SESSION 2.

MAIN SEQUENCE AND SUPERGIANT STARS - II.

Chairman : C. de Loore.

1. R. HUMPHREYS: The Cooler Supergiants (A to M): Crucial Signposts in the Lifecycles of Massive Stars.

2. W. FREEDMAN: The Distribution of Young Stars in Nearby Galaxies.

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

THE COOLER SUPERGIANTS (A to M): CRUCIAL SIGNPOSTS IN THE LIFECYCLES OF MASSIVE STARS

Roberta M. Humphreys
University of Minnesota

The intermediate and late-type supergiants are the visually brightest stars. They are among the first stellar objects observed in other galaxies and provide our first clues to the conditions of massive star evolution in galaxies of different types. They are not as massive as the hottest and most luminous stars in the upper left of the HR diagram. Nevertheless, these somewhat lower mass stars ($\approx$20-50 $M_{\odot}$) with relatively cool temperatures play a major role in our efforts to understand massive star evolution. These supergiants are usually considered to be post hydrogen burning stars, and their relative numbers in the HR diagram provide essential comparisons with models for the later stages of massive star evolution. Most importantly, the most luminous cooler supergiants define the stability limit for massive stars in the HR diagram.

1. Fundamental Properties

For the purpose of this review paper, the intermediate and late-type supergiants will be the stars with spectral types A through M. For the essential comparisons with stellar structure models and evolutionary tracks we must know the effective temperatures and total luminosities, which are determined from the total energy distribution of the stars. The effective temperatures for these supergiants range from about 10000°K to 3000°K. With the increased use of infrared observations, the measurement of these fundamental quantities has been greatly improved for the cooler supergiants (Lee 1970; Ridgway et al. 1980; Elias, Frogel and Humphreys 1985). In this paper I am using the summary by Flower (1977) with the bolometric corrections for M supergiants by Elias et al. (1985).

We are of course very interested in the luminosities of these stars both for stellar evolution studies and to evaluate their potential as distance indicators. Nearly all of these stars are too distant for direct measurement of their distances and thus their luminosities. In our galaxy, their visual and bolometric luminosities are derived from membership in clusters and associations with known distances (e.g.,

C. W. H. De Loore et al. (eds.), Luminous Stars and Associations in Galaxies, 45–59.

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

Humphreys 1978). A fundamental reference for this procedure is Blaauw (1965). Recent luminosity calibrations by Walborn (1972, 1973), Schmidt-Kaler (1983) and Humphreys and McElroy (1984) show small differences for some of the groups of stars, but overall there is little change even with the much more extensive data available now. These luminosity calibrations typically have a standard deviation of 0.5 mag for an individual luminosity and standard errors of the mean of 0.1 to 0.2 mag. For a star in a stellar aggregate, the luminosities are better determined with typical errors of ± 0.25 mag due to uncertainties in the distance moduli.

In any study of the stellar populations and stellar evolution in other galaxies we must know the distances. For the most part, we rely on published distances from the Cepheid period-luminosity relation, and the uncertainties for Local Group galaxies are ± 0.2 to ± 0.5 mag.

Another fundamental parameter for massive stars is of course mass loss, which has figured significantly in recent model calculations for massive star evolution. As a result of observations in both the ultra-violet and infrared, we now realize that mass loss is very likely occurring to some degree in all stars in the upper part of the HR diagram. Reviews by Hutchings (1978), Barlow (1978, 1981), and Zuckerman (1980) summarize the situation for the hot and cool supergiants and recent papers by Hagen, Humphreys and Stencil (1981), Lambert, Hinkle and Hall (1981), and Kunasz and Morrison (1982, 1983) discuss the mass loss rates for the intermediate type supergiants.

In Table 1 I have summarized the range of physical parameters for the luminous stars of different spectral types or temperatures based on observations in our galaxy and the Magellanic Clouds.

Table 1

	Hot	Intermediate	Cool
Spectral Types	O,B	A,F,G	K,M
Effective Temperature(°K)	50000-12000	11000-4000	<4000
Luminosity Range($L/L_\odot$)	10^4-5×10^6?	10^4-8×10^5	10^4-5×10^5
Mass Range($M/M_\odot$)	15-200 or 300	15-60	15-50
Size Range($R/R_\odot$)	10-200	30-1000	300-2000
Mass Loss($\dot{M}$)	10^{-7}-10^{-5}	10^{-7}-10^{-5}(10^{-4}:)	10^{-7}-10^{-4}

Although the cooler, more evolved supergiants are not the most massive or most luminous stars, they are without doubt the largest!

2. Observations of the Cooler Supergiants in Our Galaxy and Others

For our studies of massive star evolution in different galaxies we want to know how their basic properties, luminosity and mass, may depend on their environment and whether they vary from galaxy to galaxy. Comparisons of stellar models with observations hinge on the HR diagram, for which we need spectra and accurate photometry for the individual stars. However, there are numerous uncertainties in the resulting HR diagrams. How universal are the colors, the effective temperatures and bolometric corrections and the interstellar extinction law? The best evidence to date suggests that the differences, if any, are probably small, but we must know the true distances to galaxies if we want to compare the star formation rates, the luminosity and initial mass functions and study the effects of morphological type on stellar evolution. Many of the differences we are looking for may be rather small effects, and errors in the distance can lead to erroneous conclusions about the factors influencing stellar evolution.

Our galaxy and the Magellanic Clouds provide an excellent comparison of massive star evolution in different environments and with different metallicities. The HR diagrams are an efficient way to compare the properties of the luminous stars in these three galaxies. The M_{Bol} vs. log T_{eff} diagrams are shown in Figures 1, 3 and 4 in Humphreys and McElroy (1984). The luminosities for the nearly 2300 galactic supergiants are from their membership in 91 associations and clusters. The basic data for the Magellanic Cloud stars come from many sources in the literature cited in Humphreys and McElroy (1984). Their luminosities, corrected for extinction, are derived from the adopted true distance moduli of 18.6 mag and 19.0 mag for the LMC and SMC, respectively, based on Cepheids and RR Lyrae stars.

Comparison of the galactic and LMC HR diagrams reveal similar populations of luminous stars in both galaxies. The LMC and our solar region have essentially the same upper envelopes to their stellar luminosities. The HR diagram for the SMC shows some differences. The hottest, most luminous stars are fewer in number and are noticeably less luminous than stars of comparable temperature in the solar region and LMC, but the large scale features of the three HR diagrams are similar. The upper luminosity boundary for the late supergiants is the same in all three galaxies, although there are no known high luminosity yellow supergiants (FGK) in the SMC.

Figure 1 shows the composite HR diagram (M_{Bol} vs. log T_{eff}) for the stars with $M_{Bol} \leq -8.5$ mag in the Galaxy and Magellanic Clouds. The evolutionary tracks from models with mass loss by Maeder (1981b, 1983) are also shown for comparison. The effects of mass loss have been discussed by numerous authors (de Loore et al. 1978; Chiosi et al. 1978; Stothers and Chin 1979; Maeder 1980, 1981a,b, 1983; de Loore and de Greve 1981; Chiosi 1981; Falk and Mitalas 1981, 1983; Sreenivasan and Wilson 1982; Brunish and Truran 1982a,b). For this paper we are especially interested in the post main-sequence evolution for comparison with the observations of intermediate and late-type supergiants.

In 'conservative' evolution, with no mass loss, the stars leave the main sequence and end their lives as M supergiants (Stothers and Chin 1976; Lamb 1976). In these models the 15 to 50 $M_{\odot}$ stars begin helium burning as B supergiants and thus have very short lifetimes as red supergiants which is in sharp disagreement with the observed numbers of M supergiants in our galaxy and the Clouds.

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

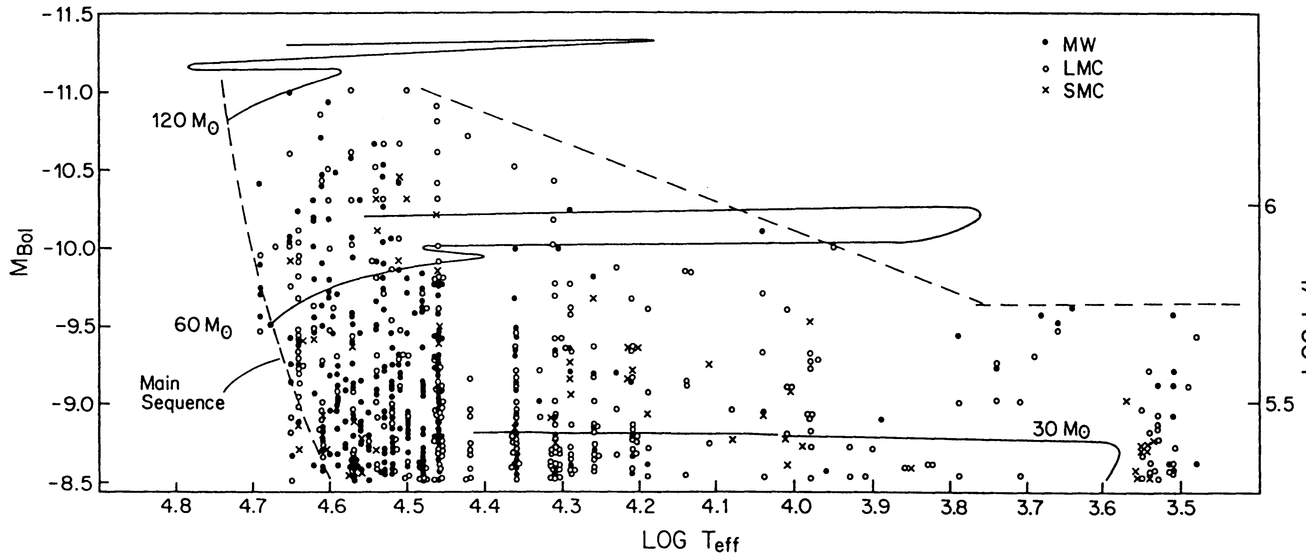

Figure 1 - The M_{Bol} vs. log T_{eff} diagram for luminous stars ($M_{Bol} \leq -8.5$ mag) in the Galaxy, LMC and SMC. The upper luminosity boundary (dashed line) is based on the distribution of the most luminous normal stars in these three galaxies.

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

Mass loss is observed in all of the luminous supergiants and their O star progenitors. Therefore, inclusion of mass loss in the models is not only physically necessary but also produces better agreement with the observations. The length of time in the red supergiant stage is increased by factors of 4 to 5 for 25 to 50 $M_\odot$ stars. High mass stars >50 to 60 $M_\odot$ never reach the red supergiant stage with mass loss at the observed rates. This result also agrees with our observations (see Figure 1) for the Galaxy and the Clouds, and explains the observed upper luminosity boundary for the intermediate and late-type supergiants.

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.

Blue to red supergiant ratios are often used as indicators of the relative lifetimes of the massive stars in different stages for comparison with the models of stellar evolution. Counts of blue and red stars are also considered possible indicators of metallicity variations. A much more complete data set is now available for the massive stars in our galaxy and the Clouds (see Table 9 in Humphreys and McElroy 1984). The B/R ratios in these three galaxies show two phenomena: 1) little or no variation with luminosity when the data is corrected for incompleteness, and 2) a gradient with location in our galaxy and a difference between our galaxy and the Clouds, which are attributed to metallicity variations. The models with moderate mass loss give much better agreement between the expected and observed ratios than do the older, non-mass loss calculations.

The later evolution of the cooler supergiants has been discussed by Chiosi et al. (1978) and Maeder (1981a,b). They suggest that the high mass loss during the red supergiant stage favors the formation of Wolf-Rayet stars. To determine the range of initial masses of stars that evolve to WR stars, Schild and Maeder (1984) and Humphreys, Nichols and Massey (1985) have studied the WR stars in young clusters and associations and find that most WR stars had initial masses greater than 40 to 50 $M_\odot$ which is larger than the initial masses of most M supergiants. Thus only the most luminous M supergiants are potential progenitors of WR stars. A small group of very luminous late-type supergiants with extensive circumstellar dust shells, known as supergiant OH/IR sources, are potential candidates for subsequent evolution to WR stars. Alternatively, they may indeed be the final evolutionary stages for 30 to 50 $M_\odot$ stars. These objects include stars like VY CMa (M4-M5Ia), VX Sgr (M4-M8I) and IRC+10420 (F8Ia-0). They have luminosities right at the upper luminosity boundary and mass loss rates $\approx 10^{-4}$ $M_\odot$/yr. Infrared observations have revealed M supergiants of this type in other galaxies. Terry Jones and I are investigating the properties of these stars for eventual evolution to the WR stage.

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

McGregor and Hyland (1981, 1984, McGregor 1981) and Elias, Frogel and Humphreys (1985) made extensive studies of spectral types, colors, and luminosities of the red supergiants in the Galaxy and the Magellanic Clouds at optical and infrared wavelengths. The effect of the well known metallicity differences among these three galaxies is very clearly illustrated by their M supergiant populations. Humphreys (1979) first pointed out the very dramatic shift in the distribution of spectral types for the red supergiants in the Galaxy and the Clouds. Figure 1 in Elias, Frogel and Humphreys (1985) is a histogram of the spectral type distributions. The shift to earlier spectral types is due to the lower heavy element abundances in the Clouds. It is well known that the position of the Hayashi track on the HR diagram depends on metallicity. The Hayashi track shifts to warmer temperatures with decreasing metallicity because the opacity depends on the number of electrons from heavy elements. Thus the lower metallicity is offset by an increase in temperature.

The infrared observations also reveal that the 10μm circumstellar silicate feature is metallicity dependent. The 10μm excess is very weak or nonexistent in the SMC M supergiants, somewhat larger in the LMC red supergiants but still smaller than for the galactic M supergiants of the same type. This is very likely due to less dust formation around the Cloud supergiants.

With a uniform set of spectral types and photometric data, Elias et al. (1985) derive a reddening law for the M supergiants, intrinsic colors from B-V to K-L, and bolometric corrections for the red supergiants in the three galaxies. In the infrared the effects of interstellar reddening are of course small and can be readily determined from the J-H vs. H-K two-color diagrams (see figure 8 in Elias et al. 1985). The bolometric luminosity is much more accurately determined in the infrared. The bolometric correction to the K mag has little variation with the spectral type, temperature, or metallicity of the M supergiant (see Table 10 in Elias et al. 1985). Variability is also minimized at the long wavelengths. Although the red supergiants are often highly variable in the visual their fluctuations at K are typically $\lesssim$0.3 mag.

It is obvious that infrared observations offer numerous advantages for studies of late-type supergiants. In other more distant galaxies for which the identification of supergiants is difficult, candidate M supergiants can be separated from foreground dwarfs in the two-color J-H vs. H-K and J-K vs. V-K diagrams, and the reddening can be estimated. With the nearly negligible extinction in the infrared, the lack of variability and the near constancy of the bolometric correction at K, we can determine their absolute K and bolometric luminosities directly from JHK photometry and the true distance of the galaxy.

Several recent studies of the late-type supergiants in Local Group galaxies illustrate the value of infrared photometry. Humphreys, Jones and Sitko (1984) have derived the interstellar extinction and infrared and bolometric luminosities of the spectroscopically confirmed M supergiants in M33 from JHK photometry. Previous extinction estimates for both the blue and red supergiants in M33 were subject to considerable uncertainty, but the position of the red supergiants on the J-H vs. H-K diagram clearly shows the effects of reddening. The resulting visual extinction is both significant and variable, ranging from 0.3 mag to 1.5 mag. The average reddening is 0.8 mag the same as has been determined recently for the Cepheids (Madore et al. 1985; Freedman 1984). The recent work on Cepheids on M33 by Freedman and by Madore et al. has confirmed earlier discussions that indicated a true distance modulus near 24.0 mag (see van den Bergh 1976; Humphreys 1980a). Their work has not supported recent suggestions that the distance was much larger ($(m-M)_o$ = 25.2 mag, Sandage 1983a) and the reddening small.

The individual red supergiants are corrected for reddening and their luminosities derived from the true distance modulus of 24.1 mag from Freedman (1984). The resulting visual and bolometric luminosities for the brightest red supergiants of -8.1 and near -9.2 mag, respectively, are in agreement with previous estimates (Humphreys 1980a, 1983; Humphreys et al. 1984).

Elias et al. (1981, 1985), and Elias and Frogel (1985) have used infrared photometry to investigate the dependence of the luminosities of the brightest M supergiants (and by implication their initial masses) on the properties of the parent galaxy in the Milky Way, M33, the Clouds, NGC 6822, IC 1613 Sextans A, NGC 3109 and DDO 210. These Local Group galaxies range in type from Sc spiral to dwarf irregular and cover more than six magnitudes in luminosity. The visual, bolometric and K (2.2μ) luminosities of the red supergiants show different dependences on the luminosity of the galaxy. The bolometric luminosity is an indicator of the initial mass of the star. Its decline with the decreasing luminosity of the galaxy implies merely that there are fewer progenitors of sufficient mass in the smaller, less luminous galaxies. This is already well known for the early-type supergiants (Sandage and Tammann 1974a; Humphreys 1983) and is a statistical effect.

The luminosity at K shows the greatest dependence on the galaxy's luminosity. There are two factors affecting the 2.2μ luminosity; the dearth of massive progenitors in the smaller galaxies as discussed above and metallicity. The V-K color is very dependent on spectral type, thus the latest type M supergiants are the most luminous at K. The smaller, less luminous dwarf irregulars usually have lower heavy element abundances and few if any late type M supergiants as in the SMC. Thus the K luminosities of their M supergiants are much lower.

The lower metallicity in the dwarf irregulars also explains the near constancy of the visual luminosities of the M supergiants over several magnitudes of galactic luminosity. Even though the bolometric luminosity of the brightest red stars is declining in these galaxies the corresponding trend to lower metallicity shifts the Hayashi track to warmer temperatures, earlier spectral types, and smaller bolometric corrections. Thus the visual luminosity stays near -8 mag over a wide range.

We know very little about the stellar content of M31, the most massive, most luminous galaxy in our Local Group. Because of its large size, high tilt angle, and tightly wound arms there are no extensive surveys for the blue and red stars. Our information has essentially been limited to observations of stars in Baade's Field IV, the only region for which a color-magnitude diagram exists.

For this reason Elly Berkhuijsen (MPFR, Bonn), Michael Newberry (U. Michigan) and I initiated a stellar content survey of M31 using the Automated Plate Scanner at the University of Minnesota. This survey has been used to generate a preliminary list of the brightest blue and red stars in a region centered on Baade's Field III and NGC 206. Spectra for classification have been obtained for 11 candidate blue supergiants in this field plus 9 additional bright stars in prominent stellar associations elsewhere in M31. Only two of these stars were confirmed to be supergiants. Nine suspected red supergiants were observed in the near infrared (6800-9000Å). The near-infrared CaII triplet is a very strong luminosity indicator, and dwarfs and supergiants can be readily separated even on low resolution spectra (10-15Å). The paper in this volume on the M supergiants in NGC 300 by Graham and Humphreys illustrates the value of the near-infrared spectroscopy. Three of the red stars in M31 are confirmed M supergiants.

The visual luminosities of these confirmed supergiants, determined from the apparent distance modulus of 24.5 mag with no correction for reddening, are significantly less luminous than the brightest stars of similar spectral type in our galaxy, M33 and the Clouds. This is in contrast to what we might initially expect in a more massive, more luminous galaxy. Although all of M31 has not been surveyed yet, the area studied is comparable in surface area to M33. These results are very preliminary and further spectroscopy is planned. If these results are confirmed in other spiral arm regions in M31, they will have very important implications for the factors influencing massive star evolution, such as morphological type.

Very little work has been done on the intermediate and late-type supergiants in galaxies beyond our Local Group. Even though these supergiants are the visually brightest stars, they are quite faint in these distant galaxies and very little spectroscopic or photometric work has been done on them (Humphreys 1980b). We (Humphreys, Aaronson, Lebofsky, McAlary, Strom and Capps 1985) have just recently finished a program of near-infrared spectroscopy and JHK photometry of candidate red supergiants in M101 (Humphreys and Strom 1983; Sandage 1983b), NGC 2403 (Sandage 1984b) and M81 (Sandage 1984a) using the KPNO 4-meter, NASA's IRTF on Mauna Kea and the MMT in Arizona. Marc Aaronson and I have also observed spectra for classification of the brightest early-type stars in these same galaxies with the reticon scanner on the MMT. The blue spectra cover 1000Å at a resolution of 1Å and are excellent for classification.

The initial results for NGC 2403 are much as we might expect for a galaxy very similar to M33 and NGC 300. The brightest M supergiants have M_V near -8 mag while the visually brightest A-type stars are $\simeq$ -9.5 mag as in M33. The results for M81 are surprising in the same sense as for M31. Adopting the distance to the M81 group from NGC 2403 the brightest red stars are near $M_V \simeq -8$, as in the other spirals and Magellanic type irregulars, but the brightest early-type supergiants identified so far are less luminous than similar stars in other spirals. These preliminary results for M31 and M81 may be our first indication of a dependence of the massive star population and the upper end of the IMF on morphological type. The luminosities of the HII regions in each of these two galaxies also suggest that there may be fewer of the most massive stars in M31 and M81 (Kennicutt 1984, 1985). The well known relation between the brightest blue supergiant (A-type) and the luminosity of the galaxy has been determined for irregulars and Sc-type spirals, but our first results for the brightest A-type supergiants in the Sb-type spirals M31 and M81 suggest they are less luminous than would be expected for the luminosities of their galaxies.

In contrast, the blue and red supergiants in M101 are over-luminous. Using a distance modulus of 29.2 mag from Sandage and Tammann (1974b) the brightest stars are a magnitude or more brighter both visually and bolometrically than the brightest known stars of the same spectral types in other galaxies (see Fig. 2). The very high luminosities near $M_{Bol} \simeq$ -11 mag correspond to initial masses of $\gtrsim$100 $M_\odot$. The uncertainties in the apparent bolometric magnitudes are very small. The bolometric magnitudes for the M supergiants determined from the infrared photometry are known to $\pm$0.1 mag and are independent of metallicity effects and uncertainties in the extinction and intrinsic colors. These luminosities lead to serious inconsistencies with our present understanding of the physics of massive star evolution and the effects of mass loss.

Modern models for massive star evolution including the effects of mass loss (see for example models by Chiosi, Nasi, Sreenivasan 1978; Maeder 1981a,b; Stothers and Chin 1983) show very clearly that stars with initial masses >50-60 $M_\odot$ do not evolve to the red supergiant part of the HR diagram. But the adopted distance modulus of M101 (29.2 mag from Sandage and Tammann 1974b) leads to luminosities that imply much greater masses. One can always argue that the evolutionary models and the effects of mass loss are grossly in error, and M supergiants with initial masses of $\approx$100 $M_\odot$ exist in M101, but there will also be serious problems with the stability of evolved stars of such high luminosity and high initial mass. Or, the proposed distance is too large; a closer distance by $\approx$.8 mag would be required to produce agreement with the physics.

3. The Stability Limit for the Photospheres of the Most Massive Stars

Humphreys and Davidson (1979) first drew attention to the lack of evolved very massive stars in the upper HR diagram. We proposed an empirical upper luminosity boundary based on the observed distribution

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

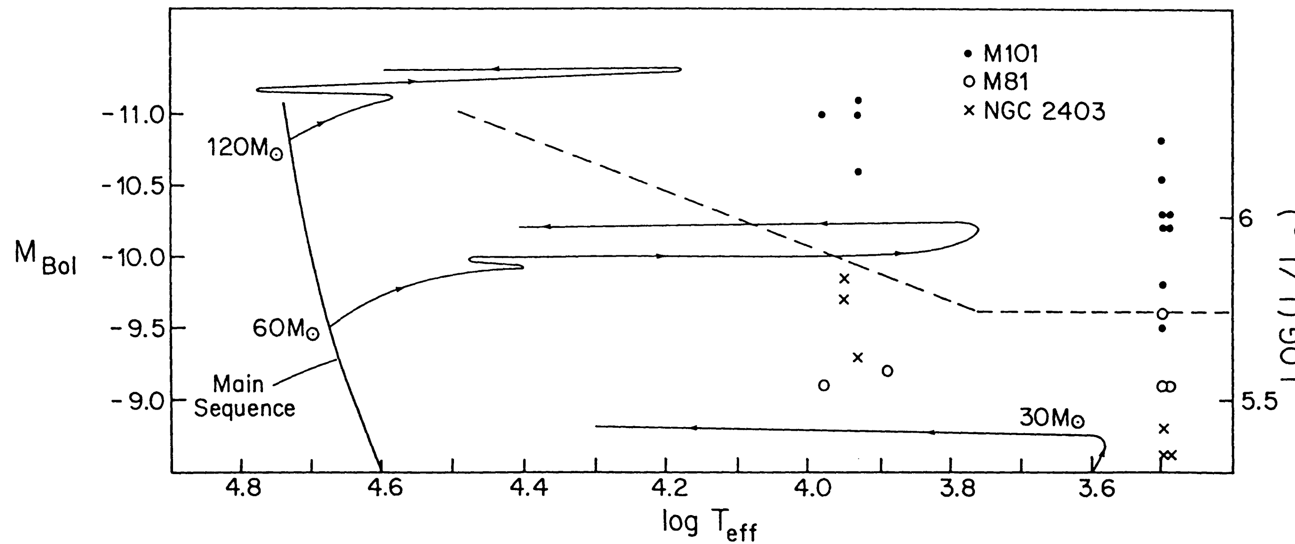

Figure 2 - The M_{Bol} vs. log T_{eff} diagram showing the positions of the confirmed supergiants in NGC 2403, M81 and M101. The dashed line is the upper luminosity boundary from Figure 1.

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

of the most massive 'normal' stars in our galaxy and the LMC. But what prevents a very massive star from evolving into a highly luminous cooler supergiant? We suggested an intuitive answer involving episodes of enhanced mass loss. We were motivated by the observations of unstable stars like η Car, P Cyg and other luminous blue variables, many of which lie near the critical boundary. Many of these stars are known to suffer spectacular episodes of mass ejection. We suggested that as the very massive stars evolve to cooler temperatures, they encounter a stability limit and suffer high mass loss, which prevents further evolution to cooler temperatures.

What is the cause of the instability? Several alternatives have been suggested, (see the review by Stothers and Chin 1983) including an internal vibrational instability, surface radiation pressure or a pressure gradient due to turbulence. In his comprehensive book, The Brightest Stars, (1979) de Jager proposed that a turbulent pressure gradient develops in the atmospheres of the cooler supergiants due to the dissipation of mechanical energy. The stability limit or de Jager limit is reached when the turbulent pressure gradient equals the acceleration due to gravity. Maeder (1983) showed that the de Jager limit for the most massive stars halts further evolution to the right and is accompanied by enhanced mass loss. After the mass ejection the stars reverse their evolution back to higher temperatures at essentially constant luminosity, in agreement with observations of the luminous blue variables between maximum and minimum (Appenzeller and Wolf 1981, Humphreys et al. 1984).

The onset of the stability limit for massive stars very likely corresponds to the observed upper luminosity boundary for the cooler supergiants. In a recent paper de Jager (1984) has shown that there is a stability limit to the atmospheres of hypergiants (spectroscopically class Ia+, Ia-0, and 0). The turbulent motions from the dissipation of the mechanical flux tend to destabilize the atmosphere. For more luminous stars the dissipation occurs deeper in the photosphere and leads to increasing mass loss. At the observed luminosity boundary ($M_{Bol} \approx -9.5$ mag) for the cooler supergiants the mass loss rates are already near 10^{-4} $M_{\odot}$/yr. and de Jager has shown that these stars are nearly unstable. A star a magnitude brighter would be losing mass at nearly a factor of 10 times higher rate. This greatly alters the evolutionary tracks for more massive stars. As they evolve to cooler temperatures they approach the stability limit for their photospheres with increasing mass loss. According to Maeder (1983), the increasingly high mass loss rates increase the mass fraction of the core and the star's evolution reverses to warmer temperatures. Thus stars greater than 50-60 $M_{\odot}$ do not evolve across the HR diagram to cooler temperatures.

The recognition of a stability limit in the upper HR diagram has been one of the most important recent developments in studies of massive stars. This stability limit is very likely defined by the most luminous cooler supergiants which de Jager has shown are near the limits for the stability of their photospheres. The higher resolution observations

https://doi.org/10.1017/S0074180900148624 Published online by Cambridge University Press

required for further study of the atmospheres of the stars all along the upper luminosity boundary will soon be possible with the larger ground-based telescopes and Space Telescope.

References

Appenzeller, I. and Wolf, B.: 1981, in "The Most Massive Stars," ed. D'Odorico, Baade, and Kjar (Garching: ESO), p. 131.
Barlow, M.J.: 1978, in "Mass Loss and Evolution of O Stars," IAU Symposium #83 (Dordrecht, Reidel), p. 119. ed. P. Conti, C. deLoore
Barlow, M.J.: 1981, in "Wolf Rayet Stars: Observations, Physics, Evolution," IAU Symposium #99 (Dordrecht, Reidel), p. 149.
Blaauw, A.: 1965, in "Stars and Stellar Systems, Vol. 3, Basic Astronomical Data," ed. K. Aa. Strand (Chicago: Univ. of Chicago Press), p. 383.
Brunish, W.M. and Truran, J.W.: 1980a, Astrophys. J. 256, p. 247.
Brunish, W.M. and Truran, J.W.: 1980b, Astrophys. J. Suppl. 49, p. 447.
Chiosi, C.: 1981, in "The Most Massive Stars," ed. D'Odorico, Baade, and Kjar (Garching, ESO) p. 27.
Chiosi, C., Nasi, E., and Sreenivasan, S.R.: 1978, Astron. Astrophys. 63, p. 103.
de Jager, C.: 1980, "The Brightest Stars," (Reidel, Dordrecht), pp. 11-14.
de Jager, C.: 1984, Astron. Astrophys. 138, p. 246.
de Loore, C., de Greve, J.P., Vanbeveren, D.: 1978, Astron. Astrophys. 67, p. 373.
de Loore, C. and de Greve, J.P.: 1981, in "The Most Massive Stars," ed. D'Odorico, S., Baade, and Kjar (Garching, ESO), p. 85.
Elias, J.H. and Frogel, J.A.: 1985, Astrophys. J. 289, p. 141.
Elias, J.H., Frogel, J.A., and Humphreys, R.M.: 1985, Astrophys. J. Suppl. 57, p. 91.
Elias, J.H., Frogel, J.A., Humphreys, R.M., and Persson, S.E.: 1981, Astrophys. J. (Letters) 249, p. 55.
Falk, H.J. and Mitalas, R.: 1981, Mon. Not. Roy. Astron. Soc. 196, p. 225.
Falk, H.J. and Mitalas, R.: 1983, Mon. Not. Roy. Astron. Soc. 202, p. 19.
Flower, P.J.: 1977, Astron. Astrophys. 54, p. 31.
Freedman, W.: 1984, Ph.D. Dissertation, University of Toronto.
Graham, J.A. and Humphreys, R.M.; 1985, in preparation.
Hagen, W., Humphreys, R.M., and Stencel, R.E.: 1981, Pub.A.S.P. 93, p. 567.
Hellings, P. and Vanbeveren, D.: 1981, Astron. Astrophys. 95, p. 14.
Humphreys, R.M.: 1978, Astrophys. J. Suppl. 38, p. 389.
Humphreys, R.M.: 1979, Astrophys. J. 231, p. 384.
Humphreys, R.M.: 1980a, Astrophys. J. 241, p. 587.
Humphreys, R.M.: 1980b, Astrophys. J. 241, p. 598.
Humphreys, R.M.: 1983, Astrophys. J. 269, p. 335.
Humphreys, R.M., Blaha, C., D'Odorico, S., Gull, T.R., and Benvenuti, P.: 1984, Astrophys. J. 278, p. 124.
Humphreys, R.M. and Davidson, K.: 1979, Astrophys. J. 232, p. 409.

Humphreys, R.M., Jones, T.J., and Sitko, M.L.: 1984, Astron. J. 89, p. 1155.
Humphreys, R.M. and McElroy, D.B.: 1984, Astrophys. J. 284, p. 565.
Humphreys, R.M., Nichols, M., and Massey, P.: 1985, Astron. J. 90, p. 101.
Humphreys, R.M. and Strom, S.E.: 1983, Astrophys. J. 264, p. 458.
Hutchings, J.B.: 1978, in "Mass Loss and Evolution of O Stars," IAU Symposium #83 (Dordrecht, Reidel), p. 3.
Kennicutt, R.C.: 1984, Astrophys. J. 287, p. 116.
Kennicutt, R.C.: 1985, private communication.
Kunasz, P.B. and Morrison, N.D.: 1982, Astrophys. J. 263, p. 226.
Kunasz, P.B., Morrison, N.D., and Spressant, B.: 1983, Astrophys. J. 266, p. 739.
Lamb, S.A., Iben, I., and Howard, W.M.: 1976, Astrophys. J. 207, p. 209.
Lambert, D.L., Hinkle, K.H., and Hall, D.N.B.: 1981, Astrophys. J. 248, p. 638.
Lee, T.A.: 1970, Astrophys. J. 162, p. 217.
Madore, B.F., McAlary, C.W., McLaren, R.A., Welch, D.L., Neugebauer, G., and Matthews, K.: 1985, Astrophys. J., in press.
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.: 1983, Astron. Astrophys. 120, p. 113.
McGregor, P.J.: 1981, Ph.D. Dissertation, Australian National University, Canberra.
McGregor, P.J. and Hyland, A.R.: 1981, Astrophys. J. 250, p. 116.
McGregor, P.J. and Hyland, A.R.: 1984, Astrophys. J. 277, p. 149.
Ridgway, S.T., Joyce, R.R., White, N.M., and Wing, R.F.: 1980, Astrophys. J. 235, p. 126.
Sandage, A.: 1983a, Astron. J. 88, p. 1108.
Sandage, A.: 1983b, Astron. J. 88, p. 1569.
Sandage, A.: 1984a, Astron. J. 89, p. 621.
Sandage, A.: 1984b, Astron. J. 89, p. 630.
Sandage, A. and Tammann, G.A.: 1974a, Astrophys. J. 191, p. 603.
Sandage, A. and Tammann, G.A.: 1974b, Astrophys. J. 194, p. 215.
Schild, H. and Maeder, A.: 1984, Astron. Astrophys. 136, p. 237.
Schmidt-Kaler, Th.: 1983, in "Landolt-Bornstein, New Series," Group 6, Vol. 2, Part B.
Sreenivasan, S.R. and Wilson, W.J.F.: 1982, Astrophys. J. 254, p. 287.
Stothers, R. and Chin, C.W.: 1976, Astrophys. J. 204, p. 472.
Stothers, R. and Chin, C.W.: 1979, Astrophys. J. 233, p. 267.
Stothers, R. and Chin, C.W.: 1983, Astrophys. J. 264, p. 583.
van den Bergh, S.: 1976, in "Redshifts and the Expansion of the Universe, IAU Symposium #37 (Paris: CNRS), p. 13.
Walborn, N.R.: 1972, Astron. J. 72, p. 312.
Walborn, N.R.: 1973, Astron. J. 78, p. 1067.
Zuckerman, B.: 1980, in "Ann. Rev. Astron. Astrophys." 18.

Discussion : HUMPHREYS.

LAMERS :

There seems to be some confusion about the nomenclature of the luminosity upper limit, which is sometimes called Humphreys-limit; de Jager-limit, Humphreys-Davidson limit or de Jager-Humphreys limit.

I propose that we give proper credit to those who discovered or predicted the different effects. I propose that we call the Observed Luminosity Upper Limit the "Humphreys-Davidson limit" (Humphreys and Davidson, 1979, Astrophys. J. 232, 409) and The Predicted Turbulent Instability Limit the "De Jager limit" (de Jager, 1980, The Brightest Stars: Reidel, Dordrecht; de Jager, 1984, Astron. Astrophys, 138, 246). The interesting astrophysical question is : is the De Jager-limit equal to the Humphreys-Davidson limit?

(This proposal was accepted by the participants).

LORTET :

Did you take into account the possibility that many bright stars may be member of a (undiscovered) tight cluster?

HUMPHREYS :

Yes. The spectra allow me to distinguish when the stars are composite. For example one of the supergiants in M31 had a composite spectrum, one of the blue stars in M101 is very likely more than one star and several of the blue star candidates in M101, M81 and NGC 2403 were found to be HII regions.

SREENIVASAN :

You suggested that morphological features might be a factor determining stellar evolution. Could you indicate how the physics would be different if it were the case?

HUMPHREYS :

Our first look at the luminous supergiants in M31 and M81 suggests that the most massive star progenitors are fewer numerous in the Sb type spirals. Presumably the the massive star formation rate is lower in the Sb spirals than in Sc spirals, like M33 and Magellanic Irregulars (i.e. LMC). This suggests that the morphological type may influence star formation. Perhaps the shock associated with the density wave or whatever mechanism initiates star formation is not so strong and does not produce as many massive stars in Sb type spirals.

RENZINI :

How were these M-type supergiants picked up? I mean, in which bands were the surveys done? Surveys limited to BV bands are indeed likely to miss bolometrically bright stars of late M spectral type.

HUMPHREYS :

You are correct. Humphreys and Strom used BVRI plates to select the candidate M supergiants in M101. The candidate red supergiants from Sandages work are found from blinking B and V plates.