A&A 386, 576–582 (2002)
DOI: 10.1051/0004-6361:20020262
© ESO 2002

Astronomy
&
Astrophysics

The blue to red supergiant ratio in young clusters at various metallicities

P. Eggenberger, G. Meynet, and A. Maeder

Geneva Observatory CH–1290 Sauverny, Switzerland
e-mail: `Georges.Meynet@obs.unige.ch`, `Andre.Maeder@obs.unige.ch`

Received 6 December 2001 / Accepted 18 February 2002

Abstract. We present new determinations of the blue to red supergiant ratio (B/R) in young open clusters at various metallicities. For this purpose, we examine the HR diagrams of 45 clusters in the Galaxy and of 4 clusters in the Magellanic Clouds. The identification of supergiants is based on spectroscopic measurements (with photometric counts to check the results). The new counts confirm the increase of the B/R ratio when the metallicity increases with the following normalized relation: $\frac{B/R}{(B/R)_\odot} \cong 0.05 \cdot \mathrm{e}^{3\frac{Z}{Z_\odot}}$, where $Z_\odot = 0.02$ and $(B/R)_\odot$ is the value of B/R at $Z_\odot$ which depends on the definition of B and R and on the age interval considered (e.g. for spectroscopic counts including clusters with $\log age$ between 6.8 and 7.5, $(B/R)_\odot \cong 3$ when B includes O, B and A supergiants).

Key words. stars: evolution – stars: supergiants – galaxies: Magellanic Clouds

1. Introduction

The variation with metallicity Z of the number of blue and red supergiants is important in relation to the nature of the supernova progenitors in different environments (Langer 1991a,b) and its effects on the luminous star populations in galaxies (e.g. Cervino & Mas-Hesse 1994; Origlia et al. 1999). This ratio also constitutes an important and sensitive test for stellar evolution models, because it is very sensitive to mass loss, convection and mixing processes (Langer & Maeder 1995). Stellar evolution models can usually, by adjustement of parameters such as the rate of mass loss by stellar winds, reproduce the observed ratio for a given metallicity, but are not able to reproduce its variation with the metallicity. Thus, the problem of the blue to red supergiant ratio (B/R ratio) remains one of the most severe problems in stellar evolution.

Since the last studies of the B/R ratio in the Galaxy and in the Magellanic Clouds more than fifteen years ago (Meylan & Maeder 1982; Humphreys & McElroy 1984), many new spectroscopic and photometric measurements have been performed. Our aim here is to reexamine this question accounting for these recent observational improvements. We chose to use stellar clusters instead of field stars for obvious reasons: stars are at the same distance, with the same age and above all have the same chemical composition. Moreover, the knowledge of the age of the clusters enables us to estimate the initial masses of the supergiants used to derive the B/R ratio.

Thus, the present work is in the continuity of the work of Meylan & Maeder (1982). However, the present study presents two significant improvements. First, the identification of supergiants is based on spectroscopic measurements instead of on photometric colours. Spectroscopic measurements allow a more accurate differentiation between supergiants and main sequence stars (see however the discussion in Sect. 4). Second, the number of stellar clusters in our galactic sample is increased by a factor of four.

In Sect. 2, we review the various studies about the B/R ratio. Section 3 presents the new counts. Our results are discussed in Sect. 4, and conclusions are given in Sect. 5.

2. Previous studies

Walker (1964) observed that the B/R ratio in M 33 decreases when the distance to the centre of the galaxy increases. Van den Bergh (1968) explained this variation by a radial metallicity gradient in the disk of M 33, the metallicity being higher in the inner parts. Humphreys & Sandage (1980) reexamined the B/R ratio in M 33 and confirmed its decrease when the galactocentric distance increases. Freedman (1985) contested the results of Humphreys & Sandage (1980) concerning the variation of the B/R ratio in M 33 and concluded that this was

---

Send offprint requests to: P. Eggenberger,
e-mail: `eggenbe7@etu.unige.ch`

Article published by EDP Sciences and available at http://www.aanda.org or
http://dx.doi.org/10.1051/0004-6361:20020262

just an effect of incompleteness. However, Ivanov (1998) concluded that the diminution was real and was in good agreement with the radial metallicity gradient observed in M33 (McCarthy et al. 1995).

Hartwick (1970) noticed the decrease of the B/R ratio in the Milky Way as the galactocentric radius increases. Robertson (1973, 1974), Hagen & van den Bergh (1974) compared theoretical evolutionary tracks to observed HR diagrams (HRD) of stellar clusters in the Galaxy and in the Large Magellanic Cloud (LMC). They attributed the observed differences between the HRD to differences in the metal content.

Humphreys (1979a) investigated the variation of the B/R ratio in the LMC. She concluded that the radial variation of this ratio must be weak or absent, in agreement with the study of the chemical composition of the HII regions made by Pagel et al. (1978). In a study of the supergiants in the Galaxy and in the LMC, Humphreys & Davidson (1979) found a decrease of the B/R ratio when the metallicity decreases. Cowley et al. (1979) examined the variation of the B/R ratio across the face of the LMC and found that it increases by a factor of 1.8 when the metallicity increases by a factor of 1.2.

The first study of the B/R ratio using stellar clusters in the Galaxy, the LMC and the SMC (Small Magellanic Cloud) was made by Meylan & Maeder (1982), who concluded to a steep increase of B/R when the metallicity increases, with a difference of about an order of magnitude in B/R between the Galaxy and the SMC. Humphreys & McElroy (1984) reexamined the B/R ratio in the Galaxy, the LMC and the SMC, and gave new values which accounted for the incompleteness of the data. They found a B/R ratio about ten times higher in the central parts of the Galaxy than in the SMC.

Langer & Maeder (1995) summarized some results about the values of the B/R ratio and gave a B/R ratio approximately six times larger in the solar neighborhood than in the SMC. After comparison of different stellar models with observations, they concluded that most massive star models have problems reproducing the decrease of B/R when the metallicity decreases. Deng et al. (1996) used the supergiant stars catalogue from Blaha & Humphreys (1989) to make new counts in the Galaxy and in the LMC. They found a B/R ratio about five times higher in the Galaxy than in the LMC.

To summarize the B/R ratio appears to be an increasing function of metallicity. This trend is observed by studies in the Galaxy, the Magellanic Clouds as well as in the Triangulum galaxy. In this work we shall take the opportunity of recent improvements brought to our knowledge of Galactic and Magellanic clusters to reexamine carefully this question.

3. Results from new cluster studies in the Galaxy, LMC and SMC

3.1. Spectroscopic counts

We select in the Webda database (Mermilliod 1995; `http://obswww.unige.ch/webda`) young clusters with $\log age$ between 6.8 and 7.5, corresponding to masses at the turn off between 8 $M_\odot$ and 24 $M_\odot$ and to initial masses of the supergiants between about 8 and 30 $M_\odot$ (Meynet et al. 1993). Let us note that this interval of masses for the supergiants probes a region of the HR diagram below the observed upper limit for the luminosity of the red supergiants, i.e. below $M_{\rm bol} \sim -9.5$ (Humphreys & Davidson 1979, 1984).

We only keep the clusters with spectroscopic measurements for the brightest stars in order to distinguish supergiants from main sequence stars. In this way, 45 clusters are selected. For each cluster, we count the number of supergiant stars of spectral type O, B, A, K and M. In a few cases, the spectroscopic class for the same star is different depending on the authors. In these cases, we adopt the most recent determination. The galactocentric distance R of each cluster is calculated from the values of its galactic coordinates and from its distance to the sun given by the Webda database. For each galactocentric radius, a metallicity is associated by taking a value of $Z = 0.02$ at the solar position (we take $\mathrm{R}_\odot = 8.5$ kpc for the solar galactocentric distance) and an averaged radial metallicity gradient of -0.08 dex kpc^{-1}. This value has been chosen from various studies of the galactic gradient determined by means of spectroscopic and photometric indices of stellar populations in open clusters (see the discussion by Alibés et al. 2001).

The results are given in Table 1, where B represents the number of O, B and A supergiants, while R is the number of K and M supergiants. $N_{\rm O}$, $N_{\rm B}$, $N_{\rm A}$, $N_{\rm K}$ and $N_{\rm M}$ indicate the number of supergiants with spectral type O, B, A, K and M respectively. Each cluster age is given in logarithm and taken from the Webda database. The region noted GC refers to the region inside the solar circle and includes all the clusters with a galactocentric distance shorter than 8.5 kpc. Likewise, the GAC region corresponds to the region outside the solar circle and includes the clusters with a galactocentric distance higher than 8.5 kpc.

On the basis of these results, we examined the variation of the B/R ratio with the galactocentric radius by grouping open clusters in different distance bins. In Fig. 1, two different binnings are shown. In the first one, clusters are grouped in three main galactocentric distance intervals (6.5–8.0, 8.0–9.0 and 9.0–11.5 kpc), in order to have the same number of clusters (15) in each bin. We also separate the clusters in five distance intervals (6.5–7.5, 7.5–8.0, 8.0–8.5, 8.5–10.0 and 10.0–11.5 kpc) to check whether the variation of the B/R ratio observed when considering three intervals is still present (due to the small number of supergiants counted for each clusters, it is not pertinent

Table 1. Number of supergiant stars in galactic open clusters with log *age* between 6.8 and 7.5. The quantity R is the galactocentric radius and Z is the metallicity. GC means clusters toward the galactic centre, GAC toward the galactic anticentre. The identification of supergiants is based on spectroscopic measurements. B includes O, B, A supergiants and R includes K, M supergiants (see text).

Cluster	log *age* [y]	R [kpc]	Z	B	R	N_{O}	N_{B}	N_{A}	N_{K}	N_{M}
GC										
NGC 6611	6.88	6.85	0.027	2	0	0	2	0	0	0
NGC 6604	6.81	6.91	0.027	2	0	1	1	0	0	0
Pismis 20	6.86	7.06	0.026	4	0	0	4	0	0	0
NGC 6530	6.87	7.18	0.025	1	0	0	1	0	0	0
NGC 6613	7.22	7.25	0.025	3	0	0	3	0	0	0
Trumpler 27	7.06	7.29	0.025	8	1	1	7	0	0	1
NGC 6231	6.84	7.32	0.025	3	0	2	1	0	0	0
NGC 6664	7.16	7.45	0.024	0	1	0	0	0	1	0
NGC 4755	7.22	7.60	0.024	5	1	0	4	1	0	1
NGC 6514	7.37	7.69	0.023	3	0	0	1	2	0	0
NGC 6823	6.82	7.71	0.023	1	0	0	1	0	0	0
NGC 5281	7.15	7.85	0.023	1	0	0	0	1	0	0
NGC 3603	6.84	7.92	0.022	3	0	2	1	0	0	0
IC 2944	6.82	7.92	0.022	3	1	1	2	0	0	1
NGC 3766	7.16	7.95	0.022	2	2	0	2	0	2	0
NGC 3590	7.23	8.05	0.022	1	0	0	1	0	0	0
Trumpler 18	7.19	8.11	0.021	1	0	0	1	0	0	0
Collinder 228	6.83	8.11	0.021	2	1	1	1	0	0	1
Trumpler 15	6.93	8.14	0.021	1	1	1	0	0	0	1
Bochum 10	6.86	8.14	0.021	1	0	0	1	0	0	0
NGC 6871	6.96	8.17	0.021	2	0	0	2	0	0	0
NGC 3293	7.01	8.18	0.021	2	1	1	1	0	0	1
IC 2581	7.14	8.23	0.021	2	0	0	1	1	0	0
NGC 6913	7.11	8.32	0.021	3	0	1	2	0	0	0
NGC 6910	7.13	8.35	0.021	1	0	0	1	0	0	0
Berkeley 87	7.15	8.37	0.020	0	1	0	0	0	0	1
GAC										
Collinder 135	7.41	8.62	0.020	0	1	0	0	0	1	0
Trumpler 37	7.05	8.67	0.019	5	2	0	4	1	0	2
Collinder 121	7.05	8.77	0.019	4	1	0	4	0	1	0
NGC 1976	7.11	8.83	0.019	0	1	0	0	0	1	0
NGC 7419	7.28	9.05	0.018	0	5	0	0	0	0	5
NGC 7235	7.07	9.53	0.017	1	1	0	1	0	1	0
NGC 2244	6.90	9.81	0.016	0	1	0	0	0	1	0
NGC 2384	6.90	9.86	0.016	1	0	1	0	0	0	0
NGC 663	7.21	9.86	0.016	7	1	0	7	0	0	1
NGC 957	7.04	9.89	0.015	1	0	0	1	0	0	0
NGC 654	7.15	9.91	0.015	1	0	0	0	1	0	0
IC 1805	6.82	9.92	0.015	1	0	1	0	0	0	0
NGC 581	7.34	10.00	0.015	1	2	0	1	0	0	2
NGC 869	7.07	10.07	0.015	6	1	0	6	0	0	1
NGC 457	7.32	10.13	0.015	1	1	0	0	1	0	1
NGC 884	7.03	10.29	0.014	4	5	0	2	2	0	5
NGC 2439	7.25	10.64	0.013	1	1	0	1	0	0	1
NGC 2414	6.98	10.99	0.013	1	0	0	1	0	0	0
Ruprecht 55	6.85	11.12	0.012	1	0	0	1	0	0	0

to adopt a finer binning). The metallicity of each bin is obtained by averaging the metallicities of all the clusters in this bin. We precise here that the metallicities are not obtained from stars in each clusters, but from an adopted metallicity gradient of -0.08 dex kpc^{-1}. In this way, we assign a metallicity for each distance interval mentioned above (e.g. for the GC and GAC region we take respectively $Z = 0.023$ and $Z = 0.016$). The increase of the B/R ratio with the metallicity is shown in Fig. 1 and in Table 3.

In order to obtain values of the B/R ratio for lower metallicities, we select young clusters in the Magellanic Clouds. According to a discussion by Maeder et al. (1999), the average value of the metallicity is $Z = 0.007$ for the LMC and $Z = 0.002$ for the SMC. Without sufficient spectroscopic data for the young clusters of the LMC, it is not possible to give a reliable value for B/R in the LMC. In the SMC, the only cluster satisfying the age criteria and having spectroscopic measurements is NGC 330 (log *age* $= 7.00$ according to Cassatella et al. 1996). This cluster has been well studied and so different values exist for the B/R ratio: $B/R = 7/12$ (Cayrel et al. 1988), $B/R = 9/15$ (Carney et al. 1985; Brocato & Castellani 1992; Bomans & Grebel 1994), $B/R = 12/15$ (Grebel & Richtler 1992). In these ratios, B only includes B supergiants. Thus, the value of the B/R ratio for NGC 330 lies somewhere between 0.5 and 0.8 (when only B supergiants

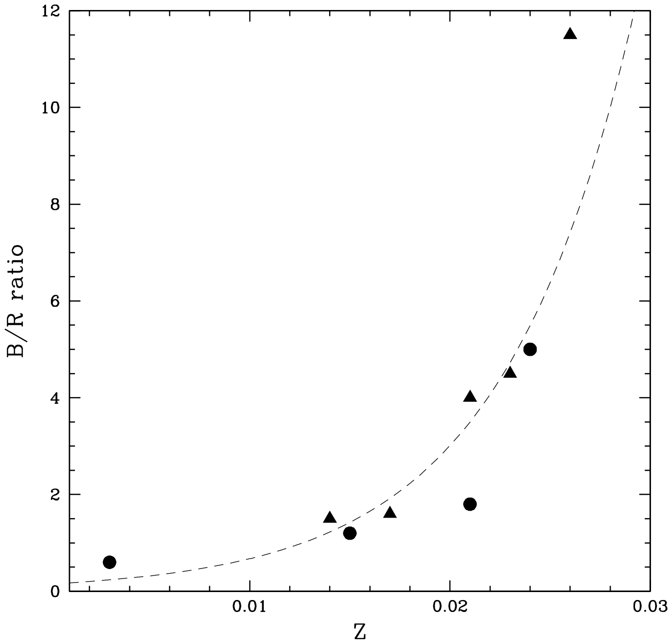

Fig. 1. B/R ratio in the Galaxy and the SMC for clusters with log *age* between 6.8 and 7.5. The distinction between blue and red supergiants is based on spectroscopic measurements. The triangles refer to B including O, B and A supergiants and correspond to five different distance intervals in the Galaxy (6.5–7.5, 7.5–8.0, 8.0–8.5, 8.5–10.0 and 10.0–11.5 pc). The dots refer to B including only B supergiants; they correspond to one value for the SMC and three distance intervals in the Galaxy (6.5–8.0, 8.0–9.0 and 9.0–11.5 kpc). The dashed curve corresponds to the fit for B including O, B and A supergiants with $(B/R)_{\odot} = 3.0$ (see text).

are counted). The value of 0.6 is currently accepted and is reported in Fig. 1.

3.2. Photometric counts

In order to complete counts based on spectroscopic measurements, we perform counts based on colour indices in the same way as Meylan & Maeder (1982). To this purpose, we select among the 45 open clusters mentioned in Table 1, those having photometric measurements down to $M_v = -2$ and with at least 15 stars brighter than this magnitude. Hence 23 clusters are selected. The distinction between blue and red supergiants is made in the following way: when $(B - V)_0 \leq 0$, the star is considered to have a O, B or A spectral type and is included in B, whereas for $(B - V)_0 \geq 1.2$, the star is considered to be a K or a M and is included in R. This distinction remains valid for the SMC, where late-type supergiants are of earlier type than in the Galaxy and LMC (Humphreys 1979b; Elias et al. 1985). We then count all the stars in these two colour intervals down to a certain limit $M_{v\mathrm{lim}}$ of the absolute magnitude. In order to be sure that the results do not depend on the value of this arbitrary chosen limit, the counts are made for four different limits: $M_{v\mathrm{lim}} = -3.25$, $M_{v\mathrm{lim}} = -3.0$, $M_{v\mathrm{lim}} = -2.5$ and $M_{v\mathrm{lim}} = -2.0$. The 23 selected clusters and the results are listed in Table 2. Because of the small number of clusters selected in this case, it is not pertinent to subdivide the clusters in several distance intervals or age intervals, and so we consider all the clusters with log *age* between 6.8 and 7.5 and only the two main regions GC and GAC to calculate the B/R ratio (see Table 3).

For the Magellanic Clouds, we use the data from Elson (1991), except for the SMC cluster NGC 330 (Vallenari 1994). Cluster ages are taken from Cassatella et al. (1996). The same criteria of selection as those used for galactic clusters give a total of 3 clusters selected in the LMC. In the SMC, NGC 330 is the only cluster satisfying both the criteria for age and for the number of stars brighter than $M_v = -2$. The counts are made in exactly the same way as for the Milky Way. The selected clusters and the results of the counts are given in Table 2, while Table 3 summarizes the values of the B/R ratio found in the four main regions (GC, GAC, LMC and SMC). Let us note here that our selected clusters have a mean age approximately the same in the GC, GAC and SMC regions (respectively 7.0, 7.1 and 7.0) which is a nice feature for the comparisons performed here.

From the results for spectroscopic and photometric counts, we find the following average relation:

$$\frac{B/R}{(B/R)_{\odot}} \cong 0.05 \cdot \mathrm{e}^{3\frac{Z}{Z_{\odot}}} \qquad (1)$$

where $Z_{\odot} = 0.02$ and $(B/R)_{\odot}$ is the value of B/R at $Z_{\odot}$ which depends on the definition of B and R and on the age interval considered. For clusters with log *age* between 6.8 and 7.5 (initial masses of the supergiants between ∼8 and 30 $M_{\odot}$), $(B/R)_{\odot} \cong 3.0$ for spectroscopic counts when B includes O, B and A supergiants, and $(B/R)_{\odot} \cong 2.5$ when only B supergiants are counted. For photometric counts, $(B/R)_{\odot}$ equals 17.2, 18.5, 23.0 and 24.0 for $M_{v\mathrm{lim}} = -3.25$, $M_{v\mathrm{lim}} = -3.0$, $M_{v\mathrm{lim}} = -2.5$ and $M_{v\mathrm{lim}} = -2.0$, respectively.

4. Discussion of the results

Figure 1 clearly shows that the present study, based on the most recent spectroscopic measurements found in the literature, confirms the trend already found in previous works, namely the decrease of the B/R ratio with the metallicity. In the Galaxy, B/R is approximately 3 times higher in the GC than in the GAC (Table 3). This variation can also be observed by separating the Galaxy in three or five galactocentric distance intervals. Moreover, the B/R ratio in the SMC confirms the results obtained for the Galaxy, with a value approximately 2 times lower than in the GAC region. Figure 1 shows also that the decrease is stronger at high metallicity than at low metallicity. This is in good agreement with recent results from Massey (2002) who found a B/R ratio only slightly higher in the LMC than in the SMC.

Concerning photometric counts, we can see in Table 3 that B/R is higher in the GC region than in the GAC

Table 2. Number counts down to a limit magnitude $M_{v\mathrm{lim}}$. The values of $(m_v - M_v)_0$ and $E(B-V)$ mentioned for the galactic clusters are from the Webda database (Mermilliod 1995) and from van den Bergh (1998) for the clusters in the Magellanic Clouds. B includes stars with $(B-V)_0 \leq 0$ and R stars with $(B-V)_0 \geq 1.2$ (see text).

					$M_{v\mathrm{lim}} = -3.25$		$M_{v\mathrm{lim}} = -3.0$		$M_{v\mathrm{lim}} = -2.5$		$M_{v\mathrm{lim}} = -2.0$	
Cluster	age	$E(B-V)$	$(m_v - M_v)_0$	Z	B	R	B	R	B	R	B	R
GC												
NGC 6611	6.88	0.78	11.21	0.027	15	0	16	0	21	0	35	0
NGC 6530	6.87	0.33	10.62	0.025	6	0	9	0	13	0	16	0
NGC 6231	6.84	0.44	10.47	0.025	13	0	14	0	16	0	28	0
NGC 4755	7.22	0.39	11.48	0.024	13	1	16	1	28	1	35	1
NGC 6823	6.82	0.85	11.39	0.023	17	0	18	0	30	0	45	0
NGC 3603	6.84	1.34	12.80	0.022	37	2	42	3	63	3	91	6
IC 2944	6.82	0.32	11.27	0.022	13	1	16	1	21	1	25	1
NGC 3766	7.16	0.18	11.21	0.022	5	2	11	2	16	2	23	2
Collinder 228	6.83	0.34	11.71	0.021	4	0	7	0	13	0	18	0
NGC 6871	6.96	0.44	10.99	0.021	15	0	16	0	20	1	25	1
NGC 3293	7.01	0.26	11.83	0.021	20	1	21	1	28	1	33	1
IC 2581	7.14	0.42	11.94	0.021	31	0	35	0	39	0	42	1
GAC												
NGC 7419	7.28	1.83	10.70	0.018	3	5	4	5	8	7	20	7
NGC 7235	7.07	0.93	12.25	0.017	19	2	25	2	36	2	60	2
NGC 2244	6.90	0.46	10.80	0.016	21	1	23	1	29	2	32	2
NGC 663	7.21	0.78	11.45	0.016	19	2	26	2	46	2	65	2
NGC 957	7.04	0.84	11.29	0.015	5	0	8	0	14	0	19	0
NGC 654	7.15	0.87	11.55	0.015	1	0	2	0	5	0	8	0
IC 1805	6.82	0.82	11.38	0.015	41	0	46	0	70	1	96	3
NGC 869	7.07	0.58	11.59	0.015	22	0	29	0	47	0	66	0
NGC 457	7.32	0.47	11.93	0.015	8	1	11	1	14	1	21	1
NGC 884	7.03	0.56	11.85	0.014	22	5	24	5	41	5	51	5
NGC 2439	7.25	0.41	12.93	0.013	7	1	8	1	14	1	22	1
LMC												
NGC 2004	6.9	0.13	18.50	0.007	29	7	41	7	58	7	72	8
NGC 2100	7.2	0.13	18.50	0.007	19	11	20	12	33	13	39	13
NGC 1818	7.4	0.13	18.50	0.007	12	6	18	6	32	7	54	8
SMC												
NGC 330	7.0	0.06	18.85	0.002	67	20	79	21	139	23	211	40

Table 3. B/R ratio for the galactic centre (GC), the galactic anticentre (GAC), SMC and LMC. B in the column called "Spectroscopy" only includes B supergiants, while R includes K and M supergiants. In the other columns, B includes stars with $(B-V)_0 \leq 0$ and R stars with $(B-V)_0 \geq 1.2$ (see text).

		Spectroscopy			$M_{v\mathrm{lim}} = -3.25$			$M_{v\mathrm{lim}} = -3.0$			$M_{v\mathrm{lim}} = -2.5$			$M_{v\mathrm{lim}} = -2.0$		
	Z	$B^{\dagger}$	R	$B^{\dagger}/R$	B	R	B/R	B	R	B/R	B	R	B/R	B	R	B/R
GC	0.023	41	10	4.1	189	7	27.0	221	8	27.6	308	9	34.2	416	13	32
GAC	0.016	29	23	1.3	168	17	9.9	206	17	12.1	324	21	15.4	460	23	20.0
LMC	0.007	-	-	-	60	24	2.5	79	25	3.2	123	27	4.6	165	29	5.7
SMC	0.002	9	15	0.6	67	20	3.4	79	21	3.8	139	23	6.0	211	40	5.3

† Counting only B supergiants.

region. The increase of the B/R ratio when the limit magnitude increases is simply due to the fact that more main sequence stars are included in B. The results are stable for the limit magnitudes -3.25, -3.0, and -2.5, for which B/R is approximately 2.5 times higher in the GC than in the GAC (in good agreement with Meylan & Maeder 1982 and with the results from spectroscopic counts). For the limit magnitude of -2.0, the value of B/R for the GC seems relatively low, which likely reflects problems of completeness.

The B/R ratios in the LMC (Table 3) confirm the decrease of B/R when the metallicity decreases. However, the results for the SMC seem less clear. This is probably due to the fact that ratios for the SMC are based on one single cluster (NGC 330). This is obviously insufficient to obtain precise B/R ratios and thus, in this case, results must be regarded with circumspection.

What are the effects of grouping clusters of different ages on the results? Let us recall that we selected clusters with $\log age$ between 6.8 and 7.5. This means that the B/R ratio we obtain are for supergiants with initial masses between about 8 and 30 $M_{\odot}$. Adopting narrower age intervals would give indication on the B/R ratio in a smaller range of initial masses. One can wonder to which extent the decrease of the B/R ratio with the metallicity would remain the same, if smaller age (mass) intervals were adopted. To check this point, we considered different age intervals (i.e. different intervals of initial masses for the supergiants). It is obvious that a finer age interval means less clusters selected and so a less reliable statistic. Therefore, we choose larger distance intervals when finer age intervals are considered. First, we calculate the B/R ratio in the same three distance intervals considered above (6.5–8.0, 8.0–9.0 and 9.0–11.5 kpc) for two

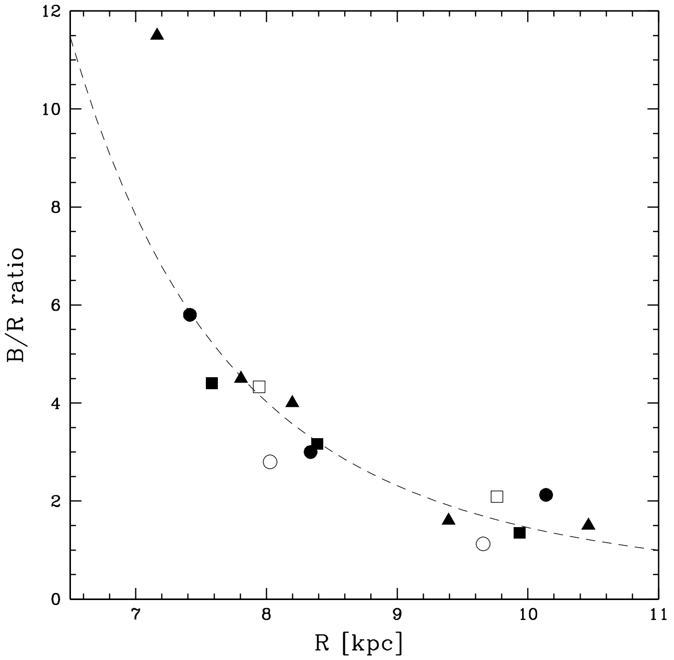

Fig. 2. B/R ratio in the Galaxy for different age intervals, with distinction between blue and red supergiants based on spectroscopic measurements. B includes O, B and A supergiants. As in Fig. 1, triangles correspond to five different distance intervals in the Galaxy (6.5–7.5, 7.5–8.0, 8.0–8.5, 8.5–10.0 and 10.0–11.5 kpc). Filled squares and circles correspond to three distance intervals in the Galaxy (6.5–8.0, 8.0–9.0 and 9.0–11.5 kpc) and open squares and circles correspond to the two main distance intervals GAC and GC. Triangles include clusters with $\log age$ between 6.8 and 7.5 (i.e. initial masses of the supergiants between ~8 and 30 $M_\odot$). Filled circles refer to clusters with $\log age$ between 6.8 and 7.2 (initial masses of the supergiants between 12–30 $M_\odot$), while filled squares include clusters with $\log age$ between 7.0 and 7.4 (initial masses of the supergiants between 9–18 $M_\odot$). Open squares correspond to clusters with $\log age$ between 6.9 and 7.1 (initial masses of the supergiants between 14–23 $M_\odot$) and open circles to clusters with $\log age$ between 7.1 and 7.3 (initial masses of the supergiants between 10–15 $M_\odot$). The dashed curve corresponds to the same fit as in Fig. 1.

age intervals: $\log age$ between 6.8 and 7.2 (initial masses of the supergiants between 12–30 $M_\odot$) and $\log age$ between 7.0 and 7.4 (initial masses of the supergiants between 9–18 $M_\odot$). We also choose two finer age intervals, $\log age$ between 6.9 and 7.1 (initial masses of the supergiants between 14–23 $M_\odot$) and $\log age$ between 7.1 and 7.3 (initial masses of the supergiants between 10–15 $M_\odot$), for which we calculate the B/R ratio in the two main distance intervals GC and GAC. The results of these counts are shown in Fig. 2. We precise that the value of the galactocentric radius R of each distance interval is obtained by averaging the galacocentric radii of the clusters found in the bin.

We observe that for different age intervals, the B/R ratio always remains higher for larger metallicities. Figure 2 shows clearly that the variation of the B/R ratio with the galactocentric radius remains more or less the same whatever the interval of ages (masses) considered. Moreover, we can see that considering finer age intervals changes only slightly the values of the B/R ratio. In that respect, the age interval between 6.8 and 7.5 appears to be a good compromise between the necessity to select a sufficiently high numbers of clusters to have a reliable statistics, and the necessity to somewhat restrain the domain of masses.

Finally, let us stress that when comparisons with stellar evolution models are made, the same definitions of the blue and the red supergiants used for obtaining the observed B/R ratios has to be used to determine the theoretical B/R ratios. In that respect, it is worthwhile to recall here that even if a star is classified as a blue supergiant, it may belong to the upper end of the Main Sequence.

5. Conclusions

The decrease of the B/R ratio with the metallicity does not appear to be an artifact due for instance to incompleteness but instead a robust feature that stellar evolution models should be able to reproduce. The fact that the present day grids of stellar models are still unable to account for this feature demands some caution when evolutionary population synthesis models are used to interpret the integrated luminosity of high redshift galaxies.

Recent studies by Maeder & Meynet (2001) show that the inclusion in the stellar models of the effects of rotation changes the B/R ratios. Physically, this results from the mild mixing, which leads to more helium in the region of the H–shell burning. The opacity is lower and the intermediate convective zone less important or absent. As convection implies a polytropic index $n = 1.5$, which means a relative compactness of the internal convective regions, the absence of an intermediate convective zone is a necessary condition for stellar expansion to the supergiant stage. Interestingly, rotating models are able to account for the numerous red supergiants seen at low metallicity, a feature that standard models could not reproduce.

Acknowledgements. We would like to thank J.-C. Mermilliod for his help in using the Webda database.

References

Alibés, A., Labay, J., & Canal, R. 2002, A&A, submitted, [`astro-ph/0107016`]
Blaha, C., & Humphreys, R. M. 1989, AJ, 98, 1598
Bomans, D. J., & Grebel, E. K. 1994, Space Sci. Rev., 66, 61
Brocato, E., & Castellani, V. 1992, Mem. S.A. Italy, 63, 121
Carney, B. W., Janes, K. A., & Flower, P. J. 1985, AJ, 90, 1196
Cassatella, A., Barbero, J., Brocato, E., Castellani, V., & Geyer, E. H. 1996, A&A, 306, 125
Cayrel, R., Tarrab, I., & Richtler, T. 1988, ESO Messenger, 54, 29
Cervino, M., & Mas-Hesse, J. M. 1994, A&A, 284, 749
Cowley, A. P., Dawson, P., & Hartwick, F. D. A. 1979, PASP, 91, 628
Deng, L., Bressan, A., & Chiosi, C. 1996, A&A, 313, 159
Elias, J. H., Frogel, J. A., & Humphreys, R. M. 1985, ApJS, 57, 91

Elson, R. A. W. 1991, ApJS, 76, 185
Freedman, W. L. 1985, AJ, 90, 2499
Grebel, E. K., & Richtler, T. 1992, A&A, 253, 359
Hagen, G. L., & van den Bergh, S. 1974, ApJ, 189, L103
Hartwick, F. D. A 1970, ApJ, 7, 151
Humphreys, R. M. 1979a, ApJS, 39, 389
Humphreys, R. M. 1979b, ApJ, 231, 384
Humphreys, R. M., & Davidson, K. 1979, ApJ, 232, 409
Humphreys, R. M., & Davidson, K. 1984, Science, 223, 243
Humphreys, R. M., & McElroy, D. B. 1984, ApJ, 284, 565
Humphreys, R. M., & Sandage, A. R. 1980, ApJS, 44, 319
Ivanov, G. R. 1998, A&A, 337, 39
Langer, N. 1991a, A&A, 248, 531
Langer, N. 1991b, A&A, 252, 669
Langer, N., & Maeder, A. 1995, A&A, 295, 685
Maeder, A., Grebel, E. K., & Mermilliod, J.-C. 1999, A&A, 346, 459
Maeder, A., & Meynet, G. 2001, A&A, 373, 555
Massey, P. 2002, ApJS, 139, in press
McCarthy, J. K., Lennon, D. J., & Venn, K. A. 1995, ApJ, 455, L135
Mermilliod, J.-C. 1995, in Information and On-Line data in Astronomy, ed. D. Egret, & P. A. Albrecht (Kluwer), 127
Meylan, G., & Maeder, A. 1982, A&A, 108, 148
Meynet, G., Mermilliod, J.-C., & Maeder, A. 1993, A&AS, 98, 477
Origlia, L., Goldader, J. D., Leitherer, C., Schaerer, D., & Oliva, E. 1999, ApJ, 514, 96
Pagel, B. E. J., Edmunds, M. G., Fosbury, R. A. E., & Webster, B. L. 1978, MNRAS, 184, 569
Robertson, J. W. 1973, ApJ, 180, 425
Robertson, J. W. 1974, ApJ, 191, 67
Vallenari, A., Ortolani, S., & Chiosi, C. 1994, A&AS, 108, 571
van den Bergh, S. 1968, JRASC, 62, 69
van den Bergh, S. 1998, in The Galaxies of the Local Group (Cambridge University Press, Cambridge Astrophys. Ser.), 35, 93
Walker, M. F. 1964, AJ, 69, 744