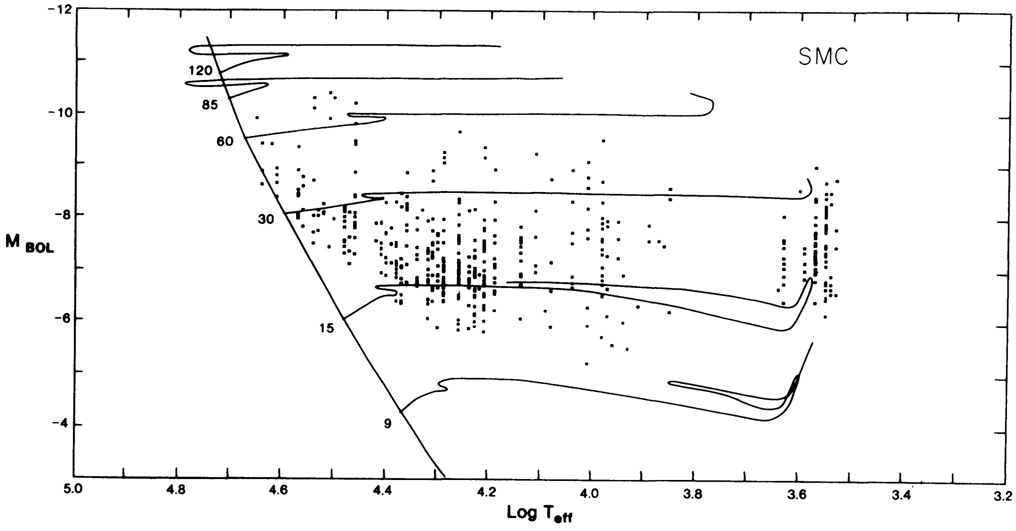

Figure 3 - The M_{Bol} vs. log T_{eff} diagram for confirmed and suspected luminous stars in the Small Magellanic Cloud.

Overall this comparison reveals very similar massive star populations and presumably similar evolutionary histories in our galaxy and the Large Cloud.

In the Small Cloud (Figure 3) there are obvious and significant differences. The hottest stars in the SMC are both less luminous and fewer in number (Humphreys 1983a). On the basis of presently available spectra and photometric data there appear to be no stars in the SMC with initial masses much above 80 $M_{\odot}$. There are no known O3 stars and only one star has been classified O4 III by Walborn (1978), but there is no photometry for it. It is shown on the HR diagram using the luminosity calibration. Conti, Garmany, Massey, and I have a program to classify the candidate O stars in the SMC to determine if the lack of highly luminous hot stars is real. Nevertheless, there are fewer of the brightest stars at all of the early spectral types in the SMC. This may be a size of sample effect in the Small Cloud which is a much smaller, less luminous galaxy, although it is also possible that star formation produces a different statistical distribution of initial masses in the SMC. It is not due to chemical composition differences.

Even with these differences in mind, the large scale features of the HR diagram for the Small Cloud are essentially the same as for the Galaxy and the Large Cloud. It is especially important to note that the upper luminosity boundary for the late-type supergiants is similar.

It is well known that the Small Cloud has a significantly lower heavy element abundance than either the solar region of our galaxy or the LMC. The effects of the lower metallicity show up very strongly in the spectral type distribution of the M supergiants in the Small Cloud. Histograms of the M supergiant spectral types for our solar region, the LMC and SMC (Figure 2 in Humphreys 1979a and Figure 1 in Elias et al. 1983) show a shift to earlier spectral types from our galaxy to the LMC and SMC. This is most likely due to the shift of the Hayashi track, the nearly vertical slope of the red giant branch, to warmer temperatures with lower metallicity. As the heavy element abundance decreases the surface temperature increases because of the lowered opacity. This effect is also observed for the red giant branches of globular clusters, and will very likely explain the Blanco/McCarthy (Blanco, McCarthy, and Blanco 1980) results for the ratio of M giants to carbon stars between our galaxy and the Clouds. If the M giants have also shifted to earlier spectral types then the early M giants should be searched for in the Clouds and compared with the carbon star population.

Another consequence of the lower metallicity in the SMC is smaller mass loss rates. Hutchings (1980, 1982) has found from IUE observations of hot supergiants in the Magellanic Clouds that the stellar wind phenomena are either lacking or very weak in the SMC stars, and while stronger in the LMC stars, they are weaker than in galactic stars. He concludes that the mass loss rates may be two or more times lower than in their galactic equivalents. This is attributed to the lower metal abundances. Interestingly recent infrared observations at 10μm by Elias, Frogel, and Humphreys (1983) of the M supergiants in the Clouds, reveal that the strength of the 10μm circumstellar silicate feature depends on metallicity. The 10μm excess is very weak or nonexistent in the SMC M supergiants. It is somewhat larger in the LMC red supergiants, but smaller than for the galactic M supergiants of the same type. This may be due either to lower mass loss rates or less dust formation around the Cloud M supergiants. These results may be important for evolutionary models for the Cloud stars because as discussed later mass loss may influence massive star evolution.

A few evolutionary tracks for massive stars have been computed with the chemical abundances of the LMC (Maeder 1980, Brunish and Truran 1982b) and SMC (Hellings and Vanbeveren 1981, Brunish and Truran 1982b). The principal difference is that the models are bluer and slightly more luminous at comparable evolutionary stages.

Our knowledge of massive star evolution in the more distant members of the Local Group is more limited. For observational reasons only the visually brightest stars have been observed, so we are lacking information on the individual hottest, most luminous stars. We are naturally very interested in stellar evolution in our two neighboring spirals M31 and M33.

We know very little about the stellar content of M31. Because of its large size, high tilt angle and tightly wound arms there are no extensive surveys for the blue and red stars in the most massive galaxy in our Local Group. Our information is essentially limited to Baade's Field IV (Baade and Swope 1963), one of four fields in M31 selected by Baade along the major axis south of the nucleus. It is the only field for which a color-magnitude diagram exists, and I have taken spectra of several of the brightest stars in this field. Figure 4 in Humphreys (1979b) shows the color-magnitude diagram for the four associations in Field IV. Field IV is in the outermost part of M31, 18.5 kpc from the nucleus, which when scaled to the Milky Way corresponds to about 14 kpc from the center. The color-magnitude diagrams, ages and dimensions of the associations and even the blue-to-red supergiant ratio are all very similar to what we observe in the spiral features in the outer parts of our galaxy. The evolution of the Population I members of M31 is presumably similar to that in our solar region, although the results apply to only one small region in one spiral arm. Detailed studies in other regions of M31 are definitely needed.

M33 is a much easier galaxy to study for this purpose because of its more open spiral arms and nearly face-on appearance. Consequently, Sandage and I (Humphreys and Sandage 1980) completed a survey for its brightest stars, and spectra have been taken (Humphreys 1980b) of some of the visually brightest blue and red supergiants. We also identified 143 stellar associations. Figures 18 and 19 in HS show the color-magnitude diagrams for the stars inside and outside the associations. There are clear differences; the visually brightest blue stars inside the association boundaries are more than two magnitudes brighter than those outside the stellar groups. Nevertheless, it is also clear that non-association OB stars exist as in our galaxy. Color-magnitude diagrams were also measured for a few of the individual associations and ages were estimated from the main sequence turnoff. All six associations have essentially the same age of $\simeq 5 \times 10^6$ yrs.

The M_{Bol} vs. log T_{eff} diagram has been determined for the stars in M33 with spectra (Figure 4 in Humphreys 1980b). The lack of hot stars on the diagram is because only the visually brightest stars were observed. Comparison with the observed color-magnitude diagram shows that many candidate OB stars are present. By analogy with our galaxy we would expect the brightest O stars to appear at $M_V \simeq -7$ mag, and they do in M33. Most of these stars will occupy the region between $M_{Bol} = -9$ mag to -11 mag. There is one star with a spectrum as early as B0 with a total luminosity $M_{Bol} \simeq -11$ mag and an initial mass near 100 $M_\odot$. Using the HS stellar content survey, Berkhuijsen (1982) finds similar IMF's for M33 and the Galaxy. The fraction of high mass stars is similar in the two galaxies, but the rate of star formation per unit HI mass is smaller in M33.

The upper luminosity boundary based on the HR diagrams for our solar region and the LMC is also appropriate for M33. On the basis of this first look at the brightest stars in M33 there is no reason to suspect any significant differences in the evolution of the Population I stars in our galaxy, the Large Cloud and in M33.

The brightest stars have also been observed in the two dwarf irregular galaxies NGC 6822 and IC 1613 (see Figures 3 and 4 in Humphreys 1980a). In both galaxies there are confirmed supergiants with initial masses near 80 $M_{\odot}$, but very massive stars near 100 $M_{\odot}$ appear to be missing as in the SMC. Again comparison with the observed HR diagrams show that there are candidate OB stars in each galaxy, but the brightest candidates appear to be visually less luminous than in the spirals and the LMC ($M_V \simeq -6.5$ in NGC 6822 and IC 1613). Therefore we do not expect any stars much more massive than 80 $M_{\odot}$ in these two galaxies. In contrast the red supergiants in both these small galaxies have upper luminosities comparable to those in the more luminous galaxies. Interestingly, in IC 1613 there are no known M supergiants classified later than M1 similar to the SMC, but in NGC 6822 I have recently classified one as M3-M4. These results correlate with the known metallicities of the two galaxies. IC 1613 has lower metallicity even than the SMC (Davidson and Kinman 1982) while NGC 6822 is intermediate between the LMC and SMC in heavy element abundances (Pagel and Edmonds 1981). IC 1613 also has a different luminosity function (Lequeux et al. 1980) from the other dwarf irregulars (SMC and NGC 6822) which means either a low star formation rate or a very different IMF (Hoessel et al. 1983).

Among the six Local Group galaxies for which M_{Bol} vs. log T_{eff} diagrams are available, the primary difference is that the smaller galaxies have fewer of the most luminous, hot stars. Otherwise, the HR diagrams for each galaxy show the same upper envelope of declining luminosity with temperature for the hot stars and the upper luminosity limit for the cool supergiants.

Observational HR diagrams (M_V vs. color) and photometry of the brightest stars have recently been observed for a few of the even smaller, less luminous dwarf irregulars in our Local Group; Sextans A (Sandage and Carlson 1982, Hoessel, Schommer, and Danileson 1983), Pegasus (Hoessel and Mould 1982, Christian and Tully 1983), GR 8 (Hoessel and Danielson 1983) and LGS 3 (Christian and Tully 1983). Hoessel and his associates conclude that the luminosity function for Sextans A is similar to that for our galaxy and the LMC, that recent star formation (>15 $M_{\odot}$) in Pegasus has been very subdued, and that GR 8, the lowest luminosity galaxy studied, has a flat luminosity function which may mean an unusual IMF. Using the distances adopted by Hoessel, the visual luminosities for both the brightest blue and red stars show a sharp decline among these three galaxies.

The dependence of the visual luminosity of the brightest blue star on galaxy luminosity is well known (Sandage and Tammann 1974, Sandage and Tammann 1982, Figure 1; Humphreys 1983b, Figure 1). The visually brightest stars are all late B or A-type supergiants. As we have already seen, the most massive, most luminous stars in the fainter, smaller galaxies are both fainter and fewer in number. As their numbers decrease in a galaxy, the probability of finding A-type supergiants at a certain luminosity should also decrease. When there are fewer of the most massive star progenitors, the visually brightest star should be less

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luminous; consequently, there should be a similar relation between M_{Bol} for the most luminous stars and galaxy luminosity (Figure 2 in Humphreys 1983b). This correlation for the most luminous stars shows that the relation for the visually brightest stars is due to differences in the massive star populations (>50-60 $M_\odot$). It is not caused by metallicity differences, but may be due to statistical effects because of smaller population samples in smaller galaxies or possibly to real IMF variations. Very likely both play a role.

The situation for the brightest red supergiants is very different. We have already emphasized the observed upper limit to the luminosities of the M supergiants. Figure 4 in Humphreys (1983b) shows the visual luminosities for the brightest M supergiants in six Local Group galaxies covering a range of nearly six magnitudes in galaxy luminosity. This very tight upper limit is not fortuitous. It is a consequence of massive star evolution discussed at the end of this paper.

2. THE INITIAL MASS FUNCTION AND BLUE TO RED SUPERGIANT RATIOS

Variations in the observed luminosity function and the initial mass function have been mentioned above as possible causes of some of the observed differences among the massive star populations in different galaxies. Lequeux and his associates (1979a,b, 1980, Vangioni-Flamm et al. 1980) have made several studies of this type, and conclude that there are real variations in the rate of massive star formation per unit gas mass from galaxy to galaxy with some tendency for it to be smaller in less evolved galaxies. They also found no reason to suspect that the IMF significantly differs in any galaxy from that of the solar region. Recently, however, Garmany, Conti, and Chiosi (1982) reported a significant variation in the slope of the IMF for O-type stars in our galaxy with galactocentric distance. Their data set was restricted to O-type stars and was volume-limited to 2.5 kpc from the Sun.

Their result is sufficiently important and interesting that it is worth repeating with a more complete data set. We compiled a list of all known supergiants, O-type stars and less luminous B-type stars from the catalogues of stars with Mk types by Buscombe (Kennedy and Buscombe 1974, Buscombe 1977, 1980, 1981). Our list includes 5044 stars; 2354 of these are in 91 stellar associations and clusters, and the sample is complete to 3 kpc from the Sun for which there are 4058 stars. Our IMF is defined as the number of stars per kpc^2 per year per log mass ($M_\odot$) and is determined for mass intervals defined by Maeder's evolutionary tracks (see Figure 1).

The IMF for the massive stars within 3 kpc is shown in Figure 4. The IMF for >30 $M_\odot$ clearly deviates from the Miller-Scalo IMF (Miller and Scalo 1979) for the solar region ($r < 1$ kpc). For the least squares solution the points were weighted by the number of stars in each mass interval. The data is incomplete for the 9-15 $M_\odot$ interval and likely for the 15-30 $M_\odot$ interval, as well. Also notice that the data point is very low for the highest mass interval. The IMF calculation has been repeated for the same data set divided between inside and outside the solar circle (Figure 4). The significant difference with galactocentric distance (Garmany et al. 1982) is confirmed. The IMF interior to the sun's orbit is flatter meaning that more of the most massive stars are formed. It is too early to conclude that there is an IMF gradient in the galactic disk, because these results depend strongly on the stars in a few associations.

For comparison we have also determined the IMF for the Magellanic Clouds. There are nearly 1300 stars in the Large Cloud and 500 stars in the Small Cloud for which spectral types or two-color photometry is available. The results are shown in Figure 4. The IMF's for the LMC and very likely the SMC, as well, are both more like the outer galactic region and their slopes are consistent with the Miller-Scalo IMF for the solar neighborhood. Because there are no stars above 80 $M_\odot$ in the SMC and the lower mass intervals are incomplete, this solution for the SMC is based only on two points. The results for the IMF's are summarized in Table 1.

Table 1
The Initial Mass Function for Massive Stars

Milky Way ($M \geq 15\ M_\odot$)

$r \leq 3$ kpc $\psi = 1.2 \times 10^{-3} (M/M_\odot)^{-1.38}$

Inner $R \Theta 10$ kpc

$\psi = 3 \times 10^{-4} (M/M_\odot)^{-0.96}$

Outer $R \geq 10$ kpc

$\psi = 7.2 \times 10^{-3} (M/M_\odot)^{-1.98}$

LMC ($M \geq 15\ M_\odot$)

$\psi = 5.5 \times 10^{-3} (M/M_\odot)^{-1.90}$

SMC ($M \geq 30\ M_\odot$)

$\psi = 3.0 \times 10^{-3} (M/M_\odot)^{-1.50}$

The IMF's for the Large and Small Cloud and the outer parts of the solar region are essentially the same. Why then is the inner part of the solar region so different? Is there an IMF gradient? This question can best be answered by observations of luminous stars in other spiral galaxies. Interestingly, all four regions have very few if any stars in the highest mass interval. Of course these are small number statistics, but in addition, it is very difficult to produce the most massive stars. Perhaps the shape of the IMF for massive stars may be more accurately represented by a power law plus an exponential.

The IMF for the SMC is especially important because of suggestions that the IMF's for some dwarf irregulars may be different. This IMF

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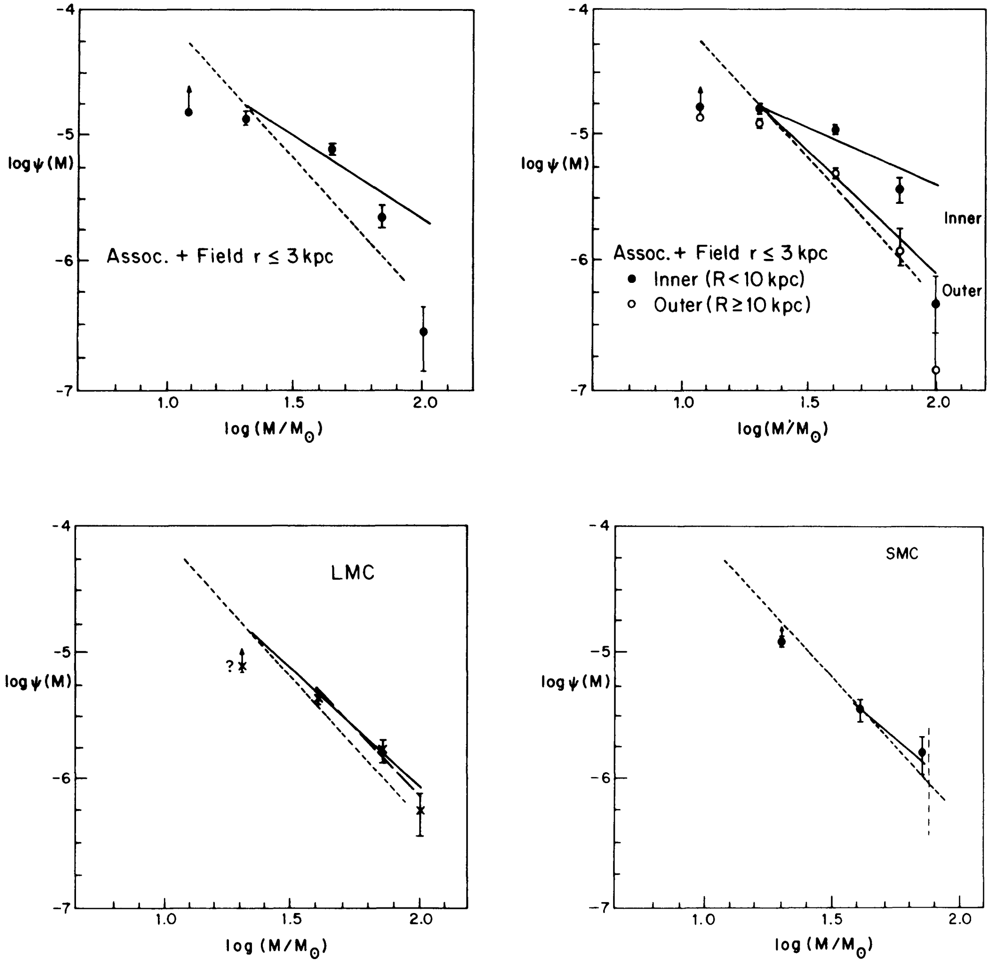

Figure 4 - The initial mass function $\psi(M)$, the number of stars $kpc^{-2}\ yr^{-1}\ (\log M/M_{\odot})^{-1}$ for the solar region ($r \leq 3$ kpc), the inner and outer sections of the solar region, the LMC, and the SMC. The solid lines are the least squares solutions to the observed points. The dashed line is the Miller-Scalo IMF for the solar neighborhood ($r < 1$ kpc).

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would predict 5 stars between 85 and 120 $M_\odot$ in the SMC, but none are observed. This difference is significant with a probability of less than 1%, but the same is true for the galactic and LMC IMF's, because of the sharp turn down in the observed numbers of the most massive stars in all three galaxies. Final conclusions on the IMF for the Small Cloud hinge on observations in progress.

Blue to red supergiant ratios are often used as diagnostics to test models of stellar evolution, and counts of blue and red stars in other galaxies are considered possible indicators of metallicity variations. But interpretation of the B/R ratio is not entirely straightforward. They may be affected by other factors such as variations in the IMF. A much more complete data set is now available for the massive stars in our galaxy and the Clouds. Their blue to red ratios are summarized in Table 2.

Table 2
The Blue to Red Supergiant Ratio in the Galaxy and the Magellanic Clouds

M_{Bol} (mag)	Mass Range ($M_\odot$)	Milky Way (8-10 kpc)	Milky Way (10-12 kpc)	LMC	SMC
-10.5 to -11.5	100-200	-	-	-	-
- 9.5 to -10.5	60-85	-	-	-	-
- 8.5 to - 9.5	40-60	46	22	11	4.6
- 7.5 to - 8.5	25-40	30	20	7(10)	3.8
- 6.5 to - 7.5	15-25	15(31)	7(16)	11(13)	7(6)

The B/R ratio shows two phenomena: 1) little or no variation with luminosity when the data is corrected for incompleteness, and 2) a gradient with distance in our galaxy and between us and the Magellanic Clouds which is attributed to metallicity variations. Comparison with the expected ratios from evolutionary tracks is not especially good, but models with moderate mass loss give much better agreement with the observed ratios than do the older, non-mass loss calculations. Suggestions (Brunish and Truran 1982a,b) that the number of red supergiants have been overestimated by contamination from intermediate mass stars are incorrect. Red intermediate mass stars near $M_{Bol} \simeq -7$ mag are at the tip of the assymptotic giant branch. They are very rare; they are long period variables and have very late spectral types. They will not be mistaken for M supergiants. The smaller B/R ratios in the LMC and SMC imply that the lifetimes of the M supergiants are longer in these galaxies with lower metallicity and presumably lower mass loss rates. Unfortunately the models by Brunish and Truran (1982b) for Magellanic Cloud abundances predict the opposite.

The gradient in the blue to red ratio is dependent on the luminosity interval used. At the lower luminosities ($M_{Bol} \leq -8.5$ mag) where the effects of possible IMF variations is less important, the B/R gradient is less steep. The B/R ratios in the $M_{Bol} \simeq -6.5$ to -8.5 mag interval are probably the best indicators of the metallicity gradient between our galaxy and the Clouds. Unfortunately in other galaxies we usually do not know M_{Bol} for the stars, but instead counts of blue and red stars are available only to some limiting visual magnitude (M_V). If the B/R ratio is used to infer an abundance gradient in a galaxy, the results will depend strongly on the brightness of the stars being used. The effects of metallicity and IMF variations will be mixed. For a distant galaxy, only the visually brightest stars would be resolved, and one might conclude that a steep abundance gradient exists when one may also be observing the effects of IMF differences. I do not recommend use of B/R ratios as probes of stellar evolution in a galaxy unless additional information is available.

3. EVOLUTION OF THE MOST MASSIVE STARS

How well do the current models for massive star evolution explain the observed upper envelope of luminosities for normal stars on the HR diagram? Figure 5 is a schematic HR diagram for the most massive stars ($L > 5 \times 10\ L_\odot$, $M_{Bol} \simeq -9$ mag) based on the composite of the M_{Bol} vs. log T_{eff} diagrams for the six Local Group galaxies. The empirical upper boundary of stellar luminosities for normal stars shows the envelope of declining luminosity with decreasing temperature for the hottest stars and the upper limit to the luminosities of the cooler supergiants observed in all six galaxies. The temperature dependence of the luminosity boundary suggests that this defines a critical location on the HR diagram for massive star evolution. Stars with initial masses less than 60 $M_\odot$ can apparently evolve all the way across the diagram to the red supergiant region. Why then are the hottest, most luminous stars restricted to the left side of the HR diagram? What prevents a very massive star from evolving into a highly luminous cooler supergiant?

A group of very luminous, hot stars with peculiar spectra that are also known to be unstable and undergoing unsteady mass loss provide important clues to the evolution of the most massive stars and their eventual fate. The famous star η Car is probably the most massive and most extreme member of this group. These stars have spectra with emission lines of hydrogen, HeI, HeII, FeII and [FeII], often with P Cygni profiles. Many of them are also known irregular variables with extended maxima and minima of several years. Their observed mass loss rates range from 10^{-5} to 10^{-3} $M_\odot$/yr with a possible high of 10^{-1} $M_\odot$/yr for η Car. Other well known examples are P Cyg and S Dor. As a group they are known as the S Dor variables and as the Hubble-Sandage variables in M31 and M33. Many of these stars are known in our galaxy, the Large Cloud and in M31 and M33; however, only two are recognized in the Small Cloud, and there are no candidates in IC 1613 and NGC 6822. This is a consequence of the significant difference in the distribution of stellar masses between the less massive galaxies and the spirals and LMC.

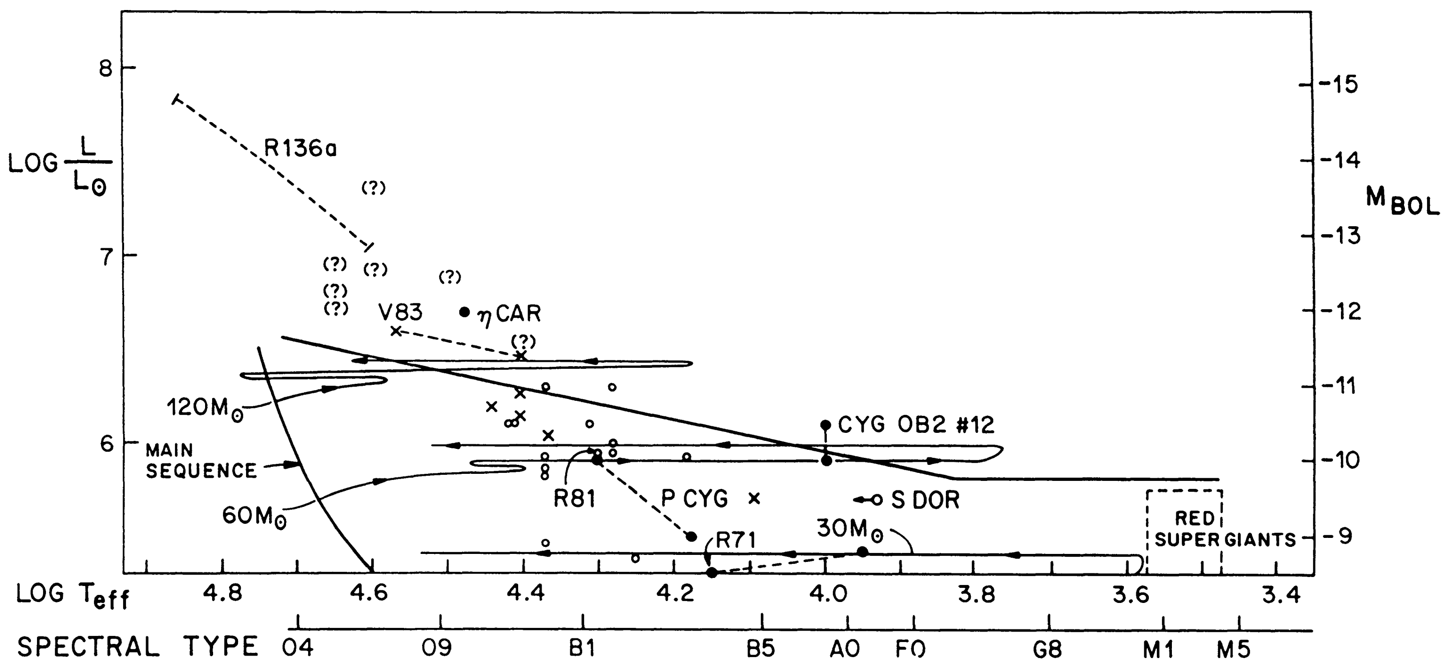

Figure 5 - Schematic HR diagram for the most luminous stars ($L \geq 5 \times 10^5\ L_\odot$). The empirical upper luminosity boundary for normal stars is shown by a solid line. The location of the S Dor or Hubble-Sandage variables are shown and some of the individual stars are indicated. The possible location of R136a and the suspected supermassive Wolf-Rayet stars in M33 (?) are also shown. The evolutionary tracks for 30, 60 and 120 $M_\odot$ are from Maeder (1981, 1983).

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Information on temperatures, luminosities and mass loss rates have recently been determined for many of these stars primarily as a result of ultraviolet spectroscopy with the IUE (references are given in a review by Humphreys 1984). Their location on the HR diagram is shown in Figure 5. η Car, P Cyg, and some of the H-S variables (Var A and Var 83 in M33), thought to suffer spectacular episodes of mass ejection, are near or even above the critical upper luminosity boundary. Walborn (1983) and Stahl et al. (1983) have just reported that another of this class, R127 in the LMC, is presently undergoing an outburst.

These stars inspired us (Humphreys and Davidson 1979) to propose a scenario in which the most massive stars are prevented from evolution to cooler temperatures by an instability limit accompanied by sudden mass loss. (The line drawn in Figure 5 is an empirical envelope for 'normal' stars. The true instability boundary may be above this; perhaps η Car marks its location.) A star may evolve to this critical limit several times (Davidson 1983). The sudden instability may cause an η Car-like outburst which ejects a fraction of a percent of the star's mass. This moves the star slightly away from the critical line and temporarily relieves the instability, but then in a few centuries or decades the star evolves back to the limit and suffers another outburst; and so on until it is reduced to a Wolf-Rayet star, unless it becomes a supernova first.

This sequence of events is supported by data for η Car. We know that it has undergone more than one episode of large mass ejection (Walborn et al. 1978, Ringuelet 1958). Davidson, Walborn, and Gull (1982) have found that η Car is nitrogen-rich but carbon and oxygen-poor; thus confirming that it is indeed an evolved very massive star. Many of the S Dor or H-S variables are also known to be nitrogen-rich (Shore and Sanduleak 1984, Walborn 1982). This suggests that these hot, luminous and often unstable stars are on their way to becoming Wolf-Rayet stars of the late WN type. Several years ago, Conti (1975) proposed a scenario for the production of WR stars progressing from O to Of type stars to late WN stars and eventually to classical WN and WC stars, but the observed mass loss rates for the O stars were insufficient (see review by Maeder 1981). If we add the H-S variable stage, with its episodes of enhanced mass loss, a possible evolutionary sequence for stars $\gtrsim 60\ M_\odot$ is O → Of → HS var → WN7-9.

The exact cause of the proposed instability is not known, but there are several alternatives (Stothers and Chin 1983). An internal vibrational instability is a possibility, but more likely surface radiation pressure is involved, because many of these stars are near the Eddington limit for their temperatures at a given L/M ratio.

Maeder (1983) has recently proposed a very promising explanation for the instability boundary - the de Jager limit (1980). A deep external convective zone develops in the outer layers of very massive stars as they evolve to cooler temperatures and gives rise to a turbulent pressure gradient which can oppose gravity if the star's luminosity is sufficiently high. The de Jager limit is reached when the turbulent pressure gradient equals the acceleration due to gravity. The instability occurs when turbulence exceeds gravity. The de Jager limit halts further evolution to the right and is accompanied by enhanced mass loss. Maeder's models show that after the enhanced mass ejection the star evolves blueward on short time scales at essentially constant luminosity but its visual luminosity decreases. This corresponds to the observations of R71 and S Dor (Appenzeller and Wolf 1981) between maximum and minimum and Var 83 in M33 (Humphreys et al. 1984).

The onset of the instability limit very likely corresponds to the observed boundary for the luminosities for the late-type supergiants. The enhanced mass loss at the de Jager limit increases the mass fraction occupied by the core. Previous models (Chiosi et al. 1978, Maeder (1981a) show that when the core becomes larger than a critical value the evolutionary tracks reverse to warmer temperatures. This result is independent of chemical composition in agreement with the observations for the late type supergiants. The upper luminosity limit for cool supergiants should be the same in all star forming regions, and stars with initial masses greater than $\simeq 50\ M_{\odot}$ simply do not become M supergiants.

Conspicuous in the upper left of the HR diagram in Figure 5 is R136a, the possible supermassive star in the LMC. It is shown with a plausible range of temperatures and luminosities if it is a single star (Savage et al. 1983). But R136a is definitely a binary (Innis 1927, Worley 1983, Chue and Wolfire 1983), and very likely a multiple system (Weigelt 1983) similar to NGC 3603 (Walborn 1973). These considerations will reduce the mass estimates for the primary to a few hundred solar masses. This is still a very high mass, comparable to or greater than that of η Car. The suspected supermassive Wolf-Rayet stars in M33 (Massey and Hutchings 1983) are also shown in Figure 5.

The formation of these individual very massive stars and especially the large aggregates of very massive stars represented by the η Car group (Tr 14, 15, 16) and NGC 3603 in our galaxy and the R136 complex in the LMC is an important problem for the future.

In conclusion I want to emphasize the similarities of massive star evolution in the solar region of our galaxy, in the Large Cloud, in M33, and very likely in M31 as evidenced by their HR diagrams and the properties of their brightest stars. Most of the differences we observe in the HR diagrams for the less massive irregular galaxies, specifically the Small Cloud, are most likely due to small variations at the high mass end of the IMF and to statistical effects from the smaller sample size. The lower metallicity in the SMC produces a shift to earlier spectral types in the M supergiants and smaller blue to red star ratios which may mean longer lifetimes as M supergiants. The lower metallicity may also cause lower loss rates which should be included in evolutionary tracks for the Magellanic Cloud stars.

Overall, stellar evolution has produced similar massive star populations in the spirals and Magellanic-type irregular galaxies in our Local Group. Studies of the fainter stars in less massive members of our Local Group and in more distant galaxies will soon be possible with larger ground-based telescopes and the Space Telescope.

REFERENCES

Appenzeller, I. and Wolf, B.: 1981, in "The Most Massive Stars," ed. D'Odorico, Baade, and Kjar (Garching: European Southern Obs.), p. 131.
Baade, W. and Swope, H.H.: 1963, Astron. J. 68, p. 435.
Berkhuijsen, E.M.: 1982, Astron. Astrophys. 112, p. 369.
Blanco, V.M., McCarthy, M.F. and Blanco, B.M.: 1980, Astrophys. J. 242, p. 938.
Brunish, W.M. and Truran, J.W.: 1982a, Astrophys. J. 256, p. 247.
Brunish, W.M. and Truran, J.W.: 1982b, Astrophys. J. Suppl. 49, p. 447.
Buscombe, W.: 1977, "MK Spectral Classifications" (Northwestern Univ., Evanston).
Buscombe, W.: 1980, "MK Spectral Classifications" (Northwestern Univ., Evanston).
Buscombe, W.: 1981, "MK Spectral Classifications" (Northwestern Univ., Evanston).
Chiosi, C., Nasi, E. and Sreenivasan, S.R.: 1978, Astron. Astrophys. 63, p. 103.
Christian, C.A. and Tully, R.B.: 1983, Astron. J. 88, p. 934.
Chu, Y.H. and Wolfire, M.: 1983, Bull. Am. Astron. Soc. 15, p. 644.
Conti, P.S.: 1975, Mém. Soc. Roy. Sci. Liège, 6^3 serie, tome 1K, p. 193.
Davidson, K.: 1983, private communication.
Davidson, K. and Kinman, T.D.: 1982, Publ. Astr. Soc. Pac. 94, p. 634.
Davidson, K., Walborn, N.R. and Gull, T.R.: 1982, Astrophys. J. Letters 254, p. L47.
de Jager, C.: 1980, "The Brightest Stars" (Reidel, Dordrecht), pp. 11-14.
Elias, J.H., Frogel, J.A. and Humphreys, R.M.: 1984, Astrophys. J., in press.
Flower, P.J.: 1977, Astron. Astrophys. 54, p. 31.
Garmany, C.D., Conti, P.S. and Chiosi, C.: 1982, Astrophys. J. 263, p. 777.
Hellings, P. and Vanbeveran, D.: 1981, Astron. Astrophys. 95, p. 14.
Hoessel, J.G. and Danielson, G.E.: 1983, Astrophys. J., in press.
Hoessel, J.G. and Mould, J.R.: 1982, Astrophys. J. 254, p. 38.
Hoessel, J.G., Schommer, R.A. and Danielson, G.E.: 1983, Astrophys. J., in press.
Humphreys, R.M.: 1978, Astrophys. J. Suppl. 38, p. 389.
Humphreys, R.M.: 1979a, Astrophys. J. 231, p. 384.
Humphreys, R.M.: 1979b, Astrophys. J. 234, p. 854.
Humphreys, R.M.: 1980a, Astrophys. J. 238, p. 65.
Humphreys, R.M.: 1980b, Astrophys. J. 241, p. 587.
Humphreys, R.M.: 1983a, Astrophys. J. 265, p. 176.
Humphreys, R.M.: 1983b, Astrophys. J. 269, p. 335.
Humphreys, R.M.: 1984, in "Structure and Evolution of the Magellanic Clouds," IAU Symposium No. 108 (Reidel, Dordrecht), p. 145.

Humphreys, R.M. and Davidson, K.: 1979, Astrophys. J. 232, p. 409.
Humphreys, R.M. and Sandage, A.: 1980, Astrophys. J. Suppl. 44, p. 319.
Humphreys, R.M., Blaha, C., D'Odorico, S., Gull, T.R. and Benvenuti, P.: 1984, Astrophys. J., in press.
Hutchings, J.B.: 1980, Astrophys. J. 237, p. 285.
Hutchings, J.B.: 1982, Astrophys. J. 255, p. 70.
Innis, R.T.A.: 1927, "Catalogue of Double Stars."
Kennedy, P.M. and Buscombe, W.: 1974, "MK Spectral Classifications" (Northwestern Univ., Evanston).
Kudritzki, R.P.: 1981, in "The Most Massive Stars," ed. D'Odorico, Baade, and Kjar (Garching: European Southern Obs.), p. 49.
Lequeux, J.: 1979a, Astron. Astrophys. 71, p. 1.
Lequeux, J.: 1979b, Astron. Astrophys. 80, p. 35.
Lequeux, J., Martin, N., Prevot, L., Prevot-Burnichon, M.L., Rebeirot, E. and Rousseau, J.: 1980, Astron. Astrophys. 85, p. 305.
Maeder, A.: 1980, Astron. Astrophys. 92, p. 101.
Maeder, A.: 1981a, Astron. Astrophys. 99, p. 97.
Maeder, A.: 1981b, Astron. Astrophys. 102, p. 401.
Maeder, A.: 1981c, in "The Most Massive Stars," ed. D'Odorico, Baade and Kjar (Garching: European Southern Obs.), p. 173.
Maeder, A.: 1983, Astron. Astrophys. 120, p. 113.
Massey, P. and Hutchings, J.B.: 1983, Astrophys. J., in press.
Miller, G.E. and Scalo, J.M.: 1979, Astrophys. J. Suppl. 41, p. 533.
Pagel, B.E.S. and Edmonds, M.G.: 1981, Ann. Rev. Astron. Astrophys. (Ann. Reviews. Palo Alto), 19, p. 77.
Ringuelet, A.E.: 1958, Z.f. Astrophys. 46, p. 276.
Sandage, A. and Carlson, G.: 1982, Astrophys. J. 258,p. 439.
Sandage, A. and Tammann, G.A.: 1974, Astrophys. J. 191, p. 603.
Sandage, A. and Tammann, G.A.: 1982, Astrophys. J. 256, p. 339.
Savage, B.D., Fitzpatrick, E.E., Casinelli, J.P. and Ebbets, D.C.: 1983, Astrophys. J., in press.
Shore, S.N. and Sanduleak, N.: 1984, Astrophys. J., in press.
Stahl, O., Wolf, B., Klare, G., Cassatella, A., Krautter, J., Persi, P. and Ferrari-Toniolo, M.: 1983, Astron. Astrophys., in press.
Stothers, R. and Chin, C.-W.: 1983, Astrophys. J. 264, p. 583.
Vangioni-Flam, E., Lequeux, J., Maucherat-Joubert, M. and Rocca-Volmeranga, B.: 1980, Astron. Astrophys. 90, p. 73.
Walborn, N.R.: 1973, Astrophys. J. 182, p. 121.
Walborn, N.R.: 1978, Astrophys. J. Letters 224, p. L133.
Walborn, N.R.: 1982, Astrophys. J. 256, p. 452.
Walborn, N.R.: 1983, in "Workshop on MK Spectral Classification: Criteria and Applications," University of Toronto.
Walborn, N.R., Blanco, B.M. and Thackeray, A.D.: 1978, Astrophys. J. 219, p. 498.
Weigelt, G.: 1983, private communication.
Worley, C.E.: 1983, unpublished.

DISCUSSION

Alcaino: Following the study of the very luminous galaxies M33 and M101, Sandage has recently suggested a dependence of the absolute visual magnitude of the brightest red giants with the luminosity of the parent galaxy from a mean of $M_V \doteq -8$ up to $M_V = -9$, hence jeopardizing the use of these stars as useful distance indicators. Perhaps you would like to place a comment whether you believe this to be a true effect, or just an overestimation of the distance to these galaxies, due to an underestimation of absorption?

Humphreys: I think that Sandage has probably overestimated the distance to M33 because of reddening of the Cepheids. For M33 I have used Madore's preliminary distance modulus of 24.6-24.7 mag. from infrared observations of the Cepheids. The difference with Sandage of 0.6-0.7 mag is probably due to reddening. Our very recent JHK photometry of the known M supergiants in M33 shows that they are definitely reddened, some by a magnitude in A_V. For M101 Sandage and Tammann had not found any M supergiants down to $m_V \sim 21$ mag. Strom and I (1983) subsequently identified candidate M supergiants in the arms of M101. The brightest are V ~ 20.7 mag. Sandage then re-examined his plates and also found candidate M supergiants even brighter than those found by Strom and myself. On the basis of these stars he derived an M_V of $\simeq -9$ mag. for the brightest red stars in M101 with his former distance modulus of 29.3 mag. Strom and I used the luminosity calibration of the M supergiants from the local group galaxies ($M_V \simeq -8$ mag.) to derive a somewhat closer distance. Aaronson, Strom, Copps, Lebofsky and I have obtained JHK photometry of six of Sandage's 7 brightest red candidates. Four are foreground M dwarfs, one is definitely an M supergiant and one is uncertain. The M supergiant has $V \simeq 20.4$ mag. comparable to the brightest Humphreys and Strom M supergiants. The luminosities of these stars depend on the distance to M101 which in my opinion is not known yet.

Frogel: Is number density of supergiants in HR diagram consistent with evolutionary rates? Would a model maker care to comment on disagreement?

Humphreys: The observed HR diagrams for the massive stars in the Milky Way, LMC and SMC all show evidence for a broader main sequence than predicted by the models.

Maeder: As frequently mentioned there are too many stars outside the main-sequence band. I shall come back to this topic in my talk. However, note that it was first necessary to make models to see whether standard evolution fits or not.

de Groot: In view of the difficulties of determining accurate parameters for the hottest stars, do you consider it possible that the upper luminosity boundary is a straight line sloping slightly across the top

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of the HRD, instead of a line which is sloping for the hotter stars and horizontal for the cooler stars? Would such a straight line make it easier for the theoreticians to tell us why it is there?

Humphreys: I think the bolometric corrections are fairly well known now even for the very hottest stars thanks to the work of Kudritzki and his associates. For the coolest supergiants the bolometric corrections are now well determined from infrared photometry. Consequently I think the upper envelope of stellar luminosities is nearly correct.

Westerlund: I was surprised to hear yesterday and again today that observers believe that all O stars inside 3.5 kpc from the Sun are known now. I believe that there may still be a fair number not discovered because of heavy absorption.

Humphreys: The total data set of O-type stars, supergiants and less luminous B stars is complete to 3 kpc. The O-type stars alone may only be complete to a smaller distance (≈ 2.5 kpc, Garmany et al, 1982). Of course the distribution of all of these stars is highly irregular and is determined by the local spiral structure. Consequently, any of these completeness estimates are somewhat misleading.