THE ASTROPHYSICAL JOURNAL, 268:264–273, 1983 May 1

THE BINARY NATURE OF THE BARIUM STARS. II. VELOCITIES, BINARY FREQUENCY, AND PRELIMINARY ORBITS

ROBERT D. MCCLURE
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics
Received 1982 August 16; accepted 1982 October 19

ABSTRACT

A series of radial velocity observations has been obtained over the last 3 years of a sample of 20 Ba II stars. Seventeen of these (85%) are found to show long-term velocity variations ranging in amplitude from a few to tens of km s^{-1}. Thus it seems likely that all Ba II stars are binary systems. An additional Ba II star in the open cluster NGC 2420 is also found to have a variable velocity. Orbits for seven Ba II stars indicate low-mass companions, compatible with their being white dwarfs. Separations are large, about 2 AU on average. The peculiar abundances are not explained, but the fact remains that multiplicity must bear a causal relationship to these peculiarities.

Subject headings: radial velocities — stars: Ba II — stars: binaries — stars: evolution

I. INTRODUCTION

The Ba II stars are Population I giants that have enhanced abundances of *s*-process elements, and enhanced carbon (Burbidge and Burbidge 1957). They were recognized as a group by Bidelman and Keenan (1957) from their strong Sr II and Ba II lines and CH, CN, and C_2 bands. The most extensive survey of this class of star was conducted by MacConnell, Frye, and Upgren (1972), who detected over 200 Ba II stars on the Michigan Spectral Survey of the southern sky. They estimated that these stars are about 1% as frequent as normal red giants in the vicinity of the Sun, and from proper motions they concluded that the luminosities of the Ba II stars are equivalent to normal giants. Numerous estimates of the luminosities of Ba II stars based on proper motions and spectroscopic parallaxes agree with this, but it is generally believed that the range in luminosity is several magnitudes (Bidelman and Keenan 1957; Warner 1965; Baument 1974; Kemper 1975). Eggen (1972) concluded that they are old disk population objects of 1–1.5 $M_\odot$, lying somewhat above the giant branch. The Ba II star found by McClure, Forrester, and Gibson (1974) in the old disk cluster NGC 2420 confirms this for at least this one star. Culver and Ianna (1976, 1980) and Culver, Ianna, and Franz (1977) found luminosities similar to normal giants and masses between 1.7 and 3 $M_\odot$ for three Ba II stars that are members of visual binary systems.

It has been assumed generally (e.g., Warner 1965) that the peculiar abundances of the Ba II stars are due to mixing of material to their surfaces that has undergone carbon production in their interiors. Therefore this class of star should provide important information concerning the advanced stages of evolution. However, it has proven difficult to understand the structure and evolution of Ba II stars. We know how carbon and *s*-process elements can be produced and mixed to the surface in stars of intermediate mass, but not in stars of low mass ($<3\ M_\odot$) like the Ba II stars.

Recently, McClure, Fletcher, and Nemec (1980, hereafter Paper I) concluded that Ba II stars are all members of binary systems, and that the binary nature of these stars must therefore bear a causal relationship to their peculiar abundances. They suggested that the companions to the Ba II stars may be white dwarfs which originally were stars of intermediate mass that mixed and spilled some contaminated material onto the star we now see as the Ba II star. The *IUE* observations by Böhm-Vitense (1980) of the Ba II star ζ Cap, which shows excess UV light, supported this suggestion. Smith, Sneden, and Pilachowski (1980) discuss several alternative hypotheses for the production of Ba II stars, considering their abundance analysis of ζ Cap and the evidence from Paper I for multiplicity.

In Paper I, the sample of stars was divided into two groups, strong Ba II and marginal Ba II stars. Nine out of 11 of the strong Ba II stars showed velocity variations that were significantly larger than the errors of measurement. Because of the long periods involved, compared to the limited observation span, Paper I could say very little about the orbits of these binary systems. Griffin and Griffin (1980) soon published the "first ever" orbit for a Ba II star, HD 101013, and the period for this system is about 5 years. The conclusion of Paper I that *all* Ba II stars are binaries has been criticized by Culver and Ianna (1980) and regarded as speculation by Griffin and Griffin (1980). In addition, Culver and Ianna (1980) suggest that the division of the sample into strong and marginal Ba II stars in Paper I is not valid.

In the present paper more data are presented in the continuing observational program of radial velocities for Ba II stars. Several stars now have enough observations to determine orbital elements. A total of 20 Ba II stars has now been observed over a time span long enough

TABLE 1

OBSERVATIONS OF STARS OBSERVED ON Ba II PROGRAM, JD −2,440,000 AND VELOCITY (km s^{-1})

HD 11658	3906.63	3.42
	3942.70	3.77
	3943.63	3.28
	3966.67	3.26
	3970.69	3.32
	4073.96	3.29
	4085.97	3.54
	4110.94	3.40
	4141.96	4.03
	4177.91	3.52
	4191.92	3.23
	4261.65	3.21
	4298.69	3.71
	4493.82	3.10
	4606.73	2.99
	4781.90	3.45
	4870.86	3.26
	4876.89	3.13
	4935.85	3.50
	5051.68	3.20
HD 16458	3942.68	23.86
	3943.65	24.29
	3966.72	23.79
	3970.70	24.18
	4073.96	22.31
	4085.95	22.31
	4110.94	21.25
	4141.96	21.06
	4177.91	20.69
	4184.92	20.28
	4191.98	20.07
	4219.82	19.72
	4263.70	18.25
	4298.70	17.11
	4331.76	16.62
	4493.83	14.28
	4606.73	14.29
	4607.84	13.63
	4668.78	14.51
	4781.91	15.57
	4870.87	16.70
	4935.86	16.63
	5051.70	18.07
	5068.67	19.17
HD 31487	3906.66	−10.88
	3942.73	−11.68
	3943.66	−11.79
	3970.71	−9.78
	4073.97	−9.06
	4085.93	−8.21
	4110.99	−8.17
	4141.98	−6.69
	4177.92	−5.11
	4191.97	−4.78
	4263.72	−2.04
	4298.68	0.11
	4331.73	0.98
	4493.93	1.87
	4500.04	2.20
	4606.74	0.53
	4607.84	0.24
	4668.77	−1.45
	4781.91	−5.59
	4817.99	−8.32
	4876.95	−9.66
	4935.86	−10.97
	5046.68	−11.05
	5068.66	−11.09
HD 46407	3906.69	5.72
	3942.79	5.70
	3943.68	5.72
	4142.04	−12.08
	4178.05	−11.69
	4184.99	−11.11
	4187.04	−12.05
	4191.96	−11.67
	4219.93	−8.06
	4229.84	−8.15
HD 46407	4256.86	−3.57
	4263.81	−4.02
	4298.67	0.76
	4331.65	3.62
	4486.03	−1.96
	4494.05	−4.12
	4499.05	−3.88
	4606.81	−11.99
	4607.85	−11.87
	4640.87	−12.26
	4668.77	−9.31
	4683.74	−8.34
	4877.02	3.96
	4936.06	−0.93
	5046.69	−12.28
	5068.66	−12.42
HD 49641	3906.70	3.32
	3906.73	2.82
	3942.78	3.06
	3943.70	3.36
	3970.72	3.46
	4142.04	4.40
	4178.06	4.70
	4184.99	5.39
	4192.05	5.24
	4219.94	6.19
	4263.82	6.17
	4304.75	6.43
	4331.72	6.29
	4606.91	6.55
	4607.86	7.33
	4640.88	7.21
	4668.79	6.94
	4877.03	4.87
	4936.06	5.01
	5046.70	4.29
	5068.66	4.36
HD 58368	3906.82	32.32
	3943.71	33.17
	4185.00	43.65
	4192.05	44.36
	4304.77	44.19
	4331.77	42.50
	4606.92	33.46
	4607.87	32.76
	4640.85	33.63
	4668.80	34.20
	4676.84	34.24
	4712.75	35.29
	4713.71	36.12
	4877.04	44.24
	4935.07	46.42
	5046.71	38.86
	5068.75	37.29
	5083.74	36.32
HD 65854	3906.85	0.42
	3943.76	0.29
	3943.76	0.04
	3970.83	−0.43
	4185.01	1.18
	4192.07	0.21
	4304.77	0.55
	4331.78	−0.18
	4382.73	0.53
	4606.98	0.93
	4607.88	1.21
	4668.81	0.61
	4713.72	0.26
	4751.78	0.01
	4936.10	0.48
	5051.77	0.08
	5068.77	0.44
	5083.75	0.38
HD 67447	3906.75	−11.18
	3918.84	−11.08
	3942.82	−11.20
HD 67447	3943.74	−11.39
	3970.73	−11.27
	4026.73	−11.35
	4038.76	−12.06
	4178.07	−11.74
	4192.06	−12.12
	4304.75	−11.23
	4331.77	−11.66
	4382.70	−11.20
	4428.73	−11.40
	4606.98	−11.38
	4751.77	−11.99
	4877.05	−11.82
	4936.09	−11.07
	5051.77	−11.10
	5068.76	−11.32
HD 77247	3906.77	−26.38
	3906.83	−27.08
	3918.88	−25.78
	3942.84	−13.53
	3943.78	−13.03
	3970.74	−19.36
	4011.83	−20.53
	4026.74	−12.04
	4038.77	−10.90
	4178.08	−17.82
	4185.04	−13.15
	4191.99	−11.05
	4198.96	−11.51
	4219.95	−23.44
	4304.76	−25.40
	4319.81	−26.52
	4331.79	−21.80
	4352.70	−10.77
	4382.72	−25.22
	4428.72	−12.02
	4485.68	−24.92
	4499.04	−18.11
	4500.04	−17.62
	4605.96	−12.73
	4607.02	−13.15
	4607.96	−13.58
	4640.86	−26.95
	4668.81	−12.93
	4669.02	−13.46
	4676.83	−9.82
	4683.84	−11.66
	4712.76	−27.29
	4713.73	−27.32
	4751.77	−12.12
	4781.73	−22.78
	4799.71	−26.77
	4936.11	−17.97
	5051.78	−23.59
	5068.77	−14.31
	5083.78	−10.35
HD 77912	3902.97	16.12
	3906.78	15.92
	3918.91	15.82
	3942.85	15.09
	3943.79	15.73
	3970.76	15.92
	4026.73	15.86
	4038.75	15.45
	4142.05	16.65
	4178.09	15.88
	4192.10	15.59
	4304.76	15.76
	4331.84	15.49
	4352.86	15.32
	4382.70	15.33
	4428.73	15.03
	4607.03	16.16
	4751.79	15.59
	4936.11	15.30
	5051.78	15.73
	5068.80	16.16
	5083.78	15.48
HD101013	3902.96	−12.28
	3918.91	−11.88
	3942.86	−10.87
	3943.81	−11.03
	3970.80	−10.37
	4011.85	−9.69
	4026.75	−8.93
	4038.79	−8.64
	4073.73	−8.30
	4085.73	−8.20
	4110.69	−8.63
	4149.63	−8.70
	4178.09	−8.63
	4185.05	−8.46
	4192.10	−8.96
	4220.05	−8.30
	4256.95	−8.72
	4304.88	−9.54
	4319.82	−9.84
	4331.84	−9.93
	4352.71	−10.57
	4382.74	−9.95
	4428.72	−11.31
	4435.75	−11.22
	4485.67	−11.57
	4605.96	−14.39
	4607.98	−13.85
	4668.92	−14.89
	4713.77	−16.32
	4751.79	−16.63
	4781.76	−17.07
	4936.11	−18.59
	5051.79	−19.78
	5068.91	−19.94
	5105.72	−19.98
HD104979	3902.98	−32.78
	3918.95	−32.18
	3918.97	−32.38
	3942.87	−32.37
	3943.89	−32.68
	3970.81	−32.69
	4011.86	−32.74
	4026.75	−33.71
	4038.79	−32.61
	4085.74	−32.34
	4304.88	−32.41
	4331.85	−32.45
	4352.85	−32.82
	4382.75	−32.22
	4428.71	−32.39
	4607.06	−32.58
	4751.79	−32.01
	4936.12	−32.48
	5051.79	−32.23
	5068.91	−31.67
	5105.72	−32.03
HD130255	3970.90	41.19
	4305.01	41.22
	4331.94	40.76
	4352.92	41.12
	4382.84	40.59
	4668.96	41.03
	4712.98	41.41
	4751.80	40.51
	4781.75	40.29
	4799.74	41.42
	5068.92	41.10
	5105.75	41.08
HD131670	3943.00	−27.11
	3970.94	−29.93
	4305.01	−29.11
	4331.95	−29.17
	4352.93	−29.73
	4382.82	−29.57
	4668.98	−31.50
	4712.99	−30.94
	4751.81	−29.28
	4781.75	−27.85
HD131670	4799.73	−26.28
	4799.73	−26.64
	5052.04	−29.44
	5068.93	−28.50
	5105.76	−28.37
HD139195	3919.01	10.42
	3943.02	10.04
	3970.93	9.92
	4011.87	10.04
	4026.76	10.26
	4026.85	9.76
	4038.80	9.94
	4073.73	10.27
	4141.65	10.44
	4305.00	9.61
	4331.95	9.41
	4352.94	9.35
	4382.84	9.40
	4428.73	9.42
	4435.78	8.76
	4482.68	8.25
	4485.66	8.96
	4607.07	8.93
	4668.98	7.88
	4751.82	6.99
	4781.76	7.08
	4799.72	7.06
	4870.63	6.25
	5052.07	5.98
	5068.93	4.95
	5105.76	5.74
HD178717	4011.91	13.59
	4026.90	13.21
	4038.91	13.77
	4073.83	13.38
	4085.75	14.11
	4110.83	14.05
	4149.64	13.41
	4163.63	14.42
	4191.58	15.40
	4305.07	17.48
	4320.05	17.08
	4332.04	17.72
	4428.85	19.00
	4435.79	18.78
	4482.75	17.97
	4606.56	19.43
	4607.57	19.21
	4669.07	19.11
	4713.96	19.44
	4751.95	18.74
	4781.83	19.15
	4870.65	19.32
	4935.58	18.87
	5068.98	18.30
	5116.88	17.73
HD183915	4011.92	−50.36
	4026.91	−50.34
	4038.92	−49.52
	4073.84	−48.85
	4085.88	−49.33
	4110.84	−49.31
	4163.64	−49.78
	4191.59	−50.19
	4305.07	−50.12
	4332.04	−50.09
	4428.85	−50.43
	4435.79	−50.18
	4482.75	−50.46
	4606.56	−50.37
	4669.08	−50.59
	4677.06	−51.13
	4713.97	−50.65
	4751.95	−51.29
	4781.84	−51.35
	4870.65	−50.25
	4935.59	−50.97
	5068.98	−50.65
HD183915	5116.91	−51.05
HD196673	3943.07	−26.20
	4011.92	−27.66
	4026.91	−27.47
	4026.93	−27.36
	4038.92	−28.01
	4073.87	−27.79
	4085.88	−28.17
	4110.89	−28.56
	4141.86	−28.31
	4149.82	−28.09
	4173.78	−28.34
	4177.79	−29.04
	4191.75	−28.82
	4305.09	−29.04
	4332.05	−28.51
	4428.91	−28.24
	4435.80	−27.87
	4482.77	−28.19
	4499.76	−26.93
	4606.62	−27.51
	4669.07	−27.73
	4677.04	−27.74
	4751.96	−26.47
	4781.84	−26.86
	4870.75	−27.05
	4935.61	−27.14
	5052.06	−25.94
	5069.01	−26.01
HD199394	3943.05	−8.70
	3943.05	−8.39
	4011.93	−9.11
	4026.93	−8.90
	4038.93	−8.65
	4073.88	−8.63
	4085.89	−8.76
	4110.89	−8.65
	4141.88	−8.17
	4149.83	−8.36
	4173.78	−9.32
	4184.71	−8.79
	4191.77	−8.57
	4305.08	−8.95
	4428.91	−7.97
	4435.80	−8.11
	4482.78	−8.45
	4606.63	−7.36
	4677.05	−7.50
	4684.04	−7.16
	4713.98	−7.80
	4751.96	−7.19
	4781.84	−7.46
	4870.75	−6.59
	4935.62	−6.70
	5052.06	−6.63
	5069.02	−5.82
HD199939	3943.06	−37.45
	4011.94	−33.45
	4026.94	−33.03
	4038.93	−32.59
	4085.91	−34.44
	4110.90	−38.69
	4141.88	−42.36
	4149.84	−43.89
	4173.79	−46.05
	4177.80	−46.50
	4191.78	−47.53
	4305.08	−47.91
	4320.06	−47.42
	4332.04	−46.89
	4353.02	−47.36
	4428.91	−43.46
	4435.82	−43.39
	4482.79	−41.04
	4493.77	−40.31
	4499.77	−39.59
	4606.63	−32.83
	4669.05	−35.04
HD199939	4677.05	−36.58
	4684.05	−37.38
	4713.04	−41.10
	4713.98	−41.46
	4751.96	−45.80
	4781.85	−48.12
	4799.77	−47.83
	4817.98	−48.87
	4870.75	−46.84
	4935.63	−46.75
	5052.05	−41.72
	5069.02	−40.29
HD204075	4073.90	4.95
	4110.85	4.99
	4184.64	5.24
	4191.61	4.63
	4428.93	4.54
	4482.80	3.32
	4485.79	4.17
	4493.77	3.54
	4499.77	3.89
	4606.55	3.49
	4751.99	2.86
	4781.97	2.98
	4870.76	3.28
	4935.63	3.45
HD205011	4026.95	15.27
	4038.96	15.42
	4073.90	15.14
	4085.91	15.18
	4110.85	14.45
	4141.92	14.28
	4149.87	13.12
	4173.80	12.54
	4177.79	13.67
	4191.74	12.93
	4332.05	10.89
	4428.94	9.98
	4485.80	9.59
	4493.78	9.46
	4499.78	8.96
	4606.64	8.43
	4669.08	8.09
	4714.00	7.69
	4751.97	8.55
	4781.89	8.35
	4870.77	7.99
	4935.64	7.94
	5069.02	8.20
HD223617	4073.95	32.31
	4085.93	32.44
	4110.91	32.54
	4141.95	32.64
	4149.88	32.24
	4177.82	32.79
	4184.79	32.38
	4191.74	32.57
	4428.98	29.41
	4499.80	28.02
	4870.78	25.91
	4935.75	27.13
	4935.75	27.13
	4935.75	27.13
NGC2420 X	4683.80	85.19
	4713.75	83.16
	4935.98	82.25
	5068.72	78.07
	5083.76	78.46
	5116.73	76.24

that significant velocity variations can be detected if the stars are binaries with reasonably small separations. With these new data, it seems very likely that all Ba II stars must be members of binary systems, and we now have a good understanding of the nature of these systems.

II. THE STELLAR SAMPLE AND OBSERVATIONS

Several sets of data have been obtained to determine the frequency of spectroscopic binaries among the Ba II stars. First, a sample of stars included in MacConnell, Frye, and Upgren's (1972) list of certain Ba II stars was observed, supplemented by three stars that Williams (1975) suggested have enhanced barium based on a photometric index. The sample includes most of the bright ($V < 8.5$ mag) Ba II stars in the Northern Hemisphere. For comparison, a sample of 40 K giants was observed to determine the frequency of spectroscopic binaries found under similar observing techniques for normal K giants in the solar neighborhood. This sample includes all *Bright Star Cataloque* (Hoffleit 1964) K stars of luminosity class III between right ascension 13^h and 22^h, with declinations greater than 50°. The constant-velocity stars in this sample also serve the purpose of providing data on the precision of the radial velocity measurements. In addition, a sample of *IAU* standard stars has been observed, with the purpose of determining both the precision and zero point of the velocities. Finally, observations of asteroids have been used to monitor further the zero point of the instrument and provide confidence that the radial velocities reported here are not systematically in error.

The instrument used for these observations was a photoelectric radial velocity spectrometer attached to the coudé spectrograph (2.4 Å mm^{-1}) of the Dominion Astrophysical Observatory (DAO) 1.2 m telescope. This instrument, which is described in detail by Fletcher *et al.* (1982), operates under the principles of the radial velocity spectrometers developed by Griffin (1967) at Cambridge, and Griffin and Gunn (1974) at Palomar Observatory. The mask that was used was based on the spectrum of Arcturus, which matches the spectra of the Ba II stars very well. Radial velocities measured for Ba II stars with this instrument have now been obtained at approximately 1 or 2 month intervals throughout the seasons for almost 3 years, setting the binary star frequency on a firm basis, and providing orbital data for those stars with periods of less than this interval. Observations of the random sample of K giants and *IAU* standards have been made at somewhat less frequent intervals throughout the same time span under identical observing conditions.

Table 1 lists the velocity data for stars observed on the Ba II star program. Following the heading for each star, the Julian date (−2,440,000) and radial velocity (km s^{-1}) are listed. The observed radial velocities have been corrected by adding a 0.42 km s^{-1} zero point offset discussed by Fletcher *et al.* (1982) to bring the K star mask velocities onto the "DAO RVS" system described in that paper.

III. THE FREQUENCY OF SPECTROSCOPIC BINARIES

a) Random Sample of K-Giant Stars

Fletcher *et al.* (1982) discuss the accuracy of the DAO radial velocity spectrometer and conclude that the standard deviation of an observation with this instrument is slightly better than ± 0.40 km s^{-1}. Table 2 lists the mean and standard deviations for the K giants observed by the present author, from the observations of Harris and McClure (1982). Stars with standard deviations of less than 0.5 will be assumed to be constant velocity stars for the purposes of this investigation. It is quite possible that a few of these stars could have variable velocities on a longer time scale than 3 years, but this does not concern us for the comparison with Ba II stars discussed in this paper. Four of these normal giants are obvious binaries. For two of the others, HD 139669 and HD 180610, there is a general trend with Julian date,

TABLE 2

STANDARD DEVIATIONS OF VELOCITIES, K-GIANT STARS

STAR				
HD	HR	Other	σ (km s^{-1})	VARIABLE?
113092	4928	9 Dra	0.66	V?
118536	5126	...	0.31	...
123977	5302	...	0.38	...
124547	5321	4 UMi	9.03	V
127700	5430	5 UMi	0.32	...
129245	5479	...	0.31	...
131507	5552	...	0.29	...
131873	5563	β UMi	0.40	...
134493	5648	...	0.22	...
136726	5714	11 UMi	0.26	...
137759	5744	ι Dra	0.39	...
139669	5826	θ UMi	0.91	V
148293	6126	...	0.36	...
150275	6191	...	0.37	...
150449	6199	...	1.36	V
154391	6348	...	0.29	...
159966	6566	27 Dra	0.62	V?
163588	6688	ξ Dra	0.43	...
164058	6709	γ Dra	0.27	...
166207	6790	...	3.50	V
167042	6817	...	0.38	...
170693	6945	42 Dra	0.25	...
171779	6983	...	...	...
173398	7042	...	0.33	...
176524	7180	ν Dra	4.17	V
180610	7309	54 Dra	0.58	V
181276	7328	κ Cyg	0.32	...
181984	7352	τ Dra	0.38	...
184936	7448	...	0.23	...
188056	7576	20 Cyg	0.39	...
190940	7685	ρ Dra	0.29	...
191277	7701	66 Dra	0.23	...
195820	7854	...	0.22	...
196925	7908	74 Dra	0.35	...
202987	8150	...	0.33	...
206040	8275	...	0.29	...
206509	8290	...	0.21	...
206952	8317	11 Cep	0.30	...
207130	8324	...	0.26	...
209960	8426	20 Cep	0.22	...

and it is therefore likely that these are low-amplitude long-period binaries. The data are insufficient in the case of two others, HD 113092 and HD 159966, as to whether they are binaries or not. The velocities show no systematic trends in these cases. The K giant sample is discussed in more detail by Harris and McClure (1982), who conclude that, for this sample of 40 stars, six to eight, or 15%–20%, are detected binaries. This is considerably lower than the frequency of 30% quoted by Gunn and Griffin (1979) for field giant stars, but, as Harris and McClure (1982) point out, more binaries may be detected with a longer time span of observations, and also, with a statistical sample as small as 40 stars, it is not improbable that the true frequency could be as great as 30%.

b) *Radial Velocity Standard Stars*

IAU radial velocity standard stars observed with the DAO spectrometer are being discussed separately by Batten *et al.* (1982). However, the data for those stars observed by the present author, throughout the Ba II star program only, are summarized in Table 3. This table lists the standard deviations of the velocities, the number of observations, and in the final column an indication of radial velocity variability. A V indicates that the star is considered to be a binary. This indication is based on an examination of its velocity as a function of time. Four out of 12 stars are considered as binaries, and therefore the binary frequency for *IAU* standards was found to be quite similar to that for random K giants.

c) Ba II *Stars*

Classification of Ba II star anomalies based on Warner's (1965) scale have been taken from Yamashita and Norimoto (1981). On this basis, the stars will be considered in two groups. The first group contains three stars that were put on the Ba II star observing list originally but which do not show the Ba II enhancement according to Yamashita and Norimoto (1981). These stars are HD 11658, which was included in MacConnell, Frye, and Upgren's (1972) list, and HD 67447 and HD 77912, which are two of the stars from Williams's (1975) list of giants suspected of being Ba II stars on the basis of photometric observations. A summary of the data for these stars is given in Table 4. The standard deviations of their observations are similar to what is expected for the precision of the instrument, and no binaries have been detected among them. These stars will not be considered further.

TABLE 4

STANDARD DEVIATIONS OF VELOCITIES, NON-Ba II STARS

STAR HD	HR	TYPE	σ (km s^{-1})
11658	...	K0 III	0.25
67447	3182	G8 II	0.34
77912	3612	G7 II	0.39

The second group contains the rest of the stars, that have been classified as Ba1 to Ba5 on Warner's (1965) scale, and a summary of the velocity data on these stars is given in Table 5. The velocities are plotted as a function of Julian date in Figure 1 (except for those stars with orbits calculated in § IV). Those stars marked with a V in Table 5 are considered binaries. Similarly, for those with no entry in the last column of Table 5, it is clear that no evidence has been found for multiplicity. There will always be, of course, a few cases where the velocity variations are only a little larger than the precision of the instrument, and the question of multiplicity of the stars is less certain. Although the velocity variations for HD 183915, HD 196673, HD 199394, and HD 204075 are relatively small, they all show systematic trends with Julian date. A χ^2 test (Trumpler

TABLE 3

STANDARD DEVIATIONS OF VELOCITIES, *IAU* STANDARD STARS

STAR HD	HR	Other	σ (km s^{-1})	VARIABLE?
26162	1283	43 Tau	0.34	...
35410	1787	27 Ori	1.23	V
66141	3145	...	0.49	...
89449	4054	40 Leo	0.88	V
103095	4550	...	0.53	...
107328	4695	16 Vir	0.29	...
144579	...	...	0.31	...
161096	6603	β Oph	0.40	...
184467	...	...	6.12	V
186791	7525	γ Aql	0.48	...
212943	8551	35 Peg	0.42	...
223311	9014	...	1.39	V

TABLE 5

STANDARD DEVIATIONS OF VELOCITIES, Ba II STARS

STAR HD	HR	Other	TYPE	σ (km s^{-1})	VARIABLE?
16458	774	...	K0 III–Ba3	3.40	V
31487	...	...	G9 III–Ba3	4.90	V
46407	2392	...	G9 III–Ba3	6.59	V
49641	...	...	K1 III–Ba3	1.43	V
58368	...	...	G8 III–Ba2	4.89	V
65854	...	...	G8 III–Ba1	0.43	...
77247	...	...	G5 III–Ba1	6.38	V
101013	4474	...	K0 III–Ba3	3.89	V
104979	4608	o Vir	G8 III–Ba1	0.40	...
130255	...	...	G4 IV–Ba1	0.36	...
131670	...	...	G7 III–Ba1	1.47	V
139195	5802	16 Ser	K0 III–Ba1	1.63	V
178717	...	...	K3 II –Ba5	2.44	V
183915	...	...	G8 III–Ba3	0.64	V
196673	...	...	K0 III–Ba1	0.86	V
199394	...	...	G8 III–Ba2	0.90	V
199939	...	...	K0 III–Ba4	5.22	V
204075	8204	ζ Cap	G5 II –Ba3	0.79	V
205011	...	...	G9 III–Ba2	2.92	V
223617	...	...	G9 III–Ba2	2.40	V

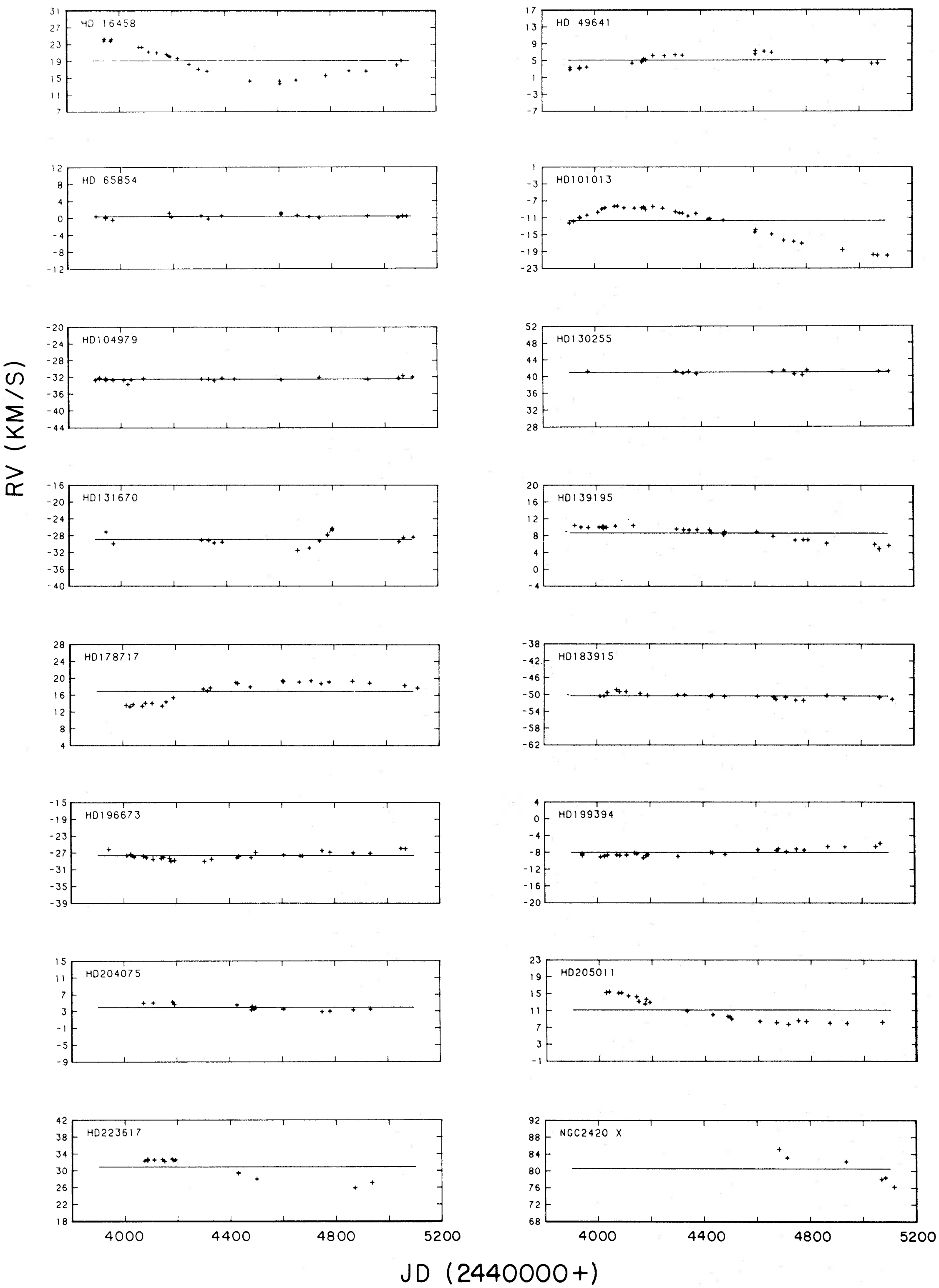

FIG. 1.—Velocities as a function of Julian Date for Ba II stars. The horizontal line indicates the mean of the velocities measured over this interval.

and Weaver 1953) on all four of these stars indicates that the hypothesis that they are not variable must be rejected at a level of significance of 0.001, given the precision of the instrument to be $\sigma = \pm 0.40$ (Fletcher *et al.* 1982). There is no reason to expect the latter value to be an underestimate for the Ba II stars which are strong lined, quite bright, and observed in the same way as all other stars used in determining the instrumental precision. In addition, the velocities of these four stars show systematic variations with time rather than just random scatter. It is highly unlikely that there are systematic errors as a function of time due to the spectrograph, because of the many non-variable velocity stars that have been observed under identical conditions on the same nights. Also, the trends in velocity with time do not go systematically in one direction for the four stars. Finally, Culver (1981) has presented an orbit for one of these four stars, HD 204075, at a recent meeting of the American Astronomical Society. Therefore, it seems safe to conclude that these four stars are variable velocity stars, and of the 20 Ba II stars in the sample, variations have been detected in the velocities of 17, or 85%. Since the periods of some are very long relative to the time span of the observations (for example, HD 101013 has a period 1.5 times longer than the time span of the present observations [Griffin and Griffin 1980]), a few binaries may escape detection. It seems likely, therefore, that all Ba II stars are members of binary systems.

There appears to be no obvious correlation of velocity amplitude with barium line strength. However, it is interesting that of the three stars for which no variations were detected, all are classed as Ba1, the weakest barium class. In addition, two of the K giants from Table 2, HD 127700 and HD 131873, are mild barium stars (Griffin 1982*b*; Keenan and Pitts 1980), and they exhibit no velocity variations. Several more years of observations are needed to determine whether all these stars are single, or have longer term velocity variations. Even so, Griffin (1982*a*) has suggested that most marginal Ba II stars seem to be binaries. In the present study we now find that more than half the Warner (1965) class Ba1 stars have variable velocities, and in addition one of the velocity variables in the K giant sample of Table 2, HD 176524, is classified as a mild Ba II star by Keenan and Pitts (1980). Clearly, a longer term detailed study needs to be done to classify the marginal Ba II stars and to determine their binary frequency in order to determine whether or not a second mechanism must be invoked for them as suggested by Sneden, Lambert, and Pilachowski (1981).

IV. ORBITS

Because of the long periods for most Ba II star velocity variations relative to the 3 years that observations have been made, orbits for only a few of the stars can be computed, and most of these must be considered preliminary. With these orbits, however, a good estimate can be made concerning the nature of these binary systems as a class, so that this exercise is worthwhile at this time. Relatively good orbits can be computed for four of the stars, HD 46407, HD 58368, HD 77247, and HD 199939, which have the shortest periods. For one other star, HD 31487, the observations have barely completed one cycle, but an orbit can be computed with some confidence. The elements for these orbits are listed in Table 6, and the orbits are plotted in Figure 2. Several spectroscopic binary computer codes available at DAO were used in these computations. Phases and residuals from the orbit solutions are listed for the individual observations in Table 7. For two other stars, HD 101013 and HD 204075, orbits have been published by Griffin and Griffin (1980) and Culver (1981), respectively.

V. DISCUSSION

From examination of orbits in § IV, two characteristics are obvious. First, the secondary masses are quite small. If one were to assume that the primaries were 1.5 $M_\odot$ (see § I for a discussion), then the secondary minimum masses, $m_2 \sin^3 i$, would be in the range of 0.2–0.6 $M_\odot$. It seems reasonable that the secondaries of the Ba II binary systems could be white dwarfs, as suggested by the ultraviolet excess observed for the Ba II star ζ Cap (HD 204075) by Böhm-Vitense (1980).

Second, the separations of the binary components

TABLE 6

Orbital Elements for Ba II Stars

Star	P (days)	V_0 (km s^{-1})	K (km s^{-1})	e	ω	T (JD 2,440,000+)	rms Residual (km s^{-1})	$f(m)$
HD 31487	1051 ± 18	−4.28 ± 0.13	6.98 ± 0.12	0.044 ± 0.028	193° ± 23°	3978 ± 64	0.40	0.037
HD 46407	457.7 ± 2.7	−3.30 ± 0.13	9.12 ± 0.15	0.0	...	4380.2 ± 1.3	0.49	0.036
HD 58368	679 ± 5	37.95 ± 0.10	6.94 ± 0.16	0.234 ± 0.020	27.°1 ± 6.°5	4286.0 ± 9.3	0.30	0.022
HD 77247	80.54 ± 0.03	−19.42 ± 0.05	8.45 ± 0.07	0.094 ± 0.009	33.°7 ± 5.°3	4040.3 ± 1.2	0.31	0.005
HD 101013[a]	1707 ± 9	−13.71 ± 0.10	6.08 ± 0.12	0.196 ± 0.019	301° ± 7°	2240 ± 30	0.7	0.037
HD 199939	581.4 ± 1.8	−42.00 ± 0.08	8.00 ± 0.12	0.292 ± 0.013	49.°6 ± 2.°5	4670.7 ± 3.6	0.42	0.027
HD 204075[b]	2300	1.8	3.7	0.33	...	...	...	0.011

[a] From Griffin and Griffin 1980.
[b] From Culver 1981.

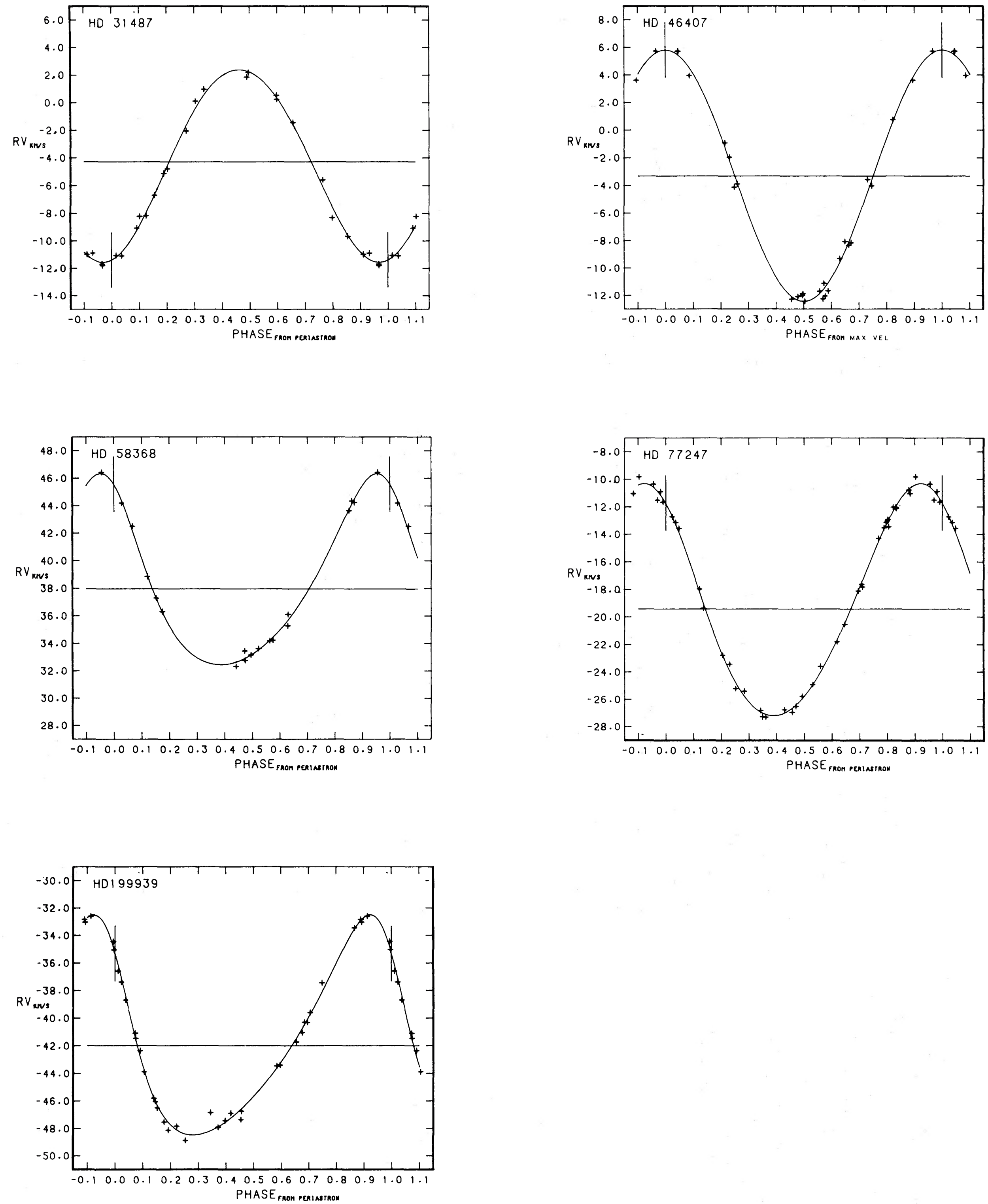

FIG. 2.—Computed orbits for Ba II stars (*solid curves*) from the elements listed in Table 6. The observed velocities from which these orbits were calculated are also plotted.

TABLE 7

EPHEMERIDES FOR ORBITAL SOLUTIONS

HD31487

JD (+2440000)	RV (km s^{-1})	(O-C) (km s^{-1})	Phase
3906.66	-10.88	0.47	0.932
3942.73	-11.68	-0.13	0.966
3943.66	-11.79	-0.24	0.967
4073.97	-9.06	0.16	0.091
4085.93	-8.21	0.60	0.102
4110.99	-8.17	-0.30	0.126
4141.98	-6.69	-0.08	0.156
4177.92	-5.11	-0.02	0.190
4191.97	-4.78	-0.29	0.203
4263.72	-2.04	-0.45	0.271
4298.68	0.11	0.49	0.305
4331.73	0.98	0.38	0.336
4493.93	1.87	-0.43	0.490
4500.04	2.20	-0.06	0.496
4606.74	0.53	0.18	0.598
4607.84	0.24	-0.08	0.599
4668.77	-1.45	0.18	0.657
4781.91	-5.59	0.53	0.764
4817.99	-8.32	-0.76	0.798
4876.95	-9.66	-0.05	0.854
4935.86	-10.97	0.06	0.910
5046.68	-11.05	0.12	0.016
5068.66	-11.09	-0.31	0.037

HD46407

JD (-2440000)	RV (km s^{-1})	(O-C) (km s^{-1})	Phase
3906.69	5.72	0.13	0.965
3942.79	5.70	0.25	0.044
3943.68	5.72	0.30	0.046
4142.04	-12.08	0.29	0.480
4178.05	-11.69	0.15	0.558
4184.99	-11.11	0.38	0.573
4187.04	-12.05	-0.68	0.578
4191.96	-11.67	-0.61	0.589
4219.93	-8.06	0.63	0.650
4229.84	-8.15	-0.51	0.671
4256.86	-3.57	0.87	0.730
4263.81	-4.02	-0.45	0.746
4298.67	0.76	0.10	0.822
4331.65	3.62	-0.23	0.894
4486.03	-1.96	0.29	0.231
4494.05	-4.12	-0.87	0.249
4499.05	-3.88	0.00	0.260
4606.81	-11.99	0.45	0.495
4607.85	-11.87	0.57	0.497
4640.87	-12.26	-0.68	0.570
4668.77	-9.31	0.23	0.631
4683.74	-8.34	-0.29	0.663
4877.02	3.96	-0.55	0.086
4936.06	-0.93	0.38	0.215
5046.69	-12.28	-0.18	0.456
5068.66	-12.42	0.02	0.504

HD58368

JD (-2440000)	RV (km s^{-1})	(O-C) (km s^{-1})	Phase
3906.82	32.32	-0.32	0.441
3943.71	33.17	0.01	0.496
4185.00	43.65	-0.05	0.851
4192.05	44.36	0.25	0.862
4304.77	44.19	-0.24	0.028
4331.77	42.50	0.29	0.067
4606.92	33.46	0.56	0.473
4607.87	32.76	-0.16	0.474
4640.85	33.63	0.10	0.523
4668.80	34.20	-0.03	0.564
4676.84	34.24	-0.22	0.576
4712.75	35.29	-0.37	0.629
4713.71	36.12	0.42	0.630
4877.04	44.24	-0.22	0.871
4935.07	46.42	0.09	0.956
5046.71	38.86	-0.15	0.121
5068.75	37.29	0.00	0.153
5083.74	36.32	0.04	0.175

HD77247

JD (-2440000)	RV (km s^{-1})	(O-C) (km s^{-1})	Phase
3906.80	-26.83	0.10	0.342
3918.88	-25.78	0.19	0.492
3942.84	-13.53	0.11	0.790
3943.78	-13.03	0.11	0.801
3970.74	-19.36	-0.38	0.136
4011.83	-20.53	-0.07	0.646
4026.74	-12.04	-0.04	0.831
4038.77	-10.90	0.22	0.981
4178.08	-17.82	-0.44	0.711
4185.04	-13.15	0.18	0.797
4191.99	-11.05	-0.41	0.883
4198.96	-11.51	-0.67	0.970
4219.95	-23.44	0.45	0.230
4304.76	-25.40	0.36	0.283
4319.81	-26.52	-0.10	0.470
4331.79	-21.80	-0.13	0.619
4352.70	-10.77	-0.04	0.879
4382.72	-25.22	-0.50	0.252
4428.72	-12.02	0.30	0.823
4485.68	-24.92	0.05	0.530
4499.04	-18.11	0.00	0.696
4500.04	-17.62	-0.12	0.708
4605.96	-12.73	-0.07	0.023
4607.02	-13.15	0.13	0.036
4607.96	-13.58	0.29	0.048
4640.86	-26.95	-0.29	0.457
4668.81	-12.93	0.12	0.804
4669.02	-13.46	-0.51	0.806
4676.83	-9.82	0.57	0.903
4683.84	-11.66	-0.26	0.990
4712.76	-27.29	-0.28	0.349
4713.73	-27.32	-0.21	0.361
4751.77	-12.12	-0.19	0.834
4781.73	-22.78	-0.01	0.206
4799.71	-26.77	0.24	0.429
4936.11	-17.97	0.19	0.122
5051.78	-23.59	0.45	0.559
5068.77	-14.31	0.23	0.770
5083.78	-10.35	0.23	0.956

HD199939

JD (-2440000)	RV (km s^{-1})	(O-C) (km s^{-1})	Phase
3943.06	-37.45	0.64	0.748
4011.94	-33.45	0.07	0.867
4026.94	-33.03	-0.20	0.893
4038.93	-32.59	-0.06	0.913
4085.91	-34.44	0.45	0.994
4110.90	-38.69	-0.30	0.037
4141.88	-42.36	0.49	0.090
4149.84	-43.89	-0.08	0.104
4173.79	-46.05	0.01	0.145
4177.80	-46.50	-0.15	0.152
4191.78	-47.53	-0.35	0.176
4305.08	-47.91	-0.03	0.371
4320.06	-47.42	0.12	0.397
4332.04	-46.89	0.34	0.417
4353.02	-47.36	-0.76	0.454
4428.91	-43.46	0.12	0.584
4435.82	-43.39	-0.14	0.596
4482.79	-41.04	-0.32	0.677
4493.77	-40.31	-0.25	0.696
4499.77	-39.59	0.10	0.706
4606.63	-32.83	0.06	0.890
4669.05	-35.04	0.06	0.997
4677.05	-36.58	-0.43	0.011
4684.05	-37.38	-0.23	0.023
4713.04	-41.10	0.39	0.073
4713.98	-41.46	0.16	0.074
4751.96	-45.80	0.01	0.140
4781.85	-48.12	-0.55	0.191
4799.77	-47.83	0.30	0.222
4817.98	-48.87	-0.46	0.253
4870.75	-46.84	1.33	0.344
4935.63	-46.75	-0.19	0.456
5052.05	-41.72	-0.30	0.656
5069.02	-40.29	0.14	0.685

appear to be quite large. The minimum separations ($a_1 + a_2$) range from 0.12 to 1.9 AU, but the actual separations are likely to be considerably larger than these. Not only will they be increased by $(\sin i)^{-1}$, but also a_2 will be larger than a_1 by the ratio of the masses m_1/m_2. If we assume 1.5 $M_\odot$ for the primaries on the average, and a sin i of 0.85, then taking the mean mass function $f(m_1) = 0.022$, a typical mass ratio of $m_1/m_2 =$ 3.0 results, and $m_2 = 0.5\ M_\odot$. Also, a typical separation $a_1 + a_2 = 2$ AU results.

The large separation, and the low mass of the secondary component of such a system, make it difficult to imagine that the secondary can have a large enough gravitational effect on the primary to affect its interior structure to induce mixing. One the other hand, stars do grow to AUs in size during their giant branch evolution, and mass transfer to the present primary would be possible from a former giant that has since evolved to become a white dwarf. This is especially true for stars of several solar masses or more, which reach larger sizes. As discussed by Iben and Truran (1978), models for these intermediate-mass stars are shown to mix *s*-process elements to their surfaces, so that it would appear that this evolution and mass transfer in a binary system should be an explanation for the Ba II star phenomenon. The *s*-process elements are produced in intermediate-mass stars in solar system proportions, however, whereas the Ba II stars are found to have Ba/(Sr, Y, Zr) abundance ratios which can be well in excess of the solar system value (Scalo 1976; Scalo and Miller 1979; Truran 1981). In addition, the ^{22}Ne(α,n)^{25}Mg reaction, which is the source of neutrons for the *s*-process in intermediate-mass stars, should also result in a large overabundance of ^{25}Mg and ^{26}Mg relative to ^{24}Mg as pointed out by Scalo (1978), but Tomkin and Lambert (1979) find normal isotopic abundances of Mg in the Ba II star HR 774. These results imply that the *s*-process elements in Ba II stars were produced in *low*-mass ($<3\ M_\odot$) stars where the ^{13}C(α,n)^{16}O reaction is the neutron source, but where the mixing event that can bring the contaminated material to the surface is not understood.

Since low-mass stars do not reach as large a size, and models do not show mixing of *s*-process elements to the surface, it seems that the binary star characteristics still do not explain the peculiar abundances of the Ba II stars in this way. On the other hand, when a class of stars is found to be made up completely of binary systems, there must be some causal connection, and the theory must invoke multiplicity in some way to explain the peculiar abundances in these systems. The two possible explanations for the Ba II star phenomenon are (1) the present Ba II star has mixed contaminated material to its surface, the mixing being caused in some way by the presence of a companion, or (2) the contaminating material has been dredged up from the interior of the companion star and dumped onto the present Ba II star in a process of binary mass exchange. Detailed theoretical models are needed to determine which of these possible processes are at work. In regard to the first explanation, if Ba II stars are second-ascent giant branch stars, they possibly could have gained angular momentum from their companions during their lifetimes near the tip of the giant branch when they had relatively large radii compared with their orbital separations. Perhaps this angular momentum could then cause the *s*-process material in their interiors to be mixed to the surface, a mixing event that does not occur normally. In regard to the second explanation, if the separation of components in such a binary system is not too large for significant mass exchange, the restructuring of the atmosphere of the mass-losing component perhaps causes carbon and *s*-process material to emerge. If this material is rich enough in the contaminating elements, it could after mass exchange cause the star we now see to exhibit Ba II star characteristics.

I would like to thank Murray Fletcher for help in the operation of the radial velocity spectrometer with which these observations were made, and Murray Fletcher, Graham Hill, Phil Massey, and Chris Morbey for use of their spectroscopic binary codes. I also thank Robert Kraft for a stimulating discussion concerning possible mixing events for the Ba II stars, Linda Stryker, and Roger Griffin the referee for numerous comments on this paper.

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R. D. McClure: Dominion Astrophysical Observatory, 5071 W. Saanich Road, Victoria, B.C., Canada, V8X 4M6