Relative Content of Be Stars in the Young Open Clusters

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Based on high and medium resolution spectra, we analyze the population of Be stars in young open clusters. We have found a clear dependence of the relative content of early-type (B0–B3) stars on the cluster age. The relative concentration of Be stars of spectral types B0–B3 gradually increases with the cluster age, reaching its maximum value of 0.46 in clusters with ages of 12–20 Myr. The almost complete absence of Be stars in older clusters can be easily explained by the fact that B stars leave the main sequence. The few emission objects in clusters with ages of 1–7 Myr are most likely Herbig Be stars. Such a distribution of Be stars in clusters unequivocally points to the evolutionary status of the Be phenomenon. We also briefly consider the causes of this pattern.

1 Introduction

The Be phenomenon, the presence of emission (usually HI) lines in the spectra of normal B-type dwarfs and giants, is widespread. The relative content of Be stars is currently estimated to be about 17% of total number of Galactic B stars [1]. It is not completely clear why the geometrically thin and extended disks are formed [2]. These can be both the weakly decretion disks of single stars or binaries after mass exchange and the accretion disks of massive binaries at the first mass exchange stage [3]. The Be phenomenon is commonly observed in stars with a rotation velocity higher than its average and is probably unrelated to the ordinary outflow of matter from the star's equator [2, 4] unless it rotates with a critical velocity [5].

One of the key problems for understanding the Be phenomenon is to answer the question of whether the disks around B stars appear immediately after they have reached the main sequence (MS) or this is a characteristic of objects at the end of their MS life. Young open clusters undoubtedly are a good test for verifying these assumptions.

One of the first investigation of Be stars in open clusters was made in [6] where it was concluded that stars with a high angular momentum become Be stars at the end of their evolution on MS. In [7] the authors also obtained a similar result that Be stars occupy the entire MS, but the fraction of Be stars is at a maximum in clusters with the turn-off point in the region of spectral types B1–B2, and their

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V. Grinin et al. (eds) Radiation mechanisms of astrophysical objects. Yerevan: Edit Print, 2017, pp. 253–260.

population decreases with increasing age. No clear age dependence was revealed in subsequent papers [8, 1].

Later on, the authors of [9] showed that the Be phenomenon is nevertheless an evolutionary stage and is observed for B stars in the second half of their MS life. Using photometry and spectroscopy for Be stars in open clusters, they concluded that emission objects are present in clusters with ages of less than 10 Myr, but these are mostly Herbig Ae/Be stars or other pre-main-sequence objects. In contrast, classical Be stars appear in clusters with age of 10 Myr, and the maximum number of such objects is observed in clusters with age of 12–25 Myr.

A plot of the relative population of Be star against the cluster age was constructed in [10]. It showed no clear dependence, although a larger number of Be stars is contained in clusters with ages of 25–100 Myr and, according to [11], in clusters with ages of 10–40 Myr. The authors of [11] point out that the maximum fraction of B stars with emission in their spectra is observed in clusters with ages 0–10 and 20–30 Myr. When studying the population of Be stars, the authors of [12] investigated objects of spectral types B0–B3 and separately B4–B5. They found that the fraction of Be stars of spectral types B0–B3 increases in clusters of the Magellanic Clouds with ages of 10–25 Myr.

As we see, the available data are so far insufficient, they give a blurred and largely contradictory picture of the nature of the Be phenomenon. Since the number of well-studied clusters is small, most of the authors analyzed Be stars of all spectral types, when studying the Be phenomenon, while objects of later spectral types (later than B3) are known to usually exhibit a weak line emission. Given that many authors studied the emission based on narrow-band Hα photometry or low-resolution spectroscopy, there is a high probability that not all later-type Be stars have been identified. These methods do not allow a weak emission to be clearly revealed in Be stars. In addition, the MS lifetime of late B stars is longer by order of magnitude. Therefore, since most authors use

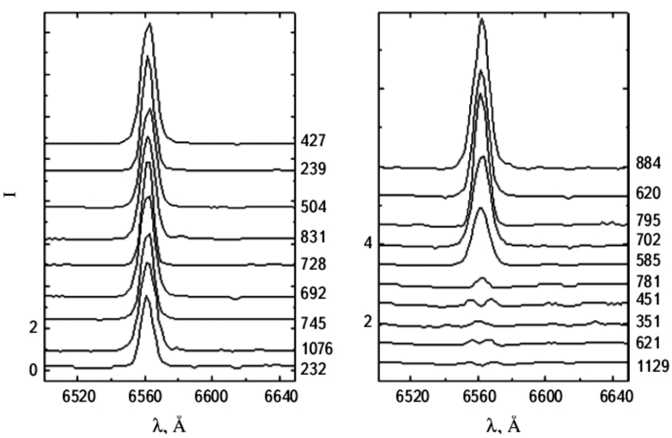

Figure 1: The Hα profiles of the selected Be stars in the open stellar cluster NGC 7419 [15]. Estimated age of the cluster is 14 Myr.

observational data for all B and Be, the age dependence of the fraction of Be stars is indistinct. For a proper analysis of the evolutionary status of Be stars, it is also important to determinate their position on the color-magnitude diagram and, accordingly, to determine the reddening coefficient. Considering Be stars in open clusters can partly help in this determinations. In some cases, however, significant reddening non-uniformity is observed within the cluster field, besides the additional reddening introduced by the envelopes of the Be stars themselves cannot be accurately taken into account either.

The spectroscopic data and, what is important, homogeneous studies of the age dependence of the population of B stars are very scarce, and the question about the nature of Be phenomenon currently remains unsolved [13, 14]. Therefore, the problem of studying Be stars in young open clusters based on high and medium resolution spectra remains topical.

2 Observations and age dependence of the Be stars fraction in clusters

During the last decade, based on high and medium resolution spectra taken with the 2.6 m telescope of the Crimean Astrophysical Observatory, we studied B and Be stars in nine open clusters with ages of 30–40 Myr: NGC 457, NGC 659, NGC 663, NGC 869, NGC 884, NGC 6871, NGC 6913, NGC 7419 and Berkley 86. To obtain a sample being complete and identical for B and Be stars and to analyze the age dependence, where possible, we restricted our study only to objects of early spectral types (B0–B3) when investigating the population of Be stars in young open clusters. Accordingly, the choice of clusters was also limited by the age less than 40 Myr, although there are Be stars in relatively older clusters, but these are generally stars of later spectral types (later than B3). We considered at least 60% of the Be stars in NGC 869, NGC 884, NGC 6913, NGC 7419 and took the spectra of all Be stars in NGC 457, NGC 659, NGC 5871 and Berkley 86. The example of Hα profiles of found and new Be stars in the open stellar cluster NGC 7419 is presented in Fig. 1. The results of our analysis of the relative content of early-type Be stars in the clusters studied are presented in [15, 16, 17, 18] and Table 1.

Table 1: The content of Be stars of spectral types B0–B3 in open clusters

Cluster name	Age, Myr	N(Be)	N(B+Be)	N(Be)/N(B+Be)
Berkley 86	6–8	1 (3)	15	0.07
NGC 457	11–20	4 (5)	15	0.27
NGC 659	12–20	4 (5)	16	0.25
NGC 663	18–25	16 (20)	50	0.32
NGC 869	12–14	20	47	0.43
NGC 884	12–14	18	39	0.46
NGC 7419	14	35 (37)	80	0.43
NGC 6871	6–12	2 (3)	14	0.14
NGC 6913	3–6	3	43	0.07

When constructing the age dependence of the fraction of Be stars, we took into account the data only for B0–B3 stars. However, since there is no spectral classification for some cluster member, we used the spectra in the wavelength range 4050–5200 Å for all observed objects to estimate their atmospheric parameters or to perform their spectral classification. The fraction of Be stars in the clusters was found as the ratio of the number of Be stars to the number of all B0–B3 objects (including the Be stars). When constructing the dependence, we also took into account the uncertainty in the relative number of Be stars and the estimated cluster ages. We calculated the upper limit for the estimated fraction of Be stars by taking into account the identified Be stars of spectral types B0–B3 and the Be candidates of the same spectral type.

The objects without any well-defined spectral type but with a probability that they are B0–B3 stars (as a rule, we used color-magnitude diagram for clusters) or objects, whose low-resolution spectroscopy showed some features indistinctly designed by the authors of the papers, were considered to be candidates. The third column (N(Be)) in Table 1 gives the number of Be stars and the possible maximum number of Be stars in the cluster (in parentheses), i.e. the sum of the identified Be stars and Be candidates.

Apart from the absence of spectral classification, the problem of cluster age determination also arose, because the estimations obtained by different methods often differ significantly. In addition, there are also large discrepancies in age determination when using the same method but with a different sample of program objects. We attempted to critically estimate the cluster ages. For all clusters, we constructed their color-magnitude diagrams with a set of isochrones (constructed from the data from [19]). We constructed the isochrones for each cluster by taking into account the already available reddening and distance modulus and then chose the most satisfactory reddening and distance modulus parameters. An example of this procedure is presented in Fig. 2. This allows us to estimate the age in a more homogeneous way. Our estimates of the ages, the number of B and Be stars, and the fraction of Be stars in each of clusters are given in Table 1.

In Fig. 3 the relative content of Be stars in the program clusters is plotted against the age. These data have a sufficient statistical significance, because we investigated almost all of the B0–B3 objects for their belonging to Be stars. As we see from the figure, the fraction of Be stars increases appreciably in clusters with ages of more than 10 Myr. This suggests that with a high probability the Be phenomenon is an evolutionary effect.

3 Discussion

Let us analyze in more details the data presented in Fig. 4 showing the gradual increase in the relative fraction of Be stars of spectral types B0–B3 with the cluster age.

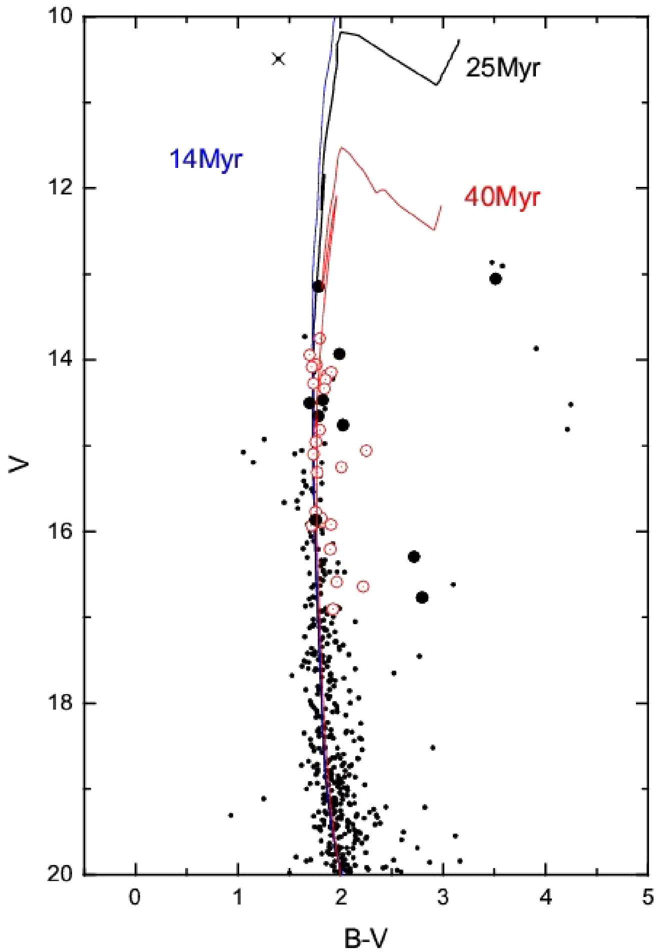

Figure 2: Example of the color-magnitude $((B-V)-V)$ diagram for the open stellar cluster NGC 7419 [16]. Open circles are for observed spectroscopically Be stars, large black circles for observed B stars. Three isochrones are presented for 14, 25 and 40 Myr.

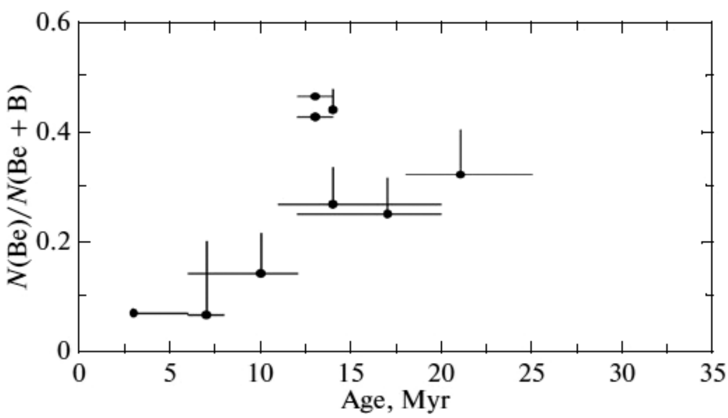

Figure 3: Relative number of Be stars versus cluster age (based on the data from Table 1).

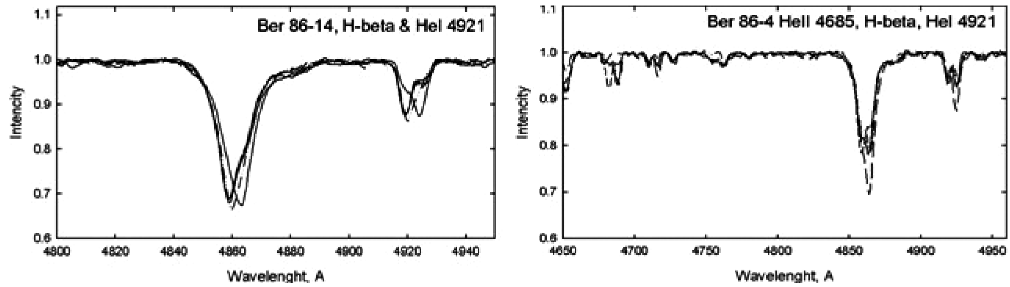

Figure 4: Two examples of spectral variability of the line double systems Ber 86 - 14 (P_{orb} < 4 days) and Ber 86-4 (P_{orb} < 2 days) in a very young open cluster Berkley 86 with age 6-8 Myr. Both systems have MS components.

According to [20], three evolutionary scenarios leading to the formation of disks around B stars are possible:

(A) Be stars were born as rapidly rotating B stars, and the HI line emission is observed throughout their MS life.

(B) The Be phenomenon arises in a single, sufficiently rapidly rotating B star during the change in its V/V_{crit} ratio (where V is the star's equatorial rotation velocity and V_{crit} is the critical equatorial rotating velocity) as the star moves from the zero-age main sequence (ZAMS) to the terminal age main sequence (TAMS) [13].

(C) Be stars are binary systems at the stage after active mass exchange.

Case A should probably be excluded from consideration. As we can see from Fig. 3, classical Be stars are observed very rarely in very young clusters, with ages of less than 8 Myr, and can be Herbig Be stars or pre-main-sequence objects with a high probability.

Case B, where V/V_{crit} ratio increases in the second half of the MS life of a rapidly rotating B star, was considered in detail in [13]. In particular, they showed that when the star is on MS, the equatorial rotation velocity of the star decreases significantly at the very end of its MS life. Thus, the V/V_{crit} ratio becomes the most important parameter. Assuming $V/V_{crit} \geq 0.7$ and solar metallicity for Be stars, any non-stationarities of the outer layers of Be stars, such as, for example, non-radial oscillations, can contribute to the outflow of matter from the stellar photosphere. According to these authors, a noticeable fraction of Be stars, 10-20% or, in a more optimistic case, up to 35%, are formed from single, rapidly rotating B stars during their MS life. For B0–B3 stars, this corresponds to an age of about 15–25 Myr. A comparison of these data based on the evolution theory and Fig. 3 obtained from observations suggest that this scenario is possible.

Case C, the formation of Be stars through mass and angular momentum exchange in close binary systems, was considered in detail by several authors (see [20, 21]). Spectroscopic studies of several young clusters in [14] point to an appreciable fraction of massive binaries in young clusters (about 25% of the total number of B stars). Moreover, since the latter authors performed only 2–3 episodic observations at close dates, one might expect that they revealed only short-period ($P_{orb} < 20$ days) massive binaries and did not detect numerous systems with the periods of 30–1000 days, typical of Be stars and mass ratio differing noticeably from one. Thus, the data from [14] may be reliably considered to be a lower limit for the fraction of binaries with B-type components in young open clusters. Clearly, all of the detected binaries will enter the phase of rapid mass exchange as soon as the more massive component leaves MS. In this case, the previously more massive component will become inaccessible to optical observations, because it will become either a helium star, or a white dwarf, or, in the most massive systems, an X-ray binary [20].

Our spectroscopic observations confirm data of [14]. In Fig. 4 we present two examples of spectroscopic binaries in a very young open cluster Berkley 86 (age of 6–8 Myr). The cluster has only one (possibly 3) early type Be stars but we found at least three short orbital period double systems and all of them have MS components.

Obviously, the scenario C is most natural as was pointed out, for example, in [21], and qualitatively describes our dependence of the relative content of Be stars at the end of their MS life. In the case where the V/V_{crit} ratio for a single B star evolves, it is necessary to prove that this star is actually a single object rather than a binary system with $P_{orb} < 1000$ days and a secondary degenerate component. This problem is known to be difficult and allows one to investigate only the brightest objects, which usually do not include the B and Be stars in open clusters.

Modern statistical investigations of the field B stars showed that among OB stars, whose evolution leads to the phase of active mass exchange, the relative fraction of double systems decreased with decreasing of spectral type of the primary MS component. As it was shown, for example, by authors of [22], among of O7–O9 stars relative concentration of double systems reaches 80%, 65% for B0–B1.5 stars and 55% for MS stars of spectral types B2–B3. Nearly the same values were found during the studying of Scorpios OB2 association [23]. These authors found that the relative fraction of double and multiple systems among B0–B3 stars and B4–B9 stars is 80% and 50%, respectively. All these statistical data again support the scenario C as the most natural explanation of our statistical results presented in Table 1 and Fig. 3.

4 Conclusions

The data considered revealed the pattern of distribution of the relative content of early-type Be stars in clusters of different ages. The maximum number of Be stars is observed in clusters with ages of 12–25 Myr. The increase in the number of Be stars in clusters with a certain age confirms the hypothesis that Be stars emerge when they leave the main sequence. On the other hand, the Be phenomenon can arise in binaries when the more massive component leaves the main sequence, which leads to mass exchange in the system and produces hydrogen emission lines in the spectrum. Both these effects operate simultaneously for single stars and binary systems.

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* The color figure is available online in the Proceedings at *http://www.astro.spbu.ru/sobolev100/*.