Be STARS:
SINGLE AND BINARY COMPONENTS

Douglas R. Gies
Center for High Angular Resolution Astronomy, Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, U.S.A.
gies@chara.gsu.edu

Abstract There is growing evidence that a significant number of the rapidly rotating Be stars were spun up through mass transfer in massive close binary stars. We observe Be stars in several kinds of binaries predicted by theory: (1) Be + a cool, Roche-filling companion (so-called "hot Algols"), (2) Be + He star (the stripped down core of the mass donor), and (3) Be + neutron star (Be X-ray binaries). There are no known examples of Be + white dwarf binaries (although EUVE observations of the system λ Sco may have revealed the first rapidly rotating B star + white dwarf binary). Here I review the observational data on Be stars in binaries for comparison with model predictions. Because the detection of hot, faint (He star and white dwarf) companions is so difficult, we still cannot estimate accurately the fraction of such systems among the Be star population. Thus, the actual percentage of Be stars formed by binary mass transfer processes remains unknown.

Keywords: Stars: emission-line, Be — binaries: spectroscopic — stars: evolution

1. INTRODUCTION TO Be STARS

One of the main consequences of mass transfer in close binary stars is an increase in the rotational velocity of the mass gainer. We find among the massive stars a population of rapid rotators known as Be stars which are distinguished from normal B-type stars by the presence of strong and variable hydrogen Balmer emission lines. Because the detection of these stars is relatively straight forward (through spectroscopy or narrow-band imaging), there has been an irresistible urge among many astronomers to identify the Be stars as the manifestation of close binary processes (despite the non-detection of a companion in most cases). My goal in this paper is to review the evidence linking the Be stars to binary evolutionary processes and to motivate observers and theoreticians alike to reconsider what can be learned from the Be stars.

A good working definition of a Be star comes from Jaschek et al. (1981): a non-supergiant B-type star whose spectrum has, or had at some time, one or more Balmer lines in emission. The origin of the emission lines was a matter of heated debate for many decades (Slettebak 1988), but recent work has demonstrated clearly that the emission lines form in a circumstellar disk. The most dramatic evidence comes from the direct resolution of the emitting disks by radio interferometry (Dougherty & Taylor 1992) and by Hα optical interferometry (Quirrenbach et al. 1994, 1997; Stee 2000). These observations establish that the emission originates in a flattened cloud centered on the Be star. Even before these observations, however, there was strong circumstantial evidence for disks from the extent of linear polarization (Quirrenbach et al. 1997; Bjorkman 2000a), the infrared excess (Waters 1986; Waters et al. 2000), and the double-peaked appearance of the emission lines (Hummel 2000). Detailed studies of variability in certain Be stars (Telting et al. 1998; Telting 2000) indicates that there is a net outflow of gas in the disk, so that the disk gas originates in the Be star itself.

Be stars comprise from $\approx$ 18% of Galactic field B-type stars (Abt 1987) up to $\approx$ 39% of B-type stars in the SMC (Maeder, Grebel, & Mermilliod 1999). Be stars in clusters first appear in clusters $\approx 10^7$ years old and become rare in clusters older than 10^8 years (Mermilliod 1982; Fabregat & Torrejón 2000). Their positions in the Hertzsprung-Russell diagram span from the zero-age main sequence to the terminal age main sequence (Mermilliod 1982).

The key problem that has eluded solution for nearly a century is the origin of their circumstellar disks. Most Be stars have broad spectral lines, clearly indicating that they are rapid rotators, and Struve (1931) first proposed that all Be stars suffer mass loss from their equatorial zones due to the high rotational velocities. However, subsequent work by Slettebak (1979) demonstrated that while Be stars are indeed rapid rotators their equatorial velocities are generally below the critical rate where centripetal forces balance gravitational forces. Furthermore, the spectra of Be stars are notoriously time variable so that constant fast rotation alone is insufficient to explain their variable circumstellar disks. There are many well documented cases (e.g., γ Cas; Doazan et al. 1983) in which the spectrum transforms from a Be type to a Be "shell" spectrum (in which narrow absorption cores appear which are presumably formed far out in the disk), then to a normal B-type spectrum (lacking emission), and then back to a new Be outburst phase on timescales of years to decades. Furthermore, almost all Be stars display rapid photometric (Balona 2000) and spectroscopic variability (Baade 2000; Smith 2000) on timescales of hours to days.

It appears that rapid rotation is a necessary but not sufficient condition to create a Be star (since we do find rapidly rotators among B-type stars, usually indicated by a letter "n" appended to their spectral classification, which are not known Be stars). Thus, we are forced to seek some additional cause or causes which may act in concert with rapid rotation to produce the circumstellar disks. There is still no consensus about the defining processes but several promising explanations are being explored (Bjorkman 2000b):

• Bjorkman & Cassinelli (1993) have proposed a wind compressed disk model in which stellar wind flows from northern and southern hemispheres follow trajectories which cross at the equator and form an enhanced density region. Although this mechanism must occur at some level, Owocki, Cranmer, & Gayley (1996) found that models that include non-radial forces result in equatorial densities reduced to levels far below those observed (see Bjorkman 2000b).

• Many Be stars display absorption line variations that can be explained by photospheric nonradial pulsations (Baade 2000), and these pulsations may help to promote mass loss into an equatorial disk. The most striking example of this process is seen in the Be star μ Cen. Rivinius et al. (1998) have demonstrated that Be outbursts in this star occur at times of constructive interference between the 6 pulsational modes observed.

• Smith (2000) has found evidence of transient heating events in Be star atmospheres which can be interpreted as mass ejections presumably related to magnetic loops (or more generally mass loss by magneto-centrifugal acceleration; see Balona 2000).

• During the months prior to this meeting, the B-star δ Sco brightened and developed emission lines at the time of a close periastron passage of a binary companion (Fabregat et al. 2000; Hartkopf, Mason, & McAlister 1996). Thus, episodic tidal effects may also be a means of creating a Be disk around a rapid rotator.

Whatever the mechanisms of disk formation that actually occur, the central question remains how these B stars obtained their rapid spin. There are two probable explanations: (1) spin up at the end of core hydrogen burning, or (2) spin up by mass transfer in a close binary.

Models of massive star evolution that include rotation (Meynet & Maeder 2000; Heger & Langer 2000) show that there is a core contraction at the end of the main sequence phase that results in an increase in the rotational velocity of the outer layers. However, Mermilliod (1982) and others have shown that Be stars occupy the entire band of the main sequence, and are not confined to the terminal age portion.

The idea that Be stars are spun up by mass transfer in binaries has come in and out of fashion over the course of the last few decades. Kříž & Harmanec (1975) originally made the bold suggestion that all Be stars were spun up by binary mass transfer, and that their disks are formed by the mass transfer process (as accretion disks). However, if Be stars are active mass gainers, then their Roche-filling companions should be cool and large, and the companions would be detectable in the near-IR where they would contribute a larger fraction of the flux. A number of careful searches for cool companions were made and these were generally (but not totally) unsuccessful (Baade 1992; Waters, Coté, & Pols 1991; Floquet et al. 1989). The lack of Roche-filling companions led Baade (1992) to conclude that "... the explanation of the 'Be phenomenon' should not be sought from binarity," or, more specifically, Be disks are generally not formed by accretion from a companion.

Nevertheless, there are now many observational clues that some considerable fraction of the Be stars are rapid rotators because they are *post-mass transfer binaries*. The first line of evidence came from the discovery that most of the massive X-ray binaries consist of Be stars with neutron star companions. Rappaport & van den Heuvel (1982) proposed an evolutionary scenario for these Be X-ray binaries (BeXRBs) in which the mass donor transfers both mass and angular momentum to the gainer, and the donor, if massive enough, eventually explodes as a supernova leaving a neutron star orbiting a rapidly rotating Be star. Pols et al. (1991) showed that other kinds of Be companions should exist (stripped-down helium star cores and white dwarfs) that are intrinsically faint and difficult to detect. It is only in the last few years that we have finally detected these predicted Be binaries with faint companions.

In the following sections, I review the predictions from binary models about the numbers and kinds of Be binaries that may exist, and then I summarize the exciting progress that has occurred in the observation of these binaries. Because the detection of some types of companions is so difficult, it is still premature to determine what fraction of the rapid rotators (and Be stars) results from binary mass transfer.

2. BINARY EVOLUTION MODELS

Models of the evolution of intermediate mass close binaries are now well established (and less beleaguered by issues related to systemic mass loss which are important in the most massive stars). One evolutionary path is illustrated in Figure 1 (from a model by van den Heuvel & Rappaport 1987) which shows many of the common stages of development. The model begins with a close binary system of two main sequence B-type stars. The initially more massive star is the first to expand to fill its Roche lobe, and Roche lobe overflow begins (usually assumed to occur during H shell burning, or Case B). The gas accreted by the mass gainer causes that star to spin up. In fact, as little as $0.1M_\odot$ of accreted gas is sufficient to attain break-up velocity (Packet 1981). This spin up process is observed in lower mass Algol binaries where the gainers are often found to spin faster than the orbital synchronous rate (Šimon 1999; Etzel & Olson 1993). The system separation decreases until the mass ratio is inverted, and then the system widens (increasing the orbital period) until mass transfer is cut off. The mass transfer rate begins very high and then is followed by an extended period of reduced mass transfer (van der Linden 1987), in which the donor finally loses most of its envelope. The end result is the small, stripped down core of the mass donor (often referred to as helium star) orbiting a rapidly rotating gainer (usually assumed to be a Be star).

There are several possible outcomes of the binary interaction:

- In small mass ratio systems ($q = M_2/M_1 < 0.2$), the mass accretion rate is too large for the gainer to accept, and the gainer swells into a contact configuration. Such systems then experience a common envelope phase in which the gainer spirals into and merges with the donor. The rejeuvenated star might appear as a single rapid rotator (Be star).
- If the remnant He star mass exceeds $2.2M_\odot$ (after a possible second mass exchange phase), then the remnant will explode as a peculiar supernova (lacking hydrogen lines in its spectrum). If the total mass lost in the explosion is relatively small, then the neutron star (NS) remnant will remain bound to the gainer (producing a BeXRB). On the other hand, if there is significant mass loss or if the remnant obtains a substantial asymmetric "kick" velocity during the SN, then the binary will be disrupted leaving a single rapid rotator (Be star) and separate NS.
- Finally, if the He star mass is $< 2.2M_\odot$, then the system will continue to widen as the He star loses mass by a second phase of mass transfer (Case BB) or by stellar wind. The system will eventually appear as a rapid rotator (Be star) with an orbiting white dwarf (WD).

Numerical models of this process (Pols et al. 1991; Portegies Zwart 1995; Lipunov, Postnov, & Prokhorov 1996; Van Bever & Vanbeveren 1997) require input parameters describing the binary frequency, distributions of mass, mass ratio, and period, the fraction of mass accreted versus lost to system, the angular momentum lost, the kick velocity during the supernova, and the relative lifetimes in the various stages. Large uncertainties remain about the correct assumptions for all these parameters, and consequently, the final results about the numbers of binary products can be quite diverse. A common result is that there should be significant

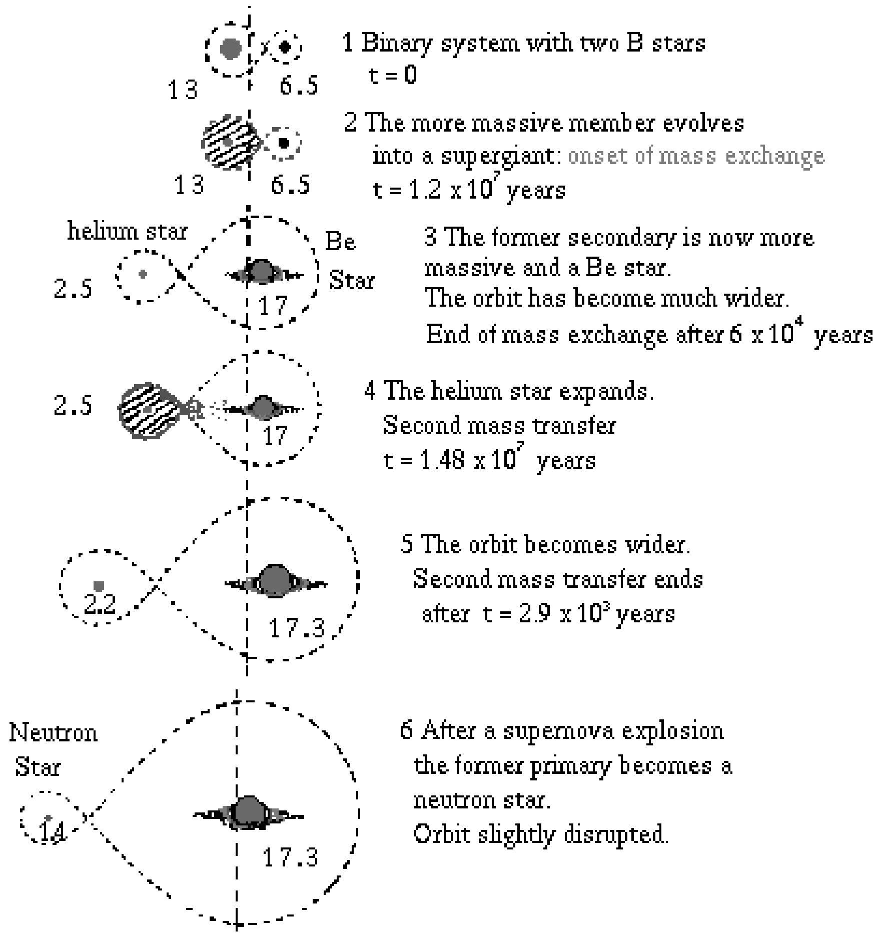

Figure 1. An evolutionary scenario beginning with a pair of 13 and $6.5 M_{\odot}$ stars in a 2.6 d orbit and ending with a BeXRB with a 30.6 d orbit (from van den Heuvel & Rappaport 1987; courtesy of I. Negueruela, BeppoSAX/ESA; see http://www.sdc.asi.it/ignacio/bex.html).

numbers of Be + WD and Be + He systems relative to the more readily observed Be + NS systems (cf. Fig. 1 of Portegies Zwart 1995). The predicted number of mass gainers as a fraction of the observed population of Be stars varies from $5 - 20\%$ (Van Bever & Vanbeveren 1997) to $\approx 50\%$ (Pols et al. 1991). Taken at face value, these results suggest that a significant fraction of the Be stars must have obtained their rapid spin by means other than mass transfer in a binary. However, given the uncertainties surrounding these calculations, we should not rule out binary mass transfer as the main cause of spin up.

3. OBSERVATIONAL RESULTS

Abt & Cardona (1984) explored the binary frequency of Be and B stars over a wide range in orbital period. They found that both groups generally have the same binary frequency for orbital periods greater than 1 year, a result confirmed in a speckle interferometric survey of Be stars by Mason et al. (1997). However, Abt & Cardona found a marked deficit of short period binaries (especially with $P < 0.1$ yr) among the Be stars compared to the B stars. They suggest that the Be stars are born as rapid rotators and maintain their fast spin because of a lack of tidal braking from close companions. However, recent models of the evolution of rotating stars (Meynet & Maeder 2000; Heger & Langer 2000) indicate that most single stars spin down during their main sequence lifetime.

The perceived absence of short-period systems is partially due to the practical difficulties of measuring radial velocities in Be stars: their photospheric lines are broad and shallow, usually show distortions related to rapid variability, and are often affected by shell absorption, disk emission, and/or gas streams (cf. Harmanec 1987). Furthermore, if theories of close binary evolution are correct, then the companions will have small masses, and the orbital semi-amplitudes of the Be star primaries will be small (only a few km s^{-1}). These difficulties explain why there are relatively few orbital solutions from optical spectra for BeXRBs (Negueruela 1998; Wang & Gies 1998). Nevertheless, hard and determined observational work (particularly by Harmanec, Tarasov, Koubsky, Peters, and others) has led to the discovery of a significant number of Be binaries with periods shorter than 10 yr (the limit for interaction) that were unknown to Abt & Cardona (1984). The following subsections summarize our current knowledge of binaries among the Be stars.

3.1. KNOWN BINARIES AMONG CLASSICAL Be STARS

In a recent literature search (Gies 2000), I found 27 classical Be stars in binaries with orbits (and 13 more suspected or needing confirmation). Two new single-lined spectroscopic binary systems have been discovered since then: π Aqr ($P = 84$ d; Bjorkman, Miroshnichenko, & Krugov 2000) and γ Cas ($P = 204$ d; Harmanec et al. 2001). The fact that these two are among the brightest and best studied Be stars in the sky testifies to the difficulties in detecting such low velocity amplitude binaries. The total numbers of binaries are summarized in Table 1 according to the following groups: binaries with bright companions, binaries with faint or undetected companions, suspected binaries, and BeXRBs (Coe 2000).

Notes and references for the individual targets can be found in Gies (2000) and Coe (2000).

Table 1. Galactic Be Stars in Binaries ($P < 10$ yr)

Category	Number	Example
Bright Companions (Algols)	16	CX Dra (B2.5 Ve + F5 III)
Faint/Undetected Companions	13	ϕ Per (B0.5 III-Ve + sdO)
Possible Binaries	13	FY CMa (B0 IVep)
Be X-ray Binaries	> 24	HDE 245770 (O9.5 III-Ve)

The kinds of binaries observed generally support the binary formation scenario for Be stars:

• There are 16 systems with cool, Roche-filling companions which represent the stage of active mass transfer (Tarasov 2000). Many of these systems have accretion disks that result from mass transfer as originally proposed by Křiž & Harmanec (1975).

• There are 13 systems with faint or undetected companions which plausibly include the post-mass transfer stages of Be + He and Be + WD stars (with long periods, small eccentricities, and few if any eclipsing systems).

• Significant by their absence is the complete lack of Be + B or Be + Be binaries in the list. If the Be phase was a common stage in the evolution of single stars, then we would expect to find many normal B-type companions.

• Note that the list is not drawn from a complete or uniform sample; the BeXRBs, for example, are faint while the group with faint companions represents some of the brightest stars in the sky. This suggests that many more Be + faint companion systems await discovery.

3.2. Be + HELIUM STAR BINARIES: ϕ PERSEI AND 59 CYGNI

The first positive detection of a He star companion to a Be star was recently made by Gies et al. (1998) through the identification of its spectral lines in high signal-to-noise UV spectra made with the Goddard High Resolution Spectrograph and *Hubble Space Telescope*. These high excitation absorption lines were found to move in anti-phase to the known radial velocity curve of the Be star ($P = 126.6731$ d; Božić et al. 1995), and Gies et al. used measured radial velocities of both components to arrive at a double-lined spectroscopic orbital solution. They estimated that the system inclination was large, $i > 63^\circ$, based on limits on the axial ratio of the resolved circumstellar disk (Quirrenbach et al. 1994) and the statistics of the occurrence of shell type spectra (Hanuschik 1996). Gies et al. then calculated masses of $8.9 < M_p/M_\odot < 9.6$ and $1.09 < M_s/M_\odot < 1.18$ for the Be star and He star, respectively. They used the new radial velocity curves to extract the individual component spectra from the ensemble of observed spectra using a Doppler tomographic reconstruction algorithm (Bagnuolo et al. 1994). The reconstructed spectra were matched using spectrum synthesis methods to arrive at the spectral classifications, projected rotational velocities, temperatures, gravities, and radii listed in Table 2.

Table 2. Parameters for the Components of ϕ Per (Gies et al. 1998)

Parameter	Primary	Secondary
Spectral Classification	B0.5 III-Ve	sdO
$V \sin i$ (km s^{-1})	450	0
$T_{\rm eff}$ (°K)	29300	53000
$\log g$ (c.g.s.)	3.7	4.2
R ($R_\odot$)	7	1.3

The hot subdwarf that orbits ϕ Per is clearly the remains of the originally more massive star that transferred both mass and angular momentum to the Be star (one of the fastest rotators in the sky). Thus, we now have in ϕ Per a firm example of a Be star formed by close binary evolution. The stars are well separated and there is no evidence of active mass transfer at present, so the Be star's disk results from outflow from the Be star (a painting of the system by Bill Pounds appears in Fig. 2). Vanbeveren et al. (1998) present a conservative evolutionary scenario for the system that starts with a $6M_\odot + 5M_\odot$ pair in a 13.5 d orbit. This picture may need revision since the current luminosity of the subdwarf is more in line with the predictions for the remnant of a 12 $M_\odot$ progenitor (see Fig. 9.2 in Vanbeveren et al. 1998). In fact, the secondary of ϕ Per is the brightest hot subdwarf in the sky but was lost in the glare of the Be star prior to the *HST* observations. Interestingly, the Be star is also overluminous for its mass (see Fig. 2 of Schönberner & Harmanec 1995) which may indicate that the Be star has undergone large scale mixing as the result of the mass transfer (see a different interpretation in Harmanec 2000).

Rivinius & Štefl (2000) have recently presented a radial velocity curve for the Be binary, 59 Cyg ($P = 28.17$ d, and a small mass function

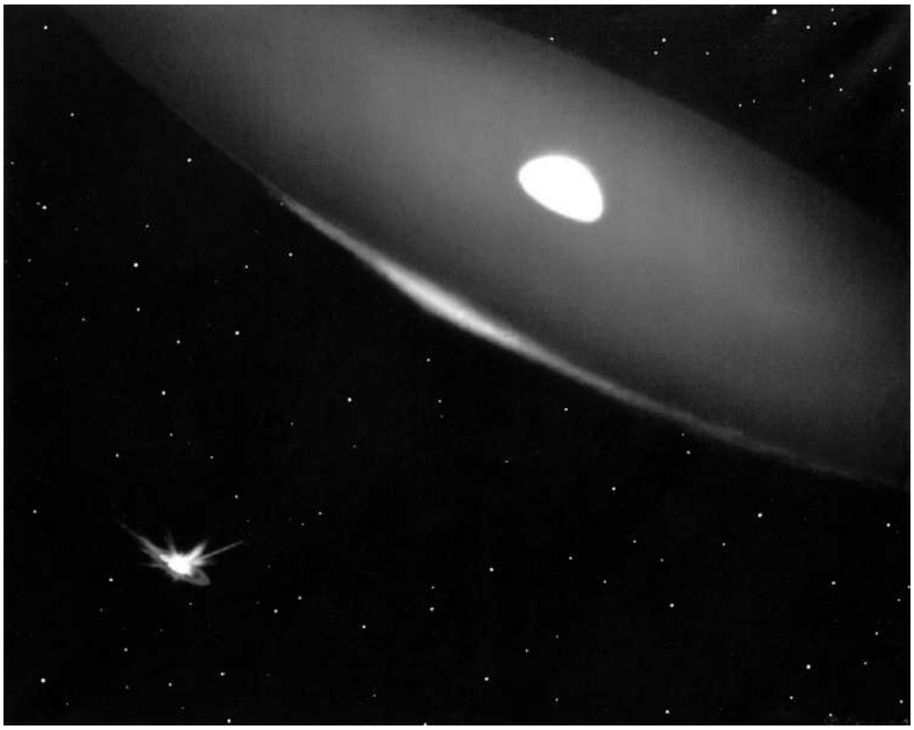

Figure 2. A painting of the ϕ Per system by Bill Pounds.

indicating a low mass companion). Rivinius & Štefl find several optical emission lines which move in anti-phase motion as they do in ϕ Per, and these suggest the presence of a hot companion. I have verified their orbit with velocity measurements from UV high dispersion spectra in the *IUE* archive. The mass ratio is unknown at present, but a preliminary tomographic reconstruction with a mass ratio $M_1/M_2 = 3$ and a flux ratio $F_2/(F_1 + F_2) = 0.1$ shows evidence of a secondary UV spectrum indicative of a very hot companion. Thus, 59 Cyg is probably the second known example of a Be + He system.

3.3. Be + WHITE DWARF BINARIES

Unfortunately, there are no known representatives of this class (Meurs et al. 1992) despite the predictions that many should exist (Waters et al. 1989; Raguzova 2000). This is perhaps not surprising, since WD companions are probably very difficult to detect by conventional means. However, there have been several reports in the last few years of WD companions to normal B-type stars discovered through *EUVE* observations of the extreme UV and soft X-ray flux from the WD companion (Burleigh & Barstow 1999, 2000; Vennes 2000; Berghöfer, Vennes, & Dupuis 2000). The only known B + WD system with a separation small enough to be interacting is λ Sco, and Berghöfer et al. (2000) suggest that this consists of a $1.3M_\odot$ WD plus a B1.5 IV primary in a $P = 5.96$ d orbit. It interesting to note that although the primary is not a known Be star, it is a fast rotator (4$\times$ synchronous; De Mey et al. 1997). Thus, if confirmed, λ Sco may represent the first recognized example of a B + WD system formed through binary mass transfer.

3.4. Be + NEUTRON STAR BINARIES

The BeXRBs form the largest subgroup of massive X-ray binaries (Coe 2000). The binary periods lie in the range 16 d – 400 d, and the orbits are wide and eccentric (and possibly inclined to the disk around the Be star). The BeXRBs display large variations in X-ray flux, and frequently X-ray outbursts are observed that are associated with the passage of the NS through the disk of the Be star. The primaries mainly have spectral types in the range B0 – B2 and luminosity classes in the range III – V. Thus, the BeXRBs have primaries at the high mass end of the distribution of Be stars as a whole. Supernovae that occur in binaries with lower mass primaries may lead to disruption of the binary in most cases. The evidence collected to date indicates that the known BeXRBs have companions that are neutron stars (and not black holes or white dwarfs; Negueruela 1998).

3.5. RUNAWAY Be STARS

Rinehart (2000) compared *Hipparcos* proper motions of the Be and B-type stars, and showed that they have very similar distributions. This work was extended to a study of proper motions and radial velocities in a sample of 344 Be stars by Berger & Gies (2001) who found that although most Be stars have slow random speeds, there is a fraction $(3 - 7\%)$ which have peculiar space motions > 40 km s^{-1}.

The binary scenario for the formation of Be stars predicts that the surviving post-SN systems will achieve a "runaway" velocity given by (Nelemans, Tauris, & van den Heuvel 1999)

$$v_{\rm sys} = 213 \left(\frac{\triangle M}{M_\odot}\right) \left(\frac{m}{M_\odot}\right) \left(\frac{P_{\rm re-circ}}{\rm day}\right)^{-\frac{1}{3}} \left(\frac{M_{\rm rem} + m}{M_\odot}\right)^{-\frac{5}{3}} {\rm km\ s^{-1}} \quad (1)$$

where $\triangle M$ is the mass lost during the supernova, m is the mass of the surviving companion, $M_{\rm rem}$ is the mass of the neutron star remnant, and $P_{\rm re-circ}$ is the orbital period after subsequent re-circularization of the orbit. Based on the typical parameters for the BeXRBs and their orbits (Coe 2000), we expect to find space velocities that are proportional to the mass lost in the SN, $v_{\rm sys} \approx 8\ (\triangle M/M_\odot)$ km s^{-1}.

If Be stars are formed in close binaries, then the small fraction of Be runaway stars and the relatively slow systemic velocities of most BeXRBs (Chevalier & Ilovaisky 1998) indicate that those in which a SN occurred suffered significant mass loss prior to the SN event ($\triangle M/M_\odot$ of order unity). However, Be binaries that avoided a SN (those with He or WD companions) also avoided receiving any runaway velocity boost. Thus, the low velocity distribution characteristic of most Be stars is consistent with the binary formation scenario if (1) a substantial fraction avoided a SN, and (2) the progenitors lost most of their mass prior to the SN in systems where a SN did occur.

4. CONCLUSIONS

There are now many examples known of Be stars in the kinds of binary systems predicted by models including (1) Be + a cool, Roche filling companion (hot Algols), (2) Be + He star (ϕ Per, 59 Cyg), and (3) Be + neutron star (BeXRBs). Thus, we are now confidant that some of the rapidly rotating massive stars (the source of Be stars) can be formed through binary processes.

What is still unknown is whether or not all Be stars are spun up this way. Current models of binary evolution (Van Bever & Vanbeveren 1997) suggest that only a modest fraction of the observed Be population are formed by the binary route (so that the majority form from stars spun up at the end of core hydrogen burning or from stars born with large spins). The observational side of this question is still fraught with uncertainty. The recent discovery of the He star companion to ϕ Per (Gies et al. 1998), one of the brightest and best studied Be stars in the sky, shows how difficult it can be to find faint, low mass companions (WD, He star). Furthermore, we know that there are some binary paths that can lead to truly single Be stars (systems disrupted in a SN explosion and Be stars formed by mergers).

Despite these difficulties, we can expect progress in the observational picture in the near future. There is evidence that Be stars first appear in clusters some 10^7 yr after birth (Fabregat & Torrejón 1999), and we would like to know if there is also a general increase in the distribution of rapid rotators at that time. Several groups are currently involved in measuring projected rotational velocities for large numbers of B stars in clusters, and such data will provide important clues on the time evolution of rotation in massive stars. The systems with suspected low mass companions are especially worthy of intensive spectroscopic observation, and some of the nearby systems may be resolved directly with the new generation of optical interferometers. Since the suspected companions are likely hot, spectroscopic studies in the FUV and EUV will be especially important. If a large number of hot companions exist, they would be significant contributors to the EUV flux budget of galaxies, and understanding these systems will be important in our interpretation of the optical and IR spectra of high redshift galaxies.

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