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Be STARS IN BINARIES

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ABSTRACT

We considered the known companions to 80 Be stars and 355 B stars listed in the *Bright Star Catalogue* in the range B1–B7 III–V and north of $\delta = -30°$. We confirm the known near-absence of Be binaries with periods less than 10^{-1} yr. For longer periods up to the limit of 10^4 AU of this survey, the Be and B stars do not differ in binary frequencies. This result implies that during pre–main-sequence contraction, the tidal braking in binaries wider than 0.5 AU was inadequate to prevent the formation of stars with nearly the break-up rotational velocities. The fraction of Be and B stars that have companions is higher in clusters and associations (38%) than among field stars (25%), confirming that escapees from clusters tend to be single stars. There is some evidence that the companions of Be stars that occur in the same luminosity range tend also to be Be stars; that result was expected because in visual binaries there is a known tendency for rapidly rotating primaries to have rapidly rotating secondaries.
Subject headings: stars: Be — stars: binaries — stars: rotation — stars: spectral classification

I. INTRODUCTION

This is a study of Be stars (B stars with hydrogen emission lines) in binary systems of all periods; it is partly relative to a concurrent study of normal B stars as a control. The study was motivated by several questions or observations: (1) Since all Be stars are rapid rotators (Slettebak 1949), are they found less frequently in binary systems, which might happen if there was extensive tidal braking of rotational velocities during the earlier stages of star formation when the protostars are dimensionally comparable to the separations within the binaries? (2) We know that there is a fair correlation in rotational velocities between members of visual multiples (Steinitz and Pyper 1970; Bernacca 1972); this would imply that the (rapidly rotating) Be stars should tend to have Be companions. Do observations confirm such a tendency for Be stars to have Be companions?

In this study we will be interested in binaries of all periods and thus discovered by all techniques: unresolved binaries, discovered spectroscopically or by means of eclipses, and resolved systems, discovered by lunar occultations, speckle interferometry, and standard visual methods. This study will be confined to stars in the *Bright Star Catalogue* (Hoffleit and Jaschek 1982) for which many data are already available and that lists the nearest Be and B stars. At least we will assume that where data are lacking, such as the lack of a sharp cutoff in apparent magnitude in the catalog or the absence of occultation data for stars outside of the declination limits of the Moon, these effects are not biased toward one group (Be or B), relative to the other.

The selection of Be and B stars for study was those in the *Bright Star Catalogue*, north of $\delta = -30°$, and between right ascensions 18^h and 8^h. Since Be stars on or near the main sequence in clusters tend to occur with absolute magnitudes $-3.8 \leq M_V \leq -0.7$ mag (Abt 1979), we considered stars (Be and B) of types B1–B7 III, IV, or V. We noted for each star the evidence for physical companions. In a few cases we had to decide whether the companions had common proper motions and whether the spectral classifications implied physical association. In three cases we searched the literature, starting with the bibliographies by Wackerling (1970) and Jaschek, Ferrer, and Jaschek (1971), to determine the reality of the reported emission. Since the *Bright Star Catalogue* calls many stars "spectroscopic binaries" on the basis of radial velocities that are variable for several reasons and includes some orbital elements of dubious validity, we decided to rely upon Batten, Fletcher, and Mann (1978) for all decisions regarding spectroscopic orbits. A small disadvantage is that orbital elements published after 1976, the closing date of the Batten *et al.* catalog, were eliminated, but probably those omissions are not biased toward the Be stars or the B star controls. This study is therefore conservative in assuming stars to be spectroscopic binaries only if they have published orbital elements of convincing quality.

For a few stars in visual systems we obtained spectra for classification to help determine whether the companions are physically associated or optical coincidences. The spectra were obtained with the Kitt Peak 2.1 m Cassegrain spectrograph. The spectra have a dispersion of 39 Å mm^{-1}, width of 1.2 mm, and resolution of 1.0 Å. They were classified on a Boller & Chivens spectra comparator against standards by Morgan, Abt, and Tapscott (1978) and other standard sources. The spectral classifications and conclusions from them are listed in Table 1.

There are 80 Be stars and 355 B stars in this study. These are listed in Tables 2 and 3. For the spectroscopic (SB1 and SB2), apsidal (APS), and visual (VB) binaries with known periods, those are listed. For the occultation (OCC), speckle (SPEC), and common proper-motion (CPM) pairs where only separations of components are available, we computed orbital periods by assuming that the current separations are their semimajor axes. Such "periods" are crude but adequate. We

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TABLE 1

NEW SPECTRAL CLASSIFICATIONS

HR	ADS	Classification	Conclusion
154B	513B	Am (K/H/M = A3/F0/F2)	Physical companion
1165B	...	A0 V	Pleiades cluster member
C	...	Am (K/H/M = A5/F0/F2)	Pleiades cluster member
D	...	F2 V	Pleiades cluster member
1497C	...	A1 V	Physical companion
1842A	4123A	B1 IV	
B	B	B1.5 V	Physical companion
1847B	4131B	B8 V	Physical companion
1863 CD	4150CD	A0 V	Physical companion
7339C	...	G5: III	Optical
7628C	...	Am (K/H/M = A2/A8/A8)	Physical companion
8146B	14831B	G8.5 V	Optical
8384A	...	B3 V	
B	...	K5 III–IV	Probably optical

TABLE 2

Be AND B STARS WITH KNOWN COMPANIONS

HR	Kind, separation, period
	Be Stars
193	CPM 33".6 (230,000 yr)
335	VB 0".047 (371.6 yr)
496	SB2 (126^d.696)
1142	SB1 (100^d.46) = OCC 0".010 (0.49 yr),
	OCC 0".062 (6.2 yr)
1165[a]	OCC 0".031 (1.2 yr)
1660	OCC 0".3 (510 yr)
1910	SB1 (132^d.91) = OCC 0".007 (0.007 yr)
2284	CPM 4".2 (38,000 yr)
2309	CPM 23".2 (170,000 yr)
2343[b]	CPM 0".2 (56 yr)
2356	CPM 7".1 (10,000 yr), CPM 2".8 (2600 yr)
	CPM 25".9 (100,000 yr)
2370	CPM 16".1 (200,000 yr)
2577	B3 IVe + K2 II
2628	CPM 0".1 (190 yr)
2745	OCC 0".098 (40 yr)
2921	CPM 5".2 (31,000 yr), CPM 19".6 (2x10^{5}yr)
7963	VB 0".777 (391.3 yr)
8047	CPM 20".1 (210,000 yr)
8153	SB1 (5^d.4136), SB1 (225^d.44), CPM 4".1
	(67,000 yr)
8260	OCC 0".0047 (0.3 yr)
8375	CPM 1".4 (3200 yr)
8603	CPM 22".4 (210,000 yr)
8762	SPEC 0".34 (75 yr)
	B Stars
91	SB1 (27^d.8), CPM 0".2 (150 yr)
154	SB2 (143^d.6065), CPM 35".2 (90,000 yr)
226	SB2 (4^d.2828)
836	SB1 (3^d.854) = OCC 0".00004 (10^{-3} yr),
	CPM 3".2 (3900 yr)
890	CPM 11".9 (21,000 yr)
927	CPM 0".2 (120 yr), CPM 5".2 (17,000 yr)
938	OCC 0".03 (18 yr)
1005	OCC 0".15 (73 yr), CPM 0".67 (690 yr)
1044	CPM 0".8 (520 yr)
1131	SB2 (4^d.4192), CPM 1".0 (1900 yr)
1140	OCC 0".0062 (0.5 yr)
1141	CPM 6".5 (14,000 yr)
1145	OCC 0".012 (0.7 yr)
1153	SB1 (2^d.4079)
1163	SB2 (1^d.9406), CPM 3".2 (20,000 yr)
1174	CPM 9".2 (27,000 yr)
1199	CPM 0".4 (210 yr)
1239	SB1 (3^d.9540), APS (33^d.025)
1240	SB1 (5^d.9537)
1243	CPM 12".0 (46,000 yr)
1462	CPM 17".5 (220,000 yr)
1497	SB2 (2^d.9565) = 0".0005 (0.006 yr), CPM
	= OCC 0".1 (16 yr), CPM 62".8 (2.6x10^5 y
1520	SB1 (7^d.3589)
1552	SB1 (9^d.5191)
1567	SB1 (3^d.700373)
1600	CPM 39".2 (230,000 yr)
1659	SB1 (58^d.31) = OCC 0".0004 (0.016 yr)
1735	CPM 36".0 (130,000 yr)
1749	SB1 (35^d.5)
1764	CPM 32".7 (290,000 yr)
1788	SB2 (7^d.9841), SPEC 0".04 (9.2 yr)
1803	SB1 (2^d.8884)
1808	OCC 0".1 (25 yr), CPM 10".1 (290,000
	yr), CPM 9".8 (200,000 yr)
1810	OCC 0".1 (46 yr)
1811	SB2 (2^d.5260), APS 44.8 yr), CPM 2".7
	(9100 yr)
1839	VB 1".293 (586 yr)
1842	CPM 1".9 (6000 yr)
1847[c]	CPM 9".6 (38,000 yr)
1861	CPM 2".0 (14,000 yr)
1863	CPM 1".8 (4800 yr)
1868	SB1 (1^d.4854)
1892	CPM 1".6 (4200 yr)
1898	CPM 4".2 (42,000 yr)
1900	CPM 1".1 (5100 yr)
1911	CPM 5".2 (53,000 yr)
1924	OCC 0".00001 (0.0001 yr)
1928	SB1 (27^d.864) = OCC 0".0003 (0.006 yr),
	CPM 0".32 (220 yr)
1944	CPM 0".6 (530 yr)
1946	VB 0".19 (78.4 yr)
1993	CPM 17".8 (190,000 yr)
2052	SB2 (7^d.9969) = OCC 0".0006 (0.031 yr)
2128	CPM 1".9 (3500 yr)
2154	CPM 28".9 (210,000 yr)
2159	SB1 (131^d.211)
2438	CPM 0".8 (1400 yr)
2522	CPM 0".7 (380 yr)

TABLE 2—*Continued*

HR	Kind, separation, period
2614	CPM 0″.2 (460 yr)
2800	CPM 8″.2 (58,000 yr)
2948	CPM 9″.9 (9500 yr)
6773[d]	SB2 (2^d.24815)
6787	CPM 23″.4 (200,000 yr)
6924	CPM 5″.5 (36,000 yr)
6946	CPM 12″.3 (100,000 yr)
7033	CPM 0″.2 (140 yr), CPM 25″.0 (170,000 y
7035	OCC 0″.04 (7.5 yr)
7131	SB1 (88^d.352)
7166	CPM 0″.4 (340 yr)
7174	SB1 (2^d.911557)
7179	CPM 19″.0 (180,000 yr)
7200	SB1 (15^d.9526)
7258	SB1 (1^d.0309)
7298	CPM 28″.3 (200,000 yr)
7466	SPEC 0″.1 (54 yr), CPM 20″.6 (140,000 y
7474	SB2 (1^d.9503)
7485	CPM 15″.3 (160,000 yr)
7486	SB1 (2^d.4968), CPM 0″.1 (34 yr)
7572	CPM 13″.5 (1500 yr)
7593	CPM 35″.7 (150,000 yr)
7607	CPM 9″.3 (48,000 yr)
7642	CPM 1″.9 (6200 yr)
7721	SB1 (5^d.7797)
7735	SB2 (3784^d.3)
7739	CPM 0″.7 (440 yr)
7777	SB2 (2^d.9847)
7844	CPM 17″.8 (160,000 yr)
7861	SB1 (5^d.3828)
7889	VB 0″.257 (122 yr) = OCC 0″.052 (18 yr)
7929	CPM 3″.0 (11,000 yr), CPM 25″.7 (270,000
8001	SB2 (2^d.854825), APS 203 yr)
8040	CPM 1″.8 (2100 yr)
8064	CPM 0″.2 (310 yr)
8107	CPM 1″.3 (4000 yr)
8238	SPEC 0″.025 (4.6 yr), CPM 13″.4 (51,000 y
8301	SB1 (26^d.33)
8335	SB1 (72^d.0162)
8357	SB2 (17^d.3263), CPM 18″.3 (83,000 yr)
8384	SB2 (2^d.9899)
8427	SB1 (2^d.1727)
8513	CPM 6″.2 (24,000 yr)
8523	SB2 (2^d.6164)
8549	CPM 4″.3 (36,000 yr)
8579	SB1 (880^d)
8606	SB2 (10^d.9188)
8768	CPM 7″.4 (80,000 yr)
8800	SB1 (3^d.3378)
8803	SB2 (7^d.2511)
8808	CPM 0″.18 (160 yr)
8887	CPM 0″.5 (570 yr)
8926	SB1 (6^d.0663), APS (1600 yr), CPM 1″.1 (1700 yr)
9011	CPM 0″.9 (2600 yr)
9071	CPM 2″.8 (11,000 yr)

[a] The distant companions B, C, and D are other members of the Pleiades cluster.
[b] Other companions are distant or optical.
[c] According to Andrews 1968, it is the rapidly rotating secondary that may have hydrogen emission, but the evidence is not convincing.
[d] The visual companion at 13″.3 is beyond the 10^4 AU limit.

imposed an upper limit of 10^4 AU on semimajor axes (corresponding to a period of $\sim 10^{5.5}$ yr), partly to avoid including all members of clusters and associations as binary companions and partly in accord with the work of Ambartsumian (1937) and Retterer and King (1982) that shows that for stars in the solar neighborhood, the maximum separations of stable binaries is $\sim 10^4$ AU. For a mean distance of the binaries of 210 pc, this limiting separation corresponds to 48″.

II. RESULTS

Of the 355 B stars, 111 have one or more companions for a total of 135 companions, or an average of 0.38 ± 0.03 companions per star. Because of incomplete data, this is a lower limit; Abt and Gomez (see Abt 1983) found 0.70 companions per B star, based on more complete spectroscopic data. But as long as our incompletenesses are the same for the Be and B stars, the conclusions should be valid. Of the 80 Be stars, 22 have a total of 28 companions, or 0.35 ± 0.07 companions per star. Thus the binary frequency of the Be stars is statistically the same as for the B stars.

The distribution of periods is shown in Figure 1 for the B stars (*solid bar graph*) and Be stars (*dots and probable error bars*). For both distributions there is a minimum between 10^{-1} and 10^2 yr, corresponding to separations of 0″.002 to 0″.2. Those periods are too long for spectroscopic measures among stars, many of which have broadened lines, and are too short for conventional visual double-star measures; this minimum is gradually being filled in by occultation and speckle techniques.

We see in Figure 1 the nearly complete absence of Be binaries with periods less than 10^{-1} yr. This is a well-known observational result (e.g., Abt 1983). This near-absence is unlikely to be an observational selection: because Be stars have broader lines than B stars, it is more difficult to detect small-amplitude Be binaries. But this difficulty should not interfer with the detection of binaries with periods less than 10^{-2} yr or even 10^{-1} yr, which have velocity amplitudes of the order of 100 km s^{-1}, although it would affect longer periods. Usually short-period binaries cannot have rapidly rotating

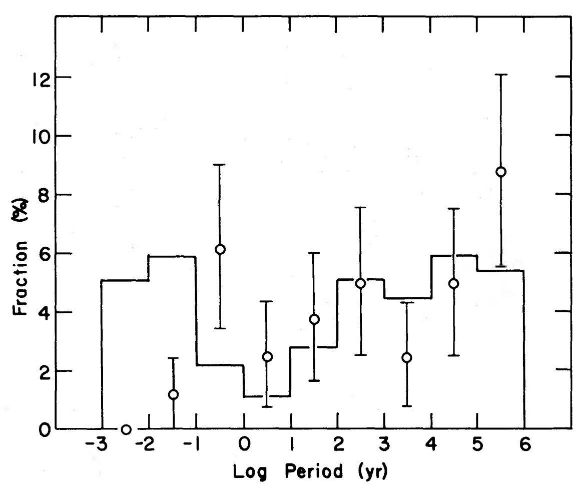

FIG. 1.—The bar graph shows the fraction of 355 B stars that have companions (spectroscopic ones with known orbital elements or occultation, speckle, or visual ones) of various periods. The circles and probable-error bars represent the fraction of 80 Be stars with companions.

TABLE 3

Be AND B STARS WITHOUT KNOWN COMPANIONS

HR	HR	HR	HR	HR	HR	HR	HR	HR	HR	HR
Be Stars	6984	8758	896	1350	1783	2199[cj]	2603	6851	7516	8136
	7084	8773	910	1363	1786	2205	2611	6941	7556	8141
985[a]	7249	9068	930	1378	1790	2213	2613	6943	7591	8144
1087	7335	9070	950	1397	1798	2222[j]	2616[l]	7073	7608	8158
1156	7403		987[c]	1399	1820	2223	2623	7081	7613	8161
1160[a]		B Stars								
1273	7554		989	1415	1833	2224[k]	2625	7100	7620	8215[c]
	7565[c]	28	1011	1420	1840	2226	2633	7115	7628	8218
1423	7647[c]	38	1029	1463	1848	2232	2640	7121	7651	8227
1508	7708[c]	39[c]	1034[c]	1469	1851	2246	2688	7171	7656	8292
1622[b]	7719	62	1037	1512	1860	2248	2695	7185	7688	8341
1679		78								
1761	7763		1047[h]	1553	1864	2266	2699[m]	7202	7700	8385
	7807	121	1072	1574	1871	2271	2704[j]	7210	7709	8397
1789	7890	144	1074	1582	1873	2273	2718	7212	7757	8403
1858	7927	153	1122[h]	1595	1875[c]	2276	2733	7262	7852	8439
1934	7983[d]	155	1146	1617	1886	2292	2774	7269	7862	8452
1961		179[c]								
2142	8053[e]		1191[i]	1640	1891	2325	2779	7279	7894	8528
	8103	189	1207	1641	1906	2344	2812	7339	7899	8553
2231	8146[f]	302	1213	1646	1913	2373[j]	2840	7347	7912	8554
2249	8171	348[g]	1215	1704	1918	2374	2841	7355	7922	8640
2648	8356[c]	533[c]	1244	1719	1923	2380	2860	7358	7940	8651
2690		561								
2749	8402		1253	1731	1933	2395	2897	7372	7996	8706
	8408	679	1258	1748	1950	2433	2928	7374	8007	8725
2817	8438	702	1288	1753	1952[c]	2490	2947	7396	8022	8733
2825[c]	8520	760	1289	1757	1962	2494	2956	7397	8029	8777
3135	8539	779	1305	1763	2031	2511	2972	7409	8036	8858
6873		801[c]								
6929	8682		1312	1765[c]	2058	2537	3004	7426	8054	9005
	8690	811	1320	1770	2161	2544	3023	7447[j]	8105	
6971	8731	847	1333[c]	1781	2198[c]	2571	6845	7471	8109	

[a] Companion probably optical.
[b] Distant companion (HR 1623) is optical.
[c] SB orbital elements are not in Batten *et al.* 1978.
[d] The companion (ADS 14350B) is optical.
[e] The companion (ADS 14549B) is probably optical.
[f] Component B in ADS 14831 is a foreground star (G8.5 V), and C does not have a common proper motion.
[g] Reported as double (0".4) but not confirmed.
[h] Visual companion B is optical.
[i] The single measurement of a 13.2 mag companion at 15".1 does not prove that it is a physical system.
[j] Only one measurement of the visual companion; is it CPM?
[k] Close companion is optical.
[l] Only two measurements in 6 yr; they are inadequate to tell whether the faint companion at 10" has a CPM.
[m] Distant companion (32".5) is optical.

components because tidal braking would tend toward synchronization during their main-sequence lifetimes. There have been suggestions (e.g., Harmanec and Kriz 1976) that most or all Be stars are close binaries surrounded by a common opaque envelope, but observational evidence for this generality is lacking.

For periods longer than 10^{-1} yr there is statistically no difference between the Be and B stars: half (4/7) of the probable-error bars intersect the distribution for B stars, and half (3/7) do not. Thus tidal braking during pre–main-sequence contraction does not prevent the occurrence of rapid rotation (up to the break-up velocities) in binary systems of any periods from 10^{-1} to 10^6 yr, or separations of 0.5 to 10^4 AU.

In starting this analysis at 18^h right ascension, we found that the first 17 Be stars had no companions! Later we noticed that the 24 B stars starting at 6^h2^m right ascension had no companions. Such sequences seem incompatible with averages of 0.35–0.38 companions per star. Since these stars are less than 900 pc distant, we are not encountering possible galactic structure effects, such as possible different binary frequencies or fractions of Be stars in different spiral arms. Instead we noticed a tendency for members of clusters and associations to have higher binary frequencies than field stars, which are escapees from clusters and associations. For stars in groups, 38% ± 5% have companions, while among field stars only 25% ± 3% have companions. In right ascensions 18^h to 20^h40^m there are few northern clusters and associations with bright-star members, and in 6^h2^m to 6^h33^m the same thing is true; that fact largely explains the sequences of single stars in those right ascensions. The tendency for escapees from clusters and associations to be single has been predicted to be true by van Albada (1968), Heggie (1975), Hills (1975), and Spitzer and Mathieu (1980).

Finally we inquire about the nature of the companions to the 22 Be stars having companions. Unfortunately in 18 cases the companions are outside the luminosity range of the Be stars or we do not know the spectral types of the companions. The four useful systems and their secondary types are HR 496 = ϕ Per (B3 Ve),[3] HR 2356 = β Mon (B3ne and B3e), HR

[3] Poeckert (1981) derived a secondary mass and spectrum, and found that the secondary is an undermassive star that may be evolved; although it has a circumstellar shell giving rise to emission lines, it may not be a typical main-sequence Be star.

7963 = λ Cyg (B7 V), and HR 8603 = 8 Lac (B1.5 Vs). That is, half of the five companions are also Be stars. For comparison we note that 80 of the 435 primaries, or 18%, are Be stars, while a search at Hα by Schild and Romanishin (1976) of stars in open clusters yielded 15% Be stars. (The low fraction of 8.8% Be stars by Abt 1979 for stars in open clusters may be because he did not look at Hα, but rather in the blue spectral region.) Thus our very small sample suggests an excess of Be companions to Be primaries, which would be consistent with the tendency of rapid rotators to have rapidly rotating companions.

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