*Star clusters: basic galactic building blocks*
*Proceedings IAU Symposium No. 266, 2009*
*R. de Grijs & J. R. D. Lépine, eds.*

doi:10.1017/S1743921309991724

# Evolution and appearance of Be stars in SMC clusters

**C. Martayan,[1,2] D. Baade,[3] Y. Frémat[4] and J. Zorec[5]**

[1]European Organisation for Astronomical Research in the Southern Hemisphere,
Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
email: `cmartaya@eso.org`

[2]GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 5 place Jules Janssen,
92195 Meudon Cedex, France

[3]European Organisation for Astronomical Research in the Southern Hemisphere,
Karl–Schwarzschild–Str. 2, 85748 Garching b. München, Germany

[4]Royal Observatory of Belgium, 3 avenue circulaire, 1180 Brussels, Belgium

[5]Institut d'Astrophysique de Paris, UMR7095, CNRS, Université Marie & Pierre Curie,
98bis Boulevard Arago, 75014 Paris, France

**Abstract.** Star clusters are privileged laboratories for studying the evolution of massive stars (OB stars). One particularly interesting question concerns the phases during which the classical Be stars occur, which—unlike HAe/Be stars—are not pre-main-sequence objects, nor supergiants. Rather, they are extremely rapidly rotating B-type stars with a circumstellar decretion disk formed by episodic ejections of matter from the central star. To study the impact of mass, metallicity, and age on the Be phase, we observed Small Magellanic Cloud (SMC) open clusters with two different techniques: (i) with the ESO–WFI in slitless mode, which allowed us to find the brighter Be and other emission-line stars in 84 SMC open clusters, and (ii) with the *VLT*–FLAMES multifiber spectrograph to determine accurately the evolutionary phases of Be stars in the Be-star-rich SMC open cluster NGC 330. Based on a comparison to the Milky Way, a model of Be stellar evolution, appearance as a function of metallicity and mass, and spectral type is developed, involving the fractional critical rotation rate as a key parameter.

**Keywords.** stars: emission-line, Be, stars: fundamental parameters, stars: statistics, stars: early-type, stars: evolution, surveys, galaxies: star clusters, Magellanic Clouds

## 1. Observations and spectral analysis

We performed an H$\alpha$ survey with the ESO–WFI (Baade *et al.* 1999) in slitless mode in the central parts of the Small Magellanic Cloud (SMC). Three million low-resolution spectra were obtained. They were extracted from the images with SExtractor (Bertin & Arnouts 1996) and we developed Album (Martayan *et al.* 2009) to identify spectra exhibiting H$\alpha$ emission. After astrometric calibration, the extracted sources were cross-matched with the ogle-ii photometric catalogue (Udalski *et al.* 1998). Within the area observed, results for 84 SMC open clusters are presented. In particular, the results are compared with those from McSwain & Gies (2005) in Galactic open clusters. The ratios of clusters with and without classical Be stars are compared with respect to metallicity ($Z$), spectral type, and age. Observations were also obtained with *VLT*–FLAMES (Pasquini *et al.* 2002) of the Be-star-rich SMC open cluster NGC 330 and its vicinity. LR2 spectra (395–455 nm, $R = 6400$, H$\epsilon$, H$\delta$, H$\gamma$, HeI447.1nm, MgII448.1nm) and LR6 spectra (650–770 nm, $R = 8600$, H$\alpha$) were aquired between October 2003 and September 2004. For each star, the fundamental parameters were determined with girfit (Frémat *et al.* 2006), taking account of fast-rotation effects with FASTROT (Frémat *et al.* 2005). In particular, rotational velocities were determined as well as the statistical, fractional angular breakup velocity for Be stars of different ages (see Martayan *et al.* 2007).

## 2. Observed metallicity effect on the relative frequency of Be stars

The metallicity of the SMC is significantly lower ($0.001 < Z < 0.009$; Cioni *et al.* 2006) than that of the Galaxy ($Z = 0.020$). Figure 1 shows the fraction of Be to all B-type stars by spectral type, separately for the SMC and the Milky Way. It clearly indicates that early-type Be stars are 3–5 times as frequent in the SMC as in the Milky Way (beyond B2–B3, the SMC sample is incomplete). Note that the age ranges are comparable. The large difference in frequency is obviously most easily attributed to the difference in metallicity.

## 3. Appearance of Be stars in open clusters as a function of age

Figure 2 displays the fraction of open clusters with Be stars in the SMC and the Milky Way versus age. It appears that Be stars are preferentially hosted by young open clusters. A first decrease in the fraction of open clusters with Be stars is seen around 30–40 Myr (corresponding to early-type Be stars reaching the terminal-age main sequence; TAMS) is followed by an increase of open clusters with Be stars. The terminal decrease in older open clusters is also due to the late-type Be stars arriving on the TAMS.

## 4. Metallicity-dependent evolution of rotational velocities

To explain the overall shape of Figure 2, the temporal evolution of the fractional angular velocity ($\frac{\Omega}{\Omega_c}$) of Be stars can be reconstructed from observed rotational velocities (here we use *VLT*–FLAMES spectra) and theoretical evolutionary tracks from Maeder & Meynet (2001). From our SMC data and results obtained by Zorec *et al.* (2005) in the Milky Way, Be stars have a minimal $\frac{\Omega}{\Omega_c}$ of 0.7. If/when B-type stars rotate more slowly, Be symptoms do not seem to develop.

The evolution of the $\frac{\Omega}{\Omega_c}$ depends on stellar mass and metallicity (see figure 5 in

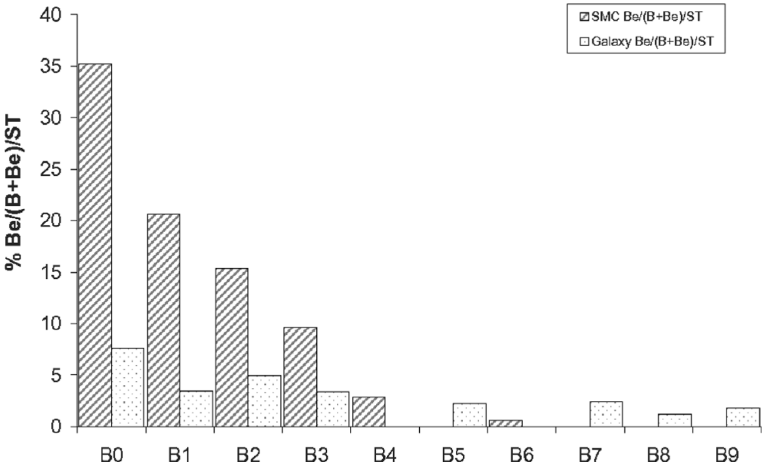

**Figure 1.** Relative abundances of Be stars in the SMC (hatched histogram) and the Galaxy (dot-filled histogram) as a function of spectral type.

Martayan *et al.* 2007), which holds the key to our understanding of the distribution seen in Figure 2:

- In massive Milky Way Be stars, $\frac{\Omega}{\Omega_c}$ is sufficient to develop Be-star symptoms at the beginning of the main sequence. Due to wind-driven mass loss, the angular momentum decreases until $\frac{\Omega}{\Omega_c}$ drops to below the threshold of 0.7 and the initial Be-star appearance will be lost after $\sim 5 - 10$ Myr. This explains the small decrease observed in the Milky Way for open clusters with Be stars (cf. Mathew *et al.* 2008).
- Intermediate-mass Be stars seem to retain a sufficently high level of $\frac{\Omega}{\Omega_c}$ during their entire main-sequence evolution to preserve their appearance as Be stars without interruption. The Be-star attributes will disappear once the TAMS is reached at ∼40 Myr, which explains the lower fraction of Galactic open clusters with Be stars of this age.
- Rapidly rotating low-mass B stars can appear as Be stars at the beginning of the main sequence but will lose this status quickly through a reorganization of the internal angular momentum. Subsequently, the standard evolution of $\frac{\Omega}{\Omega_c}$ with time (increasing radius with small angular-momentum loss), will let them reach an $\frac{\Omega}{\Omega_c}$ above 0.7, so that at an age of 40–50 Myr they are again recognizeable as Be stars. This can explain the second increase of the number of open clusters with Be stars at an age of 40 Myr. The low-mass Be stars will then begin to reach the TAMS and the number of open clusters with Be stars decreases with age.
- In the SMC, the evolution of $\frac{\Omega}{\Omega_c}$ of intermediate- and low-mass Be stars is similar to that in the Milky Way because in this mass range mass loss is too small to significantly alter the angular momentum or its internal distribution. This explains the evolution of open clusters with Be stars and ages between 30 and 100 Myr. Still older open clusters that host Be stars probably had multiple star-formation episodes or the Be stars may be blue stragglers. Note that, for the Milky Way, McSwain & Gies (2005) suspect that 75% of the Be stars are binaries.
- The evolution of more massive Be stars is different in the SMC than in the Milky Way. Because of the lower SMC metallicity, mass and angular-momentum loss are also lower, and $\frac{\Omega}{\Omega_c}$ increases with time as in low-mass Be stars. They will reach the 70% limit

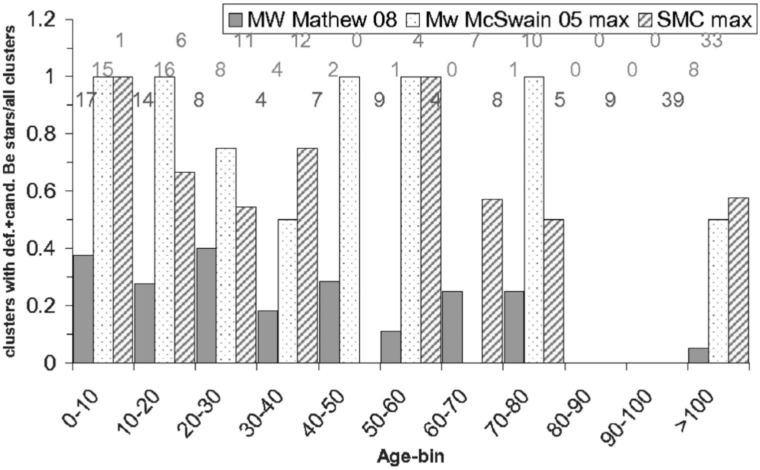

**Figure 2.** Fraction of open clusters with Be-star members in the SMC (hatched histograms) and the Milky Way (dot-filled histograms: data from McSwain & Gies 2005; filled histograms: data from Mathew *et al.* 2008) as a function of cluster age. The number of clusters studied is indicated.

at ∼$4-5$ Myr and appear again as Be stars, in contrast to massive Be stars in the Milky Way. Therefore, in the SMC very young open clusters are expected to contain Be stars.

However, for observational verification of this difference in the fraction of Be stars between very young open clusters in the Milky Way and SMC, a larger sample of open clusters younger than 10 Myr is needed. For such a comparison, one must carefully discriminate between classical Be stars and Herbig Ae/Be stars, which are still on the pre-main sequence and owe their emission lines to their parental accretion disk. A method to achieve this separation is described in Martayan *et al.* (2008).

The inferred long-term transitions between the Be and B phases will probably not be abrupt, and one may speculate whether the much faster and repetitive Be to B, and B to Be transformations observed in many Be stars are part of long-term transitions. If so, one would expect that Be stars with stable and those with more volatile circumstellar disks should not show significant differences otherwise. In fact, this is what McSwain *et al.* (2009) reported recently.

## 5. Conclusions

We conducted a study of open clusters with Be stars using two data sets,

- a low-resolution H$\alpha$ survey of 84 SMC open clusters. It indicates that Be stars are more abundant in the SMC than in the Milky Way. The fraction of open clusters with Be stars reaches a local minimum at ages around 30–40 Myr and eventually declines for clusters older than 70–80 Myr.
- Fundamental stellar parameters determined from medium-resolution spectra of B and Be stars in the SMC open cluster NGC 330 and its vicinity allowed us to study the evolution of the fractional critical angular velocity, $\frac{\Omega}{\Omega_c}$, of Be stars. Its dependence on stellar mass and metallicity can explain the distribution with age of the fraction of open clusters with Be stars and the differences between the Galaxy and the SMC.

All data and a more comprehensive discussion are presented in Martayan *et al.* (2009).

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