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A constraint on the angular momentum evolution of Be stars

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Abstract. The Be star sample of Steele et al. (1998) has a distribution of $v \sin i$'s that is luminosity dependant, with giants having lower projected rotational velocities than dwarfs. We show that this effect can be understood simply in terms of angular momentum conservation during the evolution from dwarf to giant. Any decretion disk or other angular momentum losing mechanism for such objects must cause a loss of no more than 15% of the stellar angular momentum over the Be phase lifetime.

Key words: stars: rotation – stars: emission-line, Be

1. Introduction

The importance of understanding the relationships between rotational velocity, evolutionary status and stellar temperature in causing the the Be phenomenon has long been understood (Slettebak 1982). Recently Zorec & Briot (1997) presented evidence based on a careful evaluation of the statistics of B and Be stars in the Bright Star Catalogue (Hoffleit & Jaschek 1982) that after correction for various selection effects there were no apparent differences in the spectral type distribution and frequency of Be stars with respect to luminosity class. In addition they showed the shape of the $v \sin i$ distribution with spectral type was not luminosity dependant, implying little or uniform angular momentum loss from such objects over their lifetimes. Here we extend that work by using the sample of Steele et al. (1998) to quantify the evolution of angular momentum between the dwarf and giant stages of Be stars. We show that either conservation of angular momentum or an accumulated loss of up to (but no more than) 15% of the stellar angular momentum is allowed during the main sequence + giant lifetime of Be stars.

2. Distribution functions

2.1. Description of the sample

In Steele et al. (1998) we presented optical spectra of a sample of 58 Be stars. The sample contains objects from O9 to B8.5 and of luminosity classes III (giants) to V (dwarfs), as well as three shell stars (which we neglect for the purposes of this paper as they have uncertain luminosity classes). A spectral type and value of $v \sin i$ was derived for each object in the sample. The sample is termed a "representative" sample, in that it was selected in an attempt to contain several objects that were typical of each spectral and luminosity class in the above range. It therefore does *not* reflect the spectral and luminosity class space distribution of Be stars, but only the average properties of each subclass in temperature and luminosity. The distributions of $v \sin i$ within each temperature and luminosity class were carefully investigated and the conclusion drawn that there were no significant selection effects biasing the average properties of the objects. However it was apparent that for all spectral subtypes the giants had significantly lower values of $v \sin i$ than the dwarfs.

2.2. $v \sin i$ and $\omega \sin i$ distributions

In Fig. 1 we plot the binned distribution of $v \sin i$ values for the sample for luminosity classes III, IV and V. The data have been binned into bins of width $80\,\mathrm{km\,s^{-1}}$, chosen to be considerably larger than the mean error on any one $v \sin i$ measurement, which is $\sim 20\,\mathrm{km\,s^{-1}}$. It is immediately apparent that the distributions are different, with the giants having considerably lower $v \sin i$ than the dwarfs. A simple explanation of this would be that the critical velocity for giants is lower than that for dwarfs, so that the $v \sin i$ may be lower but still give a sufficiently high $\omega \sin i (= v \sin i / v_{\mathrm{crit}})$ to cause a disk to form. To investigate this we plot in Fig. 2 the $\omega \sin i$ distributions for our sample. We calculated v_{crit} according to the prescription given by Porter (1996):

$$v_{\mathrm{crit}} = \sqrt{0.67 \times GM/R} \tag{1}$$

where R is the polar radius. Values of M and R were obtained from Schmidt-Kaler (1982), with interpolation between luminosity classes and spectral sub-types where necessary. From Fig. 2 it is apparent that this simple explanation of the necessity of a certain fractional velocity to give the Be phenomenon is insufficient to explain the discrepancy between the giants and dwarfs.

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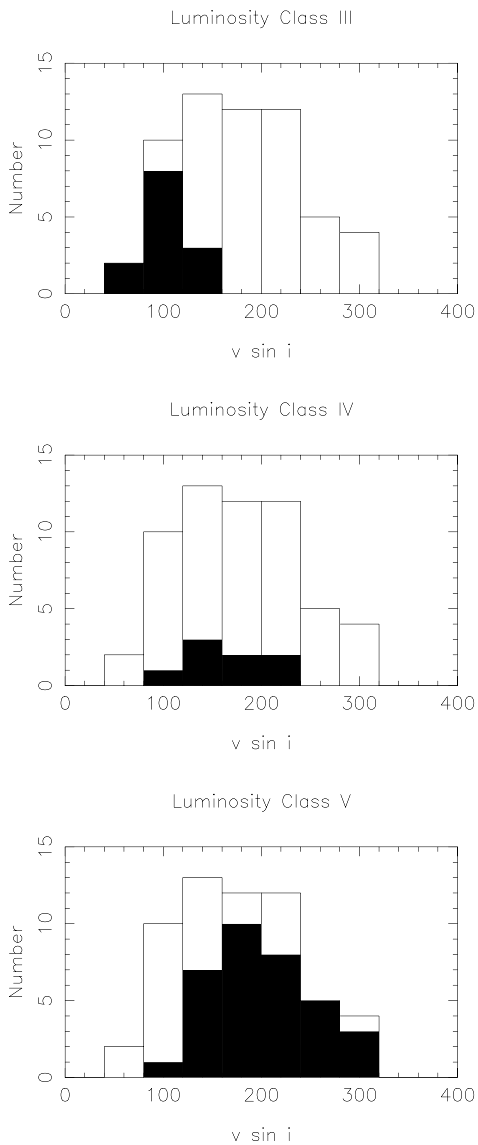

Fig. 1. $v \sin i$ distribution for the three luminosity classes (solid areas) compared with the all luminosity class distribution (hollow). A KS test shows that the probability of the giant and dwarf distributions being drawn from the same population is $< 10^{-6}$

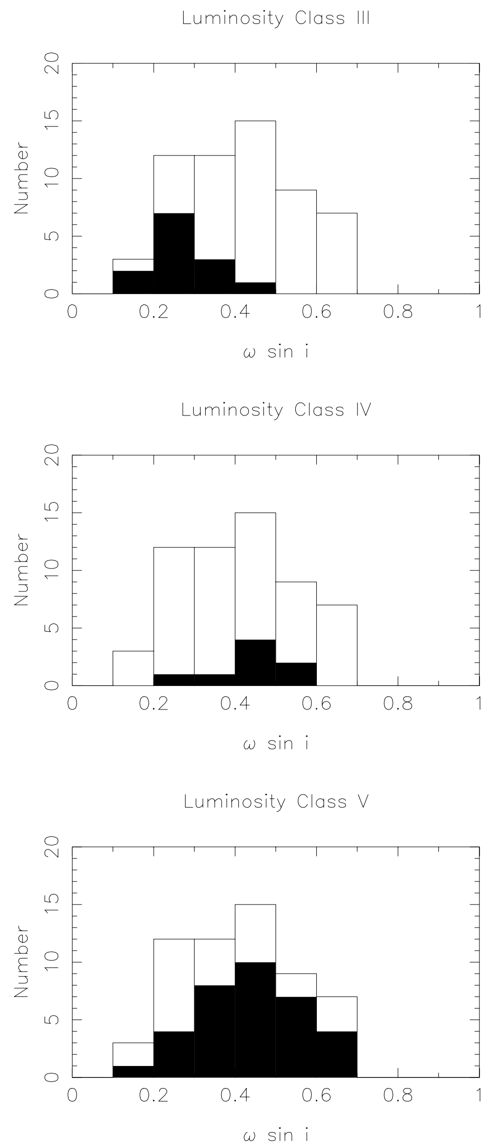

Fig. 2. $\omega \sin i$ distribution for the three luminosity classes (solid areas) compared with the all luminosity class distribution (hollow). A KS test shows that the probability of the giant and dwarf distributions being drawn from the same population is $< 10^{-4}$

2.3. Angular momentum distribution

We now consider the rotational velocity changes that result from angular momentum conservation during the evolution from dwarfs to giants. Assuming that the mass of a given star is fixed during this evolution and that angular momentum is conserved, then velocity v will simply be inversely proportional to radius R. The quantity we therefore consider is $v \sin i \times R/R_g$ where R/R_g is the fractional radius for luminosity class compared to the corresponding giant radius. From Schmidt-Kaler (1982) it is apparent that for dwarfs in the range O9 to B9 for a constant mass (*not* spectral type) the relationship $R/R_g = 1/1.8$ holds to within ~ 5 per-cent. Similarly for the subdwarfs we adopt $R/R_g = 1/1.4$. The ratio is of course unity for the giants.

In Fig. 3 we plot the distributions of $v \sin i \times R/R_g$ for all three luminosity classes. The similarity of the three distributions is striking. In order to confirm their similarity we carried out a Kolmogorov-Smirnov (KS) test between the unbinned values of $v \sin i \times R/R_g$ for the giants and the dwarfs. As noted in the captions of Figs. 1 and 2 the test was also carried out on the $v \sin i$ and $\omega \sin i$ datasets to demonstrate that they were significantly different. For $v \sin i \times R/R_g$ the probability that the giant and dwarf distributions are drawn from the same population is 0.83, confirming our opinion of the similarity of the samples, and demonstrating that the similarity was not an effect of our binning the data. It is therefore apparent that conservation of angular momentum over the Be lifetime of the object is entirely consistent with the observed angular momentum distributions.

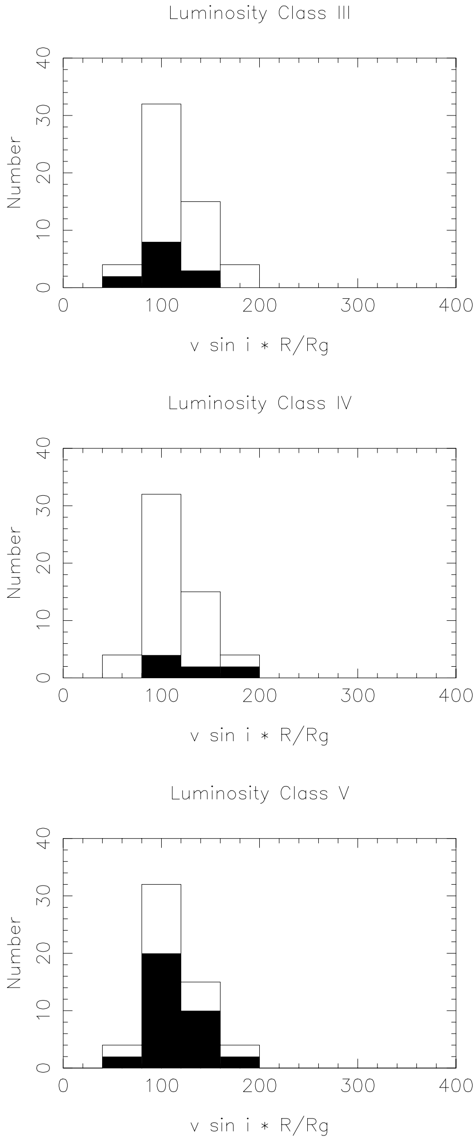

Fig. 3. $v \sin i \times R/R_g$ (a measure of relative angular momentum) distribution for the three luminosity classes (solid areas) compared with the all luminosity class distribution (hollow). A KS test shows that the probability of the giant and dwarf distributions being drawn from the same population is 0.83

3. Angular momentum evolution

In Sect. 2.3 we demonstrated that angular momentum conservation was consistent with the observed values of $v \sin i \times R/R_g$. However it may be that a certain fraction of angular momentum may be lost from the stars and the two distributions still remain consistent. To investigate this we simulated the effect of changing the system angular momentum of the giants by factors of between 0.01 and 2.0 in increments of 0.01 and redoing the KS test. The resulting distribution of probabilities is shown in Fig. 4.

From Fig. 4 it is apparent that a probability of greater than $\sim 5\%$ of the two distributions being consistent is obtained for fractional changes of angular momentum during the main sequence + giant lifetime of the star of between ~ 0.85 and ~ 1.3. Neglecting the upper value as unphysical we therefore conclude that any method of losing angular momentum that purports to explain the Be phenomenon must cause a loss of less than ~ 15 per cent of the stellar angular momentum over the main sequence + giant lifetimes of the star. From the analysis presented by Porter (1998) of the spin down of Be stars due to angular momentum transfer to the disk (i.e. a decretion disk - e.g. Lee et al. 1991) this implies that (assuming the Be phenomenon is present for most of the main sequence life of the star) the disks around Be stars are in his terminology “weak” to “medium”. This means that for a typical disk opening angle of 15° and a density of $2{\times}10^{-11}$ g cm^{-2} (Waters 1986), the initial outflow velocity must be less than 0.01 km s^{-1}. For a decretion disk this implies the viscosity parameter $\alpha < 0.01$ (Porter 1998).

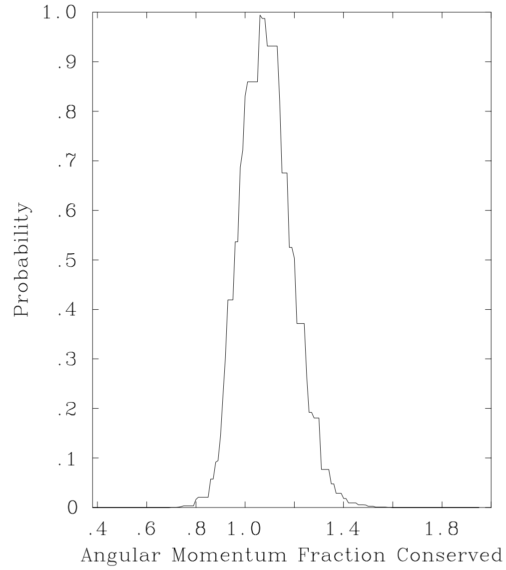

Fig. 4. Variation in KS test null hypothesis probability between giant and dwarf angular momentum distributions versus amount of stellar angular momentum conserved.

An alternative of explanation is a much “stronger” disk that is only present for short periods during the life of the star. For example if the disk were only present for 10% of the main-sequence lifetime, then we derive $\alpha \sim 0.1$.

4. Conclusions

By using the distribution of $v \sin i$ values for giants and dwarfs in the Be star sample of Steele et al. (1998) we have shown that any angular momentum loss in the system that would spin down the Be stars must cause the loss of no more than 15% of the stellar angular momentum. This implies that either the Be phenomenon is only a short phase in the life of such objects, or that any decretion disk in the system must have a low outflow velocity (< 0.01 km s^{-1}) and hence a low viscosity ($\alpha < 0.01$).

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