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Differences in the fractions of Be stars in galaxies

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Abstract. The number ratios $Be/(B+Be)$ of Be to B–type stars in young, well studied clusters of the Galaxy, the LMC and SMC are examined. In order to disentangle age and metallicity effects we choose clusters in the same age interval and for which reliable photometric and spectroscopic data are available. Number counts are made for various magnitude intervals, and the results are found to be stable with respect to this choice. In the magnitude interval $M_{\rm V} = -5$ to -1.4 (i.e. O9 to B3) we obtained a ratio $Be/(B+Be)$ = 0.11, 0.19, 0.23, 0.39 for 21 clusters located in the interior of the Galaxy, the exterior of the Galaxy, the LMC and the SMC, respectively.

Various hypotheses for these differences are examined. An interesting possibility is that the average rotation is faster at low metallicities as a result of star formation processes. The much higher relative N–enrichment found by Venn et al. (1998) in A–type supergiants of the SMC, compared to galactic supergiants, also strongly supports the presence of more rotational mixing at low metallicities. We discuss whether high rotational mixing may be the source of primary nitrogen in the early chemical evolution of galaxies.

Key words: stars: emission-line, Be – stars: evolution – stars: rotation

1. Introduction

About 50% of the B stars in the SMC cluster NGC 330 were found to be Be stars by Feast (1972). This high fraction, compared to 10 to 20% in the Milky Way, was confirmed by subsequent studies done by Grebel et al. (1992, 1996), Mazzali et al. (1996), and Keller et al. (1999). A pronounced difference between the Be star content in the Magellanic Cloud clusters and in the Milky Way was also found by Grebel et al. (1994).

The Be phenomenon is closely related to fast rotation. Suggestions were made in the past that Be stars occur near the end of the main sequence (MS) phase; however, extended studies in clusters have shown the occurrence of Be stars from the zero–age sequence to the end of the MS (Mermilliod 1982). Mermilliod has also found that the fraction of Be stars with respect to normal B stars is low in very young clusters, that it reaches a maximum for clusters with turnoff in the range of O9 to B3 and that it declines after that. Evidences for an age effect are also well shown by Fig. 5 from Grebel (1997).

Be stars are generally slightly shifted to the red of the MS band (Grebel et al. 1996; cf. also Fig. 1 below). This effect is consistent with the effect of rotational reddening found by Maeder & Peytremann (1970) and also with the effect of a circumstellar envelope, which contributes to a reddening as well as to the formation of the emission lines (Gehrz et al. 1974, Coté & Waters 1987). A physical model of the radiation-driven wind in rotating stars has been proposed by Bjorkman & Cassinelli (1993). This model, the so-called wind compressed disk (WCD) model, predicts that the isotropic wind particles travel along trajectories that go through the equatorial plane, where shocks occur. The gas is thus confined there and forms a dense equatorial disk. Owocki et al. (1998) have shown that gravity darkening, as predicted by the von Zeipel theorem, leads to a very different wind morphology, where the disk is more difficult to form. The application of the radiative wind theory to rotating stars leads to an expression (cf. Maeder 1999a) for the mass loss rates $\dot{M}(\vartheta)$ as a function of the colatitude ϑ, this expression shows that there are two main effects influencing the anisotropic mass loss: a) the "$g_{\rm eff}$"–effect, i.e. the higher gravity and $T_{\rm eff}$ at the pole of a rotating star (due to von Zeipel's theorem) enhances the polar mass loss; b) the "opacity–effect", i.e. the higher opacity, and the higher force multipliers, due to the lower temperature at the equator favour an equatorial ejection and the formation of a ring. The B[e] stars show both polar and equatorial ejections (Zickgraf 1998). The equatorial ejection is strongly favoured by the so–called bi–stability effect (Lamers 1997), i.e. a jump of the opacity near 20'000° K, i.e. close to spectral type B2 where a maximum of the fraction of Be stars is observed.

Models of rotating stars, including hydrostatic distorsion, shear mixing, meridional circulation, enhanced mass loss rates, loss of angular momentum etc. have been constructed recently (Meynet 1999; Maeder 1999b). These models show the high influence of rotation on massive star evolution. The main reason is that shear mixing, which is the most efficient mixing process, is favoured by a high thermal diffusivity as observed in massive stars (Maeder 1997); also, other effects such as merid-

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ional circulation (Maeder & Zahn 1998) and anisotropic mass loss are quite significant in massive stars. In view of the large consequences of rotation, it is particularly useful to examine whether the Be fraction is systematically higher in clusters of lower metallicities, a possibility also suspected by Grebel et al. (1992), Grebel (1997) and Mazzali et al. (1996). Sect. 2 establishes the number data of Be stars in an ensemble of clusters of the Galaxy, LMC and SMC. The relation of the results with metallicity is examined in Sect. 3, together with abundance indications related to rotation. Sect. 4 gives the conclusions.

2. Number counts of Be stars in clusters

2.1. Cluster data

Since the fraction of Be stars is rapidly changing with cluster ages (Mermilliod 1982), we must carefully separate ages and metallicity effects. We select clusters in the age range of $\log$ age = 7.00 to 7.40 which have their turnoff around the maximum of the Be star distribution. The comparison of clusters of various ages in different galaxies may lead to confusion between age and metallicity effects.

For the Milky Way the clusters were selected from the cluster data base WEBDA (Mermilliod 1999). This data base contains homogeneous photometric data with consistent estimates of reddening, distance moduli and ages. WEBDA also provides indications on known binaries, stellar peculiarities and Be star identifications based on standard spectroscopic criteria. The data base includes the recent survey of stars with Hα emission by Kohoutek & Wehmeyer(1997). Some 11 well studied clusters of the Galaxy are in the age interval considered (Table 1). On the basis of their galactocentric distances, the clusters are separated in two groups: one outside and one inside the solar location.

For the LMC the photometric data, the age determinations and the identifications of Be stars come from Grebel (1997), Dieball & Grebel (1998), Keller et al. (1999), and Grebel & Chu (in preparation). A distance modulus of 18.50 is taken in agreement with current determinations (cf. Cole 1998). Nine LMC clusters (listed in Table 1) are in the considered age interval. For the SMC the typical cluster NGC 330 is analysed with the data from Grebel et al. (1996). Unfortunately there is no other cluster with reliable Be star identification in or even near the considered age range. The cluster NGC 346 of the SMC, which contains a few Be stars, is much too young and has a turnoff far out of the age range where the maximum of Be stars occurs. Kudritzki et al. (1989) give an age of $2.6 \cdot 10^6$ yr for NGC 346, which is consistent with the presence of stars up to about 100 $M_\odot$ (Massey et al. 1989). This is in agreement with other authors (Cassatella et al. 1996; Haser et al. 1998) who notice the presence of O3 stars in NGC 346.

2.2. Number counts of Be stars in luminosity intervals

We choose to proceed to number counts in given intervals of magnitude $M_{\rm V}$ rather than in given ranges of spectral type and $T_{\rm eff}$ since spectral types are not available for all clusters. Also, we noticed that high rotation strongly modifies the average $T_{\rm eff}$ and very little the average stellar luminosities (Maeder & Peytremann 1970). Furthermore, massive stars of the same mass, but different metallicites, have rather large differences in $T_{\rm eff}$, while this is not the case for the luminosities (Schaller et al. 1992). In order to test the independence of the results with respect to the chosen $M_{\rm V}$ range we have done number counts in three intervals of $M_{\rm V}$ centered on the domain O9 to B3, i.e. $M_{\rm V}$ = -4, -2; $M_{\rm V}$ = -5, -2; $M_{\rm V}$ = -5, -1.4 (the limit $M_{\rm V}$ = -1.4 corresponds to the spectral type B3 according to the calibration of Zorec & Briot (1991) for main sequence B–type stars). Fig. 1 shows an example of the HR diagram used for the number counts in the case of NGC 884 (χ Persei cluster) with the various magnitude intervals considered.

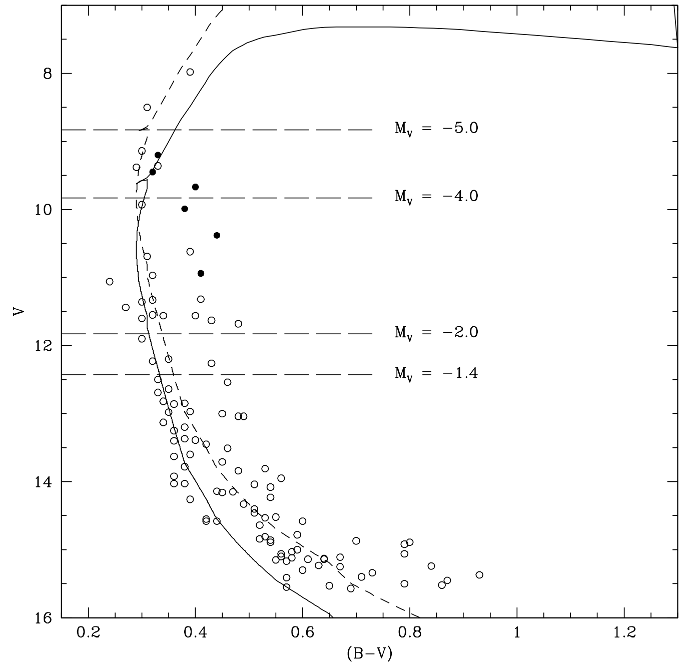

Fig. 1. Example of colour–magnitude diagram used for the number counts of Be and B stars in the case of NGC 884 from the WEBDA data base (Mermilliod 1999). The limits of the various magnitude intervals are shown: $M_{\rm V}$ = -4, -2; $M_{\rm V}$ = -5, -2; $M_{\rm V} = -5, -1.4$. Be stars are represented by black dots. The isochrone corresponding to log age = 7.1 is represented by a continuous line, and the top of the binary sequence upwards shifted by 0.75 mag. is shown by a broken line.

Table 1 shows the number counts for the 19 clusters in the four different locations considered. The 2nd column gives the $\log$ of the age, the 3rd column gives the distance moduli in the SMC and LMC, the galactocentric distance for galactic clusters is given in the 3rd column as well; the following columns give the numbers of B plus Be stars, and those of Be stars in the indicated magnitude intervals. The reference for the data is in the last column.

The average number ratios $Be/(B+Be)$ stars in the four zones and for the different magnitude intervals considered are given in Table 2. We clearly notice a systematic trend for smaller $Be/(B+Be)$ number ratios in the sequence of the four groups considered from SMC to LMC to the galactic exterior and interior. The total difference in the $Be/(B+Be)$ ratios amounts to

Table 1. Cluster data

Cluster	log(age)	DM	M_V = -5, -1.4 B+Be	Be	M_V = -5, -2 B+Be	Be	M_V = -4, -2 B+Be	Be	Ref.
SMC									
NGC 330	7.30	18.90	128	50	89	39	81	37	Grebel et al. 1996
LMC									
Hodge 301	7.30	18.50	44	10	25	9	25	9	Grebel & Chu in prep
KMHK 1019	7.20	18.50	11	2	1	1	—	—	Dieball & Grebel 1998
NGC 1818 A	7.40	18.50	94	34	58	22	51	19	Grebel 1997
NGC 1818 B	7.40	18.50	7	3	4	2	4	2	Grebel 1997
NGC 1948	7.40:	18.50	101	11	71	9	64	9	Keller et al. 1999
NGC 2004	7.40	18.50	130:	25	96:	21	82:	17	Grebel in prep.
NGC 2006	7.30	18.50	35	10	21	5	21	5	Dieball & Grebel 1998
NGC 2100	7.40:	18.50	67	19	49	16	43	15	Keller et al. 1999
SL 538	7.20	18.50	46	11	29	9	28	9	Dieball & Grebel 1998
TOTAL			535	125	354	94	318	85	
Galaxy ext.		$R_{gc}(kpc)$							
NGC 457	7.30	9.92	28	4	17	4	13	1	Mermilliod 1999
NGC 581	7.20	9.54	8	1	5	0	4	0	Mermilliod 1999
NGC 663	7.20	9.61	35	12	23	12	21	10	Mermilliod 1999
NGC 869	7.10	9.60	42	3	33	3	28	2	Mermilliod 1999
NGC 884	7.10	9.91	28	6	24	6	18	3	Mermilliod 1999
NGC 957	7.15	9.41	15	4	13	4	12	3	Mermilliod 1999
NGC 2439	7.30	10.45	31	5	21	5	21	5	Mermilliod 1999
NGC 7160	7.20	8.22	3	1	2	1	2	1	Mermilliod 1999
TOTAL			190	36	138	35	119	25	
Galaxy int.									
NGC 3293	7.20	7.70	37	1	32	1	25	1	Mermilliod 1999
NGC 3766	7.40	7.44	42	10	25	8	24	8	Mermilliod 1999
NGC 4755	7.20	7.07	47	3	27	3	23	3	Mermilliod 1999
TOTAL			126	14	84	12	72	12	

a factor of about three, which is important and also systematic in relation with the metallicities as discussed below.

2.3. Possible relations with Z

We examine the possible relation between the fraction of Be stars and the local metallicity Z in the regions where these stars were formed. Let us notice that the suggestion to determine whether the frequency of Be stars is somehow related to the metal abundance was also made by Grebel et al. (1992) and Mazzali et al. (1996).

We use the recent data on the metallicity Z for the various zones. For the solar metallicity we take a value of $Z_{\odot}$ = 0.018, which is consistent with recent solar models and helioseismological data (Brun et al. 1998). For the chemical gradient in the Galaxy the current values range between $\Delta[O/H]/kpc = -0.07$ (cf. Shaver et al. 1983; Gummersbach et al. 1998) and -0.05 (cf. Vilchez & Esteban 1996). The group of clusters towards the anticenter has an average galactocentric distance R_{gc} of about 1.5 kpc larger than that of the Sun (taken to be $R_{gc} = 8$ kpc), while this average difference is 0.6 kpc for the group of clusters towards the galactic interior. Thus we consider that the average local metallicities for the exterior and interior groups are respectively Z = 0.014 and Z = 0.020 for a galactic gradient of -0.07. For a gradient of -0.05 the Z-values would be 0.015 and 0.019 respectively, i.e. not very different from the latter values.

Table 2. Number ratios of Be to B+Be stars in the Magellanic Clouds and Milky Way.

	N_V	$\frac{Be}{B+Be}$ -5, -1.4	-5, -2	-4, -2
SMC	128	0.39	0.44	0.46
LMC	535	0.23	0.27	0.27
Galaxy ext.	190	0.19	0.25	0.21
Galaxy int.	126	0.11	0.14	0.17

For the young population in the LMC the range of estimated metallicities is rather large. For example, Olszewski et al. (1991) give [Fe/H] values in the range -0.3 to - 0.42, which corresponds to Z = 0.010 to 0.008. Jasniewicz and Thévenin (1994) find values from [Fe/H] = -0.4 for NGC 1818 to -0.55 for NGC 2004, which correspond to respectively Z = 0.008 and 0.006. Bica et al.

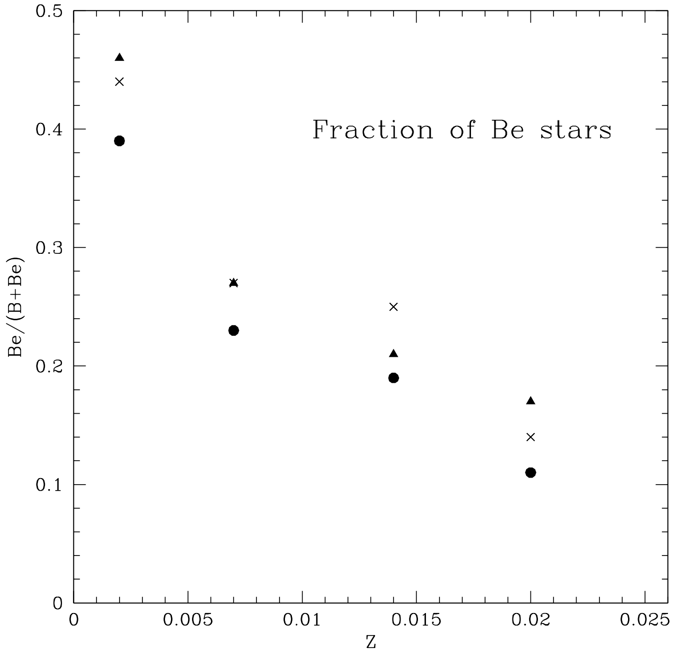

Fig. 2. Relation between the number ratio Be/(B+Be) and the local metallicity for the 4 groups of clusters considered in Table 2. To test the validity of the results, the number counts were made in different magnitude intervals, the dots refer to counts made in the magnitude interval M_V = -5, -1.4, the crosses to the interval -5, -2 and the triangles to the interval -4, -2.

(1998) obtained values Z = 0.004 to 0.005. Luck et al. (1998) find a mean [Fe/H] = -0.34 ± 0.15 for LMC field Cepheids. In this context, an average value of 0.007 seems appropriate. For the SMC field Reiterman et al. (1990), Spite et al. (1991), Grebel & Richtler (1992) give values corresponding to Z = 0.001 to 0.003. For NGC 330, Hilker et al. (1995) give a value Z = 0.002, and the results of Hill (1997) correspond to 0.003 to 0.004 and those of Oliva & Origlia (1998) to 0.001. Luck et al. (1998) find a value corresponding to Z=0.004. Gonzalez & Wallerstein (1999) find Z = 0.002. In this context an average value Z = 0.002 for the SMC is appropriate.

Fig. 2 shows the relation between the fraction $Be/(B+Be)$ and the local average metallicity. The trend is quite clear for the various magnitude intervals considered. For the sample of the 4 locations there seems to be a clear decrease of the fraction of the relative number of Be stars with the local average initial metallicity.

3. Interpretation of the results

There are various possibilities to interpret the above results.

1. Statistical effects related to the intermittence of the Be phenomenon.
2. The visibility of the Be phenomenon is enhanced at low metallicities.
3. Shell ejection is favoured at low metallicities.
4. Differences in the distribution of the rotational velocities.

The first possibility is very unlikely. In the Milky Way Be stars have generally been observed over a longer period than in the LMC or SMC. Therefore, the intermittent Be star have a higher chance to be detected in the Milky Way. Consequently, the correction of this possible effect would increase the trend observed in Fig. 2 rather than reduce it. Indeed, in the SMC cluster NGC 330 the Be phenomenon has been found to be intermittent in a number of stars re-observed over the period of several years (Grebel 1995, Keller et al. 1999). The second hypothesis also seems difficult to sustain, because at higher metallicities the ejected shell and circumstellar material would be more opaque and contain more dust, thus their visibility through emission lines as well as by their infrared continuum would be enhanced. Thus, the correction of such an effect (if feasible) would increase the observed trend.

The same kind of remark holds for the third hypothesis. Models of rotating stars with mass loss (Maeder 1999a) show two effects: a) polar ejection is favoured in rotating stars by the higher $T_{\rm eff}$ at the pole; b) equatorial ejection of a shell is favoured by larger opacities. Thus, at lower Z, it is not expected that shell ejection is favoured in the equatorial regions of a rotating star, because the opacities are lower. The possible effect of metallicity on the terminal velocities, which may follow from the wind-compressed disk model (Bjorkman & Cassinelli 1993; Grebel 1997), is found to be negligible (Maeder 1999a).

Thus we are left with the possibility that the higher fraction of Be stars at lower Z is the signature of more fast rotators at lower Z. Obviously, direct measurements in nearby galaxies are very needed and envisaged in order to confirm or reject this suggestion. For NGC 330 measurements of projected rotational velocities ($v \sin i$) by Mazzali et al. (1996) and Keller & Bessell (1998) show values of up to 400 km $\rm s^{-1}$. Furthermore, a recent study of nitrogen abundances done by Venn (1995) offers a strong support to the possibility of faster rotation in NGC 330 of the SMC.

Indeed, several authors have found that B– and A–type supergiants in the Galaxy, LMC and SMC show nitrogen enhancements not predicted by standard evolutionary models (cf. Lennon et al. 1996; Fitzpatrick & Bohannan 1993; Venn 1995; Venn et al. 1998). The current interpretation of these surface enhancements requires some additional mixing processes, possibly rotational mixing (cf. Langer 1998; Meynet 1998; Maeder & Zahn 1998). New rotating models show consistently some N–enrichments already present for medium rotation from the end of the MS onwards (Meynet 1998). A remarkable point is that part of the N–enhancement observable in B– and A–type supergiants could be of primary origin, due to the fact that some new ^{12}C resulting from the 3α burning is rotationally diffused into the H–burning shell, where the CNO cycle converts this "new ^{12}C" into ^{14}N, which is thus of primary origin.

Another interesting fact recently found by Venn et al. (1998) is that the degree of N enhancement for A supergiants is much higher in the SMC than in the Milky Way. For galactic supergiants the typical enhancement of [N/H] is about a factor of 2, while in the SMC it reaches a factor of 10–20 with respect to the standard local average [N/H] in the SMC. As a matter of fact, converting the ^{12}C entirely into ^{14}N by the end of the CN cycle (which is dominant) would lead to an increase of [N/H] by a factor of 4–5, but not as high as 20. Thus the high [N/H] enhancement observed for SMC supergiants might be a sign of primary nitrogen. We do not know, the only way to clarify is to measure the sum of CNO elements and check whether it is the same or not in supergiants as in MS stars. Anyhow, whether this is primary or secondary nitrogen, the point for now is that this higher [N/H] is the signature of much more mixing in the SMC than in the Galaxy, a fact which is quite consistent with the above suggestion of faster rotation for massive stars in the SMC. The possibility of faster rotation in the SMC has also been mentioned by Venn et al. (1998) and the results presently available on the Be star fractions as a function of Z clearly support this view.

4. Conclusions

The main result is that the relative fraction of Be stars with respect to all B stars in the spectral interval O9 to B3 is increasing for lower metallicities Z. This fact together with the much larger N-excesses observed in A-type supergiants of the SMC than in galactic supergiants strongly supports the suggestion that there are more fast rotators among massive stars at lower Z. Of course, direct observations of large numbers of $v \sin i$ in LMC and SMC clusters are very much needed in order to further substantiate the above results.

We may wonder about the origin of the possible higher rotation velocities at low metallicities. This origin is likely related to some metallicity effects in the process of star formation. There are many possibilities, for example we may notice that a lower Z implies less dust and ions in star forming regions. The coupling of the magnetic field to the matter is then weaker, the ambipolar diffusion of the magnetic field should proceed faster, thus leading to less angular momentum losses by the central contracting body. Another possibility is that during pre-main sequence evolution, the weaker opacities at lower Z are leading to an earlier disappearance of the external convective zones and thus to less magnetic coupling between the forming star and its surroundings. Also the importance and the survival lifetime of the accretion disk may increase with metallicity, thus favouring the dissipation of angular momentum at higher Z. Of course, numerical models are needed to examine these various tentative suggestions.

Looking ahead we may also mention that the consequence of faster rotation at lower Z may be considerable, with large differences in evolutionary tracks, lifetimes and nucleosynthesis. In particular we know that current models are unable to account for the occurrence of the large quantity of red supergiants in the SMC for which more mixing would be needed (cf. Langer & Maeder 1995). In the context of nucleosynthesis the possible formation of primary nitrogen at low Z is interesting in relation with the suggestion that primary nitrogen is needed in the early chemical evolution of galaxies (cf. Matteucci 1986; Pagel 1998). Appropriate stellar models would bring new insight into the interpretation of star populations in low Z galaxies, like blue compact galaxies or galaxies at cosmological distances like in the Hubble Deep Field.

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