THE BRIGHTEST STARS IN THE MAGELLANIC CLOUDS AND OTHER LATE-TYPE GALAXIES

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The brightest stars always receive considerable attention in observational astronomy, but why are we so interested in these most luminous, and therefore most massive stars? These stars are our first probes for exploring the stellar content of distant galaxies. Admittedly, they are only the tip of the iceberg for the whole stellar population and very interesting processes are occurring among the less massive, older stars, but the most massive stars are our first indicators for studies of stellar evolution in other galaxies. They provide the first hint that stellar evolution may have been different in a particular galaxy because they evolve so quickly. The most luminous stars also highly influence their environments via their strong stellar winds and mass loss and eventually as supernovae.

The brightest stars are also very important as standard candles for the distance scale. We want to know how their luminosities may depend on the morphological type or luminosity of a galaxy and on possible chemical abundance differences. For this purpose we must observe the individual brightest stars in a variety of different galaxies, and we must also understand the evolution of the most massive stars.

In this paper I will be reviewing properties of the brightest stars in the Magellanic Clouds and in other nearby galaxies. The most luminous stars in different spectral type groups will be identified and compared with the population of luminous stars in our region of the Milky Way. This discussion will focus on normal, single stars and will not include peculiar stars, multiple systems and Wolf-Rayet stars. However, later in this paper I will mention the luminous blue variables also known as S Dor or Hubble-Sandage variables. At the end of the paper I will discuss the observed upper boundary to stellar luminosities and its relationship to massive star evolution.

When we study the most luminous stars we want to know how their basic properties, luminosity and mass, may depend on their environment and whether they vary from galaxy to galaxy. To get this information we need spectra and photometry of the individual stars and the distances to

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Table 1
Basic Parameters of the Galaxies Used for the Luminosity Calibration[a]

Galaxy	Type	(mag)	App. Dist. Mod. $(m-M)_V$ (mag)	True Dist. Mod. $(m-M)_0$ (mag)	Origin
MW	Sbc (II)	-20.5:	-	- ±0.25	Clusters and associations[b]
LMC	IR III-IV	-18.5	18.7	18.6±0.1	Cepheids and RR Lyrae[c]
SMC	IR IV/IV-V	-16.8	19.1	19.0±0.1	Cepheids and RR Lyrae[d]
M33	Sc II-III	-18.9	25.0:	24.25±0.2	Cepheids[e]
N6822	IR IV-V	-15.7	24.45	23.2±0.2 -0.0	Cepheids[f]
I1613	IR V	-14.8	24.52	24.3±0.1	Cepheids[g]
N2403	Sc III	-19.0	27.75	26.7±0.2	Cepheids[h]
M101	Sc I	-20.9	29.3 28.9±0.2	28.6-0.1 +0.2	M supergiants[i]

References: a - all distances are on the old Hyades scale; b - Humphreys (1978a); c - Martin, Warren and Feast (1979), Graham (1977); d - Gascoigne (1974), Graham (1975; e - Madore (1983), Sandage (1983); f - Kayser (1967), van den Bergh (1976), Humphreys (1980a); g - Sandage (1971), Humphreys (1980a); h - Tammann and Sandage (1968), Madore (1976); i - Sandage and Tammann (1974), Humphreys and Strom (1983).

the galaxies. The intrinsic visual luminosities are then derived from the photometry corrected for interstellar reddening and the true distance modulus of the galaxy.

Table 1 summarizes the morphological types and adopted distances for the eight galaxies mentioned in this paper. The primary galaxies in this discussion are the Large and Small Magellanic Clouds and the Milky Way. The luminosities for the galactic O-type stars and supergiants are derived from their membership in over 90 stellar associations and young clusters with known distances. The adopted distances to the Magellanic Clouds are based on Cepheids and RR Lyrae stars. The basic data, spectral types and photometry, for the individual stars come from many sources in the literature. For the Magellanic Cloud stars I especially want to mention the observations by Feast, Thackeray and Wesselink (1960) who were the first to identify and classify the brightest stars in the Clouds. Due to the availability of more telescopes and better instruments there has been a great increase in the amount of spectral classification data for the brightest stars; notably the pioneering work by Walborn (1977) on the O-type stars, the extensive observations by Ardeberg and his associates (1972, 1977) and myself (Humphreys (1979a,b) on the red supergiants. These observations rely heavily on the objective prism surveys for blue and red stars (Sanduleak 1968, 1969a,b, 1975; Sanduleak and Philip 1977; Azzopardi and Vigneau 1975; Brunet et al. 1975).

A very efficient way to compare the properties of the luminous star populations in these three galaxies is to look at their HR diagrams. Figures 1 and 2 in Humphreys (1984) compare the M_{Bol} vs. log T_{eff} diagrams for the luminous stars in the Milky Way and LMC.

It is clear from comparison of the HR diagrams that the luminous star populations in both galaxies have similar distributions of luminosities and spectral types. They have several important features in common: (1) a group of intrinsically very luminous hot stars, (2) a lack of supergiants of later spectral type at these high luminosities, and (3) an upper envelope to the luminosities of the late-type supergiants at about $M_{Bol} = -9.5$ mag. The LMC and the solar region of the Milky Way have essentially the same upper envelopes to their stellar luminosities.

Figure 3 in Humphreys (1984) shows the same HR diagram for the SMC, and it is immediately apparent that there are significant differences with the luminous star populations in the LMC and Milky Way. The hottest, most luminous stars in the SMC are fewer in number and are noticeably less luminous than stars of comparable temperatures in the solar region and the Large Cloud, but the large scale features of the HR diagram are similar to the LMC and Milky Way. It is especially important that the upper luminosity boundary for the late-type supergiants is the same in all three galaxies.

The data in Table 2 summarizes the bolometric luminosities for the individual most luminous stars in three broad spectral type groups (early, intermediate and late). The most luminous stars are of course the O-type stars and early B-type supergiants. This table confirms our impressions from the HR diagram that the most luminous stars are comparable in the Large Cloud and Milky Way but significantly fainter in the SMC. Comparison of the luminosities for the intermediate (F-K) type and late (M) type supergiants shows the constancy of their upper luminosity boundary ($M_{Bol} \simeq -9.5$) also mentioned earlier. There are no known high luminosity yellow supergiants in the SMC.

We are also interested in the visually brightest supergiants because of their potential usefulness as distance indicators. The individual visually brightest stars are listed in Table 3 in three spectral type groups. The visually brightest star in each galaxy is an A-type supergiant. The lack of visually bright stars ($M_V \leq -9.0$) in the SMC is very likely due to fewer progenitors evident from its HR diagram. The brightest F-K type supergiants are also comparable in both the LMC and Milky

Table 2

The Most Luminous Stars in the Milky Way and the Large and Small Magellanic Cloud

Star	Sp. Type	M_{Bol}	Star	Sp. Type	M_{Bol}	Star	Sp. Type	M_{Bol}
HD 93129a	O3 If	-11.0	HDE 268743	O6:nn	-11.0	Sk 8	O9 +neb	-10.4
Cyg OB2 #9	O5 I	-10.9	HDE 269936	O9.5I	-11.0	Sk 80	O7 Iaf	-10.3
+40 4227	O6 Ib	-10.6	HDE 269896	ON9.7Ia+	-10.9	Sk 159	B0 Ia	-10.2
HD 151804	O8 Iaf	-10.5	HDE 269810	O3 If*	-10.6	Sk 157	O9.5 III	-10.1
HD 15570	O4 If	-10.4	HDE 270952	O6 Iaf+	-10.6	Sk 18	O7 +neb	-10.1
HD 93250	O3 V	-10.4	HDE 35517	B0 I	-10.6			
HR 8752	G0-G5 0-Ia	-9.6 to -9.4	HDE 268757	G7 0	-9.4			
RW Cep	K0 0-Ia	-9.6	HDE 269723	G4 0	-9.3			
HR 5171a	G8 0-Ia	-9.5	HDE 269953	G0 0	-9.2			
ρ Cas	F8 pIa	-9.4	HDE 271182	F8 0	-9.0			
HD 96918	G0 Ia+	-9.2	HDE 270046	G0 Ia	-9.0			
μ Cep	M2 Ia	-9.4	MG 46	-	-9.4:	Case 107-1	K5-M0 Ia	-9.0
KY Cyg	M2 Ia	-9.2	Case 46-44	M1 Ia	-9.2	HV 2084	M2 Ia	-8.8
HD 143183	M3 Ia	-9.1	Case 39-33	M4 Ia	-9.1	HV 11423	M0 Ia	-8.7
BD+24°3902	M1 Ia	-8.9	Case 46-32	M0 Ia	-9.0	Case 118-15	M0 I	-8.7
			Case 46-2	M2 Ia	-8.9	Case 106-1A	M0 Ia	-8.7

Table 3

The Visually Brightest Stars in our Galaxy and the Large and Small Magellanic Clouds

Milky Way			LMC			SMC		
Star	Sp. Type	M_V	Star	Sp. Type	M_V	Star	Sp. Type	M_V
Cyg OB2 #12	B8 Ia-0	-9.4 to -9.9	HD 33579	A3 Ia-0	-9.8	HD 7583	A0 Ia-0	-9.2
ζ Sco	B1.5 Ia+	-8.7	HD 32034	B9 Iae	-9.2			
HD 134959	B2 Ia+	-8.5	HDE 269647	A0 Ia	-9.0			
α Cyg	A2 Ia	-8.4	HDE 270086	A1 Ia-0	-9.0			
β Ori	B8 Ia	-8.4	HDE 269546	B5 Ia	-9.0			
ρ Cas	F8p Ia	-9.5	HDE 269953	G0 0	-9.2			
HR 8752	G0-G5 0-Ia	-9.4	HDE 271182	F8 0	-9.1			
RW Cep	K0 0-Ia	-9.4	HDE 269723	G4 0	-9.1			
HR 5171	G8 0-Ia	-9.2	HDE 268757	G7 0	-9.1			
HD 96918	G0 Ia+	-9.2	HDE 270046	G0 Ia	-9.0			
μ Cep	M2 Ia	-8.2	Case 46-32	M0 Ia	-8.1	Case 107-1	K5-M0 Ia	-8.2
KY Cyg	M3 Ia	-7.6	Case 46-44	M1 Ia	-8.0	HV 1475	K0-K5 Ia	-8.2
HD 143183	M3 Ia	-7.6	Case 46-39	M1 Ia	-7.7	HV 11423	M0 Ia	-7.7
BD+24°3902	M1 Ia	-7.5	Case 45-38	M1 Ia	-7.7	Case 118-15	M0 I	-7.7
			Case 46-2	M2 Ia	-7.5	Case 106-1A	M0 Ia	-7.6

Way. The brightest M supergiants are very important, because not only are their bolometric luminosities nearly constant, but so are their visual luminosities. The M supergiants have M_V's near -8 mag even in the SMC which lacks the most luminous blue stars and is a much smaller, less massive galaxy.

The visually brightest stars in other members of the Local Group, for which spectra are available (Humphreys 1980a,b), are also all late B or A-type supergiants. Figure 1 in Sandage and Tammann (1982) and in Humphreys (1983b), respectively, show the well known dependence of the brightest star on the luminosity of the parent galaxy. In addition, spectra have been taken of a few candidates in the more distant galaxies NGC2403 and M101, and A-type supergiants have been identified in each (Humphreys 1980c).

As we have already seen for the SMC, the most massive, most luminous stars in the fainter, smaller galaxies are both fainter and fewer in number. As their number decreases in a galaxy, the probability of finding A-type supergiants at a certain luminosity should also decrease. Where there are fewer of the most massive stars the visually brightest stars should be less luminous; consequently, there should be a similar relation between M_{Bol} and galaxy luminosity (Fig. 2 in Humphreys 1983b). This correlation for the most luminous stars suggests that the relation for the visually brightest stars is due to differences in the massive star populations (>50-60 $M_\odot$).

In contrast, the situation for the brightest red supergiants is very different. We have already noticed their constancy in both bolometric and visual luminosity in the Milky Way and the Magellanic Clouds. Figure 4 in Humphreys 1983 shows luminosities for the brightest M supergiants in six Local Group galaxies covering a range of nearly six magnitudes in galaxy luminosity. This very tight luminosity calibration is not fortuitous. It is a consequence of massive star evolution which is discussed at the conclusion of this paper.

I have been discussing the basic characteristics of the most luminous known stars with normal spectroscopic and photometric properties. There is also a group of very luminous stars which are distinguished by their emission line spectra and often by their variability which for some stars is often explosive. These stars are known variously as the η Car or S Dor type variables and the Hubble-Sandage variables in M31 and M33. Their spectra are characterized by emission lines of hydrogen, HeI, HeII, FeII and [FeII], many with P Cygni line profiles. Obviously not all of these emission lines are observed in all of the stars. For example, the FeII and [FeII] are most often reported at minimum light. Many of these stars display irregular variability consisting of extended maximum and minimum phases, frequently lasting several years.

In recent years, primarily as a result of ultraviolet (IUE) and infrared observations we have learned considerably more about these peculiar stars and have much greater insight into their important role in massive star evolution. Information on their temperatures and total luminosities have been determined by many investigators: η Car, Pagel (1969), Davidson (1971), Neugebauer and Westphal (1968, 1969), Robinson et al. (1973), Gehrz et al. (1973) and Hyland et al. (1979); P Cyg, Cassatella et al. (1979), Underhill (1979), and Lamers et al. (1983); S Dor, R 71, and R 81 in the LMC, Wolf et al. (1980, 1981a,b) and Appenzeller and Wolf (1981); and for the Hubble-Sandage variables in M31 and M33, Humphreys (1975, 1978b), Gallagher et al. (1981), Humphreys et al. (1984). All of these stars are shown to be hot, very luminous evolved massive stars with mass loss rates of 10^{-3} to 10^{-5} $M_{\odot}$/yr. Most recently, Shore and Sanduleak (1984) have studied spectroscopically the extreme emission line stars in the LMC and SMC and find that they have temperatures and luminosities that place them in the same regions of the HR diagram as their better known counterparts listed above.

Figure 1 is the composite HR diagram for the most luminous known stars ($L \geq 5 \times 10^5$ $L_{\odot}$, $M_{Bol} \leq -9.0$ mag) in our galaxy, the Magellanic Clouds, M33 and NGC6822 and IC1613. The most significant feature of this HR diagram is the observed upper envelope to the luminosities of normal stars (Humphreys and Davidson 1979, 1983, Humphreys 1983). This luminosity boundary declines with decreasing temperature for the hotter stars, but becomes essentially constant for the cooler supergiants. The peculiar emission-line luminous stars are shown on this HR diagram and some of the more famous ones are identified by name. The possible location of R136a, if it is single (Savage et al. 1983), and the proposed supermassive Wolf-Rayet stars in M33 (Massey and Hutchings 1983) are also indicated. The evolutionary tracks are from Maeder (1981, 1983).

In the past decade our ideas about the interior structure and evolution of the most massive stars have been radically altered. We now routinely talk about the effects of mass loss, internal mixing and convective overshooting on the evolution of the most massive stars. The upper luminosity boundary and the basic features of the observed HR diagram can be explained by models with high mass loss and internal mixing in which stars >60 $M_{\odot}$ encounter an instability limit which prevents further evolution to cooler temperatures. This boundary known as the 'de Jager limit' (de Jager 1980) involves turbulence and has been discussed in some detail by Maeder (1983). It may be the physical explanation for the tight upper limit to the M supergiant luminosities. Stars that we know to have suffered dramatic instabilities such as η Car and probably Var A in M33 are near or even above the observed "limit" for normal stars. They are stars that have already reached the critical stage in their evolution in which drastic mass loss is the consequence of the star's approach to the instability limit. It is likely that all stars above >60 $M_{\odot}$ pass through a similar critical phase. Very likely, all of the peculiar emission line stars shown in this HR diagram are either approaching or have already passed this stage. A star may even bounce recurrently on the critical line (Davidson 1983, Humphreys and Davidson 1983). When the star has evolved to this limit, the instability causes an outburst ejecting a fraction of the star's mass. The star then moves away from the critical limit and temporarily relieves

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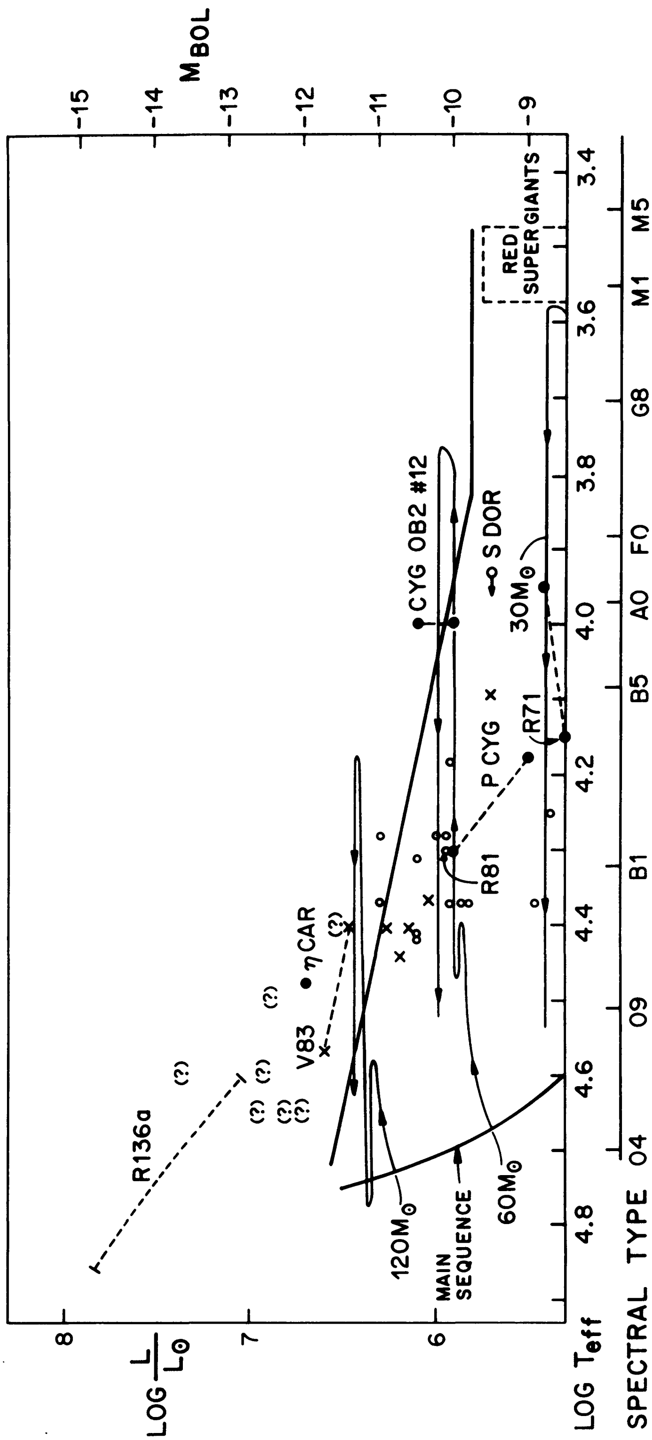

Figure 1 - A schematic HR diagram for the most luminous stars ($L \geq 5 \times 10^5\ L_\odot$). The empirical upper luminosity boundary for normal stars is shown by a solid line. The location of the S Dor or Hubble-Sandage variables are shown and some of the individual stars are indicated. The possible 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).

the instability, but then in a few centuries or decades, it evolves back to the limit, and so on, perhaps until the star is reduced to a Wolf-Rayet star, unless it becomes a supernova first.

The most luminous, most massive stars are not merely brilliant beacons in distant galaxies to be observed only as curiosities or as possible distance indicators; they are important astrophysical laboratories where interesting and often unexpected phenomena are occurring.

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DISCUSSION

Lequeux: I fully agree with the small-number statistics explanation Maeder, Schild, and you give for the apparent lack of extremely bright blue-yellow stars in the SMC. As to the red stars, this effect is compensated by the following effect. Smaller irregular galaxies have lower abundances, hence probably lower stellar mass-loss rates. As discussed by Maeder, Azzopardi, and myself in 1981, this enhances the lifetime of the M supergiant stage and raises the upper mass (thus luminosity limit) where a star can become a M supergiant. Thus we encounter relatively more M supergiants, and brighter ones, in small, low metallicity galaxies and this may explain why you find the upper luminosity of M supergiants independent on that of the galaxy. To be quantitative there are about 6 times less blue-yellow supergiants in the SMC than in the LMC while there are only about 3 times less M supergiants according to the recent Marseille surveys.

Humphreys: Yes, that is correct. The M_{bol} luminosities for the M supergiants are beginning to show a decline between the spiral galaxies and LMC and the irregular galaxies (SMC, NGC6822, and IC1613) very likely due to the smaller population of blue star progenitors. So the lower metallicity in these galaxies does not completely compensate for the smaller sample size in these galaxies. The lower metallicity also produces a shift in the Hayashi track to warmer temperatures resulting in a shift to earlier spectral types for the M supergiants which is observed very dramatically for the SMC red supergiants. This results in a generally smaller bolometric correction so that although the maximum M_{bol} for these stars is slightly lower, the M_V's are still near -8 mag. These two effects are discussed in Humphreys (1983b).

Friedjung: How sure are you that Hubble-Sandage variables belong to the same class? Eta Carinae had a more dramatic behaviour than other stars you mentioned.

Humphreys: No. I do think they are all massive (> 40 $M_\odot$), unstable stars very likely evolving to the Wolf-Rayet stage. Eta Carinae probably represents the upper mass, upper luminosity end of this group of unstable blue stars. Eta Carinae's behaviour was dramatic, but it may not be unique. Var A in M 33 has a light curve which very closely resembles that of Eta Carinae in the 19th century. It also now possesses a circumstellar dust shell.

Hutchings: Please comment on the number count ratios of Blue and Red supergiants and whether this relates to stellar wind differences among galaxies.

Humphreys: The Blue to Red supergiant number ratio does vary with galactocentric distance and from the Galaxy to the LMC and SMC. The B/R ratio gets smaller and this variation is usually presumed to be an indicator of the decreasing metallicity in our galactic disk and the LMC and SMC. One should be careful when using B/R ratios as metallicity indicators, they can be influenced by variations in the IMF. The B/R ratio also depends very much on the luminosity interval being used. We can't just lump all of the blue and red stars together for a meaningful B/R ratio (see Humphreys 1984).

Aaronson: Sandage believes now that the luminosities of the richest M supergiants do depend on parent galaxy luminosity. In some cases he assigns M_V(max) closer to -9, rather than -8. Could you comment on this?

Humphreys: The luminosity calibration depends on the distance used for the galaxy. For M 33 Sandage (1983) now says $M_V \simeq -8.7$ mag for the brightest M supergiants within his new distance modulus of 25.3 mag which assumes little or no reddening. Madore (1983) has a preliminary modulus of 24.6 to 24.7 mag from infrared (H) observations of the Cepheids. I used his distance modulus, corrected to the old Hyades scale, to derive the luminosities of the red supergiants. The difference between these two distance moduli may be due to reddening of at least 0.6 to 0.7 mag in the visual. If this is the case, there is also $\simeq$ 0.1 mag of reddening at H. Jones, Sitko and I very recently obtained JHK photometry of the known M supergiants and find that most of them are reddened by $\simeq$ 1 mag (A_V). Sandage has also very recently identified bright red supergiant candidates in M 101. He finds his brightest red stars somewhat brighter than those found by Humphreys and Strom (1983) and says that $M_V \simeq -8.9$ mag in M 101. We (Aaronson, Strom, Capps, Lebofsky and Humphreys) have observed 6 of Sandage's 7 brightest candidates in the infrared (JHK). Four are M dwarfs, one is an M supergiant and one is uncertain. The brightest M supergiants therefore are at about V $\simeq$ 20.6 to 20.7 mag. Their corresponding visual luminosities will depend on the distance to M 101 which, in my opinion, is very uncertain.

I suspect that the luminosities of the brightest M supergiants do decrease in galaxies less luminous than IC 1613. I doubt if $M_V \simeq -8$ mag is true for galaxies fainter than IC 1613.