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The Evolutionary Status of Be Stars in Clusters and in the Galactic Field

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Modern studies on the Be star population of young open clusters point towards the presence of an evolutionary enhancement of the Be phenomenon in the second half of the B stars main sequence lifetime. However, in the galactic field, Be stars are equally present in luminosity classes V to III, indicating that there is no evolutionary trend. To investigate these diverging results we have studied samples of main sequence B stars in the galactic field and in the h and χ Per clusters. From the analysis of the HR diagrams it is shown that there is no segregation between class V and class III stars, both groups being evenly distributed along the whole main sequence. We conclude that luminosity classes of main sequence B stars are not related to the evolutionary status of the stars. We propose a scenario of evolutionary enhancement of the rotational velocity to explain both the lack of relation between the evolutionary status and the luminosity classes and the evolutionary enhancement of the Be phenomenon.

Keywords: stars: emission-line, Be – stars: evolution – stars: rotation

1 Introduction

The evolutionary status of classical Be stars is a frequently raised and yet unsolved question. The main issue is to determine whether the Be phenomenon appears at a given stage in the evolutionary track of every B star, or if it originates in the conditions of formation of some stars, which include fast rotation among other facts.

Recent studies on the Be star population of young open clusters point towards the presence of an evolutionary enhancement of the Be phenomenon near the end of the B stars main sequence lifetime. On the other hand, in the galactic field Be stars are equally present in luminosity classes V to III. If we consider luminosity classes as related to the evolutionary status of the stars, this result provides evidence of no evolutionary trend. Hence we face the situation that the analysis of different stellar samples leads to contradictory conclusions. The aim of this work is to investigate the causes of these diverging results.

2 Analysis of Be star samples

2.1 Be stars in open clusters

Several modern studies of the Be star population of young open clusters point towards the presence of an evolutionary enhancement of the Be phenomenon in the second half of the B stars main sequence lifetime:

- Fabregat & Torrejón (2000) show that the Be star population reaches a maximum in clusters within the age interval of 14-30 Myr, and there are almost no Be stars in clusters younger than 10 Myr. The lack of Be stars in the youngest clusters indicates that a Be star cannot be a young object, but an object close to the end of its life in the main sequence.

- Keller et al. (2000, 2001) found most of the Be stars close to the turn-off of the clusters they observed. They interpret their results as evidence for an evolutionary enhancement of the Be phenomenon that occurs towards the end of the main sequence lifetime.

- Fabregat (2003) studied the Be star frequency as a function of the spectral subtype for the galactic clusters NGC 663, NGC 869 and NGC

	NGC 663		NGC 869 & 884	
Type	N(B+Be)	N(Be)	N(B+Be)	N(Be)
B1	2	1	17	5
B2	17	6	40	4
B3	25	8	25	2
B4	12	2	13	1
B5	12	0	14	0
B6	16	1	11	0
B7	12	0	15	0
B8	24	0	25	1
B9	68	0	58	2

Table 1: Number of B and Be stars in the surveyed cluster fields.

884, which have a high Be star content. In Fig. 1 we present the histogram of the Be star frequencies as a function of the spectral subtype for NGC 663, and in Fig. 2 for NGC 869 and 884. We have merged the NGC 869 and NGC 884 data into one histogram, to give a higher statistical significance. This is allowed by the fact that both clusters have the same age and astrophysical parameters (Capilla & Fabregat 2002). The solid line and shadowed area represent the frequencies for the galactic field population, as given by Zorec & Briot (1997). Bars represent the frequencies in the clusters. In Table 1 we present the number of B and Be stars found in the cluster surveyed fields, in order to help readers to assess the statistical significance of the results.

It is apparent that frequencies in the open clusters and in the field population are significantly different. In both clusters, the frequency of early-type Be stars is similar or greater than in the galactic field, and significantly greater at the cluster turn-off and in the blue straggler population. Conversely, late-type Be stars, which have a frequency of about 20% in the galactic field, are scarce.

Fabregat (2003) also analyzed in a similar way four open clusters in the Magellanic Clouds. As in the galactic clusters, the frequency of early-type Be stars in the MC clusters is much higher than in the Milky Way field, while late-type Be stars are significantly less abundant.

¿From the above results we can conclude that the Be star population in young open clusters is significantly different, and hence not representative, of the mean population in the Galaxy. In the analyzed clusters, early B stars are close to the end of their main sequence lifetime, and the Be phenomenon is much more frequent than in a mixed age field sample. Late-type B stars are at the beginning of the main sequence, and the Be phase is scarce or non existent. The remarkable abundance of Be stars close to the cluster turn-off also indicates that most Be stars are B stars close to the end of their main sequence lifetimes.

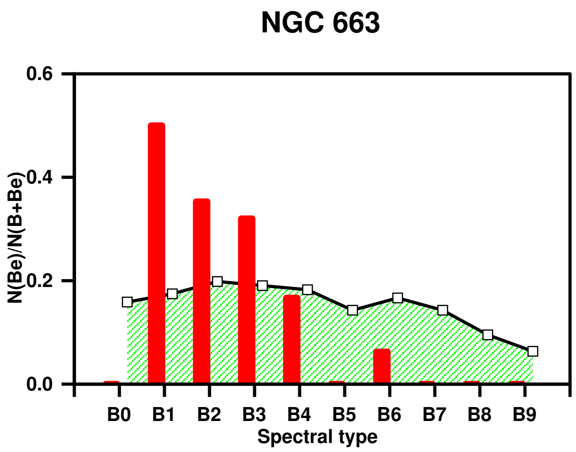

Figure 1: Relation between Be star frequencies and spectral subtypes in NGC 663. Bars represent the observed frequencies and the shadowed area the mean frequencies for field stars in the Galaxy.

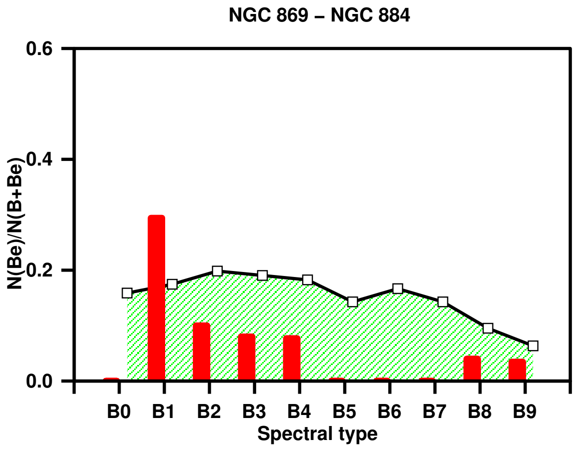

Figure 2: Relation between Be star frequencies and spectral subtypes in NGC 869 and NGC 884. Symbols as in Fig. 1.

2.2 Be stars in the galactic field

Zorec & Briot (1997) analyzed the Be star population in the galactic field, and determined the frequency of Be stars among B stars for each spectral subtype and luminosity class. They show that the galactic field Be stars are equally present in luminosity classes V to III. They interpret this fact as a proof that Be stars can hardly represent a given stage in the evolutionary tracks of B stars, and propose that the Be character can be interpreted as existing since the formation of the star.

The above conclusion is based on the assumption that luminosity classes are directly related with the evolutionary status of the stars. In the B star range, class V to class III stars are main sequence objects. It is generally assumed that BV stars are young objects close to the ZAMS, and BIII stars are evolved ones close to the TAMS, with a dividing line placed somewhere between 0.4 and 0.6 times the main sequence lifetime. However, to the best of our knowledge, this assumption has not been observationally checked so far.

With this aim, we have performed a study of the same sample that Zorec & Briot (1997) analyzed: stars with B spectral type from the Bright Star Catalogue (BSC, Hoffleit & Jaschek 1982). We have selected among them those with HIPPARCOS parallaxes with relative error lower than 20%, and with Strömgren *uvby* photometry in the Hauck & Mermilliod (1998) catalogue. We have calculated the reddening and the intrinsic photometric indices for each star individually. Absolute magnitudes have been computed from the dereddened V_0 and the HIPPARCOS parallax. Stars classified as Be have been discarded, as they occupy anomalous positions in the *uvby* photometric diagrams due to additional continuum emission of circumstellar origin (Fabregat et al. 1996).

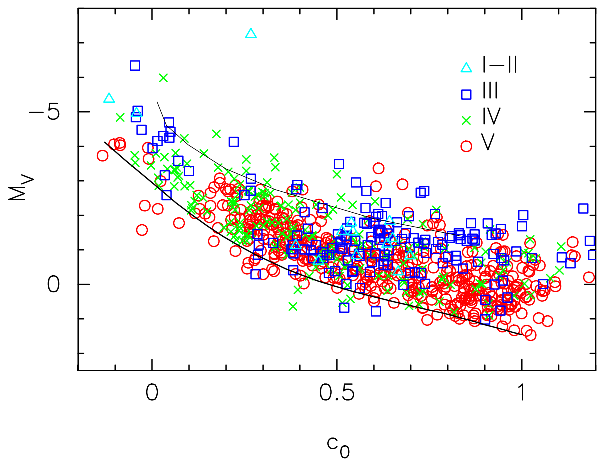

Figure 3: HR diagram for B stars in the Bright Star Catalogue with relative error in the HIPPARCOS parallax lower than 20%. Different symbols are used for each luminosity class. Solid lines represent the ZAMS and TAMS.

The resulting $M_V - c_0$ diagram is presented in Fig. 3. The c_0 index is defined to be a measure of the Balmer discontinuity depth, and is a temperature indicator for early-type stars. Hence, the $M_V - c_0$ photometric plane is an observational HR diagram. Different symbols are used for each luminosity class. We have used the luminosity classification from the BSC, and the same grouping criteria that Zorec & Briot (1997). Solid lines represent the ZAMS and the TAMS. Most stars fall between them, clearly defining the main sequence locus. From Fig. 3 it is apparent that there is no segregation between class V and class III stars, being both groups evenly distributed along the whole main sequence.

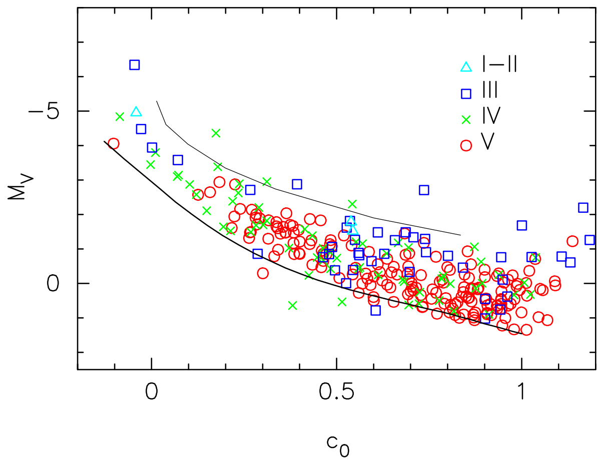

Figure 4: Same as Fig. 3 for stars with relative error in the HIPPARCOS parallax lower than 10%.

In Fig. 4 we present the same $M_V - c_0$ diagram, restricted to stars with relative error lower than 10% in the HIPPARCOS parallax, in order to have a sample with more accurately determined absolute magnitudes. In this case the main sequence is significantly less populated, mainly in the earliest subtypes. However, no segregation of luminosity classes appears, and as in the previous figure there are class III stars right on the ZAMS and class V stars close to the TAMS.

The conclusion of the above analysis is that there is not a direct relation between the absolute magnitude of the star and the spectroscopically determined luminosity class. This result has an important bearing on the widespread use of spectroscopic parallaxes to measure the distance of B type stars, which assumes the existence of different, well defined relations between spectral type and absolute magnitude for each spectroscopic luminosity class.

However, from the above figures we still cannot reach conclusions on the relation between luminosity classes and the evolutionary status of the stars. This is because we cannot assume a priori a direct relation between the position of a star in the diagrams presented in Figs. 3 and 4 and its evolutionary status. It is well known that some physical parameters, and in particular high rotational velocity, can affect the position of a star in an observational HR diagram (e.g. Townsend et al. 2004).

To progress on this issue, we have done a further analysis with the same techniques and a different sample for the B star population of the h and χ Per clusters. We selected member stars with Strömgren photometry from Capilla & Fabregat (2002) and spectral classification from Slesnick et al. (2002). As before, Be stars have not been included. The resulting HR diagram is presented in Fig. 5.

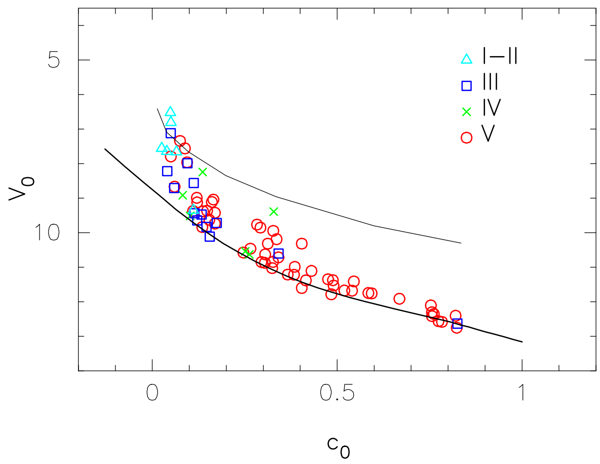

Figure 5: HR diagram for B stars in the Perseus double cluster. Symbols and solid lines as in Fig. 3.

The cluster sequence is clearly defined in the figure, and hence the evolutionary status of each star is unambiguously determined from its position in the HR diagram. In this single age stellar sample, stars close to the cluster turn-off are evolved objects near the end of their life in the main sequence, while stars in the lower part of the sequence are less massive objects still in the first half of their main sequence lifetime.

As in the previous case, there is no segregation between classes V and III. Several class V stars are found in the cluster turn-off, right on the TAMS. Conversely, a significant number of class III stars are in the lower part of the cluster sequence, right on the ZAMS. In this case, as the evolutionary status of each star is well determined from its position in the cluster HR diagram, the lack of relation between luminosity class and evolutionary status is apparent.

We can conclude that luminosity classes in the B star range are not related to the evolutionary status of the stars. As a consequence, the similar frequencies of Be stars for different luminosity classes does not argue against the evolutionary enhancement of the Be phenomenon which is apparent in the open clusters population.

3 Discussion

We propose that the above results can be explained by a scenario of evolutionary enhancement of the rotational velocity over the main sequence lifetime. The likelihood of such hypothesis is supported by recent theoretical and observational results.

¿From theoretical evolutionary models taking into account the stellar rotation, Meynet & Maeder (2000) found that there is an enhancement of the rotational velocity relative to the rupture velocity during the main sequence evolution. On observational grounds, Keller (2004) studied samples of B type stars in the vicinity of the main sequence turn-off in young clusters in the Large Magellanic Cloud and the Galaxy. He found that cluster stars exhibit significantly more rapid rotation than stars in the surrounding fields. He propose that the observed difference can be explained by an evolutionary enhancement of the surface angular momentum over the main sequence lifetime.

Within this scenario it can be assumed that a significant fraction of B type stars would approach the critical break-up velocity near the end of the main sequence. In general, rotational velocity measurements in the literature do not support this view, and establish that the rotational velocity of the fast rotating B type stars, including the Be stars, is significantly subcritical, reaching values up to 80% of the rupture velocity (e.g. Porter 1996; Chauville et al. 2001).

However, the opinion on the critical versus subcritical rotational velocities of Be stars has changed during the last few years, and the number of papers supporting a close to critical rotational velocity is increasing (Domiciano de Souza et al. 2003; Townsend et al. 2004; Frémat et al. 2005). The difference from previous work is the inclusion of gravity darkening effects in the determination of $v \sin i$. In fact, the consequences of gravity darkening for determination of rotational velocities were already pointed out by Collins (1966), but this paper remained overlooked for decades.

The consideration of gravity darkening effects show that the relation between the rotational velocity and the line width saturates at about 80% of the critical velocity. Consequently, its effects are negligible up to about 70% of the critical velocity, but get increasingly important for the higher rotational velocities. In the case of Be stars, which are in general fast rotators, Frémat et al. (2005) concluded that their average rotational velocity is 88% of the critical velocity.

The effects of gravity darkening in B type stars rotating close to the critical velocity would affect both their spectral classification and their position in photometric HR diagrams, which would be dependent of the inclination angle. Townsend et al. (2004) present in their Fig. 3 the effects of high rotational velocity in a colour-magnitude diagram. At 95% of the critical velocity, a star seen pole-on will increase its M_V by up to 1 mag., without significant colour change. The same star seen equator-on will became significantly redder, without increasing its absolute magnitude. Regarding spectral classification, the assignment of a luminosity class is performed by analyzing the effects of gravity in the stellar spectrum. In an oblate star, gravity is much higher in the poles than in the equator, and hence the luminosity class also depends on the inclination angle.

Taking into account both effects, a rapidly rotating star seen pole-on would present high luminosity and gravity, and hence would be a class V star at the top of the main sequence. If seen equator-on, it would present lower luminosity and gravity, and then be a low luminosity class III star. Both the spectral luminosity class and the position in the HR diagram for a fast rotator are likely to be more dependent on the inclination angle than on the evolutionary status.

The above qualitative explanation simply reflects the fact that the MK classification scheme is two-dimensional, directly applicable to stars which are fully characterized by their effective temperature and gravity. As it has been noted by Townsend et al. (2004), the presence of a variable third parameter, such as rotation and/or gravity darkening, will affect the direct correspondence between the spectral classification and the physical parameters.

Analysis of Fig. 5 supports the interpretation put forward above. In the lower, unevolved main sequence ($c_0 > 0.2$), almost all stars are close to the ZAMS, and have spectral luminosity class V as expected for an unevolved star. Close to the turn-off ($c_0 < 0.2$), there is no relation between the position in the HR diagram and the luminosity class. Within the scenario of evolutionary enhancement of the rotational velocity, most of the unevolved stars have significantly subcritical rotational velocities, and hence almost spherical shapes. Effects of gravity darkening are negligible, and the observed gravity and luminosity class are as expected for an unevolved star. Close to the end of the main sequence lifetime stars rotate faster, and a significant fraction are close to the critical velocity. Effects of gravity darkening become important, and the assigned luminosity class depends mainly on the inclination angle, or alternatively the MK classification scheme become unrelated to the physical parameters.

The proposed scenario of evolutionary increase in rotational velocity would also explain the enhancement of the Be star phenomenon towards the end of the main sequence lifetime. It is generally accepted that high rotational velocity is an essential ingredient of the Be phenomenon. An increase of the rotational velocity at the end of the main sequence would favour the development of Be character at this evolutionary stage.

4 Conclusions

We have shown that the spectroscopic luminosity classes in the MK system are not directly related to the evolutionary status of stars in the B star range. Hence, the similar frequencies of Be stars for different luminosity classes do not argue against the evolutionary interpretation of the Be phenomenon which is apparent in the open clusters Be star population.

An evolutionary enhancement of the surface angular momentum, leading to a rotational velocity close to the rupture velocity at the end of the main sequence evolution, would explain: i/ the lack of relation between the evolutionary status and the luminosity class; and ii/ the enhancement of the Be phenomenon towards the end of the main sequence lifetime.

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