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## **Effects of metallicity, star formation conditions and evolution of B & Be stars.**

C. Martayan, A.-M. Hubert, M. Floquet, C. Neiner

*GEPI, UMR 8111 du CNRS, Observatoire de Paris-Meudon, 92195 Meudon Cedex, France*

Y. Frémat

*Royal Observatory of Belgium, 3 avenue circulaire, 1180 Brussels, Belgium*

J. Zorec

*Institut d'Astrophysique de Paris (IAP), 98bis boulevard Arago, 75014 Paris, France*

### **Abstract.**

To study the effects of metallicity and evolution on the appearance of the Be phenomenon in the B stars population, we observed several fields in the Large and Small Magellanic Clouds (LMC and SMC, respectively) which have different metallicities. Thanks to the FLAMES-GIRAFFE multi-fibres spectrograph on the VLT-UT2, we obtained spectra of 520 stars in the LMC-NGC2004 and SMC-NGC330 regions. We used 2 settings at medium resolution:  $R=8600$  for the red setting which contains  $H\alpha$  and  $R=6400$  for the blue setting which contains  $H\gamma$ ,  $H\delta$ , He I 4026, 4388, 4471 Å. The latter setting was used to obtain fundamental parameters of the stars by fitting the observed spectrum with theoretical spectra. We used TLUSTY (Hubeny & Lanz 1995) to compute a grid of model atmospheres with abundance adopted from Korn et al. (2002) for the LMC and from Jasniewicz & Thévenin (1994) for the SMC. Thanks to the GIRFIT code (Frémat et al. 2005a), we obtained the fundamental parameters  $T_{\text{eff}}$ ,  $\log g$ ,  $V \sin i$  and radial velocity (RV) for each star of the samples. We took into account the effects of fast rotation (stellar flattening and gravitational darkening) for Be stars to correct their apparent fundamental parameters.

Then we compared the rotational velocities between fields and clusters in the SMC and in the LMC respectively, between the LMC and the SMC, and between the MC and the Milky Way (MW). The results show an increase in  $V \sin i$  with decreasing metallicity in B and Be stars populations. The evolutionary status and ages of Be stars were also investigated.

### **1. Introduction and observations**

In the Milky Way (MW), the behaviour of B and Be stars has been investigated for several decades and recently new results have been obtained. According to Fabregat & Torrejón (2000), the Be phase appears mainly in the second part of the MS; however, we do not know whether only a fraction or all B-type stars will become Be stars. According to Maeder et al. (1999), the proportion of Be stars increases with the decreasing metallicity of the environment (MW, LMC

and SMC). Porter & Rivinius (2003) have found that 1/3 of Be stars are binaries at the maximum, then the binarity cannot explain the Be phenomenon in all cases.

In the Magellanic Clouds (MC) the B and Be star populations are not well known or unknown and there is no spectral classification for these objects.

In order to investigate the effects of metallicity, star formation conditions and evolution in B & Be stars, we observed B-type stars, selected on colour-magnitude criteria, with the VLT multifibres GIRAFFE spectrograph. These observations were performed at medium resolution in 2 settings: a “blue” setting centered at 4250 Å to determine the fundamental parameters and a “red” setting centered at 6570 Å for the characterization of the emission of Be stars. Finally, we observed 177 stars in the Large Magellanic Cloud (LMC); among them, 25 are new Be stars, 22 are known Be stars and 121 stars are B stars. In the Small Magellanic Cloud (SMC), we observed 346 stars, of which 90 are new Be stars, 41 are known Be stars and 202 are B stars. In the statistical studies reported in the following sections, we have removed from the samples the binaries (B and Be stars) and we have assumed a random distribution of the inclination angle.

## 2. Fundamental parameters determination

We have determined the fundamental parameters ( $T_{\text{eff}}$ ,  $\log g$ ,  $V \sin i$ ) with the GIRFIT least squares procedure, which is able to handle large datasets and was previously developed and described by Frémat et al. (2005a). GIRFIT fits the observations with theoretical spectra interpolated in a grid of stellar fluxes computed with the SYNSPEC programme and from model atmospheres calculated with TLUSTY (Hubeny & Lanz 1995, see references therein) or/and with ATLAS9 (Kurucz 1993; Castelli et al. 1997) and with suitable abundances for the LMC (Korn et al. 2002) and for the SMC (Jasniewicz & Thévenin 1994). It accounts for the instrumental resolution through convolution of spectra with a Gaussian function and for Doppler broadening due to rotation. Use is made of subroutines taken from the ROTINS computer code provided with SYNSPEC (Hubeny & Lanz 1995). Thanks to calibration (Gray & Corbally 1994 and Zorec 1986), we have obtained the spectral classification of the stars. The main types range from B1 to B3. The luminosity classes are mainly V for LMC B stars and V & IV for SMC B stars. The luminosity classes are mainly III for LMC Be stars and IV & III for SMC Be stars. Consequently, the B stars in the SMC seem to be slightly evolved in comparison with the B stars in the LMC. The Be stars in the SMC and in the LMC seem to be evolved. However, following Fabregat & Gutiérrez-Soto (2004), there is no clear relation between the evolutionary status of a Be star and its luminosity class.

By interpolation in theoretical HR tracks with  $Z=0.004$  for the LMC (Charbonnel et al. 1993) and with  $Z=0.001$  for the SMC (Schaller et al. 1992), we have obtained other associated parameters like the luminosity, the radius, the mass and the age of the stars.

### 3. Effects of metallicity and ages on the linear rotational velocities

In order to investigate the potential effect of metallicity on the rotational velocities, we have made sub-samples of stars by mass selection. It allows to compare the results directly with the existing theoretical evolutionary tracks. We assume that the distribution of the inclination angle is random and we have removed all the detected binaries from the sub-samples. The comparisons given in the next sections are supported by statistical tests like the Student t-test.

#### 3.1. B stars

The results on the mean rotational velocities of B stars in the SMC and in the LMC are given in Table 1. Only the sub-samples of the 5-10  $M_{\odot}$  category are comparable because they have similar masses and ages while their metallicity is different. The values of the rotational velocities,  $156 \text{ km s}^{-1}$  and  $119 \text{ km s}^{-1}$  for B stars in the SMC and in the LMC respectively, show an unambiguous effect of the metallicity. The lower the metallicity is, the higher the rotational velocities are.

Table 1. Comparison by mass sub-samples of the mean rotational velocities in the SMC and LMC B stars. For each sub-sample, the mean age, mean mass, mean  $V \sin i$  and the number of stars ( $N^*$ ) are given.

	2-5 $M_{\odot}$				5-10 $M_{\odot}$			
	$\langle \text{age} \rangle$	$\langle M/M_{\odot} \rangle$	$\langle V \sin i \rangle$	$N^*$	$\langle \text{age} \rangle$	$\langle M/M_{\odot} \rangle$	$\langle V \sin i \rangle$	$N^*$
SMC B stars	8.1	4.0	$166 \pm 20$	116	7.7	6.6	$156 \pm 20$	77
LMC B stars					7.6	7.2	$119 \pm 20$	87
	10-15 $M_{\odot}$							
	$\langle \text{age} \rangle$	$\langle M/M_{\odot} \rangle$	$\langle V \sin i \rangle$	$N^*$				
SMC B stars								
LMC B stars	7.2	11.6	$116 \pm 20$	13				

#### 3.2. Be stars

Like for B stars, we have compared Be stars in the MC and in the MW. The rotational velocities of MW Be stars come from Chauville et al. (2001) and their masses and ages from Zorec et al. (2005). The results are shown in Table 2. We can compare the Be stars with similar masses and ages, for example: SMC and MW Be stars of the 2-5  $M_{\odot}$  category; SMC, LMC and MW Be stars of the 5-10  $M_{\odot}$  and 10-12  $M_{\odot}$  categories. They show a similar effect of metallicity: the lower the metallicity is, the higher the rotational velocities are. We cannot compare directly the MC and the MW Be stars of the 12-18  $M_{\odot}$  category because there are no MW Be stars at the age of MC Be stars. The Be phase seems to be longer in the MC than in the MW.

#### 3.3. ZAMS rotational velocities

Thanks to theoretical evolutionary tracks interpolated in Meynet & Maeder (2000, 2002), Maeder & Meynet (2001) and thanks to those calculated by Zorec et al. (2005 in preparation), we have interpolated the rotational velocities at the ZAMS for the Be stars in the MC (Martayan et al. 2005c in preparation) and in the MW.

The results are shown in Figure 1 and consequently, we note that:

Table 2. Comparison by mass sub-samples of the mean rotational velocities in the SMC, LMC and in the MW Be stars. The latter ones come from Chauville et al. (2001) and Zorec et al. (2005). For each sub-sample, the mean age, mean mass, mean  $V \sin i$  and the number of stars ( $N^*$ ) are given.

	2-5 $M_{\odot}$				5-10 $M_{\odot}$			
	<age>	<M/ $M_{\odot}$ >	< $V \sin i$ >	$N^*$	<age>	<M/ $M_{\odot}$ >	< $V \sin i$ >	$N^*$
SMC Be stars	8.3	3.8	277 ± 40	14	7.6	7.7	295 ± 40	82
LMC Be stars	7.3	10.9	345 ± 40	13	7.5	7.7	285 ± 30	21
MW Be stars	8.1	4.4	241 ± 10	18	7.4	7.3	234 ± 10	52
	10-12 $M_{\odot}$				12-18 $M_{\odot}$			
	<age>	<M/ $M_{\odot}$ >	< $V \sin i$ >	$N^*$	<age>	<M/ $M_{\odot}$ >	< $V \sin i$ >	$N^*$
SMC Be stars	7.3	10.9	345 ± 40	13	7.2	13.5	324 ± 40	13
LMC Be stars	7.3	11	259 ± 30	13	7.1	14.6	224 ± 30	10
MW Be stars	7.1	10.6	231 ± 10	9	6.6	14.9	278 ± 10	16

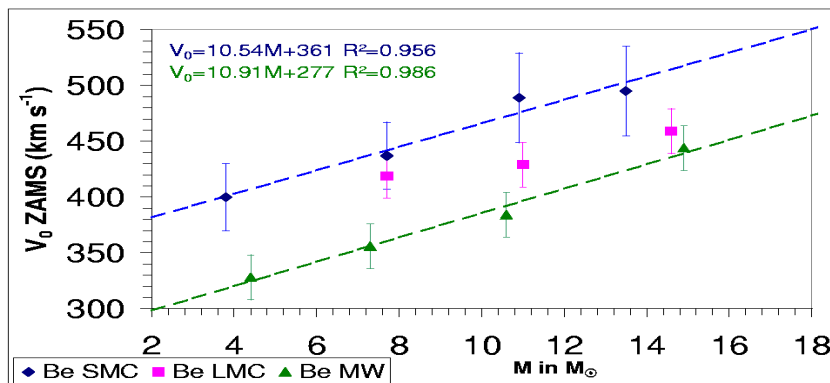


Figure 1. ZAMS rotational velocities of Be stars in the SMC (blue diamonds), in the LMC (pink squares) and in the MW (green triangles). The lines correspond to the linear regressions. Their corresponding equations and correlation coefficient are given in the upper left corner.

- The ZAMS rotational velocities depend on the mass of the stars and they present the same tendency in the SMC and in the MW.
- The lower the metallicity is, the higher the ZAMS rotational velocities are.
- At a given metallicity, there is a minimum value of mean ZAMS rotational velocities for which B stars will become or not Be stars.

#### 4. Angular velocity and evolution

With formula given in Chauville et al. (2001) and in Martayan et al. (2005a), we have obtained the ratio of the mean angular velocity to the breakup velocity ( $\Omega/\Omega_c$ ) for each sub-sample of Be stars in the MC. The results are given in Table 3 and they show:

- In average, all Be stars have a ratio greater than  $\Omega/\Omega_c=70\%$ .
- The tendency is similar in the LMC and in the MW (Cranmer 2005) while it is different in the SMC.

- Less massive stars in the SMC are close to the breakup velocity.
- Massive Be stars in the SMC, which are evolved, seem to be critical rotators. Contrary to the MW, the more massive Be stars can become critical rotators in a very low metallicity environment like in the SMC. This result is in agreement with the theoretical results of Meynet & Maeder (2000) and Maeder & Meynet (2001). The results of the comparisons will be published in Martayan et al. (2005b in preparation).

Table 3. Results of the ratios of linear and angular mean velocities to the breakup velocities for the Be stars in the SMC and in the LMC.

		LMC Be			Z=0.004
$\langle M/M_{\odot} \rangle$	$\langle R/R_{\odot} \rangle$	$\langle V \sin i \rangle$	$\frac{V}{V_c}$	$\Omega/\Omega_c$	
7.7	5.8	285	0.72	$0.85 \pm 0.13$	
11.0	9.3	259	0.69	$0.83 \pm 0.08$	
14.6	12.7	224	0.61	$0.75 \pm 0.10$	
		SMC Be			Z=0.001
$\langle M/M_{\odot} \rangle$	$\langle R/R_{\odot} \rangle$	$\langle V \sin i \rangle$	$\frac{V}{V_c}$	$\Omega/\Omega_c$	
3.8	4.1	277	0.85	$0.94 \pm 0.11$	
7.6	7.9	295	0.87	$0.95 \pm 0.11$	
10.9	15.5	345	0.99	crit $\pm 0.12$	
13.3	18.0	324	0.96	$0.99 \pm 0.14$	

## 5. Evolutionary status of Be stars in the MW, the LMC and the SMC

Following Fabregat & Torrejón (2000), the Be phase appears in the second part of the MS ( $\frac{\tau}{\tau_{MS}} > 0.5$ ) in the MW (i.e.  $\log(t) > 7$ ). According to Zorec et al. (2005) and Frémat et al. (2005b), the effects of fast rotation appear for  $\Omega/\Omega_c > 60\%$  while Be stars have ratios of  $\Omega/\Omega_c > 80\%$  in average in all galaxies. Then we must take into account the effects of fast rotation to determine the ages of the stars. We have used the FASTROT code described in Frémat et al. (2005b) and we have used ratios:  $\Omega/\Omega_c = 85\%$  for Be stars in the LMC and  $\Omega/\Omega_c = 95\%$  for Be stars in the SMC. We have obtained a redistribution from the later to earlier spectral types and a redistribution from the luminosity classes III, IV to IV, V. Then Be stars are less evolved what the “apparent” classification shows.

In the MW, Zorec et al. (2005) have obtained the evolutionary status of Be stars. They note that the massive Be stars are mainly not evolved ( $\frac{\tau}{\tau_{MS}} < 0.5$ ) while the other Be stars are mainly evolved.

We have obtained in the same way, the evolutionary status of Be stars in the LMC (Martayan et al. 2005a) and in the SMC (Martayan et al. 2005b in preparation). The results are given in Figure 2. The diagonals in this Figure come from Zorec et al. (2005) and show the area of existing Be stars in the MW. We note:

- Contrary to the MW, massive Be stars will appear in the second part of the MS ( $\frac{\tau}{\tau_{MS}} > 0.5$ ).

- Less massive Be stars are mainly evolved in agreement with Fabregat & Torrejón (2000).

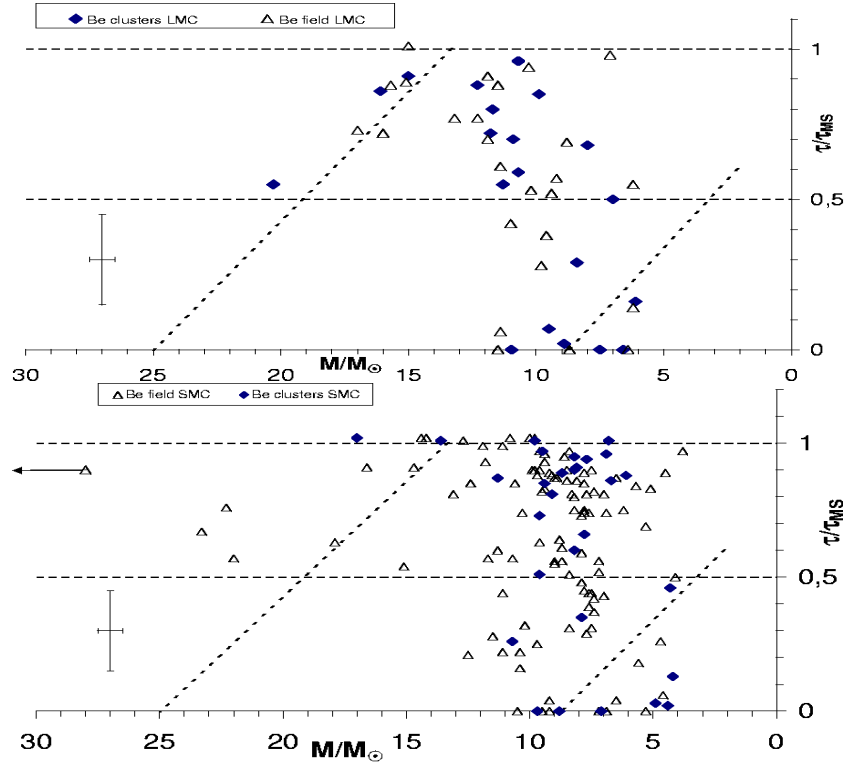


Figure 2. Higher panel: evolutionary status of Be stars in the LMC. The fast rotation effects are taken into account with  $\Omega/\Omega_c=85\%$ . Lower panel: evolutionary status of Be stars in the SMC. The fast rotation effects are taken into account with  $\Omega/\Omega_c=95\%$ . In common: The typical errors are shown in the lower left corner. The diagonals come from Zorec et al. (2005) and show the area of existing Be stars in the MW. The blue diamonds are for Be stars in the clusters and the triangles are for Be stars in the fields.

## 6. Conclusions

In conclusion, we have found an effect of metallicity on the rotational velocities for B and Be stars: the lower the metallicity is, the higher the rotational velocities are. We have also found a similar effect of metallicity on the ZAMS rotational velocities for the progenitors of Be stars. We have also found that Be stars begin their MS with a stronger rotational velocity than B stars. Then only a fraction of B stars with a sufficient initial rotational velocity will become Be stars.

Evolved massive Be stars seem to be critical rotators in the SMC. Be stars seem to be mainly evolved even after the fast rotation corrections. Contrary to the Milky Way, in the Magellanic Clouds the Be phase of massive stars appears in the second part of the Main Sequence.

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## Questions

**Dr. D. Baade:** The well-known intermittency of the Be phenomenon, which seems to be quite different for early and late spectral subtypes, may introduce a bias into number distributions of Be stars with, e. g., age or metallicity. Have you tried to correct for such a bias?

**C. Martayan:** We have not tried to correct this possible bias because we have mainly early-type stars in our samples. Moreover thanks to a cross-correlation with the MACHO database, we have obtained the light-curves for the quasi-totality of the stars in our samples and none of B stars shows a behaviour of a Be star.

**Dr. H. Henrichs:** Did you determine the metallicity in your Be stars sample?

**C. Martayan:** We have used the metallicity of Korn et al. (2002) for the stars in the LMC and the metallicity from Jasniewicz & Thévenin (1994) for the stars in the SMC. The determination of abundances is difficult with the VLT-GIRAFFE spectra, which are not adapted: low resolution, low signal to noise. However, simultaneously to GIRAFFE spectra, we have also obtained spectra with the high-resolution multifibres VLT-UVES for stars in the LMC and in the SMC. In the next months, we will determine the abundances of these stars.