Be star surveys with CCD photometry.

II. NGC 1818 and its neighbouring cluster in the LMC

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Abstract. As part of an ongoing photometric survey of young Magellanic Cloud clusters we identified Be stars in NGC 1818 and a nearby smaller cluster in the Large Magellanic Cloud. The neighbouring cluster does not appear to contain any evolved stars, and its sparsely populated main sequence does not extend to stars as massive as in NGC 1818. Both clusters are younger than the surrounding field population, but the current data do not allow to conclude whether NGC 1818 is a binary cluster or not. The small cluster is more heavily reddened than NGC 1818 indicating the presence of differential reddening, leftover gas and dust from the star formation process, or a larger distance. NGC 1818 does not seem to be significantly affected by differential reddening.

We find both clusters to be rich in Be stars. The field only contains very few Be stars as one would expect for a predominantly older population. NGC 1818 contains almost as many Be stars as the slightly younger SMC cluster NGC 330, while NGC 2004, a young LMC cluster, has a lower Be star content.

We discuss problems in comparing Be star fractions in Magellanic Cloud clusters and Galactic open clusters and possible constraints on Be star theories.

Key words: Galaxies: Magellanic Clouds – Galaxies: star clusters – Galaxies: stellar content – Stars: emission-line, Be – Stars: early-type – Stars: fundamental parameters

1. Introduction

Be stars are non-supergiant (luminosity class V to III) B type stars that show or once have shown Balmer emission (Jaschek et al. 1981) – a very wide definition. Among Galactic field B stars, 18% of B0 to B7 III–V stars are Be stars (Abt 1987). While Galactic Be stars have been extensively investigated, little is known about the Be star content of the Magellanic Clouds. The Magellanic Clouds have lower metallicity than usual for the young stellar population in the Milky Way, which affects opacity and stellar atmosphere properties, hence the study of Be stars in the Magellanic Clouds may shed light on the formation mechanisms of the Be phenomenon. The study of Be stars in clusters has the added advantage of looking at a population homogeneous in age and metallicity, and of common origin. Therefore, we have started a survey of Be stars in Magellanic Cloud clusters.

In the first paper of this Be star survey (Grebel et al. 1992: Paper I), we studied the young cluster NGC 330 in the Small Magellanic Cloud (SMC) and found it to be unusually rich in Be stars. Our photometric survey technique uses imaging in three filters, one of them an Hα filter. The colour index formed by the two other filters serves to separate blue stars from red stars. A colour index formed from the Hα filter and one of the other filters is used to distinguish stars bright in Hα from the rest. In the resulting two-colour diagrams (TCDs) Be star candidates stand out clearly. If the Hα filter is used together with a continuum filter such as Johnson-Cousins R, the strength of the Hα emission can be calibrated (Grebel et al. 1994).

A comparison of the detections from the photometric survey of NGC 330 with those from grism surveys shows excellent agreement (Paper I). The photometric method has the added advantage of being able to operate also in very crowded regions and of allowing to distinguish between Be stars and ordinary B stars. Medium-resolution
spectroscopy (Lennon et al. 1994, Grebel et al. 1996) allows one to detect very weak-lined Balmer emission stars that can not be distinguished by photometric techniques, though in practice medium-resolution spectroscopy is restricted to a few stars with the currently available instruments owing to constraints on observing time. CCD imaging with two broadband filters and an $H\alpha$ filter is an efficient tool to identify Be stars. The definition of a Be star implies that all current detections establish only a lower limit to the true number of Be stars.

In the present paper, the Be star content of NGC 1818 and the neighboring smaller cluster in the Large Magellanic Cloud (LMC) will be analyzed (Sect. 4). We compare Be star fractions in young clusters in the Magellanic Clouds and in the Milky Way and discuss the associated problems in Sect. 5. In Sect. 6 we discuss constraints on Be star theories.

2. The photometric data

$H\alpha$ frames of NGC 1818 were obtained at the New Technology Telescope (NTT) with the ESO Multi Mode Instrument (EMMI) on 03 Feb 1992 at ESO, La Silla, Chile, A Thomson 1024$^2$ chip (ESO # 18) with a pixel scale of $0\farcs43$ resulting in a field of view of $73\times73$ was used. The $H\alpha$ filter was # 654 ($\lambda_c = 6554$ Å, $\Delta \lambda = 33$ Å).

We observed one field centered on NGC 1818 on 08 Oct 1993 with the 2.2m MPIA telescope at ESO, La Silla, Chile using the ESO Faint Object Spectrograph and Camera (EFOSC2) with a $1024 \times 1024$ Thomson chip (ESO # 19). The pixel scale was $0\farcs32$, which gives a field of view of $57 \times 57$. We obtained short and long exposures in Bessell $UBV$. The $R$ filter was ESO #585 (Bessell $R$, $\lambda_c = 5949$ Å, $\Delta \lambda = 1654$ Å) from the standard filter set for the 2.2m telescope. We also observed several UBV(RI)$_C$ standard fields from Landolt (1992) in the same night resulting in a total of 47 standard star observations. The data were reduced using the standard procedures in DAOPHOT II running under MIDAS (Stetson 1992). As turned out later, during part of 1993 the telescope was mistakenly operated without sky baffle. Our $U$ and $B$ frames (and to a lesser extent, the $V$ frame) show systematic position-dependent magnitude variations of up to $\pm 0.2$ magnitudes. The effect on the $R$ filter is negligible. Such a strong position dependence of magnitudes is not visible in other EFOSC2 data we obtained in 1992 or 1995.

In December 1990, we obtained $B, V$ CCD data of NGC 1818 in direct imaging mode at the same telescope (Will et al. 1995a,b). The photometry tables are available from CDS, Strasbourg. The fields from the two observing runs largely overlap. We have used approximately 2000 common stars from both runs to create correction maps for a position-dependent magnitude correction for $BV$ photometry of EFOSC2 (Grebel & Will, in prep.). For NGC 1818, we are using the $BV$ photometry of the 1990 run (or $BV$ photometry from 1993 corrected accordingly for stars not detected previously because of poorer seeing) together with $BVR$ photometry from 1993 and $H\alpha$ photometry from 1992. There is an epoch difference of about 20 months between the $H\alpha$ and the $R$ frames for NGC 1818. Together with instrumental differences and the variability of the Be star phenomenon this may increase the possibility of not detecting weak $H\alpha$ emitters and makes the $H\alpha$ calibration less accurate.

| Instrument | date | filter | exp.time | airmass | seeing |
|------------|------|--------|----------|--------|--------|
| 2.2m,EFOSC2 | 1993 Oct 08 | $B$ | 40s | 1.25 | 1\'\3 |
|            |      | $B$ | 360s | 1.25 | 1\'\4 |
|            |      | $V$ | 10s | 1.26 | 1\'\1 |
|            |      | $V$ | 120s | 1.26 | 1\'\2 |
|            |      | $R$ | 10s | 1.26 | 1\'\1 |
|            |      | $R$ | 120s | 1.26 | 1\'\2 |
| NTT,EMMI  | 1992 Feb 03 | $H\alpha$ | 3 $\times$ 300s | 1.26 | 1\'\2 |

3. General properties and colour-magnitude diagram of NGC 1818

NGC 1818 is one of the young, blue, populous clusters in the LMC and the central cluster of Region C of the ESO Key Programme for the Coordinated Investigation of Selected Regions in the Magellanic Clouds (de Boer et al. 1989). There have been several spectroscopic abundance determinations for NGC 1818. Their results differ by more than half a dex in [Fe/H]. The most recent studies are both based on medium-resolution spectra of five red supergiants: Meliani et al. (1994) find NGC 1818 to be relatively metal-poor ([Fe/H] $= -0.9$ dex), while Jasiewicz & Thévenin (1994) find it more metal-rich ($-0.4$ dex). The latter result may be the more reliable one since care was taken to eliminate contamination by blue stars that may lead to spuriously low metal abundances. For a summary of earlier spectroscopic abundance determinations based on fewer stars see Will et al. (1995a).

The colour-magnitude diagram (CMD) of NGC 1818 shows a very wide blue main sequence and a few red and blue supergiants (Fig. 1a). In Fig. 1a only stars within 13 pc ($55''$) from the cluster centre are plotted. This radius encircles the highest concentration of stars per unit area before the density distribution becomes noticeably flatter. Thus we may assume to enclose mostly cluster members.

Though the formal photometric colour error bars for NGC 1818 are quite wide the main sequence still seems excessively wide even when omitting the Be stars. Possible reasons for this width are crowding and/or differential reddening. Both the error bars and main sequence
E.K. Grebel: Be star surveys with CCD photometry. II. NGC 1818

Fig. 1. CMDs of NGC 1818 (upper panel), small cluster (middle), and field population (bottom panel). Radii given in the top and bottom panels refer to the centre of NGC 1818, and in the central panel to the small cluster. Error bars were determined for each region individually. Geneva group isochrones fit NGC 1818 well for ages between 25 and 30 Myr, while showing little sensitivity to metallicity. Isochrones in the central and bottom panels are meant for orientation only. The small cluster is more heavily reddened than NGC 1818 (see reddening vectors) and does not contain as massive or evolved stars. The field main sequence becomes more densely populated at $V \geq 18.5$. The two clusters have a high fraction of Be stars (fat dots), but there are very few in the field.

Fig. 2. To illustrate that the very wide main sequence of NGC 1818 is caused mainly by crowding effects, we compare stars found within an annulus of $13 \, \text{pc} < \text{radius} < 8 \, \text{pc}$ (small dots) with stars found within the innermost 4 pc around the cluster centre (asterisks). The outer annulus of stars shows a quite well-defined, narrow main sequence. The innermost stars exhibit wide scatter and a much lower cutoff magnitude. Scatter toward the blue may be caused in part by contamination from unresolved blue main-sequence stars. Note how strongly the most massive stars are concentrated toward the cluster centre. Of the uncrowded field population are much narrower. In Fig. 2, we plotted stars found in an outer and an inner annulus around the centre of NGC 1818. The outermost annulus (of stars considered to be largely cluster members, see above) shows a relatively narrow, well-defined main sequence for which the isochrones serve well as an approximate blue envelope with our chosen reddening. In the innermost circle, stars fainter than $V = 18$ were not found due to crowding, and the main sequence exhibits wide scatter. The scatter may in part be due to contamination by unresolved, fainter blue main-sequence stars. The strange bifurcation pattern at the upper end of the main sequence already visible in the study by Will et al. (1995a) originates predominantly from these innermost, very crowded stars and would probably vanish in high-resolution data such as HST imaging. Fig. 2 also illustrates that the most massive stars (in particular, supergiants) are strongly concentrated toward the cluster centre.

A comparison of stars in different regions within the 13 pc radius around NGC 1818 did not show significant colour offsets indicating that effects of differential reddening across NGC 1818 are small if present at all.

Age determinations based on isochrone fits to colour-magnitude diagrams were performed by Will et al. (1995a, cf. also for older references), who found ages ranging from 20 Myr to 40 Myr depending on the amount of overshoot. From isochrone fits based on models of the Geneva group (Charbonnel et al. 1993, Schaerer et al. 1993) we find an age between 25 and 30 Myr for NGC 1818 (Fig. 3a). We
used a reddening of $E(B-V)_0 = 0.07$ mag (Will et al. 1995a, Grebel & Roberts 1995) and a distance modulus ($DM$) of 18.5 mag for the LMC (intermediate between recent distance determinations, e.g., McCall 1994, Gould 1995). The blue stars above the main-sequence turnoff as given by the isochrones and below the position of the blue supergiants are in part Be stars, and possibly in part blue stragglers and/or binaries (for a thorough discussion, see Grebel et al. 1996), and, as just demonstrated, are strongly affected by crowding (Fig. 3).

3.1. The field population(s)

We consider stars more distant from NGC 1818 than 24 pc (100") to be mostly field stars. The field around NGC 1818 contains a number of young, massive stars (Fig. 2; and spectral classifications by Sanduleak 1970 and Xiradaki et al. 1987). These stars are sparsely distributed across the field. In particular, there are very few supergiants. However, the main sequence becomes more densely populated starting at $V \approx 18.5$. From B0 V to B5 V, $M_V$ decreases by approximately 2.8 mag, while $M_{bol}$ decreases by roughly 1.1. Assuming an IMF power law as given by, e.g., Scalo (1986) with a Salpeter slope of 1.35 (Salpeter 1955), the number of stars within the above brightness interval should increase by about 1.5, or by about 1.4 when using the IMF slope determined for NGC 1818 by Will et al. (1995a). The number of stars increases by more than that though. The onset of higher stellar densities corresponds to an intermediate-age population with an age of 400 Myr and older. The lower main sequence becomes quite wide, which may be due to differential reddening and/or depth effects. The blue envelope of the main sequence fits isochrones with a reddening of $E(B-V) = 0.07$ mag. The field CMD also shows the typical clump of (older) intermediate-age red giants at $V \approx 19$. Older populations cannot be discerned in our data though since we do not reach faint enough magnitudes.

In the field surrounding NGC 1818 there are four more clusters located, all less populous than NGC 1818. These are SL 205 (northeast at a distance of 5.4 or 78 pc), NGC 1810 (northwest at a distance of 6.2 or 90 pc), an anonymous cluster (southwest at a distance of 6.6 or 95 pc), and SL 222 (southeast at a distance of 8.3 pc). The age of NGC 1810 was estimated to be 76 Myr, and its reddening to be higher ($E(B-V) = 0.12$ mag) than that of NGC 1818 (e.g., Meurer et al. 1990). No data on the other three clusters are available in the literature. Judging from the corresponding plate scan available in the STScI Digitized Sky Survey, SL 205 appears to be associated with a gaseous region and may be rather young. Judging from these clusters and the scattered supergiants in the field, widespread though sparse star formation must have taken place across the entire region within the past 25 to 80 Myr. The variations in reddening make the presence of differential reddening seem likely.

3.2. A companion cluster of NGC 1818?

About 1.5 southwest of NGC 1818 there is a second, very small cluster (see Fig. 1 in Will et al. 1995b). It is uncertain whether this cluster is a binary companion of NGC 1818 or if it is seen in chance projection. For convenience, we will refer to the main cluster as NGC 1818 or NGC 1818A and to the small cluster as NGC 1818B.

The CMD of NGC 1818B (Fig. 2b) shows a sparsely populated main sequence that does not extend to stars as massive as found in NGC 1818A. There are no evolved (i.e., supergiant) stars present in the small cluster. The lack of more massive stars may be due to small number statistics, a less massive birth cloud or subcloud, or due to disruption of star formation (Franco et al. 1994) caused by NGC 1818A if the clusters are associated. The apparent absence of evolved stars and the very sparsely populated main sequence make it difficult to assign an age to NGC 1818B. Judging from the two brightest main-sequence stars, it may be coeval with NGC 1818A.

Plotting isochrones onto the CMD of NGC 1818B indicates that the reddening of this cluster is higher than that of NGC 1818A, namely $E(B-V) \approx 0.11$ mag. This may be due to the presence of differential reddening in this area, or a larger distance and thus higher reddening for NGC 1818B. It is also possible that star formation was less efficient for NGC 1818B and that there is still a higher concentration of dust and gas in this area. The currently available data do not yet allow to conclude whether the small cluster is associated with NGC 1818A. Radial velocities and spectral types for the brightest stars would help to clarify this matter.

4. Be stars in NGC 1818 and neighbouring cluster

Detections of Be stars in NGC 1818 were simultaneously reported by Bessell & Wood (1993) and Grebel et al. (1993). Both studies use the photometric detection method described in Sect. 1. An early attempt to estimate and compare Be star fractions was performed by Grebel et al. (1994). The current study gives a table with photometry and coordinates of the detected Be stars as well as a detailed comparison with Be stars in other Magellanic Cloud clusters and Galactic open clusters.

To detect Hα-emitting stars, we plot $(R - \alpha H)$ versus $(B - V)$ (Fig. 3). Stars without Hα emission can be found around $(R - \alpha H) \approx 0$. Stars with Hα emission have $(R - \alpha H)$ indices larger than zero. A pronounced clump of stars at $(B - V) \lesssim -0.2$ mag and $(R - \alpha H) \lesssim 0$ mag can be seen. These stars are blue main-sequence stars and blue supergiants that do not currently show Hα emission. Redward of this clump there is an extended group of stars scattered around $(R - \alpha H) \approx 0$ mag. These stars are red giants belonging to the field population and red supergiants from NGC 1818A. Red giants or supergiants may show Hα emission, and there are indeed a few red stars bright
Fig. 3. Two-colour diagram for the detection of Be stars. As selection criterion for Be stars we use \((B - V) \leq 0.5\) mag and \((R - H\alpha) \geq 0.1\) mag (dashed line).

in \(H\alpha\). The third group of stars lies along a band stretching upwards to positive values of \((R - H\alpha)\) starting from the clump of blue main sequence stars and supergiants. These stars are blue stars with \(H\alpha\) emission, i.e., our Be star candidates. When a larger colour baseline involving red filters is plotted such as \((B - R)\) or \((V - I)\) is used, one can see that this band of stars is tilted such that the stars brightest in \(H\alpha\) tend to be redder than the fainter emission-line stars (see figures in Grebel et al. 1994).

Due to the scattered clump of main-sequence stars and supergiants around \((R - H\alpha) = 0\) mag we adopt \((R - H\alpha) > 0.1\) mag as selection criterion for Be star candidates. A less strict criterion would increase the number of possible weak-line Be star candidates but would also increase the probability of including non-emission line stars. As mentioned before, reliable detections of very faint \(H\alpha\) emitters are only possible spectroscopically (see also Sect. 4).

The Be star candidates that are the most luminous at \(H\alpha\) can be found at \((R - H\alpha) \approx 0.7\) mag. In Tab. 2 (available from CDS) we list \(BVRH\alpha\) photometry of Be stars in NGC 1818 (marked by an “A”) and the small nearby cluster (marked by a “B”). The field (marked by “F”) around NGC 1818 and contains almost no Be stars. The \(V\) luminosity of the two or three brightest Be stars in our list indicates that they may qualify as extreme Be stars (see Garmany & Humphreys 1985 for more information). Spectroscopic follow-up studies are needed to confirm or reject this possibility. The astrometric data, right ascensions and declinations for equinox J2000.0, were taken from Will et al. (1995b) or, where not available, interpolated using the stars from Will et al. as tertiary astrometric grid. The astrometric positions from Will et al. (1995b) themselves are based on the grid of secondary astrometric reference stars in the Magellanic Cloud Catalogue of Stars (MACS, Tucholke et al. 1996) and have an accuracy of 0\(\prime\).5 and 0\(\prime\).6.

Our identifiers for the Be stars comply with the specifications for designations of astronomical objects as suggested by IAU Commission 5 [http://astro.u-strasbg.fr/iau-spec.html]. The identifier “NGC 1818:GBe xxx” specifies the source (NGC 1818) within and around which the Be stars are located. Separated through a colon are the subcomponents, which contain the letter sequence (GBe) and three digits (xxx) to identify the individual star. “GBe” consists of the author’s initial (G) and the string “Be” to indicate the nature of the stars.

5. Be star fractions

In Grebel et al. (1994) we investigated the fraction of Be stars in comparison to ordinary B stars using simple magnitude bins whose width in \(V\) magnitude corresponded to spectral subtypes as tabulated by Schmidt-Kaler (1982). The Galactic Be star frequencies were taken from Jaschek & Jaschek (1983). However, this approach is not entirely correct. We compared Be stars of supposedly common origin and supposedly similar age and chemical composition (namely Be stars in a specific cluster) to Galactic field Be stars, thus Be stars of quite different age, composition, and formation conditions. For a valid comparison, Be star fractions in Milky Way and in Magellanic Cloud clusters should be compared. Lacking blue populous clusters in the Milky Way, young open clusters are best suited.

Secondly, the distribution of Be stars with spectral type and their overall number depends on the age of the parent cluster (Mermilliod 1982) showed. The highest Be star frequencies were found in clusters with turnoffs in the spectral region of B0.5 to B2 stars. This corresponds to the ages of the three Magellanic clusters that we have analyzed so far – NGC 330, NGC 2004, and NGC 1818 (Grebel et al. 1992, 1994, Grebel 1995, and this study). Thus, for a meaningful comparison our data must be compared to Galactic clusters of the same age group.

The detection of Be stars is, of course, affected by incompleteness. For a given cluster we are less likely to detect Be stars of later spectral type because those stars will generally have fainter magnitudes. Generally, Balmer emission is strongest for the earliest types of Be stars. Also, in a crowded region detections are biased toward the brighter stars (affecting, of course, both B and Be stars). As illustrated in Fig. 2, we are severely affected by incompleteness in the innermost areas of NGC 1818. Close to the detection limit Be stars are more likely to be detected in \(H\alpha\) than non-emission line B stars since they may be up to several tenths of a magnitude brighter. Stars with very faint Balmer emission can only be detected spectroscopically anyway (see Sect. 4).

The fact that B-type stars may appear as Be stars at certain times and as ordinary B stars at others affects the Be star census in Galactic open clusters and star clas-
ters in the Magellanic Clouds equally. It is important to remember that all numbers represent only lower limits.

The Galactic open clusters with the largest known Be star fractions are NGC 663, NGC 3766, and χ Persei (e.g., Slettebak 1985). The first two clusters also have similar ages (a few $10^7$ years) as the Magellanic Cloud clusters. The total number of known Be stars in these clusters is 24 for NGC 663 (Sanduleak 1990), 30 for h and χ Per (Slettebak 1985), and 19 for NGC 3766 (Shobbrook 1985, 1987). Many of these clusters have been observed repeatedly over many years, and spectroscopy is available for most of their bright B-type stars. Thus the data on their Be stars may be more complete than our Magellanic cluster data, two of which we observed at only one epoch.

Among early-type B stars (B0 to B5), the estimated Be star fractions are 40% in NGC 663 (Sanduleak 1990) and 25% in χ Per. Based on photometric monitoring, Waekens et al. (1990) suggest that up to 50% of the B stars in h and χ Per may be Be stars. Shobbrook’s (1985, 1987) results indicate a Be star fraction of at least 36% for NGC 3766. Similarly, Hillenbrand et al. (1993) propose that 34% of the early-type stars they studied may be Be stars.

For the LMC cluster NGC 2004, Kjeldsen & Baade (1994) carried out slitless Hα spectroscopy and found 43 Be stars in a field of $7' \times 7'$. They estimate the Be star fraction to be 30% with a peak at 45% around B3 to B4, but point out that limited photometry and spectral classification in the literature made it difficult for them to estimate Be star fractions. We find an overall larger number of Be stars within a smaller field of view.

5.1. Assigning spectral types through photometry

Since we are lacking adequate spectroscopic data for NGC 1818 and NGC 2004, we have tried to assign spectral types to the Be stars through a relationship between absolute visual magnitudes and spectral types. Commonly used calibrations of spectral type versus absolute magnitudes such as the tabulations of Schmidt-Kaler (1982) do not consider the considerable intrinsic dispersion of absolute magnitudes that exists in each magnitude (Zorec & Briot 1991). This dispersion has been found to be about one magnitude for B2 V stars, and even two magnitudes for B9 III stars (Chalongé & Divan 1973). Zorec & Briot (1991) performed a new calibration of absolute magnitudes and spectral classes for B-type stars and also determined the scatter in magnitude. They find that Be stars are as luminous or up to about 0.8 mag (in V) more luminous than B stars of the same spectral type. Due to their generally rapid rotation, departures from sphericity may lead to changes in spectral type, brightening, and intrinsic “reddening” effects including limb darkening and gravity darkening (Slettebak et al. 1980, Collins et al. 1991, see also discussion in Grebel et al. 1996). As pointed out by Collins & Smith (1985), the position of an individual rotationally displaced star in a CMD cannot be uniquely associated with a single position on the zero-rotation main sequence. Briot & Zorec (1994) corrected for effects on Galactic field Be stars introduced by the over-luminosity of Be stars, spectral type changes during constant mass evolution, and spectral type changes due to fast rotation. Furthermore, Be stars may be affected by intrinsic reddening caused by their circumstellar disks. This effect will again depend on the inclination angle. The Be star phenomenon is known to occur as well in binary systems. Be stars that are members of binaries will also be displaced from the main sequence (see, e.g., Pols et al. 1991).

Adopting the spectral class vs. $M_V$ calibration for main sequence stars given by Zorec & Briot (1991), we approximated the spectral subtypes for the Be stars as follows: $M_{V,B0} < -3.25$, $-3.25 < M_{V,B1} < -2.55$, $-2.55 < M_{V,B2} < -1.8$, $-1.8 < M_{V,B3} < -1.4$, $-1.4 < M_{V,B4} < -0.95$, $-0.95 < M_{V,B5} < -0.6$. Due to increasing photometric errors and field contamination for the Magellanic Cloud clusters we do not consider stars of presumably later types than B5.

Using these magnitude bins, we assigned spectral types to our photometric data on NGC 1818, NGC 330, and NGC 2004, and to published data on the Galactic open clusters NGC 3766, α Per, and the Pleiades. The numbers for Galactic open clusters were extracted from dereddened CMDs published by Mermilliod (1982) and Slettebak (1985). Furthermore, we used tabulations by Shobbrook (1985, 1987: NGC 3766). We adopted the distance moduli and reddenings given in these references. The ages of open clusters are from Lyngå (1987: NGC 3766) and Meynet et al. (1993: α Per, Pleiades). Spectroscopic abundance determinations were taken from Luck & Bond (1989: NGC 3766) and Boesgaard & Friel (1990: α Per, Pleiades).

For our own data, we used $DM = 18.9$ mag for NGC 330, and $DM = 18.5$ mag for NGC 1818 and 2004, and ages and reddenings resulting from best-fitting isochrones (Grebel et al. 1994, Grebel 1995, and Sect. 3). The small cluster southwest of NGC 1818 is not included in the comparison because of poor number statistics.

In Fig. 4, we plot our results for the three Galactic open clusters and the three Magellanic Cloud clusters. Comparing the diagrams, the overall fraction of Be stars among the B-type stars appears to be higher for the three Galactic clusters than for the the Magellanic clusters. The diagrams seem to indicate that Be star fractions are particularly high for the earliest B stars, i.e., B0 to B2. As we will show in Sect. 5.2, however, assigning spectral types through the photometric calibration leads to spurious results despite the careful work by Zorec & Briot (1991).

5.2. Be star fractions from spectroscopy

To assess the quality of the spectral typing through photometry, we assembled a number of Galactic open clusters for which spectroscopy of B-type stars is available. In Fig.
Fig. 4. Spectral types assigned through a photometric calibration derived from Zorec & Briot (1991) are plotted for three Galactic open clusters rich in Be stars (left panels) and our three Magellanic Cloud clusters (right panels). “N” denotes total numbers of stars. B stars in general are represented by white histograms, while the black histograms indicate the number of Be stars among them. A cutoff toward later B types is artificially introduced through lack of data. The diagrams seem to indicate that Be star fractions are particularly high for the earliest B stars (B0 to B2). However, note the significant shifts in spectral types when spectroscopic results are used instead (Fig. 5). For the Pleiades, spectral typing through photometry moved the luminous non-supergiants to too early types by up to three B sub-classes.

E.K. Grebel: Be star surveys with CCD photometry. II. NGC 1818

only stars of spectral type B and luminosity classes ranging from V to III are considered. It has to be emphasized that this stringent criterion introduces a strong selection effect not only for eligible B stars, but in particular for Be stars. Be stars are often catalogued simply as “Be” without further classification, or with spectral type but without luminosity class.

We compiled the spectroscopic data for Galactic open clusters from Slettebak (1985), Mermilliod (1988), and Buscombe (1995). The latter two catalogues are largely complete compilations of prior spectroscopic studies referenced therein. We supplemented these data by photometric detections of Be stars that had spectroscopic classifications but had not yet previously been identified as Be stars. In addition to the publications referenced in Sect. 5.1, we used results from Sanduleak (1990), Goderya & Schmidt (1994), and Massey et al. (1995).

For the clusters not already presented in Fig. 4, we used ages from Meynet et al. (1993: NGC 4755, NGC 1039, NGC 2287), from Phelps & Janes (1994: NGC 663), from Hillenbrand et al. (1993: NGC 6611), and else from Lyng˚a (1987). Metallicities were adopted from Lyng˚a as far as available. The metal abundance for χ Per was determined by Klochkova (1991).

Spectral classifications of B-type stars in the Magellanic Clouds exist for many field stars and OB associations (s. Buscombe 1995 and references therein). We extracted spectroscopic classifications for stars in 20 Lucke and Hodge (LH, 1970) OB associations from the Buscombe catalogue. In most cases, either no Be stars had been detected or they were listed without MK classification. Also, in many spectroscopic studies only the earliest B-type stars had been classified. These data cannot serve to determine fractions of Be stars. Therefore, in Fig. 4 only NGC 330 is included based on the determination and compilation of spectral types in Grebel et al. (1996). NGC 330 is the only cluster of our set with a larger database of MK classifications among its B-type stars. Based on their position in a CMD, the few Be stars classified as B2 Ie have also been included in this diagram, since they have fainter V magnitudes than the regular blue supergiants in NGC 330 and may be extreme Be stars as discussed by Schild (1966) and Garmany & Humphreys (1985).

As explained before, field Be stars are not well suited for comparisons to cluster Be stars because they span a range of ages and may have a range of metallicities. On the other hand, they may give a better idea of the overall distribution of Be stars of different spectral types, since many more field Be stars have spectral classifications than Be stars within a specific cluster. Several Be star catalogues are available electronically. We found the catalogue of Page (1984) to give the best number statistics. From this catalogue, we extracted all non-supergiant field Be stars. The 1145 field Be stars are plotted in the first panel of Fig. 4. In all cases, we counted stars classified as B1.5 as B1 stars, B2.5 stars as B2 stars, etc. Page’s (1984) catalogue lists for each star all previous spectral classifications, and different studies may differ by several subclasses. In those cases, we usually chose the most frequently occurring classification, while in other Be star catalogues preference has been given to spectral classifications from specific sources. E.g., Jaschek & Egret’s (1982) catalogue prefers the Michigan Spectral Survey (Houk & Cowley 1975, Houk 1978).
Fig. 5. Galactic Be and B stars. Only stars with spectral types and luminosity classes III to V are plotted. “N” denotes total numbers of stars. The first panel on the left shows Galactic field Be stars. The top panel on the right presents the SMC cluster NGC 330. All other panels give B (white histograms) and Be stars (black histograms) in open clusters of various ages. Iron abundances are given when known. See Sect. 5.1 and 5.2 for references. All numbers given are only lower limits owing to incomplete availability of accurate spectral classifications. This affects in particular the Be stars among the B stars.

In good agreement with earlier studies, the majority of the field Be stars is found among the early B types. The most pronounced peak can be seen for B2 emission-line stars (Slettebak 1982, Jaschek & Jaschek 1983). The B1 bin contains the second highest number of Be stars, which is in good agreement with the Jaschek & Egret (1982) catalogue when using the same spectral type binning. A small peak is seen for B8 stars in agreement with Jaschek & Egret (1982) and Jaschek & Jaschek (1983). The small peak at B5 may be an artifact of the preferred classification of stars as B3 or B5 rather than B4.

Mermilliod (1982) pointed out that the overall Be star frequency is highest for young clusters containing early-type stars, while total numbers decrease for older clusters. In good agreement with earlier studies, the majority of the field Be stars is found among the early B types. The most pronounced peak can be seen for B2 emission-line stars (Slettebak 1982, Jaschek & Jaschek 1983). The B1 bin contains the second highest number of Be stars, which is in good agreement with the Jaschek & Egret (1982) catalogue when using the same spectral type binning. A small peak is seen for B8 stars in agreement with Jaschek & Egret (1982) and Jaschek & Jaschek (1983). The small peak at B5 may be an artifact of the preferred classification of stars as B3 or B5 rather than B4.

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In Fig. 5, open clusters are arranged to form a sequence of increasing ages. We note in passing that age determinations for OB clusters may vary by up to a factor of two in different studies (e.g., Pleiades: 80 Myr according to Meynet et al. 1993, 150 Myr according to Mazzei & Pigatto 1989; α Per: 52 Myr following Meynet et al. 1993, 80 Myr according to Prosser 1992). Though small number statistics and the above discussed incompleteness affect our diagrams, they nicely demonstrate Mermilliod’s finding. Frequency peaks in the Be star distribution are found at B1 to B2 and, in the case of NGC 6611, for which spectral typing for the entire range of B stars is the most complete, at B8. As emphasized before, all B star num-
bers and especially Be star numbers represent only lower limits.

Despite incomplete spectral coverage, Be star numbers vary significantly from cluster to cluster. A young age alone does not guarantee a high number of Be stars (compare NGC 2244 to h & χ Per, NGC 6611 and NGC 663 to IC 2944, NGC 4755, and NGC 2264, etc.). Neither does metallicity, which for the displayed Galactic clusters with known metal abundances is quite similar. A likely second parameter for the formation of Be stars is rapid rotation – e.g., the stars in h and χ Per, the young Galactic double cluster so rich in Be stars, are known to be rapid rotators (Slettebak 1968). The much older α Per, where also low-mass stars often show Hα emission and Be stars start with intermediate B spectral types, contains plenty of rapid rotators (e.g., Prosser 1992). The even older Pleiades with their late-type Be stars also show quite high $v \sin i$ values (e.g., Abt 1970). In contrast, IC 4665 (age: 36 Myr according to Lyngå 1987) contains very few Be stars (not plotted in Fig. 3, but see Buscombe 1995). At the same time, it is known for its large fraction of binaries and, perhaps because of that, the low rotational velocities of its members (e.g., Schild 1967).

The young SMC cluster NGC 330 presents a pronounced frequency peak at B2 (Fig. 3). Almost all of the non-supergiant B-type stars in this cluster for which spectroscopy exists have been found to be Be stars (Lennon et al. 1994, Grebel et al. 1996) and, as is evident from the diagram, most of them are B2 stars. Spectral classifications have only been performed for the brightest stars in this cluster which explains the lack of later Be types.

A comparison of the diagrams of NGC 330, NGC 3766, α Per, and the Pleiades in Fig. 3 and Fig. 2 shows remarkable differences. Spectral typing through the photometric calibration used in Sect. 5.2 results in spectral types that are too early by two to three spectral subclasses. A comparison of individual stars shows, for instance, that most of the stars in NGC 330 that were assigned types of B0 and B1 are in fact B2 stars according to classification based on spectroscopy. For the Pleiades, the earliest B stars are of type B6 (Johnson & Morgan 1953), while the photometric calibration makes them B3 stars. This demonstrates that even very careful photometric calibrations are no substitute for spectroscopic classifications. It also implies that as of now, we cannot yet compare directly Be star fractions in young Magellanic Cloud clusters to Galactic open clusters. A lot more spectral classification work is needed for the Magellanic Cloud clusters, and it would be highly desirable also to complete spectroscopic studies of the much more easily accessible Galactic clusters.

6. Constraints on Be star theories

Our current knowledge about Be stars in the Magellanic Clouds does not yet allow to constrain Be star theories. As was emphasized by Smith (1988, observations of Galactic Be stars have shown that there seem to be at least three independent causes for the Be star phenomenon. It appears that rotation, pulsation, and multiplicity may all play a role. In the case of NGC 330, at least some of the Be stars are members of binary systems (Grebel et al. 1996). Many Galactic Be stars, perhaps even most, are members of binary systems (see discussion in Abt et al. 1987). Pols et al. (1991) present models explaining the formation of Be stars in close binary systems. Pols & Marinus (1994) use Monte Carlo simulations that convincingly reproduce binary main sequences as observed in Galactic open clusters (e.g., Mermilliod 1992, Mermilliod & Maeder 1986) and lead to the formation of blue stragglers and Be stars. The number of close, interacting binaries, however, is probably small (Slettebak 1988) both in the Milky Way and in the Magellanic Clouds (Van Bever & Vanbeveren 1996).

That either rotation (Balona 1990, Balona et al. 1991) or non-radial pulsation (Baade 1987, 1988) plays a role in NGC 330 is shown by the presence of λ Eri variables discovered by Balona (1992). NGC 2004, which we find to be not as rich in Be stars as NGC 330 and NGC 1818, also appears to contain only very few λ Eri variables (Balona 1993). Balona (1990) suggests that the correlation between projected rotational velocities and photometric periods of Be stars may be explained when the photometric period equals the rotational period. Owocki et al. (1994) predict that stars rotating with 90% of $v_{\text{crit}}$ should exhibit strong variability. High-resolution spectroscopy is needed to determine the rotational velocities of the variable stars in Magellanic Cloud clusters and to detect possible signatures of non-radial pulsations, or their absence. This will require a substantial amount of observing time at the new generation of very large telescopes.

A very elegant theory for the formation of equatorial disks, which is capable to account for many of the observed features in Be stars was presented by Bjorkman & Cassinelli (1993). This wind-compressed disk model for line-driven winds was then extended by Owocki et al. (1994) to include a full dynamical treatment of gas pressure and radiative driving. Disks form in the following way for stars with large enough rotation thresholds: At low latitudes near the surface of a star, the gravity acceleration is larger than the radiative acceleration, and fluid streamlines “fall” toward the equator, where fluids from both hemispheres collide. Standing shocks form above and below the equator, between which a dense equatorial disk is confined by the ram pressure of the wind. A disk will form when the rotation rate is above a threshold value depending on the ratio of the terminal velocity of the wind ($v_{\infty}$) and the escape velocity from the star ($v_{\text{esc}}$). For spectral types from O to B2, this velocity ratio decreases as the terminal velocity decreases. For instance, an O6 star has to rotate at 84% of its critical velocity ($v_{\text{crit}}$) in order to form a disk, while for a B2 star 48% of $v_{\text{crit}}$ suffices. Thus from the theoretical predictions the frequency peak of Be stars is expected at B2, which seems to be confirmed ob-
The rotation threshold for a B2 star is \( v_{\text{rot}} > 180 \text{ km s}^{-1} \) assuming a uniform distribution of inclination angles \( \sin(i) = \pi/4 \). Observationally, however, \( v_{\infty}/v_{\text{esc}} \) slowly continues to drop, which Bjorkman & Cassinelli (1993) attribute to a possible underestimation of \( v_{\infty} \) for B stars of later types because of weak line profiles of C iv and Si iv. Currently, the predicted disk density is by a factor of 100 too small to reproduce the observed IR excess, Hα emission, and polarization. This could be remedied if mass-loss rates are in fact higher than currently estimated, which reduces the initial acceleration of the wind by decreasing the radiative line-driving force. Furthermore, while the current model predicts both infall and outflow from the equatorial disk, the infall could be prevented by rotationally supporting the disk material. A weak magnetic field may already be sufficient to add angular momentum to the disk (Bjorkman 1994).

The Be star phenomenon should thus be enhanced by reducing the terminal velocity of the wind. The more metal-rich a star is, the more photons will be absorbed, which transfers their momentum to the absorbing material and accelerates the gas by radiation pressure. This metal-rich wind is emitted radially and may have too high velocities to be withheld by the centripetal force, thus gets lost and cannot contribute to forming a disk. However, in a metal-poor environment, the radiation pressure is obviously lower, which in turn leads to lower terminal velocities. In a metal-poor environment, stars are more likely to have terminal velocities that are smaller than the centripetal acceleration, thus the gas slows down and is more easily confined. According to this intuitive scenario (Bjorkman 1995), Be stars should form preferably in metal-poor environments. Lower wind speeds will generally lead to the formation of stronger disks (Owocki et al. 1994). However, the latest calculations by Owocki et al. (1996) indicate that the wind-compressed disk model does not work when non-radial forces and distortion due to rapid rotation are considered. Both lead to stronger poleward components of the radiative flux and prevent the formation of disks.

As we discussed in Sect. 5, the currently available data do not yet allow one to make quantitative statements about Be star fractions both in Galactic and in Magellanic Cloud clusters. Clearly, additional spectral classification and high-resolution spectroscopic studies are needed. However, we can already state that NGC 330 and NGC 1818 are rich in Be stars. High Be star fractions are also found in more metal-rich Galactic open clusters (Sect. 4). It would be interesting to determine terminal gas velocities for stars in these clusters. Of course, other factors, such as intrinsic rapid rotation, will contribute as well to the Be star phenomenon – perhaps stars in the metal-poor LMC cluster NGC 2004, which has a lower Be-star frequency, are rotating at lower velocities.

The evolutionary status of Be stars has long been under debate. That many of them appear spectroscopically and photometrically as subgiants, giants, or even bright giants may be due to effects of rapid rotation, binarity or multiplicity, and (infra-)red excess. The effects of rotation on spectral classification and on the position in the CMD were studied by Slettebak et al. (1980) and Collins et al. (1991), and Pols & Marinus (1994) showed the influence of binarity on the position of main-sequence stars. These effects can easily make main-sequence stars appear as giants. Furthermore, Be stars are known as rapid rotators. Finally, reddening caused by the circumstellar disks and the red excess of Be stars will move them further on to lower temperatures. The study of Be stars in clusters, i.e., stellar aggregates that are supposedly coeval and of the same origin, may help to constrain the evolutionary status of Be stars. The young ages of our three Magellanic Cloud clusters make it seem likely that at least there the non-supergiant B-type stars are still burning hydrogen in their cores and thus are in the evolutionary phase of main-sequence stars (Grebel et al. 1996).

7. Summary

We have combined new R and Hα photometry with our B,V photometry of NGC 1818 (Will et al. 1995b). We have used the combined data set to investigate the Be star content of NGC 1818 and surroundings using our photometric detection method (Grebel et al. 1992, 1994). A table with photometry, astrometric positions, and designations complying with IAU recommendations for all detected Be stars down to 18th magnitude in NGC 1818 and surroundings is available electronically from CDS, Strasbourg.

Re-analyzing the NGC 1818 photometry, we find a small cluster 1.5 southeast of NGC 1818 apparently not mentioned in the literature before, which we have named NGC 1818 B. This cluster seems to have an age of at least 30 Myr and a reddening of \( E(B-V) = 0.11 \text{ mag}, 0.04 \text{ mag} \) higher than what we found for the similarly old NGC 1818. Differential reddening does not seem to be present across NGC 1818. Due to its sparse main sequence and lack of evolved stars, it is difficult to assign an age to NGC 1818 B. The current data do not allow to determine whether the small cluster is associated with NGC 1818.

In both clusters, we find a large number of Be stars, while the field has almost none. The field shows a few young, massive stars comparable or slightly older than NGC 1818 in age. The majority of the field population appears to be of intermediate age.

For a valid comparison with Galactic Be stars, fractions in Galactic clusters comparable in age have to be compared to the Magellanic clusters. Only Be stars in clusters are likely to be coeval, equidistant, of the same metallicity, and to have a common origin. In attempting to determine Be star fractions in Galactic open clusters
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