Binary Be Stars and Be Binaries*

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ABSTRACT. Two hypotheses have been put forward for the rôle of binarity in Be stars: (1) All Be stars are interacting binaries. (2) Roughly one-half of the observed Be stars are post-mass exchange binaries with compact companions. Contrary to (1), (2) does not attempt to explain also the existence of disks in Be stars. After the spin-up by mass and angular momentum transfer, the B star somehow has to succeed to form and maintain the disk. Since rapid rotation is only necessary but not sufficient for this transformation, the effect of duplicity would merely be to give more stars the opportunity to become a Be star. Model (1) is not nearly realistic as is also underlined by a new spectroscopic survey for cool companions. The verification of (2) on the basis of the *ROSAT* All-Sky Survey has just begun; but a serious deficiency of white dwarf companions is already apparent. Binarity currently provides no extra clue on the origin of the Be phenomenon.

1. Introduction: the Asteropathology of Be Stars

The Symposium organizers have pre-classified Be stars as 'putative binaries'. In fact, on the one hand, Be stars have some properties for which there are no overwhelmingly coherent alternative concepts whereas binary models clearly are *sufficient* as a (partial) explanation. On the other hand, the fraction of Be stars which are known to be double is rather small so that the real issue is whether a companion is *necessary* for a B star to be/become a Be star. If so, we were concerned with Be binaries whereas otherwise one could only speak of binary Be stars which are of less interest. Making this distinction in practice is difficult because only very few conditions would prevent a given type of stars from occurring *also* in binaries. Conversely, in order to disprove a general binary hypothesis the failure to detect a companion to just one or two presumed proto-types is not enough.

A review of some general property of Be stars inevitably has to start with the author confessing what he thinks a Be star is. Some experts consider the occurrence of one emission line at one epoch as the *only* defining difference between Be and 'normal' B stars. This is almost a non-definition because it leads to a very heterogeneous group and is of little value for physical studies. The description of Be stars given below is, therefore, more restrictive. By exclusion of a number of sub-categories of emission line B stars it considerably reduces the inhomogeneity of the remaining group. This description is not intended to be a definition, and no claim is made of the purity of the group to which it applies.

The large width of the emission lines implies that they arise from a rapidly rotating disk (e.g., Hanuschik 1989). Models of the infrared excess measured by IRAS support this interpretation and suggest a slow radial expansion (Waters et al. 1987). At higher latitudes, there is a fast, highly ionized wind (e.g., Grady et al. 1987, 1989) which is still seen at lower $T_{\rm eff}$ than in the case of non-Be stars. The distribution of stellar $v \sin i$ values is consistent with the assumption that *all* Be stars are fast rotators (Lucy 1974, Balona 1975). The ratio,

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V/R, of the equivalent width of the violet and red emission components is about unity on the average but may undergo drastic changes which often appear cyclic with time scales of a few years (Copeland and Heard 1967). The total emission strength usually changes as well. Decreases typically take more time than do increases which sometimes are described as outbursts. One of the strongest events has been the 1936-1938 outburst of γ Cas (e.g., Doazan et al. 1983). At least some Be stars undergo numerous small outbursts each of which takes no more than 1-2 days to develop (Baade et al. 1988). As a rule, the repetition of outbursts does not seem to follow a distinct temporal pattern.

Apparently all Be stars earlier than ~B7 are photometrically (e.g., Percy 1987, Balona 1990, Balona et al. 1991) and spectroscopically (e.g., Baade 1987, 1989; Walker 1991) variable. Line profile variations are also widely seen in Bn stars where, however, the incidence and strength of large-scale variations seem to be much smaller (Smith and Penrod 1984, Baade unpublished). Since smaller features in rotationally broadened profiles correspond to smaller spatial patterns, Bn stars are also less variable photometrically. Many observers (e.g., Vogt and Penrod 1983, Baade 1987) interpret this variability as nonradial pulsation; others (e.g., Harmanec 1984, Balona 1990, 1991) argue for corotating surface structures.

Hereafter, B-type stars which match this description will be called Be stars. In the literature, also the term 'classical Be stars' can be found for them. B stars whose emission lines are due to a stellar wind rather than a disk are omitted because there is no evidence that the presence or not of a wind depends on binarity. This excludes B[e] stars, luminous blue variables, supergiants, and any highly evolved, compact stars. Helium variable B stars can have emission lines but their spectral variability is different (Bolton et al. 1987). Some Herbig Ae/Be stars show line profile variations which are reminiscent of the Be stars considered here (Baade and Stahl 1989). But often they display Hα emission lines with various P Cygni profiles which indicate strong mass outflow/infall (Finkenzeller and Mundt 1984), and there are members of open clusters (Mermilliod 1982, Slettebak 1985) which conform to the above description of Be stars without being pre-main sequence objects.

2. Double Cures

Algol systems often show Hα emission (Peters 1989) originating in an accretion disk from a Roche-lobe overflowing cool giant. This inspired Křiž and Harmanec (1975, Harmanec and Křiž 1976) to a general mass exchanging binary hypothesis for Be stars which was further elaborated on by Harmanec (1982, 1987). Be stars would have longer periods than Algols because in closer systems there would not be enough space for the disks required to produce the much stronger line emission of Be stars. Accordingly, the radial velocity (RV) amplitudes would be small and eclipsing systems rare, making the detection of duplicity difficult since the lines are shallow and the primaries also intrinsically variable.

The mass exchanging binary model aims at explaining several properties of Be stars:

- Accretion of angular momentum could account for the rapid rotation of the B star.
- Mass loss from the companion through the inner (outer) Lagrangian point could explain the formation of disks around the B star (the entire system).
- The slow V/R variations of double-peaked emission lines could reflect the apsidal motion of an eliptical ring in a binary (e.g., Huang 1973).
- Tidal interaction could resonantly induce oscillations of and mass loss from the B star. In an excentric orbit, the amplitude would be phase dependent.

It is difficult to imagine that any of these possibilities has *not* been realized by nature (Plavec 1987). Yet, are they necessary?

Be stars could also be *post*-mass exchange binaries (Pols et al. 1991) in which case, too, they would owe their rapid rotation to angular momentum transfer. However, the present disk is not due to accretion from the companion but somehow the B star has to accomplish its formation. The companion has evolved to a compact object, and it is it which accretes mass from the disk. This accretion would reveal itself by hard X-rays (Rappaport and van den Heuvel 1982, van den Heuvel and Rappaport 1987). [Harmanec (e.g., 1985) also considered the possibility of continued mass transfer from the contracting, rapidly rotating companion to the B star. But this is extremely unlikely to work as a general solution.]

3. **Reservations**

A discussion of binary models for Be stars would be incomplete without mentioning alternative explanations. The enumeration below shows that they combine less easily to a unified model of similar apparent persuaviness as the binary model. But their physics is at least as sound, and there are observational criteria to discriminate between different models.

- Fast rotation is not unique to Be stars. In the Bright Star Catalogue (Hoffleit 1982), there is for every Be star a Bn star which has roughly the same $v \sin i$ and spectral type but has never been observed to display emission lines. Towards later spectral types, Bn stars rapidly outnumber Be stars.
- Be stars possess a wind, i.e. lose mass anyway. Furthermore, Be stars would not be the only class of early type stars with a discontinuous component of their mass loss processes. Some observations suggest (Baade et al. 1988, Baade 1991) the possibility that discrete mass loss events are intimately linked to the stellar short-term variability. The spectroscopic data show that this variability is strongly concentrated to the stellar equatorial plane where the specific angular momentum is the largest.
- Kato (1983) and Okazaki (1991) have suggested that V/R variations are due to one-armed nonradial oscillations of the disk. A possibility to discriminate been the two models is to search for phase differences between the V/R cycles of lines formed at different radii (cf. Baade 1985) as observed in EW Lac (Kogure and Suzuki 1987).
- Balona (1990, 1991) has shown that the periods of short-term variability in Be stars correspond to the inferred stellar rotation periods to within much less than the large uncertainties of the latter. This would be difficult to understand if the variability was not intrinsic but externally induced.

Theory has raised serious doubts against a general interacting binary model because in a Case Br mass exchange the phase of slow mass transfer lasts only 2% of the helium burning stage following it (van der Linden 1987). This leads Pols et al. (1991) to conclude that "the hypothesis that *all* Be stars are in interacting binaries is clearly untenable".

For their work on post-mass exchange binaries, Pols et al. (1991) derive encouragement from a comparison of the computed distribution of spectral types with the ones observed in Be and in Bn stars. The theroretical and the observed Be distribution attain a maximum around B2 whereas the frequency of Bn stars is roughly constant over early subclasses and steeply rises in the later ones. The authors acknowledge that this agreement is significant only if whatever process turns the rapidly rotating B star into a Be star (rotation alone is not enough) does not shift this distribution. That is, the efficiency of that process is either independent of spectral type or also maximal at B2. Pols et al. do not mention that intrinsic variability peaks in a similar way (Waelkens and Rufener 1985; see also Baade 1989 and Balona et al. 1991) and that nonradial pulsation is one of the few currently proposed processes that might make a single, rapidly rotating B star become a Be star. Anyway, Pols et al. (1991) give a careful account of the observed and expected properties of this population of Be stars that would have resulted from Case Br mass exchange. But even their most 'optimistic' model does not account for more than 60% of the observed Be stars.

It would be wrong to give the impression that there are no Be stars with a companion. A list of the better (which often enough is distinctly different from well) understood objects has been compiled by Pols et al. (1991). However, it is worth noting that with the exception of V/R variations a strong case in support of one of the other arguments for the binary hypothesis has rarely been made. So far, the emphasis has mainly been on the variability of the objects, not their origin. Instead of Be binaries, many of these stars could simply be binary Be stars, i.e. intrinsic Be stars which happen to have a companion.

Finally, it is often said that the broad spectral lines and complicated variability patterns of Be stars seriously limit the detectability of orbital effects by means of a time series analysis. This is correct but ignores that there are other ways to search for companions:

- The most direct method has only recently been shown to be feasible by the interferometric resolution of the Hα emission of γ Cas (Mourard et al. 1989). However, the first results will presumably be biased against close systems and faint companions.
- Compact companions should reveal themselves through ephemeral hard X-rays due to accretion from the Be star's disk.
- In view of the time and wavelength dependent flux excesses caused by free-free and free-bound transitions in the circumstellar gas, flux distributions are not a very safe duplicity criterion. However, the recent work by Waters et al. (1991) on HR 2142 which had been widely accepted as a proto-type interacting binary among Be stars shows that this method can place uncomfortably strict limits on this interpretation. As a special case, EUV observations should easily detect ultra-hot companions provided that interstellar absorption due to neutral hydrogen is weak enough.
- In the post-photographic era, a single high-resolution low-noise spectrum should often constrain the properties of a late-type companion more strongly than the analysis of a time series of RV measurements. The restriction to late spectral types is inconseqential because earlier types are anyway easier to detect.

4. A Spectroscopic Search for Late-type Companions

4.1 THE SURVEY

Despite of the negative theoretical predictions a first small survey to search for spectral lines of late-type companions has been carried out. The available instrument was ESO's Coudé Echelle Spectrometer. Its Short Camera gives a resolving power $\lambda/\delta\lambda \geq 50{,}000$ but provides a relative wavelength coverage, $\Delta\lambda/\lambda$, of only $\sim$0.01 which makes the selection of the spectral window critical. Ideally, it would be uncontaminated by lines from the earth's atmosphere, the disk, and the B star. But it should contain lines that are strong over a wide range of possible cool companions. Finally, the window should fall in the Rayleigh-Jeans part of the continuum flux distribution of both component stars. This last condition ensures that the detectability of lines due to a secondary is a monotonic function of the temperature ratio of the components. After careful investigation the spectral region around the strong lines due to FeI λ 879.3, MgI λ 880.7 and FeI λ 882.4 was chosen. Fig. 1 shows the appearance of this spectral window in several giants between G5 and M3.

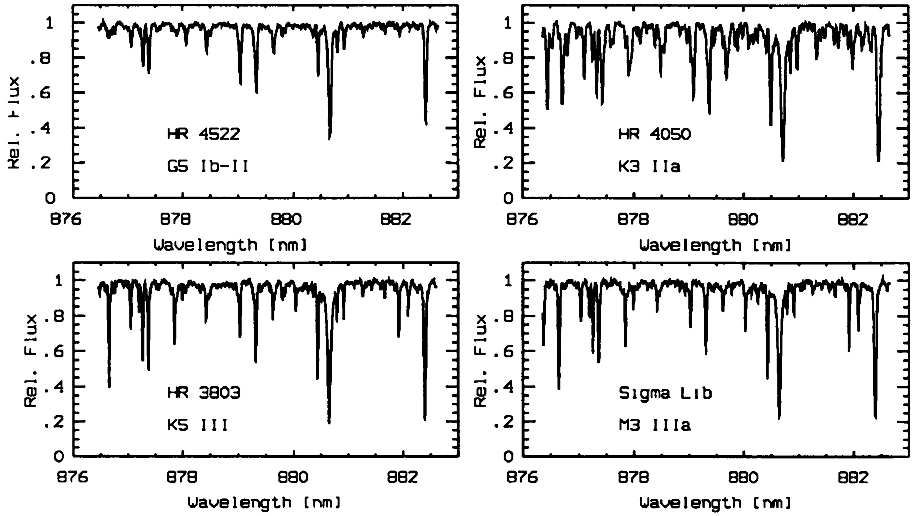

Figure 1: *The spectral window used for the survey; here observed in several cool giants as labeled. In each case, the two strongest lines are due to Mg* I λ *880.7 and Fe* I λ *882.4.*

The sample selected for the survey consists of 35 objects and comprises ~90% of all Be stars with $m_V \leq 5.5$, $7^h \leq \alpha \leq 17^h$, and $-15° \geq \delta \geq -70°$; it was observed in 1991 April. Unfortunately, strong residual CCD fringing prevented the S/N from being photon limited. The effective detection limits were, therefore, measured as the depth of the strongest fringe feature with FWHM between 5 and ~60 km s^{-1}. Because often the blue half of the spectrum was more strongly affected than the red one, the measurements were done separately for the two halves. The results are compiled in Table 1.

4.2 INTERPRETATION OF THE RESULTS

The interacting binary model postulates Roche-lobe geometry for the assumed companion. A relation for the approximate effective radius, R_{comp}, of the Roche-lobe overflowing companion in a binary with mass ratio $q = M_{comp}/M_B$, has been given by Paczyński (1971):

$$\frac{R_{comp}}{a} = 0.46224 \left(\frac{1}{1+\frac{1}{q}}\right)^{1/3}$$

Since the observed spectral region around 880 nm is in the Rayleigh-Jeans part of the spectrum even of early M stars, the monochromatic surface brightness ratio is given by:

$$\frac{B(\lambda)_{comp}}{B(\lambda)_B} = \frac{T_{comp}}{T_B}$$

If a is measured in units of the radius of the B star, the monochromatic flux ratio is:

$$\frac{F(\lambda)_{comp}}{F(\lambda)_B} = 0.21367 \left(\frac{1}{1+q}\right)^{2/3} a^2$$

where differences in limb darkening are neglected. In Fig. 2, this equation is displayed as lines of constant monochromatic surface brightness ratio in an $a \div q$ plane. The temperature

Table 1: *The 35 Be stars observed in search for spectral lines of a cool companion. The last two columns give the maximum depth (in units of the neighbouring continuum) of absorption lines with 5 km* $s^{-1} \leq FWHM \leq 60$ *km* s^{-1} *in the approximate ranges 877-880 and 880-883 nm, respectively. Note that the features measured actually are no spectral lines but residual CCD fringes. All other data are taken from the Bright Star Catalogue (Hoffleit 1982).*

HR	Other Name	m_V	Spectral Type	$v \sin i$ km s^{-1}	$d_{max,blue}$	$d_{max,red}$
2538	κ CMa	3.96	B1.5IVne	199	0.010	0.011
2745	27 CMa	4.66	B3IIIe	139	0.012	0.008
2749	ω CMa	3.85	B2IV-Ve	120	0.013	0.013
2790		5.11	B2IVne	124	0.019	0.013
2819		5.43	B5IIIne		0.007	0.005
2825		5.33	B2.5IVe	33	0.020	0.022
3034	o Pup	4.50	B0V:pe:	368	0.031	0.023
3237		4.78	B1.5IIIe	156	0.014	0.011
3330		5.17	B2Ve	158	0.008	0.007
3498		4.49	B3Vne	332	0.013	0.009
3642		4.71	B2IVe	140	0.015	0.011
3858		4.77	B6Ve	332	0.010	0.011
4037	ω Car	3.32	B8IIIe	225	0.008	0.016
4074		4.50	B3IIIe	81	0.014	0.006
4140		3.32	B4Vne	303	0.011	0.012
4221		5.23	B8-9IIIe	218	0.020	0.012
4460		4.62	B9Ve	159	0.014	0.009
4537		4.32	B3Vne	268	0.008	0.006
4618		4.47	B6IIIe	127	0.013	0.010
4621	δ Cen	2.60	B2IVne	181	0.011	0.016
4625		5.48	B3IVe	204	0.009	0.010
4696	ζ Crv	5.21	B8Vne		0.009	0.010
4823		4.93	B6IVe	185:	0.018	0.014
4830		5.31	B2pe	275	0.161	0.027
4897	λ Cru	4.62	B4Vne	317	0.010	0.013
4899	μ^2 Cru	5.17	B5Vne	201	0.007	0.008
5193	μ Cen	3.04	B2IV-Ve	175	0.017	0.012
5250	47 Hya	5.15	B8VpShell		0.014	0.016
5316		5.07	B4Vne	242	0.013	0.015
5440	η Cen	2.31	B1.5Vne	333	0.011	0.013
5646	κ^1 Lup	3.87	B9.5Vne	202	0.008	0.012
5907		5.42	B2.5Vne	349	0.007	0.007
5941	48 Lib	4.88	B5IIIpe	393	0.014	0.017
6118	χ Oph	4.42	B2IV:pe	134	0.019	0.017
6510	α Ara	2.95	B2Vne	298	0.005	0.013

ratio is assumed to be 1:6 which would roughly correspond to, e.g., a B2 star with K7 companion. This should be very fair. (Note that Figure 2 is a purely parametric representation: there may be parameter combinations which are not likely to correspond to real binaries).

The contour lines of Fig. 2 can easily be converted into lines of constant spectral line depth. Fig. 1 shows that in normal G5 to M3 giants the depths of the strongest expected lines range from 65% to 80%. With the assumption that rotation in a close binary reduces these values to not less than 40%, the shaded area in Fig. 2 indicates the bulk of the detection limits in Table 1. (These limits are conservative because they ignore that no correlation exists between the CCD fringes and the pattern of the spectral lines searched for.) In the survey no Roche-lobe overflowing cool companion has been detected with a mass ratio and linear separation larger than corresponding to this zone. For temperature ratios other than 1:6 the detection limits would, of course, be slightly shifted.

In order to compare these results with equivalent RV amplitude limits, k_B, for the B star (assuming circular orbits), Kepler's third law can be used after some trivial substitutions:

$$k_B = \sqrt{\frac{GM_B}{a}} \frac{(1+q)^{1/2}}{1+\frac{1}{q}}$$

If a is again expressed in units of the B star's radius, R_B, a value has to be adopted for the ratio M_B/R_B. For main sequence stars between B0 and B9.5, this ratio changes from 2.5 to 1.1 in solar units (Harmanec 1988). Since only its square root enters into the above relation for k_B, the actual choice is probably much less critical than the more advanced evolutionary status of Be stars. Unfortunately, no reliable radii are available for giants and subgiants. For an adopted mass-to-radius ratio of 1.85, corresponding to B2.5V, Fig. 3 displays lines of constant k_B in the same $a \div q$ plane as in Fig. 2.

Comparison of Figs. 2 and 3 shows that except for very small separations or mass ratios or both the lines of constant sensitivity intersect one another at large angles. Therefore, the two methods are complementary to one another. However, often a single high-quality, near-IR spectrum will give at least as conclusive results as does a whole series of RV measurements. Note, furthermore, that Fig. 3 is based on the most favourable assumption of an orbital plane with inclination $i = 90°$. By contrast, the visibility of spectral lines is independent of i if absorption by gas streams and equator-to-pole gradients can be neglected. Dilution by the envelope's continuum radiation is negligible at this wavelength.

If large RV amplitude systems did not generally go unnoticed, only very close systems with very small mass ratios are not exluded by the combination of the two diagrams. Such systems would have to be so close that the disk could only exist outside the orbital circle/ellipse. Although the sample has not been defined to be statistically complete and unbiased, the implication is clear: Be stars with Roche-lobe overflowing cool companions are extremely rare. One of the few possible exceptions to this rule is KX And which Floquet and Hubert (1991) observed in the region 845-860 nm where a number of narrow low-ionization metal lines were detected. If their discrepant RV is sufficient not to attribute them to the disk, they provide the first direct evidence of the long-suspected companion. It is re-assuring that with a depth of up to 10% of the continuum at slightly lower spectral resolution, lines of similar strength would not have been missed in this work.

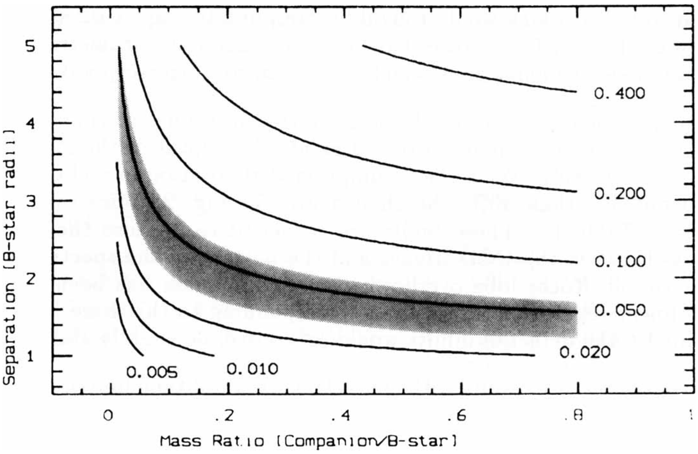

Figure 2: *Lines of constant monochromatic surface brightness ratio in an* a÷ q *plane. It is assumed that the companion fills its Roche lobe and that its temperature is one-sixth of the one of the B-primary. The shaded area corresponds to the bulk of the limits given in Table 1 for the detection of spectral lines of the companion if the depth of these lines is at least 40% of the companion's continuum flux (cf. Fig. 1). See also Sect. 4.2.*

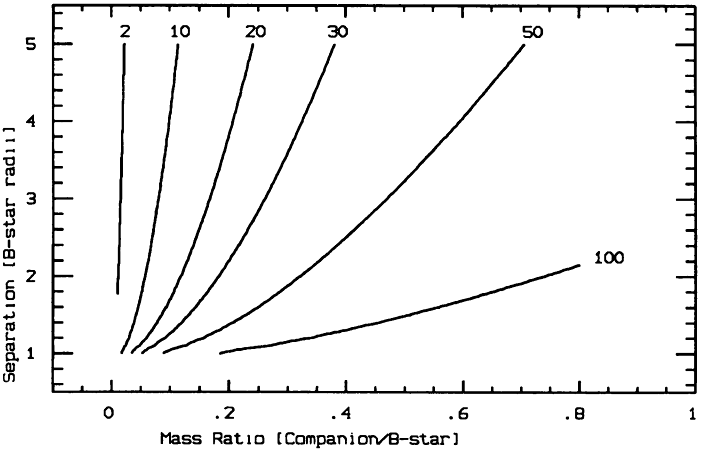

Figure 3: *Same as Fig. 2 except for lines of constant radial velocity amplitude (in km* s^{-1}*) of the B star in a circular orbit with inclination* $i = 90°$. *The mass-to-radius ratio adopted for the B stars is 1.85 (in solar units). See also Sect. 4.2.*

5. Conclusions

Current status and prospects of binary models for Be stars can be summarized as follows:

- There are extremely few interacting binary stars; a search in 35 bright Be stars for spectral lines of cool companions did not identify one new candidate. This is theoretically expected because the corresponding evolutionary phase is very short. Accordingly, the hypothesis that *all* Be stars are interacting binaries should be retired.
- Post-mass exchange binaries are predicted in much larger numbers. However, after evaluation of the first quarter of the *ROSAT* All-Sky Survey, Piters et al. (1992) report that only 8% of all bright Be stars have been detected. Since this fraction is nearly identical to the one for normal B stars (Piters et al. 1992), there is presently no evidence that Be stars owe their nature to a past mass exchange with what now is a white dwarf. [The number might increase if optical flares can be attributed to re-processing of X-rays (Apparao 1991).] On the other hand, Pols et al. (1991) predict that 80% of the evolved companions are helium stars. The all-sky survey with the EUV camera onboard *ROSAT* should provide a suitable data base for a test also of this prediction. The detection of numerous highly evolved companions would be interesting because observers have not so far noticed a dichotomy among Be stars.
- Regardless of binary percentages, there is no explanation how the transfer of angular momentum alone can make a Be star.

Therefore, most binary Be stars are no Be binaries. It would not surprise, however, if future work would soften this conclusion for late spectral subclasses. A new survey should not be magnitude- but volume-limited and therefore be less biased against late B-types. Its sensitivity to spectral lines of a cool companion can easily be improved by a factor 2-5 over the present one. It may also be more realistic to use as templates spectra of evolved components in Algol systems rather than of field giants. Nevertheless, the explanation of the 'Be phenomenon' should not be sought from binarity. The next hypothesis to be tested is that Be stars can maintain circumstellar disks by means of the bi-stability of a radiatively driven wind (Lamers and Pauldrach 1991) plus intrinsic, photospheric variability.

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