The Blue-to-Red Supergiant Ratio of Galaxies*

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Abstract

Modern color-magnitude diagrams (CMDs) of nearby galaxies are now of such high quality that they can be used to adress long-standing disagreements between observation and stellar-evolution theory. There is one piece of good news for theory: modern CMDs now exhibit a clear separation between the main sequence (MS) and blue, core-He-burning (BHeB) stars. This is the previously "missing" blue gap. Photometric data can thus be used to furnish a BHeB count without substantial MS (+BSG) contamination. However, supergiant counts based on even these modern CMDs struggle with small number statistics, and various other complications such as the potentially severe contamination of red supergiant (RSG) counts by asymptotic-giant-branch (AGB) stars. We provide luminosity functions for BHeB and RHeB stars for two extremely metal-poor dwarf galaxies using HST photometry. We find that the B/R frequency for massive stars determined from these CMDs is as low as that previously derived with photometry and spectroscopy for SMC supergiants by Humphreys (1983). This supports the idea that the B/R frequency at low metallicity is small. We also comment on evolutionary scenarios for Wolf-Rayet (WR) stars using the approach of Massey (1998).

1 Introduction

Young massive stars are such a luminous component of galaxies that they are increasingly used to probe galaxy evolution out to high redshift. Yet, a very basic problem remains in our understanding of the evolution of massive stars and their distribution across the Hertzsprung-Russell diagram (HRD). Observations indicate that the blue-to-red supergiant (SG) ratio decreases with decreasing metallicity (see Table 6 of Humphreys 1983). Yet, stellar-evolution models have not been able to predict this behavior (e.g. Langer & Maeder 1995, Maeder & Meynet 2000). Predicting the exact location of the post-MS core-He burning SGs on the HRD turns out to be a tough problem, because the core-He burning phase splits into two stages at low $T_{\rm eff}$ and high $T_{\rm eff}$, as RHeB star belonging to the RSG population and as BHeB star belonging to the BSG population. The lifetimes at low $T_{\rm eff}$ and at high $T_{\rm eff}$ provide the theoretically expected B/R frequency. The predicted B/R frequency depends critically on the internal mixing prescriptions used, as well as on the assumed mass-loss and the rotation rate of the star. These properties in turn are sensitive to the stellar metallicity. On the other hand, the data which have pointed to the discrepancy between observation and theory are quite sparse; usually only B/R frequencies for the MWG, LMC, and SMC based on Humphreys' work in the early 80s are considered. New empirical data which can further our understanding of massive-star evolution are now in hand, and are discussed in this paper.

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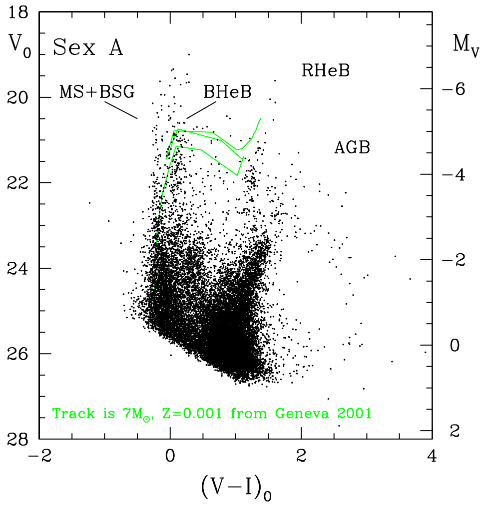

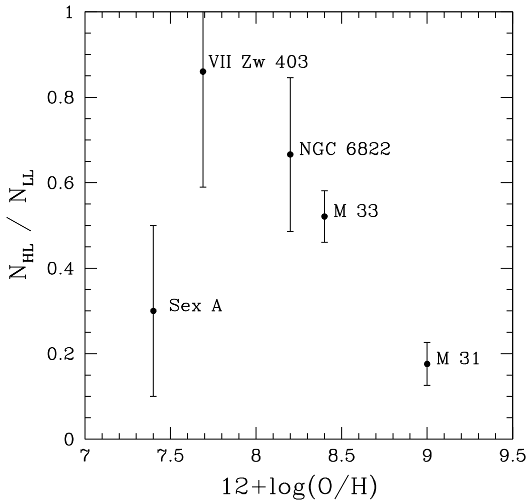

Figure 1: The HST CMD of Sex A from Dohm-Palmer et al. (1997a). The gap between MS+BSG stars, and the blue stars at the blue edges of their blue loops, labeled BHeB, is clearly seen. The track is from D. Schaerer's WWW page.

Figure 2: Using the LF along the red plume for presumably mainly RHeB stars, we derive a ratio of high- to low-luminosity RHeB stars, $N_{\rm HL}/N_{\rm LL}$. The $N_{\rm HL}/N_{\rm LL}$ ratios and oxygen abundances for NGC 6822, M 33, and M 31 were taken from Massey (1998).

2 First the Good News: The Blue Gap Is Seen

For quite some time, it has been thought that observations do not support the presence of the predicted blue gap on the HRD between the core-H and the core-He burning phases at high $T_{\rm eff}$, when stars hover at the blue edges of their blue loops. Fitzpatrick & Garmany (1990), for instance, used photoelectric photometry (dating back to the late 60s) to show that the distribution of stars on the HRD of the LMC is quite continuous beyond the MS, without a blue gap near the MS. Theorists have carried the burden of explaining this perceived discrepancy ever since (e.g. Deng, Bressan & Chiosi 1996; Salasnich, Bressan & Chiosi 1999).

The missing "Blue Hertzsprung Gap" is nowadays seen on modern CMDs. The best observational example to date is the HST CMD of Sex A (Dohm-Palmer et al. 1997a), reproduced as Fig. 1. The blue gap was also noticed in the HST CMD VII Zw 403 by Schulte-Ladbeck, Crone & Hopp (1998); another case is the VLT CMD of Aquarius by Tolstoy et al. (2000). However, the blue gap is not seen on all high-quality CMDs; we explain this with observational biases, and not with an intrinsic absence of the gap.

Two pre-requisites for detecting the blue gap on the CMD of a galaxy are low differential extinction and low crowding of stellar images in the star-forming regions. Furthermore, our ability to see the gap in modern photometric data results mainly from a) the high spatial resolution which reduces blending of stellar images – the gap is seen in HST data and in VLT data taken under excellent seeing conditions – and b) the high precision of CCD data – this reduces the color errors. Fig. 5 of Gallart et al. (1996) is an instructive illustration of how crowding and extinction make the blue gap "disappear" in the CMD of NGC 6822.

We conclude that the problem of the missing blue gap in older data is now explained.

3 Complications in Determining the B/R Frequency

Unfortunately, there is a large number of complicating factors which affect the accuracy of BHeB and RHeB counts even using modern CMDs. Some of these were already discussed by Brunish, Gallagher & Truran in 1986, and their concerns remain relevant today.

Foreground contamination: Care must be taken to eliminate Galactic foreground contamination of CMDs, in particular by the abundant K and M dwarfs. The removal of foreground stars from CMDs using just the available photometry is not possible on a star-by-star basis, and so CMDs are generally contaminated. The foreground contamination may be minimized by observing galaxies at high Galactic latitude.

Incompleteness: The tight spatial clustering of MS and BSG stars may lead to incompleteness due to crowding. Accurate starcounts cannot be recovered in such cases.

Spatial biasing: RSGs and BSGs tend to have different spatial distributions. This can be seen qualitatively in Fig. 1 of Schulte-Ladbeck, Crone & Hopp (1998). The difference in distribution of BHeB and RHeB stars in Sex A is illustrated by Fig. 17 of Dohm-Palmer et al. (1997b). Part of the difference in spatial distribution is probably due to age differences. Spatial biasing may affect star counts when the field of view of the observations does not encompass completely the corresponding BHeB and RHeB populations.

Color biasing: CMDs in V and I bands are well suited to detect both BSGs and RSGs. Blue-UV CMDs can miss RSGs (see the contribution by Schulte-Ladbeck et al. in *this volume*), leading to a color biasing of the starcounts.

Star-formation history: Work on the blue-to-red supergiant ratio has generally been performed in the field of galaxies (e.g. in a series of papers by Humphreys and collaborators) and rarely in star clusters (Meylan & Maeder 1982). Galaxies are not simple stellar populations. The B/R frequency will depend on modulations in the star-formation rate over the past few hundred Myr. Only if the SFR was constant can we expect that the B/R frequency is a result of stellar evolution, only. While many dwarfs show SF over extended periods of time, modulations by an order of magnitude on short time scales cannot be excluded (see Tosi et al. and Schulte-Ladbeck et al. in *this volume*).

Track crossings: According to the tracks, there is a degeneracy in the location of SGs on CMDs. The BHeB region is crossed by shell-H burning BSG stars, while the RHeB region is also crossed by core-C (etc.) burning RSG stars (Fig. 1, also Fig. 3 and 4 of Dohm-Palmer et al. 1997b).

AGB contamination: Many modern CMDs show that intermediate-mass, double-shell burning AGB stars in the E-AGB and the TP-AGB phases are a significant stellar component of dwarf galaxies (e.g. Schulte-Ladbeck et al. 1999). Any RSG luminosity function (LF) will be increasingly contaminated by AGB stars at lower luminosity. This effect becomes very severe at $M_{\mathrm{V}} = -4.5$.

Stochastic variations: Starcounts of the rare, luminous stars are strongly affected by stochastic variations (Schild & Maeder 1983, Greggio 1986).

Metallicity: In the argument that the B/R frequency is a function of metallicity, one uses the oxygen abundance of the interstellar medium to represent the stellar metallicities. Whether or not this assumption is correct may soon be known, since spectroscopic observations of luminous stars in external galaxies are now being obtained with large ground-based telescopes (Kudritzki &Puls 2000).

Binarity: Comparison of stellar evolution tracks with B/R fractions has generally not accounted for effects of binarity.

4 The B/R Frequency of Sex A and VII Zw 403

Sex A is a good case to study, because it has an excellent HST-based CMD in V and I (Dohm-Palmer et al. 1997a). The distance is well known, $m - M = 25.8$, and this galaxy is at high Galactic latitude, almost 40°. The ISM abundance 12+log(O/H) is 7.49 (Skillman, Kennicutt & Hodge 1989), or only about 4% of Solar, lower even than the SMC. In Table 1, we give the observed LF derived from the data shown in Fig. 1, for the MS(+BSG), BHeB and RHeB stars (keeping in mind the above caveats). Unfortunately, Sex A does not contain many luminous stars, and so the errors (square root of the counts) are large. In Sex A, stars were counted as MS+BSG if $-0.6 < (V - I)_0 < -0.1$, as BHeH if $-0.1 < (V - I)_0 < 0.3$ and as RHeB if $1.3 < (V - I)_0 < 1.65$. We also performed starcounts in VII Zw 403 ($12 + \log(\mathrm{O/H}) = 7.69$, Izotov & Thuan 1999) on the data of Schulte-Ladbeck et al. (1999), but these data show not nearly as clean a separation between BHeB and MS stars as the Sex A data. VII Zw 403 is quite distant ($m - M = 28.23$). It is also at a high Galactic latitude and exhibits low foreground contamination. In this case, stars were counted as MS+BSG if $-0.6 < (V - I)_0 < -0.2$, as BHeH if $-0.2 < (V - I)_0 < 0.4$ and as RHeB if $1.2 < (V - I)_0 < 1.95$. Both data sets are highly complete to $M_{\mathrm{V}} = -4.5$, the cut-off magnitude used for the LFs. We do not investigate the LFs above $M_{\mathrm{V}} = -4.5$ because of the obvious severety of AGB contamination. We do not count as either BHeB or RHeB stars the few yellow SGs seen on either CMD.

We give the data in M_{V} bins and do not worry for the moment about bolometric corrections. Low-metallicity tracks loop quite parallel to the color axis (see Fig. 1 and tracks in Fig. 3 & 4 of Dohm-Palmer et al. 1997b), and the blue and red counts in a given M_{V} bin pretty much count stars in a corresponding mass interval. Tracks are very steep for the MS through BSG phases, and the same bin here encompasses stars of a different mass interval. The starcounts are nevertheless provided in Table 1 so as to account for the size of the signal which could in principle confuse any starcounts of the BHeBs.

If we form the total B/R ratio for all stars below $M_{\mathrm{V}} = -4.5$, we are approximately including all stars above about a mass of 7 $M_\odot$ (Fig. 1). The resulting B/R frequencies are: for Sex A, 4.4±1.4 and for VII Zw 403, 3.0±0.5. These frequencies compare extremely well to the ratio of 4.1 which Humphreys (1983) derived for very massive stars in the SMC. For comparison, her LMC ratio is about 8, while her MWG one is about 10–40, depending on location.

5 WR Production

Massey (1998) found an increasing sparsity of the most luminous RSGs in galaxies with increasing metallicity. We used his Fig. 15 to count RSGs more luminous and less luminous than an M_{V} of -5.5, and formed the ratio $N_{\mathrm{HL}}/N_{\mathrm{LL}}$ as an indicator of the above effect. The upper limit of the N_{LL} bin was chosen at $M_{\mathrm{V}} = -4.5$ to minimize AGB contamination. Massey's data are highly complete to this magnitude limit. Fig. 2 illustrates the progression he is referring to. He interprets it to indicate that at low metallicity, most of the most luminous stars spend their lives as RSGs. In high-metallicity environs, on the other hand, he suggests that the evolution to the WR stage is favored due to high mass loss. Therefore the RSG LF at high metallicity is more quickly depleted of the most luminous RSGs than that at low metallicity.

We added our data from Table 1 to Fig. 2. As can be seen, the trend noticed by Massey continues for VII Zw 403 (as an aside, we note that the bolometric LF of the RSGs can be found as Fig. 13 of Schulte-Ladbeck et al. 1999). The situation is no longer clear for Sex A. Sex A, just like M 31, appears to lack the most luminous RSGs. This may well be due to the expected large stochastic variations in SG numbers in such a low-luminosity galaxy. In other words, the low $N_{\mathrm{HL}}/N_{\mathrm{LL}}$ ratio in Sex A may not have anything to do with mass-loss effects in its massive stellar component. A better comparison of $N_{\rm HL}/N_{\rm LL}$ would use only galaxies of similar luminosity.

6 Conclusions

There are two main conclusions which arise from the study of massive stars on modern CMDs. First, the missing blue gap has been seen in several CMDs of low-extinction dwarf galaxies. Its absence in older data can be explained with extinction, crowding, and poor data quality. Second, the CMDs of two low-metallicity galaxies expand on Humphrey's result for the SMC that indeed, the B/R frequency is low at low metallicity.

As archival databases of good-quality CMDs grow, we will be able to say more about the properties of the blue gap, and about the B/R frequency in a range of different environments. It would be particularly interesting to add a few measurements for galaxies with metallicities similar to that of the MWG.

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Table 1

Galaxy	Sex A			VII Zw 403		
$-M_{\rm V}$	MS+BSG	BHeB	RHeB	MS+BSG	BHeB	RHeB
8.5-8.01	0	0	0	0	3	0
8.0-7.51	0	0	0	0	0	0
7.5-7.01	0	0	0	0	3	2
7.0-6.51	0	1	0	1	9	2
6.5-6.01	1	8	1	2	21	6
6.0-5.51	4	5	2	6	22	9
5.5-5.01	6	11	1	26	28	9
5.0-4.51	9	32	9	37	37	13

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