V. EVOLUTIONARY STATUS OF Be STARS

GALACTIC DISTRIBUTION, KINEMATICS, LOCATIONS IN CLUSTERS AND H-R DIAGRAMS, AND DUPLICITY OF Be STARS

(Review Paper)

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Abstract. The locations of 143 B0e-B7e III-V stars listed in the Bright Star Catalogue are similar to those of the early-B Gould Belt stars. Therefore the Be stars have roughly the same ages and origins as early B stars. The frequency of runaway Be stars must be less than several percent. The radial velocities of Be stars show primarily the reflex of solar motion and show no evidence for systematically negative velocities attributable to mass-loss effects upon the absorption profiles. The scatter in the residual velocities is such that there is unlikely to be many undetected binaries with orbital amplitudes greater than 10 km s^{-1}. We are unable to state whether or not Be stars tend to occur during the overall contraction stage, but we do observe Be stars in roughly constant frequency in clusters of all ages. About 18% of the field B0-B7 III-V stars are Be stars. Clusters show both lower and higher frequencies that may be real or may be due to different observational techniques. The frequencies and distribution of binary periods for Be stars is the same as for non-emission B stars except for the lack of periods less than 10^{-1} yr. Statistically the 12 classical Be stars with known orbital elements have mass functions indicating that their secondaries are more massive than neutron stars and their secondary mass distribution is like that of normal B stars. We observe 35 companions for 100 Be primaries, so after correction for undetected companions, it seems likely that most Be stars have companions, mostly with periods of years.

INTRODUCTION

It is necessary first to define our sample of stars. I will use a fairly narrow definition of Be stars, namely those non-supergiant B stars that show hydrogen emission continuously for long time intervals in their optical-region spectra. By "long time intervals" I mean months or years or decades. If necessary, these stars can be called the "classical" Be stars.

One trouble with broadening this definition, such as to include binaries that show emission at certain phases only, is that doing so may disguise certain unique physical characteristics. An example of this in

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another field is the blue stragglers. The young (<$10^{8.3}$ yr) blue stragglers have unusually high rotational velocities and are often Be stars, while the intermediate-age ($10^{8.3}$-10^9 yr) blue stragglers have unusually low rotational velocities and usually are Ap stars. Combining the two groups would lead to a normal mean rotational velocity and a loss of important information.

GALACTIC DISTRIBUTION AND KINEMATICS

What can we learn about the Be stars from their distribution in the Galaxy and their motions? It is already clear that Be stars are young (from their occurrence in young clusters) and concentrated to the galactic plane, but it turns out that some aspects of their positions and motions provide constraints on their physical properties.

Galactic Distribution

Let us consider the Be stars listed in the Bright Star Catalogue (Hoffleit & Jaschek 1982). There are 143 stars with types B0e-B7e III-V. Because they are bright, they are nearby (within 1000 pc) so we do not learn about the occurrence in other spiral arms from this sample, but unlike the distant Be stars, they generally have well-determined motions, types, and photometry. What is the distribution of these stars in the local arm?

By comparing the measured B-V colors with intrinsic colors of B stars of known types (Johnson 1963), we can correct for reddening. For most of these bright stars these corrections are small. The effect discussed by Collins and Sonneborn (1977) of larger colors and later types for rapidly-rotating stars will partly cancel each other. We then use Blaauw's (1963) calibration of absolute magnitudes for various spectral types to derive distances, which average 310 pc.

The distribution of the local Be stars is similar to that of the early-B Gould Belt stars for the following reasons.

1. The plane is tilted such that the Be stars tend to be above the galactic plane toward Scorpius and Ophiuchus and below the galactic plane toward Orion.
2. The Sun is above the plane of the Be stars by an average of 33 pc. A similar analysis of 190 B2-B2.5 III-V stars listed in the Bright Star Catalogue yielded a solar height of 44 pc above the B-star plane. Stothers and Frogel (1974) derived a height of 12 pc for the Sun above those O-B5 Gould Belt stars that are within 600 pc.
3. The Sun is on the leading side (in the direction of galactic rotation) of the center of the Be stars; the center of the Be stars is at 65 pc toward l = 250°. For the control sample of B2 stars the values are 170 pc toward 248°. For the B2-B2.5 I-V Gould Belt stars Stothers and Frogel derived 106 pc toward l = 227°.
4. The scale height of the Be stars is 69 pc from the depressed plane. For the control sample of B2 stars we derived 66 pc. Stothers and Frogel derived 27 pc for the Gould Belt stars within 800 pc.

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Thus considering the small sizes of these samples, we see nothing about the distribution of local Be stars that departs significantly from the distribution of the Gould Belt stars of early B types near the main sequence. This implies that the Be stars have roughly the same ages and the same origin as the B stars of the same types.

We can ask whether the numbers of Be stars at high galactic latitudes or heights are normal or abnormal. A least-squares solution for stars with $|z-33| < 100$ pc from the depressed plane of the Be stars gives $N = 2.12\ (\pm 0.11)\ e^{-(z-33)/69}$ per pc. If we extrapolate that relation to 400 pc we predict 33.5 high-latitude stars and observe 29. For the control sample of B2 stars we predict 8.6 stars between 200 and 600 pc and observe 11 stars. Note that since our sampling is fairly complete to more than 500 pc in the galactic plane where there is some absorption, it should be at least as complete to similar distances above the plane. Therefore there is no excess of Be stars at 100-400 pc above the plane and the existing Be stars there require no special origin. "Runaway" Be stars must be infrequent, namely less than several percent.

The local Be stars are concentrated toward the center of the spiral arm: there are three times as many Be stars toward galactic longitudes 90^{o} and 270^{o} as toward intermediate longitudes. But a surprising result by Burki and Maeder (1977) is that the fraction of Be stars among all B0-B4 stars is larger toward Cygnus than toward the galactic center and anticenter, i.e. 27% vs. 16%. Although the result is significant at the 0.97 level by a χ^2-test, it represents an excess of only seven Be stars toward Cygnus. We find the same excess using B0e-B7e III-V and B2-B2.5 III-V stars.

Kinematics

One reason for looking at the radial velocities of Be stars is to see whether they show systematic line shifts indicating asymmetrical line profiles and mass loss. Such asymmetrical Hα lines were found by Furenlid and Young (1980) for most of the B0-B3 stars with rotational velocities in excess of 200 km s^{-1}. Their Hα lines are shifted shortward by 5-40 km s^{-1}. Wolf-Rayet stars also show such line shifts for some lines. Furenlid and Young discovered the effect in Hα; it is not known whether other lines show the effect to a lesser degree.

If we plot the published radial velocities of the 143 B0e-B7e III-V stars listed in the Bright Star Catalogue against galactic longitude, we derive the distribution shown in Figure 1; it shows primarily the reflex of solar motion. That is, the distribution shows a motion (solid line) of 19 ($\pm$2) km s^{-1} toward about $l = 60^{o}$. That agrees with the standard values of 20 ($\pm$0.5) km s^{-1} toward 57 ($\pm$1)^{o}. But in the least-squares solution there is a constant outward velocity of 4.0 km s^{-1}. Whether that 2σ result is real or not, at least it does not give any evidence for a shortward shift due to mass loss. Therefore the radial velocities of Be stars are not affected significantly by distorted line profiles or mass loss effects.

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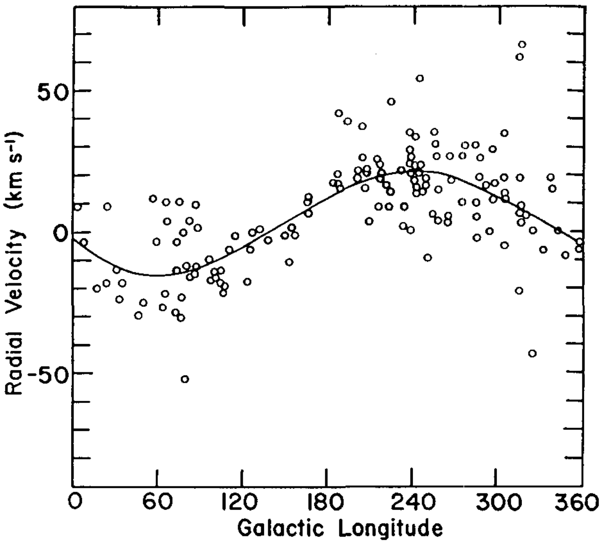
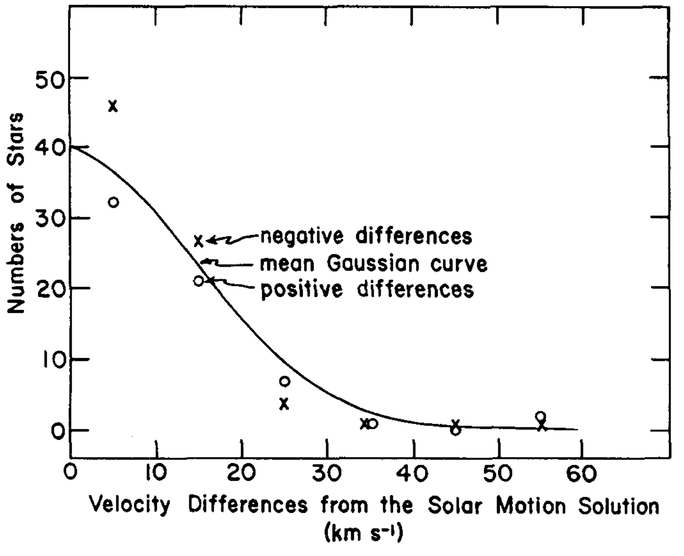
Figure 1. Published radial velocities of Be stars as a function of galactic longitude.



The radial velocities of the Be stars show a scatter of only $\sigma = 14.0$ km s^{-1} about the reflexive solar-motion solution. That dispersion is surprisingly low considering that the velocities of these broad-lined stars are difficult to measure. Abt & Levy (1978) measured about 20 coudé spectra of each of 15 Be stars that they thought have constant radial velocities and without shell oscillations. Their velocities showed a mean scatter of $\sigma = 9.7$ km s^{-1}. That leaves a scatter of only $\sigma = 10$ km s^{-1} due to (1) individual stellar radial velocities and (2) random orbital motions in undetected spectroscopic binaries. By the latter we mean that if a Be star is really a binary but has only a few velocity measures, the mean velocity may be very different than the γ-velocity of the system.The evidence that the velocity scatter due to undetected binaries must be far less than 10 km s^{-1} implies that there are very few undetected Be spectroscopic binaries with orbital amplitudes, K, greater than 10 km s^{-1}.

Finally we can ask whether the distribution of velocity residuals about the reflexive solar motion solution has a Gaussian distribution. The residuals (positive and negative) are shown in Figure 2; also shown is a mean Gaussian curve. The residuals are Gaussian within the expected errors. The data show only two stars with $|\Delta\rho|$ >50 km s^{-1}, whereas none were expected. Therefore the frequency of Be runaway stars is less than 2%.

Figure 2. The differences between the radial velocities of individual Be stars and the mean solar motion solution are given horizontally. The numbers of stars with various positive (circles) and negative (Xs) differences are plotted vertically, together with a mean Gaussian curve. The data points fit within their expected errors, i.e. the square roots of the numbers of stars. This graph shows that high-velocity or runaway stars are rare.



CLUSTERS AND H-R DIAGRAMS

On the topics of the occurrence of Be stars in open clusters and associations and their locations in H-R diagrams, we will discuss only three questions. Even then, this summary will not be very extensive because little progress has been made since other conferences on Be stars. The questions concern (1) evidence for a preferred evolutionary stage, (2) evidence for a dependence upon age, and (3) the frequencies in various clusters and in the field.

Evolutionary Stage

On the question of a preferred evolutionary stage for Be stars, the progress has been negative. Schmidt-Kaler (1964) concluded that the Be stars are preferentially at the upper edge of the main-sequence band where they are undergoing core contraction. Schild and Romanishin (1976) made a search for Be stars in 29 open clusters. They found a constant frequency of 5% Be stars near the lower edge of the main-sequence band but a jump to 20% at the onset of core contraction. More than half of their discovered Be stars are in that stage.

Unfortunately each study of the location of Be stars in clusters depends upon broad-band colors or spectral types, both of which are subject to special effects for Be stars. Collins and Sonneborn (1977)

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found that rapidly-rotating stars are shifted right in H-R diagrams and the amount of the shifts depend on the sizes and orientations of the rotations. These two factors are interconnected in the observed V sin i and for most non-eclipsing stars with V sin i < 400 km s^{-1}, we cannot separate V and i. Therefore we cannot de-shift the Be stars in H-R diagrams and determine their true evolutionary stages relative to the more slowly-rotating non-emission stars. So the evolutionary stage must be considered unknown until the rotational shifts in color of Be stars are determined, at least in a statistical way. Similar conclusions were reached previously by Slettebak (1985).

Dependence upon Age

Another approach to that question is to see whether Be stars tend to prefer clusters of certain ages. That was tried by Abt (1979), who found no dependence of the frequency of Be stars upon cluster age in the range $10^{5.7}$ to $10^{8.1}$ yr. Observations by Slettebak (1985) agree. This implies no preference for any particular evolutionary stage.

Interestingly, among the blue stragglers (Mermilliod 1982) in the youngest clusters (age < $10^{8.3}$ yr), most of them are rapid rotators and one-third are Be or Oe stars. Abt (1985) has suggested that those blue stragglers stay longer on the main sequence because of rotational mixing. This is in simile to the blue stragglers of intermediate ages, the majority of which are magnetic Ap stars and are apparently kept longer on the main sequence by magnetic mixing. Therefore the Be stars may stay on the main sequence longer than slowly-rotating stars.

Frequencies in Clusters and in the Field

What can we learn from the frequencies of Be stars in various clusters and in the field? Before we summarize the published results we should point out three complications. One is that the frequency of Be stars will depend upon whether observations are obtained at Hα or only in the blue-violet spectral region, and whether they were made over a duration of years or only at one time. In both second alternatives we would expect to obtain reduced frequencies. Second, the results will depend upon the spectral range sampled because the frequencies are different for the early, middle, and late B stars. Third, it may depend upon the mean rotational velocities of individual clusters because some clusters, such as the α Persei and Pleiades, have high average rotational velocities and many Be stars, and some have low average rotational velocities.

First let us determine the frequency of Be stars along the main sequence. This should not be done from clusters because each cluster usually can give information for only part of the B-star region and there may be differences from one cluster to another. Let's determine it from field stars, being careful to use a volume-limited sample rather than an apparent-magnitude-limited sample. If we assume that all Be stars are known with $V_0 \leq 6.0$ mag, we should have a complete sample for the B0-B7 stars within 200 pc. The results are shown at the top of Figure 3 for groups B0-B1, B2-B2.5, B3-B4, B5-B6, and B7; those groups were selected because the types B2.5, B4, and B6 are not used by some

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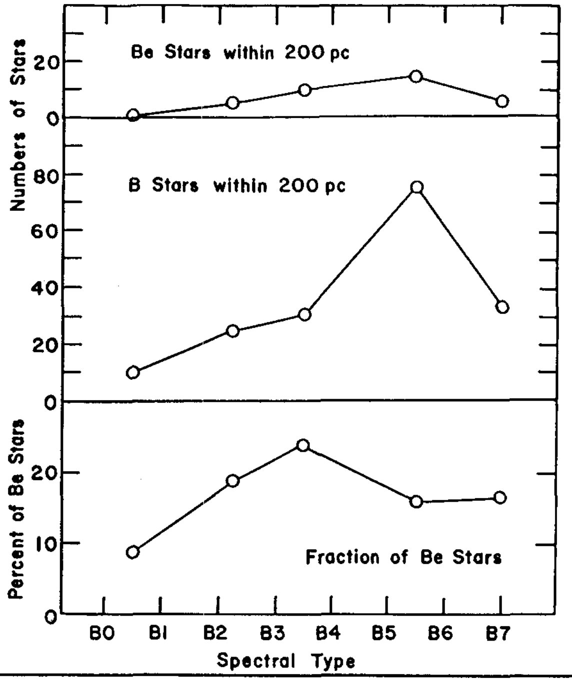
Figure 3. Data based on counts of Be and B stars within 200 pc, corrected of interstellar absorption. The types are grouped into B0-B1, B2-B2.5, B3-B4, B5-B6, and B7, and the luminosity classes are III, IV, and V. The top panel shows the distribution by type for 39 Be stars, the middle panel shows that for 176 B stars, and the bottom panel shows the fraction of Be stars among both kinds of stars.



classifiers. Then we searched the Bright Star Catalogue (Hoffleit & Jaschek 1982) for all the B0-B7 III-V stars without emission and within 200 pc (after correction for interstellar absorption). Those numbers are shown in the middle of Figure 3. We see that B0-B1 stars are rare per unit volume of space, even though they are frequent in the catalogs. Finally the bottom of the figure shows the fraction of Be stars, namely $n(Be)[n(B) + n(Be)]^{-1}$. That fraction is low near B0, has a maximum at B3-B4, and decreases slowly into the late Bs. The average in B0-B7 is 18%.

Turning to the open clusters and associations, the frequencies for well-populated groups range from 4/81 = 5% for Orion OB1 (Abt 1979) to 25% for χ Persei (NGC 884) and 17/50 = 34% for NGC 663 (Sanduleak 1979). Are those differences real? There are several reservations about their reality. One is that Abt observed clusters stars only in the blue-violet region and at one time for each; therefore he may have missed many Be stars. Schild and Romanishin (1976) also found a low frequency of Be stars but they also made observations at only single times; for NGC 663 and NGC 884 they found frequencies of only 19% and 24%, compared with Sanduleak's multi-year observations of 34% and 25%, respectively. So it may not be possible to compare frequencies

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obtained with different techniques.

Therefore the apparent lower frequencies of Be stars in clusters as derived by Abt (8±5%) and Schild and Romanishin (∿10%) compared with that for field stars (18%) may be either due to different observational techniques or to real differences from one cluster to another because some have much larger mean rotational velocities than others, and high rotation seems to be a necessary requirement to produce a classical Be star. I think that we still need a thorough survey of clusters for Be stars, perhaps done with a solid-state detector working at Hα.

BINARIES

We now come to the controversial topic of the frequency and kinds of binaries among Be stars. This topic is controversial because some people prefer to explain most or all of the characteristics of Be stars in terms of interacting binaries, but that would require showing that most or all Be stars are in such binaries.

Let us start with the widest binaries - the visual binaries - and then work toward closer systems.

Two studies (Abt & Levy 1978, Abt & Cardona 1984) considered the visual, common-proper-motion, speckle, occultation, and spectroscopic binaries among Be stars and concluded that the frequency and distribution of periods is similar for Be and B stars for periods greater than 10^{-1} yr. This is shown in Figure 4, which shows a histogram for 355 B1-B7 III-V stars listed in the Bright Star Catalogue and the data for 80 Be stars in the same type and luminosity range and in the same catalog.

The dip in the bimodal distribution is due to incomplete occultation and speckle data; that dip includes spectroscopic binaries with K < ∿20 km s^{-1}, which are difficult to detect among generally broad-lined stars, and visual systems with separations < 0".1, which are difficult to detect interferometrically and by occultation techniques that are available for only a small fraction of the stars in the sky. For late-type stars that tend to be sharp-lined and closer to us, the period distribution is a single-peaked distribution with a shallow maximum at 10 yr. But notice that the data for Be stars of periods greater than 10^{-1} yr fit the B-star data within their probable errors: half of the points are within 1 p.e. and half are outside 1 p.e., which is what one would expect statistically. This means that the frequency and period distribution above 10^{-1} yr of Be stars are the same as for B stars. These similarities make it likely, but not positive, that the two kinds of binaries have similar origins.

Kogure (1981) also obtained a period distribution for Be stars, using a different sample. He studied the binaries in the catalog by Batten et al. (1978). His bimodal period distribution with a dip at 30 days is different than ours for three reasons:
1. He included as Be stars certain eclipsing binaries, such as RW Tau,

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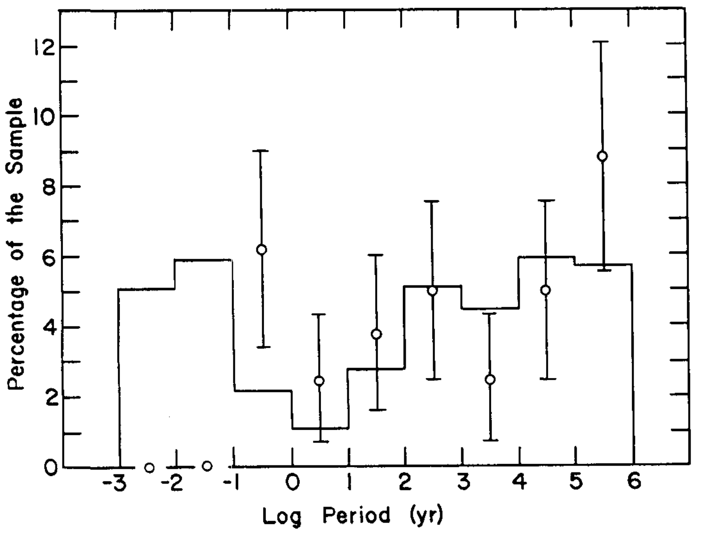
Figure 4. The histogram represents the distribution of binary periods for the 355 northern ($\delta > -30^{o}$) B1-B7 III-V stars in the Bright Star Catalogue. The open circles and probable error bars represent data for the 80 Be stars in the same type and luminosity range and from the same source. This figure is modified from that of Abt & Cardona (1984) to delete the 5-day period of the companion to HR 8153 but to include the companion to HR 7628.



that show emission at only selected phases. Those binaries are not rapid rotators and most people would not include them among the "classical" Be stars.

2. His short-period (< 30 days) binaries are systematically fainter (<V> = 7.1 mag) than his long-period (> 30 days) binaries (<V> = 5.1 mag), so his short-period group is sampling 15 times the volume of space as the long-period group. If one counted the numbers of binaries of various periods in a given volume of space, the short-period group would constitute a very weak tail on the long-period group.
3. Nearly all members of the short-period group were discovered as eclipsing binaries. Such discoveries are much easier than measuring velocity variations among broad-lined Be stars. Therefore the short-period group - again - is over-represented in the total sample in Batten et al.

Among the 355 B stars in the Bright Star Catalogue there are 136 companions to 111 primaries (90 doubles, 17 triples, four quadruples), so that even without corrections for undetected companions there are 38 companions for 100 primaries. Similarly there are 35 companions for 100 Be primaries. After applying the large corrections for undetected companions (mostly in the gap shown in Figure 4 and faint close visual companions), we would conclude that most of the B and Be primaries have

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companions, mostly with periods of years and that are not interacting binaries.

Abt & Cardona (1984) found that stars in clusters or associations are more likely to have companions (38 $\pm$5%) than field stars (25 $\pm$3%). They interpret that to be due to the tendency for clusters to eject single stars as predicted theoretically by van Albada (1968), Higgie (1975), Hills (1975), and Spitzer & Mathieu (1980). Thus the binary characteristics of stars are modified by their environments.

Now let us consider the shorter periods. The collection of new measures of 21 Be stars by Abt & Levy (1978) and the compilation of published data by Abt and Cardona (1984) on 80 of the brightest Be stars showed evidence for very few binaries with periods less than 10^{-1} yr or one month. The single (5-day) exception reported by Abt & Cardona seems to be an error because it refers to the late-type companion of the Be star HR 8153 = HD 203025 (Sanford 1926): the primary is a Be star in a 225-day binary and the late-type companion is itself a 5-day binary.

That Be stars with unevolved companions do not occur in short-period (< 10^{-1} yr) binaries makes sense because if they did occur, tidal braking would reduce their rotational velocities and they would lose a main characteristic of Be stars, namely their large rotational velocities. How effective is tidal braking? Zahn (1977) computed that stars of 10 $\mathcal{M}_{\odot}$ would have their rotational velocities fully synchronized with their orbital motions within one-quarter of their main-sequence lifetimes if P_{orb} < 3.3 days. For mid-B main-sequence stars the synchronized rotational velocities are approximately V_{rot} (km s^{-1}) = 250 P^{-1} (days), so synchronized short-period binaries would be slow rotators. Levato (1976), using known binaries having published Strömgren four-color photometry to determine luminosities above the ZAMS, found that B2-B7 binaries are fully synchronized for P_{orb} < 4-12 days, depending upon whether the stars are on or above the main sequence. Such stars would have V_{rot} = 20-250 km s^{-1} and would not be Be stars. In addition, we would expect that stars in binaries with somewhat longer periods (up to 10^{-1} yr?) would have their rotational velocities partially reduced by tidal braking. Therefore it makes sense to believe that B stars in binaries with P < 10^{-1} yr and companions in the main-sequence band would usually not be Be stars.

But the Be stars in X-ray binaries seem to violate that conclusion because such binaries tend to have periods of $\sim$15 days (Rappaport and ven den Heuvel 1982). But remember that the Be/X-ray binaries have (1) evolved neutron-star secondaries so the separations of components is larger for the same periods, (2) large mass ratios so the secondaries are less effective in producing tidal effects, and (3) probably are in an evolutionary stage of short duration so they may not have had time to synchronize. So tidal braking is much less effective in Be/X-ray binaries. We may have Be stars that originated in at least two different ways: (1) members of X-ray binaries in which angular momentum has been exchanged and the systems are highly evolved, and (2) single stars or

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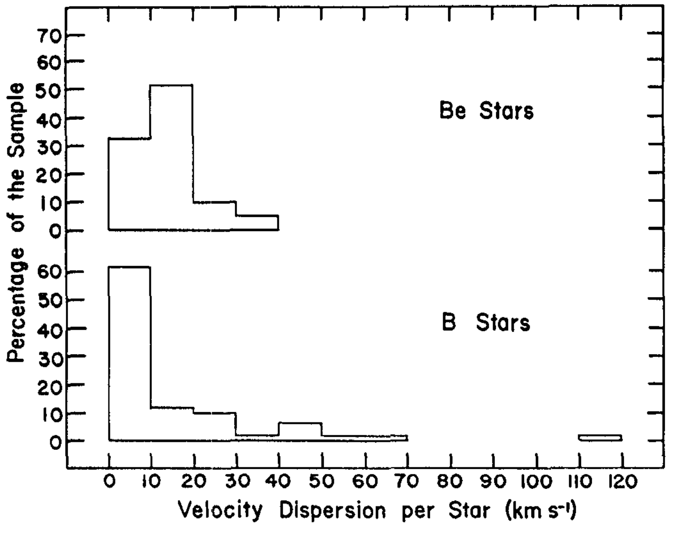
members of long-period binaries in which the high rotational velocities came from the time of star formation.

Could most or all of the Be stars be ones with neutron-star companions? At least one binary is not, namely the double-lined system ϕ Per, whose companion has a moderate mass (Suzuki 1979, Poeckert 1981). Let us consider the known "classical" Be binaries that are not X-ray binaries. There are eight systems listed by Batten et al. (Nos. 60, 136, 206, 243, 281, 555, 650, and 698). More recent discoveries are ϕ Cas and χ Oph (Abt & Levy 1978), HR 2142 (Peters 1982), and o And (Horn et al. 1982). Their mass functions, $(\mathfrak{M}_2 \sin i)^3(\mathfrak{M}_1 + \mathfrak{M}_2)^{-2}$, range from 2.39 to 0.00689 $\mathfrak{M}_\odot$. We find no single secondary mass can represent all those values of the mass function with reasonable inclinations. These mass functions, however, are well represented with expected inclination statistics and four secondaries of 9 $\mathfrak{M}_\odot$, four of 3 $\mathfrak{M}_\odot$, and four of 1 $\mathfrak{M}_\odot$. That is the same flat form of the secondary mass distribution derived by Abt & Levy (1978) for B binaries. But notice that for two-thirds of these Be binaries the secondaries are too massive to be neutron stars. Among the known Be/X-ray binaries only two stars (X per and γ Cas) are as bright as these 12 other binaries. Therefore per unit volume of space, the bulk of the known Be binaries do not have highly-evolved neutron-star secondaries.

Could there be many undetected spectroscopic binaries among the bright Be stars? The discussion above on kinematics implied not. Now consider in Figure 5 the velocity dispersions per star for the 21 Be and 42 B

Figure 5. Distribution of radial-velocity dispersions per star for 21 Be and 42 B stars are measured or quoted by Abt & Levy (1978).



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stars studied by Abt & Levy. The distributions are rather different. The differences between the first two bins are easily explained by different measuring errors among the Be stars (<V sin i> = 277 km s^{-1}) and B stars (<V sin i> = 126 km s^{-1}); the internal measuring errors average 7.5 and 3.1 km s^{-1} (s.e.), respectively, so the constant-velocity stars will tend to fall in the second bin for the Be stars and in the first bin for the B stars. But note that there are no dispersions greater than 40 km s^{-1} (actually 31 km s^{-1}) among the Be stars whereas 17% of the B stars have greater dispersions (all 17% are known binaries). The lack of large velocity dispersions among the Be stars could be due to no short periods or to low secondary masses. We learned above that in known Be binaries the secondary masses are normal, so we again conclude that the periods cannot be short. It is possible that there are some undetected small-amplitude binaries among the broad-lined Be stars. Abt & Levy measured only He I lines to avoid the (variable) effects of hydrogen emission on the Balmer lines, but perhaps newer techniques with solid-state detectors will reveal some more Be binaries.

Kriz and Harmanec (1975) showed how some of the characteristics of Be stars can be explained as interacting binaries. That model was driven by a lack of confidence (see e.g. Harmanec 1982) in rotational or outflow models. Undoubtedly mass exchange in binaries contributes to some of the Be characteristics, but we lack observational evidence that most or all Be stars can be explained in terms of interacting doubles. Note that when we concluded that probably most Be stars are in binaries, the bulk of the periods (Figure 4) are decades or more in length and are unlikely to be interacting systems. A possible solution may be to assume that the interacting binaries are often enveloped in opague common envelopes (cocoons) so that the orbital motions of the individual stars are not obvious.

I can make only three comments on the cocoon model. One is that they might be detected by their large masses, either as being more luminous than single stars or from masses derived from third components. Unfortunately the realization that the mass ratios are likely to be large (Peters 1982) makes such detections unlikely. Second is that if the cocoon periods are in the range of roughly 10-100 days, three-body stellar dynamics tells us that a third or visible companion cannot have a period less than 2-5 yr because three-body systems are unstable unless the ratio of periods is greater than 10-20. But we do observe such periods, so those particular systems cannot have cocoon pairs in them. Finally, for what it is worth, I offer a published cartoon of Dennis the Menace saying, "Lots of things are invisible, but we don't know how many because we can't see them."

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DISCUSSION FOLLOWING ABT

Plavec:

The term "core contraction stage" for stars near the end of the main-sequence phase is a misunderstanding. You should say "overall contraction stage". The core is contracting all the way until the ignition.

Abt:

I agree and stand corrected.

Plavec:

I like the idea expressed, I think by Baade, that there may be two families of Be stars: the early Be stars, which may be a continuation of the Oe stars, and to which your statistics apply; and the late Be stars, among which interacting binaries may be much more abundant.

Abt:

Perhaps a statistical test can be made, even though the Bright Star Catalogue is not complete, even within 200 pc, for late Be stars.

Harmanec:

The fact that there is no observable dependence of Be stars on age and that Be stars are found among the blue stragglers is exactly what the binary hypothesis predicts.

Abt:

OK.

Harmanec:

I am sorry that you have excluded stars of the spectral type later than B7 from your consideration. In fact, just the most easily detectable binaries, i.e. eclipsing binaries, are expected to have later apparent spectral types because of gravity darkening and envelope effects. In general, your statistics comparing Be and B stars should be corrected for these effects.

Abt:

The Bright Star Catalogue is incomplete for Be stars later than B7 and within 200 pc, but a comparison with normal B stars could be made.

Harmanec:

Most of the available mass functions are still based on the lines affected by the circumstellar matter and the true radial velocity amplitudes representing the stellar motion are probably a factor of two or three lower than the observed ones in many cases.

Abt:

That is true; but the discrepancies that were known at least back in Struve's time are much smaller than the effects that I discussed.

Underhill:

A surplus of Be stars in the direction of Cygnus is similar to what occurs for WR stars. According to my model for generating Be and WR spectra this implies larger than natural interstellar magnetic fields in Cygnus and a greater than normal residue of star formation clouds of plasma there.

Abt:

Would this be true also for the opposite direction - toward l=270° or Carina?

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Underhill:

The Carina nebula region is very complex and it contains quite a few Wolf-Rayet stars. My inference is when stars formed in this young region, larger than normal magnetic fields were present in some areas. The dearth of Wolf-Rayet stars in the direction of Orion might imply a low abundance of magnetic field lines there. However, if Pudritz and Norman (1986) are correct, there are significant magnetic field lines running through some of the clouds in Taurus. Taken to extremes my hypothesis about Be and WR stars might let one infer the distribution of interstellar magnetic fields 10^6 or so years ago.

Polidan:

I would like to comment on your statement regarding the expectation of low rotational velocities in close binaries. This assumes that mass accretion does not occur. In interacting binaries the mass receiving star, the Be star in this case, is accreting high angular momentum material from the accretion disk. Observations of eclipsing Be stars (Algol systems with emission lines) show that all B primary stars are rotating well above synchronism, some as high as 300 kms^{-1} or more. We do not know of a binary containing an accretion disk in which the accreting star is rotating near the synchronous velocity.

Abt:

So only for the detached systems does the exclusion apply. In addition, detached binaries with periods near 1 day will have moderate rotational velocities, i.e. near 250 kms^{-1}.

Kogure:

In your Be star frequency survey in Cygnus and in other fields, what is the limiting magnitude and I wonder whether you have examined the spectral dependence of the frequency or not.

Recently we have finished a survey observation of Be stars in the CMa region. We have detected about 90 Be stars up to the limiting magnitude of 15 mag in a region of 58 square degrees. We also surveyed early-type stars up to 12.5 mag for the same region, and we have found that the Be-star frequency is about 23% for early Be and several percent for late Be stars, in agreement with the spectral distribution in the Bright Star Catalogue.

Abt:

The study by Burkl and Maeder was also limited to stars in the Bright Star Catalogue; their study was limited to B0-B4 stars.

van den Heuvel:

I have problems with the reliability of detection of the binary character of Be-stars with evolved companions because if we look at the 19 known Be X-ray binaries, for which we do know that they are binaries, there is only one for which the optical star has been detected as a spectroscopic binary. My feeling is therefore that it is very difficult to detect the binary character in those Be-stars that are in post-mass-transfer binaries. The reason why this is so difficult may be the fact that post-mass-transfer systems have systematically smaller mass ratios (of order 0.1) and longer orbital periods than unevolved B-type spectroscopic binaries. This is due to the fact that unevolved systems tend to have mass ratios close to unity. So, mass transfer with conservation of mass and orbital angular momentum will carry them to much longer orbital periods, as the mass of the remnant is only about 0.1 that of its companion. So, it may be especially difficult to detect the binary character of Be stars with evolved companions (either helium stars, or white dwarfs or neutron stars).

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Abt:

That is true. While the X-ray binaries tend to have larger mass ratios, making perturbations of the Be primaries smaller and more difficult to detect, their periods are shorter and that aids detection, or perhaps only the short-period binaries are detectable from motions of their primaries.