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KINEMATIC AND SPATIAL DISTRIBUTIONS OF BARIUM STARS: ARE THE BARIUM STARS AND Am STARS RELATED?

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ABSTRACT

From kinematic and spatial distribution analyses, barium stars appear to be disk objects of intermediate age (2.4×10^9 yr) with masses $\approx 1.5\,\mathscr{M}_\odot$, although the formal errors indicate that the mean kinematic age could be as young as 5×10^8 yr (corresponding to a mean mass of around $2.4\,\mathscr{M}_\odot$) or as old as 4.2×10^9 yr (corresponding to a mean mass of around $1.2\,\mathscr{M}_\odot$). The distribution also appears to indicate a range of ages in which the younger stars are overrepresented. These characteristics imply that barium star precursors are main-sequence stars of intermediate mass, and are most likely A and/or F dwarfs. Based upon their ages, long-period binary nature, lack of complete orbital circularization, and true mass function, it would appear that barium star precursors are intermediate-mass binaries with close to intermediate orbital separations. Age, binarity, and orbital characteristics capable of satisfying subsequent mass-transfer models place restrictions on the number of suspected progenitors. Since most A and early F binaries that are close enough to undergo mass transfer without completely circularizing their orbits are metallic-line A (or Am) stars, the suggestion is made that these might be barium star progenitors. Orbital parameters, mass ratios, spatial densities, and other characteristics of both types of systems indicate that such an evolution is reasonable, and it is possible that mass transfer might play a role in the later development of Am systems. The same mechanism is not necessarily responsible for the peculiar elemental abundances found in atmospheres of each stellar type. These appear to have been brought to the surfaces of the slowly rotating Am primaries (and/or secondaries) via diffusion from tidal interactions and/or evolutionary expansion, whereas the barium stars may have been enriched through mass transfer in a binary system, post-main-sequence stellar evolution, or through some combination of these. However, exact details of such an evolutionary sequence are unknown. Mass transfer and loss from systems with a range of masses and orbital separations might explain many statistical peculiarities of barium stars such as (1) a large dispersion in absolute magnitude, (2) a large range of elemental abundances from star to star, and (3) a small number of stars with large peculiar velocities. Kinematic and spatial distributions, along with binary incidence, imply that the R carbon stars and carbon-rich Miras probably do not share an evolutionary relationship with the barium stars. Some (or perhaps all) of the S stars might be evolutionarily related. The N carbon stars might represent an early post-main-sequence evolutionary phase of barium star evolution through a mass-transfer model, but binary incidence and any binary system characteristics of N carbon stars have yet to be established.

I. INTRODUCTION

The classical barium stars (or Ba II stars) are G and K post-main-sequence stars (Bidelman and Keenan 1951) which show enhanced optical lines of *s*-process elements (particularly Ba II at $\lambda\,4554$ and Sr II at $\lambda\,4216$), as well as bands of CH, CN, and C_2, and an unexplained broadband depression around 4000 Å (Bond and Neff 1969). It is convenient to subclassify them by "barium intensity" (Warner 1965), which indicates the $\lambda\,4554$ Ba II absorption-line strength (5 = strongest to 1 = weakest). This scheme has been extended to "marginal," "mild," and other barium-weak stars whose barium intensities are less than one (e.g., Keenan and Pitts 1980).

The rare earths are thought to be produced through slow neutron capture (*s*-process) during post-main-sequence burning (Cameron 1955; Burbidge *et al.* 1957) using iron-peak elements as the "seed" nuclei. The exact source of neutrons and the evolutionary stage during which the production of *s*-process elements occurs are unknown at present, but would depend upon the mass of the barium star within which they are produced (if this model is correct).

The mechanism responsible for bringing *s*-process elements to the surface of a barium star is also unknown, but low amounts of the short-lived technetium isotope ^{99}Tc (Little-Marenin and Little 1986) suggest that events leading to the upheaval of heavy elements are not generally recent or ongoing.

Barium stars appear to comprise only a small fraction of normal G and K post-main-sequence stars, implying that few stars evolve into barium stars or that many stars spend relatively small fractions of their post-main-sequence lifetimes as barium stars. The latter hypothesis, however, appears to be excluded on the grounds that all barium stars likely belong to binary systems (McClure *et al.* 1980; McClure 1983). Low-amplitude radial-velocity variations coupled with relatively long orbital periods (1–5 yr) indicate mass ratios of about 3:1 for barium star systems. Marginal barium stars are possibly binaries with longer periods (Warner 1965; Griffin 1982). Some models suggest that the binarity causes an increase in depth of the convective zone base through tidal stirring, post-main-sequence mass loss, or a combination of these. No evidence of this hot-bottom convection has been found, however, from isotopic oxygen abundances (Harris *et al.* 1985).

Another mechanism used to explain the peculiar atmospheric abundances is mass transfer in a binary system. In this model, the evolved primary expands to fill its Roche lobe and dumps much of its mass through the inner Lagrangian point onto the secondary (McClure 1983), or through a stellar wind preceding or accompanying planetary nebula formation (Boffin and Jorissen 1988). The secondary becomes more massive and is enriched by *s*-process elements presumably formed during the more rapid primary evolution. The remaining core of the evolved star becomes a white dwarf, while the secondary evolves into a giant with enhanced *s*-process elements.

Much evidence supportive of a mass-transfer model exists to date. Webbink (1986) observed that average orbital eccentricities for seven barium star systems are slightly less than those of normal G and K giant systems, indicating that at least some orbital dissipation has occurred (which is suggestive of Roche lobe overflow). McClure (1989) has found that the true mass function of barium stars indicates that the masses of barium star companions are highly correlated with those of the barium stars (which is also suggestive of Roche lobe overflow). Böhm-Vitense *et al.* (1984) found four marginal barium stars to have ultraviolet excess indicative of white dwarf companions, as well as indirect evidence suggesting that three other systems also contain white dwarf companions (other barium stars, including the luminous barium star ζ Cap, are known to have or are suspected of having white dwarf companions). A few barium stars also exhibit 10 μm excesses suggestive of weak circumstellar dust shells (Hakkila 1988; Hakkila 1989), which might be remnants of recent mass transfer. The ultraviolet excesses (which are attributed to white dwarf companions) and the 10 μm excesses do not appear to be atmospheric in nature (Hakkila 1989), whereas several other broadband peculiarities apparently are. These features (Catchpole *et al.* 1977; Feast and Catchpole 1977; Lü and Sawyer 1979; Lü *et al.* 1983; Hakkila and McNamara 1987), like the Bond–Neff depression, are most likely due to atmospheric line blanketing (Luck and Bond 1982).

The peculiar elemental abundances and binary natures of barium stars supply a starting point from which a search for evolutionary counterparts may begin. It has been suggested recently that evolution of the barium stars may be related to evolution of the S stars, based on binarity (Jorissen and Mayor 1988), or perhaps only to that of the Tc-poor MS and S stars (Smith and Lambert 1988). The SC and CS stars suggest a transition between the S stars and the cool (N) carbon stars based upon spectroscopic characteristics, and it has been suggested that barium stars evolve via mass transfer from binary systems in which the more massive component was an N star (Lambert 1988). A relationship between barium stars and the hot (R0–R4) carbon stars is doubtful, as only a small fraction of these appear to be radial-velocity variables and hence binaries (McClure 1989). The unknown incidence of binarity among the R5–R9 and the N carbon stars makes it difficult to ascertain whether or not these stars are directly related to barium stars. Main-sequence progenitors of the barium stars are unknown.

II. STATISTICAL INDICATORS OF BARIUM STAR AGES

One recurrent problem in modeling barium stars is that their masses and ages are not well determined. Masses of few individual binary barium stars have been calculated from detailed studies, while statistical age-determination methods are inhibited by problems such as inhomogeneous spectral classification, difficulties in determining individual absolute magnitudes, and incomplete sky coverage. Statistical studies in the past have indicated that barium star masses lie somewhere between those of young and old disk stellar populations, and it is generally agreed upon that they have masses less than 4.0 $\mathcal{M}_\odot$.

a) Kinematics

The kinematics of any stellar type can help identify the range of stellar ages and/or masses. The solar motion with respect to the group and the residual velocity distribution yield information about the age and spatial distribution of the sample.

Barium star kinematics have been studied by other authors (e.g., Eggen 1972; Williams 1975; Catchpole *et al.* 1977; Holtzer 1985). However, two important problems make this technique ongoing rather than definitive: (1) accurate spectral classification of barium star candidates is needed to update and extend the sparse existing list of these objects, and (2) individual barium star absolute magnitudes are needed to convert proper motions into accurate tangential velocities. Both problems arise because enhancement of *s*-process elements can be confused with luminosity effects at low dispersion (Warner 1965), leading to misclassification between barium-weak stars, normal K giants, and Population II CH stars. Additionally, barium star absolute magnitudes are found to extend from luminosity class Ib to luminosity class IV (Lü *et al.* 1983; Hakkila 1986), indicating an intrinsic dispersion in absolute magnitude of $\sigma \geqslant 1.2$ mag (Jaschek *et al.* 1985; Hakkila 1987). The absolute-magnitude estimate for an individual barium star must be obtained with extreme caution, and is difficult to do accurately using MK classification criteria.

The stars used in this study have been chosen so as to minimize errors arising from both of these problems. Most have been taken from the second-generation catalog of Lü *et al.* (1983), who reclassified stars from previous catalogs (finding that some had been misclassified) and attempted to homogenize the dataset. Other stars have been added from recent papers of Bidelman (1981, 1983, 1985). There are 261 stars in the combined list.

Proper motions are from the AGK3 (1975) and Yale Zone catalogs (1960–1983) when possible, and from the SAO (1966) otherwise. There are 231 stars with identified proper motions.

Radial velocities are from Catchpole *et al.* (1977), McClure (1983), and Abt and Biggs (1972). Many of the 114 stars with known radial velocities have only been observed a few times. This should not complicate the kinematic results significantly, even though barium stars are all suspected binaries, because the long orbital periods observed in barium star systems will only lead to a small deviation from each system's mean velocity.

Absolute magnitudes have been obtained for only a few barium stars using trigonometric parallaxes. Other methods that have been employed for individual stars include Hα absorption-line widths (Kemper 1975), K line emission reversals (Warner 1965; Eggen 1972), open cluster membership (McClure 1973; McClure *et al.* 1974), and membership in moving groups (Eggen 1972). For this study, the number of stars with absolute magnitudes found in some nonstatistical manner is 44, of which only 32 have observed radial velocities and proper motions.

The compilation of barium stars with associated proper motions, radial velocities, and absolute magnitudes is shown in Table I. The limited number of barium stars precludes examining their stellar statistics as functions of spectral type

TABLE I. Barium star values used in this study. Barium stars with spectral types, positions, and barium intensities are taken from the catalog of Lü *et al.* (1983, referred to as LDUW) and the lists of Bidelman (1981, 1983, 1985). Proper motions in right ascension and declination are given in seconds/year and arcseconds/year, respectively. Sources are the AGK3 (A), the Yale Zone (Y), and the SAO (S) catalogs. Radial velocities are given in km/s, and their sources are M = McClure (1983), C = Catchpole *et al.* (1977), and O = Abt and Biggs (1972). Absolute magnitudes are obtained using a variety of methods, which are referenced in the text.

Stardesig.	Sp	Ba	α(h,m)	δ(°,')	m_V	pmα	pmδ	pmS	RV	RVS	M_V	M_VS
HD 218	K5	3	00 01.8	-71 09	8.0	.0020	.006	Y				
HD 749	K0		00 06.6	-50 13	8.1	.0025	-.058	Y				
HD 4084	K2	3	00 38.1	-56 24	8.62	-.0013	-.019	S	-2.5	C		
+38 118	K2	5	00 44.5	38 43	10.2	-.0004	.001	A			+2.9	Hα
HD 5322	K1	1	00 49.9	-57 57	7.4	.0005	.005	S				
HD 5395	K2	2	00 50.7	58 38	4.66	-.0120	-.036	A	-47.0	O		
HD 5424	K1	4	00 50.9	-28 26	9.48	-.0015	-.055	Y	5.7	C		
HD 5825	K0	2	00 54.7	-35 11	7.66	-.0002	.025	Y	8.5	C		
+39 263	K0		01 02.4	40 08	8.43	.0031	-.001	A				
+32 247	K0		01 19.1	32 30	9.13	.0008	-.003	A				
-38 585	K2	2	01 37.1	-38 20	10.02				25.0	C		
HD 10613	K1	2	01 38.4	-38 31	9.59	.0066	.017	Y	85.0	C		
HD 11026:	G5		01 43.2	43 14	8.6	.0018	.000	A				
HD 11544	G5		01 51.6	56 20	7.0	.0010	-.016	A	-26.6	O		
HD 11658	K2	1	01 49.3	51 11	7.2	.0098	-.017	A	3.4	M	+3.0	Hα
HD 12392	K5		01 56.4	-05 17	8.9	-.0023	-.016	Y				
HD 13551	F6	1	02 07.1	-61 14	9.5	-.0050	.019	S				
HD 13787:	K0		02 09.2	38 41	8.1	-.0003	-.008	A				
HD 14585	G5		02 16.3	37 15	8.0	.0016	.008	A				
HD 15589	K0	3	02 25.3	-36 35	8.92	.0014	-.071	Y	65.0	C		
HD 16458	K1	5	02 33.4	81 01	5.76	.0094	-.056	A	19.1	M	+1.5	trig
HD 17067	K5		02 39.3	-04 56	8.70	.0008	.015	Y				
HD 17939:	G5		02 47.9	35 38	8.7	.0013	.001	A				
HD 18182	K0	1	02 50.1	-04 43	8.95	-.0005	-.011	Y				
HD 18361	K4	1	02 51.9	-24 43	8.5	-.0009	-.011	Y				
HD 18379	K2		02 52.1	49 07	8.6	-.0005	.007	A				
HD 18418:	K0		02 52.5	38 00	7.4	.0003	-.003	A				
HD 19014	K4	5	02 58.4	-85 34	8.18	-.0059	.006	Y	21.0	O		
-15 564	K0	2	03 10.5	-14 51	10.39				70.8	O		
HD 20394	K0	4	03 11.7	01 59	8.72	-.0007	.014	A			+0.3	Hα
HD 21682	K0	1	03 24.8	-44 00	9.0	.0003	.034	Y				
HD 21989	K1	2	03 27.5	-64 18	8.15	.0009	-.014	S	9.8	C		
HD 22285	G8	2	03 30.1	-35 08	8.78	.0000	-.006	Y	-8.6	C		
HD 22589	G5	1	03 33.0	-07 18	9.00	-.0003	-.054	Y				
HD 22772	K2	2	03 34.5	-68 11	8.69	.0013	-.039	Y	13.3	C		
HD 24035	K4	4	03 44.6	-72 55	8.48	.0006	.002	Y	-10.4	C		
HD 24286	K0		03 46.8	36 31	8.5	.0002	-.006	A				
HD 26886	G8	1	04 09.9	-01 15	7.97	.0012	-.030	A				
HD 27271	G8	1	04 13.3	02 13	7.49	-.0011	-.077	A				
-18 821	K0		04 18.0	-18 10	9.46	-.0011	.002	Y				
HD 29370	K2	3	04 32.4	-42 12	9.30	.0010	-.000	Y	16.0	O		
HD 29685	K1	1	04 35.4	-30 48	8.91	-.0005	-.024	Y	36.4	O		
HD 30240	K0	1	04 40.7	-26 57	8.03	-.0028	-.004	S	5.1	O		
HD 30554	K0	2	04 43.5	-79 39	7.99	.0101	.028	Y				
HD 30616	K0		04 44.1	41 24	8.1	.0011	-.021	A				
HD 31487	K1	5	04 51.2	51 47	8.0	-.0006	-.004	Y	-5.9	M	-2.0	Hα
HD 31812	K0	1	04 53.7	-24 25	8.57	.0016	.004	Y				
HD 32712	K0	2	05 00.0	-58 40	8.49	-.0000	-.050	S	14.1	C		
HD 32901	K2	2	05 01.3	-21 33	8.39	.0019	.002	Y	25.3	C		
HD 33409	G5		05 04.9	-57 41	8.98	-.0007	.008	S				
HD 33709	G5		05 07.0	-24 28	7.91	.0009	-.001	Y				
-49 1595	G8	2	05 07.2	-49 11	9.60							
-27 2233	K0	2	05 19.1	-27 29	9.01				-3.6	O		
HD 35993	K1	2	05 23.4	-25 26	9.55	-.0019	.007	Y	22.6	C		
HD 36598	K2	4	05 27.7	-70 09	8.02	-.0002	-.001	Y	47.9	O		
HD 36650	K1	1	05 28.1	-68 09	8.74	-.0032	-.036	S	36.1	O		
-42 2048	K2	4	05 34.9	-42 23	9.30							

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TABLE I. (continued)

Stardesig.	Sp	Ba	α(h,m)	δ(°,')	m_V	pmα	pmδ	pmS	RV	RVS	M_V	M_VS
HD 288174	K0	1	05 35.2	02 01	8.99						+0.1	Hα
HD 38488	K2	2	05 41.0	-41 09	8.61	.0001	.013	Y	3.7	C		
HD 39778	G8	1	05 49.6	-43 08	9.0	.0001	.020	Y				
HD 40430	K0	1	05 53.6	-10 53	8.07	-.0005	-.008	Y				
HD 41596	K3	2	06 01.0	-56 56	7.16	.0007	.043	S				
HD 252117	K2	2	06 02.3	09 15	8.7	.0002	.005	A				
HD 42411	K0	1	06 05.4	-07 05	8.2	-.0013	-.002	Y				
HD 42537	K4	5	06 06.1	-52 31	8.93	.0016	-.017	S				
HD 43389	K2	5	06 10.8	-02 21	8.32	-.0008	-.018	A				
HD 44896	K3	5	06 19.2	-33 34	7.26	.0001	-.004	Y	51.0	C		
HD 45483	K0	1	06 22.5	-86 23	8.7	.0044	.004	Y				
HD 46040	K0	3	06 25.9	-40 20	7.8	-.0016	-.013	S	18.0	C		
HD 46407	K0	3	06 28.1	-11 06	6.28	-.0013	-.011	Y	-5.6	M	+0.1	Hα
HD 49641	K1	3	06 44.3	03 49	7.14	-.0018	-.008	A	5.1	M	-0.1	Hα
HD 49841	G8	1	06 45.3	05 46	8.7	-.0003	.008	A			+4.9	Hα
HD 50075	K1	2	06 46.1	-27 50	8.88	.0008	-.007	Y				
HD 50082	K0	4	06 46.5	06 43	8.1	.0014	.012	A				
HD 50264	G2	2	06 47.3	-29 28	9.05	.0029	.092	Y	56.9	C		
HD 50716	G5	1	06 49.3	-67 14	8.5	.0033	-.089	S				
HD 50843	K1	1	06 49.8	04 46	8.13	-.0017	-.003	A				
HD 51959	K2	1	06 54.3	-06 58	8.95	-.0006	-.002	Y	42.5	C		
HD 53199	G8	2	06 59.1	13 23	9.08	-.0001	.004	A				
HD 55496	G5	1	07 08.0	-22 48	8.36	.0006	-.020	Y	322.0	C		
HD 58121	K0	1	07 19.1	06 21	7.93	.0005	-.007	A	14.0	O		
HD 58368	K0	2	07 20.2	07 46	8.3	.0005	-.006	A	38.0	M	+2.3	Hα
HD 59852	G9	1	07 26.8	-04 09	8.67	.0002	-.011	S				
HD 60197	K3	5	07 28.2	-29 25	7.74	-.0009	.006	Y	51.1	C		
NGC2420x	?K		07 32.5	21 48	11.41	-.0009	.002	M	80.6	M	+0.0	oc
HD 62017	G8	2	07 36.9	02 59	8.81	-.0009	-.003	A				
HD 64425	K0	2	07 48.7	-55 20	9.20				19.0	C		
HD 65314	K0	1	07 53.0	-40 19	8.80	-.0010	.041	Y				
HD 65699	G5	1	07 54.8	-23 02	5.07	-.0012	-.002	S	11.0	O	-2.6	Hα
HD 65854	K1	3	07 55.7	54 27	8.9	-.0023	-.048	A	0.4	M		
HD 66291	K0	2	07 57.7	-28 07	8.46	.0002	-.011	S	31.8	C		
HD 67036	K1	2	08 01.0	-29 39	8.11	-.0001	.042	Y	1.5	C		
HD 67447	G5		08 02.9	68 46	5.5	.0006	.019	A	-11.5	O		
-46 3977	K0	1	08 12.9	-46 22								
-62 1013	K1	2	08 22.2	-62 27	9.76							
HD 71458	K2	1	08 22.4	-32 35	7.70	-.0019	.029	Y	31.9	C		
-61 1941	K0	2	08 25.6	-61 45	9.44							
HD 74950	K2	2	08 41.9	-35 14	9.44	-.0012	.015	Y				
-14 2678	K0	1	08 47.2	-14 17	9.81	-.0007	.020	Y				
HD 77247	G5	2	08 56.3	53 39	7.1	.0001	-.011	A	-18.1	M	-1.1	Hα
HD 77912	G5		09 00.2	38 51	4.7	-.0009	-.012	A	15.7	M	-2.2	Hα
HD 78522	K2	2	09 03.6	-31 38	7.91	.0015	-.006	Y	10.4	C		
HD 82221	K2	3	09 25.6	-32 53	7.93	-.0017	.012	Y	-5.0	C		
HD 83548	K0	1	09 34.1	-42 44	5.50	.0022	-.035	S	3.1	O	+2.1	Krev
HD 84610	K0	1	09 41.3	-37 17	7.82	-.0049	.016	Y	28.9	C		
HD 84678	K2	4	09 41.7	-75 13	9.00	-.0009	.021	Y				
-34 6139	K0	1	09 42.2	-34 19	9.7	-.0008	-.000	Y				
HD 85205	G8	1	09 45.2	-35 30	8.3	-.0051	-.025	S				
HD 87080	G2	2	09 57.6	-33 12	9.39	-.0066	.039	Y	-2.0	C		
HD 88035	K0	3	10 03.9	-19 50	9.13	-.0012	.003	Y	1.0	C		
HD 88495	K2	1	10 07.2	-37 04	8.5	-.0006	-.038	Y				
HD 88562	K2	4	10 07.7	-15 23	8.54	-.0017	-.003	Y			-1.3	Hα

TABLE I. (continued)

Stardesig.	Sp	Ba	α(h,m)	δ(°,')	m_V	pmα	pmδ	pmS	RV	RVS	M_V	M_VS
HD 89175	G5	3	10 12.0	-52 08	7.72	-.0024	-.009	S				
HD 89948	G2	1	10 17.7	-29 04	7.3	-.0013	.079	Y				
HD 90127	K0		10 19.1	-04 26	7.36	.0006	-.001	Y				
HD 91208	K0	1	10 26.7	-16 34	8.02	-.0026	-.008	Y			-0.9	Hα
HD 91979	K0	2	10 32.1	-31 09	8.48	-.0028	.018	Y	19.4	C		
HD 92482	K0		10 35.6	29 05	8.4	-.0008	-.006	A				
HD 92626	K0	5	10 36.6	-47 30	7.10	-.0041	-.001	Y	13.6	C		
LDUW 102	K5	1	10 38.4	-44 24								
-30 8774	K1	1	10 47.0	-30 49	9.5	.0009	-.030	Y				
-25 8291	K3	2	10 47.7	-25 26	9.58							
HD 95193	K0	1	10 54.4	-13 38	8.28	-.0003	.012	Y				
HD 95345	K2	1	10 55.4	04 09	4.83	.0013	.000	Y	6.1	O	+2.1	Hα
-29 8822	K1	1	10 58.8	-29 11	9.82	.0043	.065	Y				
-30 9002	K1	2	11 06.1	-31 06	9.1	-.0003	.004	Y				
-34 7430	K0	1	11 20.1	-34 35	9.4	-.0038	.040	Y				
HD 100012	K1	1	11 25.3	-25 15	6.7	-.0005	.017	Y			-0.9	Hα
HD 100503	K3	5	11 28.8	-30 32	8.74	-.0019	-.006	Y	-4.4	C		
-08 3194	K1	3	11 29.5	-08 46								
HD 101013	K0	5	11 32.4	51 10	6.15	-.0049	-.012	A	-11.9	M	+1.3	Hα
HD 101079	K2		11 32.8	-00 37	8.3	-.0015	-.001	Y				
HD 102762	K2		11 44.8	-04 18	8.1	.0001	.011	Y				
HD 104340	G5	2	11 55.8	-20 41	8.16	-.0007	-.046	Y				
HD 104979	K0	1	12 00.1	09 18	4.16	-.0149	.043	S	-32.5	M	+2.1	trig
HD 105424	K2		12 03.2	30 49	7.78	-.0001	-.014	A				
HD 105902	K1	3	12 06.2	-07 20	8.75						+3.3	Hα
HD 107264	K1	2	12 14.8	-41 23	8.65	-.0039	-.069	S				
HD 107270	K0	1	12 14.8	-64 05	7.2	-.0019	-.008	S				
HD 107541	K0	4	12 16.5	-34 13	9.39	-.0028	-.039	Y	87.4	C		
HD 109061	K1	1	12 26.7	-42 59	8.0	-.0010	-.024	Y				
HD 110483	K0	2	12 37.3	-47 22	8.48	-.0035	.009	Y	-22.8	C		
HD 110591	K1	1	12 38.1	-25 56	9.33	.0029	-.007	Y				
HD 111315	K0	1	12 43.3	-71 26	5.55	.0013	-.006	Y	-7.1	C		
HD 113195	K1	1	12 56.9	-33 14	9.0	-.0017	.018	Y				
HD 113291	K1	3	12 57.6	-26 58	8.59	-.0027	-.004	Y	-7.8	C		
HD 114678	K0		13 06.9	-03 34	8.9	.0009	.019	Y				
HD 115927	G5		13 15.2	36 34	7.68	-.0063	.035	A				
HD 116713	K1	3	13 20.3	-39 14	5.11	.0160	-.056	Y	65.4	O	+1.0	Hα
HD 116869	K2	2	13 21.4	-03 55	9.47	.0028	-.011	Y				
HD 119185	K0	1	13 36.6	-12 32	8.91	-.0015	.040	Y				
HD 120571	K1	2	13 45.2	-20 05	9.29	-.0009	-.008	Y	-30.5	C		
HD 120620	K0	4	13 45.5	-03 47	9.62							
HD 121447	K7	5	13 50.3	-17 45	7.85	-.0024	.017	Y	2.9	O	-1.5	Hα
HD 122687	K0	2	13 58.2	-48 03	9.18							
HD 123396	K0	2	14 02.2	-83 05	8.97	-.0029	-.065	Y				
HD 123585	F8	2	14 03.4	-43 53	9.27	.0032	-.038	Y	16.8	C		
HD 123701	K0	2	14 04.1	-29 58	8.50	.0015	.012	Y	-26.3	C		
HD 123949	K6	4	14 05.5	-18 41	8.73	.0020	.024	Y				
HD 125079	G8	2	14 12.1	-03 48	8.5	-.0001	.014	Y				
HD 125809	G8	1	14 16.7	-46 58	6.39	-.0030	-.002	S				
HD 126313	K0	2	14 19.6	-32 31	7.58	-.0015	-.000	Y	-23.9	C	-0.5	bin
HD 127392	G8	1	14 26.0	-30 47	9.66	-.0028	-.014	Y	-53.6	C		
-03 3668	K1	2	14 40.8	-04 04	10.77							
HD 130255	K0	1	14 42.0	01 48	8.4	.0022	-.049	S	41.0	M	+2.8	Hα
HD 131670	K1	1	14 49.9	-06 53	8.00	.0019	-.010	Y	-28.9	M	-0.9	Hα
-01 3022	K1	1	15 02.2	-01 55	9.0	-.0005	-.013	A				

TABLE I. (continued)

Stardesig.	Sp	Ba	α(h,m)	δ(°,')	m_V	pmα	pmδ	pmS	RV	RVS	M_V	M_VS
HD 134698	K1	1	15 06.2	-10 07	8.5	-.0009	.003	Y				
HD 136636	K0	3	15 16.6	-65 41	8.64				-7.4	C		
-87 0079	K1	2	15 22.5	-87 18	9.33	.0148	.127	Y				
HD 139195	K1	1	15 31.7	10 21	5.26	.0028	-.138	Y	8.3	M	+2.3	trig
HD 141706	K2	1	15 45.3	-53 31	7.9	-.0011	.007	S				
HD 142491	K0	1	15 49.7	-58 24	8.8	-.0033	.004	S				
HD 142751	K1	2	15 51.1	-30 30	8.14	-.0036	.031	Y	-63.3	C		
HD 143899	G8	1	15 57.9	-19 18	8.30	.0024	.002	Y				
-09 4337	K4	3	16 10.1	-09 38	9.66							
-10 4311	G0	1	16 18.7	-10 59	9.89	-.0073	-.071	Y				
HD 147884	K0	1	16 19.3	-67 33	8.68	.0040	.023	Y	16.5	C		
HD 148177	K2	1	16 21.1	-66 30	8.40							
HD 148892	G8	1	16 26.1	-87 44	9.20	-.104	-.030	Y				
HD 148897	G8	1	16 26.2	20 42	5.3	-.0063	-.063	A	17.4	O		
HD 150430:	K0		16 35.9	35 17	8.1	-.0003	-.026	A				
HD 150682	G0	1	16 38.6	-25 02	5.9	-.0003	-.035	A	-12.6	O		
HD 153639	K0	1	16 55.5	-44 42	7.05	.0000	-.004	S				
HD 154430	K2	4	17 00.2	-59 09	8.74				-33.5	C		
HD 160507	K0		17 35.2	32 47	6.45	-.0009	-.014	A	-15.1	O		
HD 162806	K0		17 47.7	-61 26	8.51	-.0014	.031	S	-40.8	C		
LDUW 163	G5	5	17 56.1	-67 14	10.90							
HD 164774	K0	1	17 57.6	-34 03	6.01	.0031	-.021	Y				
HD 165141	K0	1	17 59.4	-48 15	7.1	.0015	.051	S				
HD 166248	K1	1	18 04.6	-47 24	8.8	.0005	.018	Y				
HD 166751	K1	1	18 06.9	-47 59	8.2	.0001	.012	Y				
HD 167849	K0	1	18 11.9	-40 29	9.4	.0017	-.029	Y				
HD 168214	G9	1	18 13.5	-40 19	7.96	-.0029	-.042	Y	18.8	C		
HD 168560	K2	2	18 15.2	-42 59	8.09	.0011	.003	S	11.3	C		
HD 168791	K3	2	18 16.4	-55 01	7.70	-.0002	-.013	S				
HD 169106	K0	1	18 17.9	-49 45	8.1	.0005	-.010	Y				
+29 3331	K0		18 40.3	29 52	9.0	.0018	.031	A				
HD 175674	K3	1	18 51.3	-48 38	6.63	-.0027	.002	S				
HD 176105	K1	1	18 53.5	-50 19	7.96	-.0010	-.016	Y	3.8	C		
HD 177192	K1	1	18 58.5	-71 22	8.98	.0016	.007	Y				
HD 177304:	K		18 59.0	17 42	8.3	-.0001	.013	A				
HD 177539	K1	1	19 00.0	-55 43								
HD 178717	K4	5	19 04.4	10 04	7.10	.0015	.013	A	16.9	M	-1.2	Hα
HD 180622:	K2		19 12.1	00 20	7.53	-.0016	-.014	A				
-53 8144	K0	2	19 18.3	-53 04	9.17							
HD 182300	K1	2	19 18.9	-19 05	9.37							
HD 183915	K0	2	19 26.7	11 25	7.28	-.0001	-.007	A	-50.3	M	-1.0	Hα
HD 184001	G8	1	19 27.1	-43 41	9.0	.0009	-.008	Y				
HD 187308	K1	2	19 44.2	-26 58	7.45	.0024	.030	Y	6.5	C		
HD 188985	G2	1	19 52.7	-49 14	8.5	-.0058	.019	Y				
HD 192558:	K2		20 10.4	34 40	8.2	-.0002	.007	A	-16.0	O		
HD 193530	K2	2	20 15.5	-61 37	9.11				6.7	C		
HD 194703	K1	3	20 21.9	-56 11								
HD 196445	K2	4	20 32.3	-40 43	9.08	.0003	.007	Y	-21.2	C		
HD 196673	K2	2	20 33.8	33 01	6.98	.0021	.015	S	-27.7	M	-1.2	Hα
HD 198590	K0	1	20 46.2	-39 29	6.9	-.0008	-.000	Y				
HD 199394	G8	1	20 51.8	45 58	7.00	-.0016	-.055	A	-8.0	M	+0.4	Hα
HD 199435	G8	3	20 52.0	-77 56	8.29	-.0010	.003	Y	-6.0	C		
HD 199939	K0	4	20 55.2	44 01	8.1	-.0003	.000	A	-41.9	M	+4.3	Hα
HD 200063	K5		20 56.0	00 39	7.45	.0011	.021	A				
HD 200995	K2	2	21 01.7	-20 54	8.20	.0013	.000	Y	-1.5	C		
HD 201657	K1	4	21 05.9	16 35	8.1	.0024	.001	A			-0.1	Hα

TABLE I. (continued)

Stardesig.	Sp	Ba	α(h,m)	δ(°,')	m_V	pmα	pmδ	pmS	RV	RVS	M_V	M_VS
HD 201824	K0	4	21 07.0	-08 47	8.91	.0015	.008	Y	-34.3	C		
HD 202109	G8	1	21 08.7	29 49	3.20	-.0012	-.056	A	17.0	O	+0.4	trig
HD 202400	F2	1	21 10.4	-70 30	9.20	.0100	-.039	Y				
HD 204075	G5	2	21 21.0	-22 51	3.75	.0001	.027	S	4.0	M	-2.8	Hα
HD 204886	K2	3	21 26.4	-57 31	8.2	.0046	-.026	S				
HD 205011	K1	1	21 27.3	23 25	6.5	.0009	.008	A	10.7	M	+0.1	Hα
HD 206778	K2	1	21 39.3	09 25	2.38	.0020	.005	S	4.7	O	-2.8	bin
HD 206983	K3	2	21 40.7	-15 42	9.42	.0009	-.091	Y	-309.9	C		
HD 207277	K2	2	21 42.6	-39 32	8.11	.0001	-.002	Y	-16.7	C		
HD 207585	G5	2	21 44.9	-24 38	9.80	.0021	-.023	Y	-52.3	C		
HD 210030:	K0		22 02.4	-10 34	7.46	.0021	-.018	Y				
HD 210709	K0	1	22 07.1	-35 56	9.23	-.0033	.003	Y	41.7	C		
HD 210910:	G5		22 08.5	-04 16	8.7	.0033	-.042	Y				
HD 210946	K1	1	22 08.7	01 07	8.07	.0001	-.003	A				
HD 211173	K0	1	22 10.2	-32 22	8.46	.0034	.017	Y	-22.8	C		
HD 211594	K0	4	22 13.1	-06 21	8.11	.0006	.018	S			+3.5	Hα
HD 211954	K2	5	22 15.7	-27 45	10.21				-7.4	C		
HD 212320	K0		22 18.3	-07 42	6.11	.0017	.010	Y	-13.7	O		
+34 4688	RK0		22 22.8	34 48	9.13	-.0014	-.014	A				
HD 213084	K1	2	22 23.8	-74 12	9.27	.0015	-.011	Y				
HD 214579	K2	2	22 34.1	-23 17	8.22	.0020	-.020	Y	6.5	C		
HD 214889	G5		22 36.2	-08 25	8.9	.0023	.023	Y				
HD 215555	K0		22 40.9	-12 41	8.7	.0056	.026	Y				
+30 4815	K0		22 44.6	30 17	8.5	.0008	-.014	A				
HD 216219	G5	1	22 46.0	17 28	7.9	.0024	.001	A			+2.3	Hα
HD 216809	K2		22 50.9	-14 06	8.3	-.0004	.013	Y				
HD 217143	K1	2	22 53.4	07 06	7.96	.0030	.045	A			+2.4	Hα
HD 217447	G8	2	22 55.6	-19 53	7.50	.0000	.015	A	13.7	C	+0.6	Hα
HD 218356	K2	2	23 02.0	24 56	4.77	.0009	-.016	A	-26.8	O	-2.2	mgrp
HD 219116	K1	3	23 08.3	-17 54	9.25	.0015	.014	Y	-40.9	C		
-64 4333	K0	4	23 10.5	-64 00	9.60				23.3	C		
HD 221879	K2		23 30.7	-16 51	8.1	.0018	-.037	Y				
HD 222349	G2	1	23 34.6	-57 18	9.2	.0077	.079	S				
HD 223586	K2	2	23 45.6	-18 51	7.06				-5.8	C		
HD 223617	K2	2	23 46.0	01 41	6.94	.0004	-.001	A	30.3	M	+1.6	Hα
HD 223646	K1	2	23 46.2	-79 43	9.16	.0017	.005	Y				
HD 223938	G8	1	23 48.6	-50 34	8.5	.0063	.041	Y				
HD 224276	K2		23 51.4	45 27	8.2	.0012	.010	A				

or barium intensity. Such a study using a larger dataset is near completion by Lü (1988).

Determination of the solar motion follows the method described in Chap. 6 of Mihalas and Binney (1981) for stars with known radial velocities. Of the 114 stars available for this analysis, 112 are used to obtain the final solution. Two stars with very peculiar motions (HD 55496 and HD 206983) are not included in the analysis, as their high radial velocities place each of them about 11σ outside of the mean. This is quite peculiar, as all other stars have residuals within 3σ of the mean. Closer inspection indicates that these stars quite possibly have retrograde Galactic orbits.

The solar motion is found to be $u_\odot = -15.6$ km/s, $v'_\odot = 16.3$ km/s, $w_\odot = 10.5$ km/s (with errors for each being ± 2.6 km/s), and $S_\odot = 24.9 \pm 2.6$ km/s, with the apex located at Galactic coordinates $l_A = 46°$, $b_A = 25°$. These results are given in Table II and are compared to values for normal stars (from p. 396 of Mihalas and Binney 1981) and some peculiar-abundance stars (Dahn 1964; Dean 1976; Stephenson 1978; Ochsenbein and Holtzer 1985). It is certainly difficult to infer anything about main-sequence barium star progenitors from an analysis of the solar motion. At best, it can be said that the barium stars have a solar motion most similar to A5–K0 dwarfs, which is hardly enlightening except to eliminate the possibilities that all barium star progenitors are extremely high- or extremely low-mass stars. The barium star solar motion does not appear to be noticeably different from that of the S stars. The N stars display similar values of $v'_\odot$ and $w_\odot$, although the $u_\odot$ component is fairly different from the barium star value. The R star solar motion (excluding Miras) is somewhat different from that of barium stars.

The residual velocity distribution in the u–v plane is obtained for barium stars with known absolute magnitudes using the methods described in Mihalas and Binney (1981). Barium star u–v velocities can be compared with early A stars and Population I K giants (from Delhaye 1965), even though the same absolute-magnitude restriction used for the barium stars has not been applied to these stars (MK luminosity classification yields $\sigma_M = 0.4$ mag for dwarfs and $\sigma_M = 0.8$ mag for giants). The individual barium star absolute magnitudes still have sizeable errors associated with them (although only a small amount of data exist for comparison). Other types of errors, such as velocity errors resulting

TABLE II. Solar motion with respect to different stellar groups. Values for S stars, R and N carbon stars, and Am stars are from Stephenson (1978), Dean (1976), Dahn (1964), and Ochsenbein and Holtzer (1985), respectively. All others are from Mihalas and Binney (1981). The solar motion suggests that precursors of barium stars are most likely A5–K0 dwarfs. Solar motions with respect to other peculiar-abundance stars are generally different from the solar motion with respect to the barium stars, but observational selection effects might be responsible for some of these peculiar results.

Type of Star	$u_\odot$ (km/sec)	$v'_\odot$ (km/sec)	$w_\odot$ (km/sec)	$S_\odot$ (km/sec)
Barium Stars	-15.6	16.3	10.5	25
Main Sequence Stars				
B0	-9.6	14.5	6.7	19
A0	-7.3	13.7	7.2	17
A5	-8.5	7.8	7.4	14
F0	-11.1	10.8	7.2	17
F5	-10.1	12.3	6.2	17
G0	-14.5	21.1	6.4	26
G5	-8.1	22.1	4.3	24
K0	-10.8	14.9	7.4	20
K5	-9.5	22.4	5.8	25
M0	-6.1	14.6	6.9	17
Other Peculiar-Abundance Stars				
Am Stars	-19.1	6.9	7.7	22
R0 to R4 Carbon Stars	-7.1	13.5	-1.0	15
N Carbon Stars	-6.5	16.3	10.1	24
S Stars	-10.5	21.3	14.8	28

from Galactic shear effects (as many barium stars are farther away than the 100 pc recommended for this technique), also cause an increase in the residual velocity distribution. Overall, the moderate u–v velocity errors found for these barium stars are estimated to be of the same order as those of the dwarfs and giants to which they are compared.

It is seen from Fig. 1 that 72% of the stars reside in the "A box" (in which 85% of stars of spectral type A0–A3 reside), whereas only around 55% of a sample of normal K giants is found to occupy this region. Thus it appears that most barium stars are younger (and hence evolved from more massive precursors) than normal field giants. Because of the large number of barium stars found in the "A box," Williams (1975) has suggested that barium stars belong to a young disk stellar population, whereas Eggen (1972) has claimed that too many stars of relatively high velocity are present and that the sample is more indicative of a typical old disk population. The actual kinematic distribution, as found from this analysis, apparently lies somewhere between these estimates.

A more proper way to analyze this peculiar velocity distribution statistically is to characterize it in terms of the u, v, w, and total velocity dispersions, then compare them to stellar samples of known ages. The barium star velocity distribution is found to have the following characteristics: $\sigma_u = \langle u^2 \rangle^{1/2} = 24 \pm 4$ km/s, $\sigma_v = \langle v^2 \rangle^{1/2} = 16 \pm 3$ km/s, $\sigma_w = \langle w^2 \rangle^{1/2} = 15 \pm 3$ km/s, and $\sigma = 24 \pm 6$ km/s from the sample of 32 stars with absolute magnitudes, proper motions, and radial velocities. There are not enough stars in the sample to obtain a realistic value for the vertex deviation.

These kinematic values may be used to obtain an average sample age, provided a reasonable age-dispersion calibration exists. The calibrations shown in Fig. 2 are taken from combining the studies of kinematics done by Mayor (1974), de Strobel (1974), Jahreiss and Wielen (1983), and Strömgren (1987) while assuming only random errors in their combined results. Relationships are obtained for σ_u, σ_v, σ_w and σ

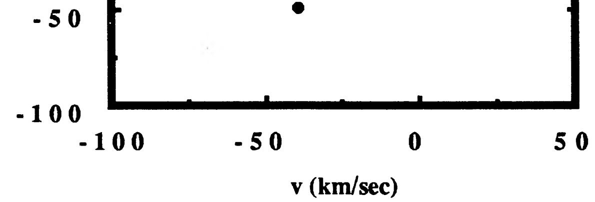

FIG. 1. Velocities of barium stars in the u–v plane. Only stars with well-determined absolute magnitudes, radial velocities, and proper motions are included. Although many barium stars are found outside of the region occupied by 85% of A0–A3 stars (the "A box"), the fraction of barium stars found here (72%) is significantly larger than that of normal K giants ($\approx 55\%$). Thus barium stars appear slightly older than early A stars, indicating that they probably belong to a disk population of intermediate age.

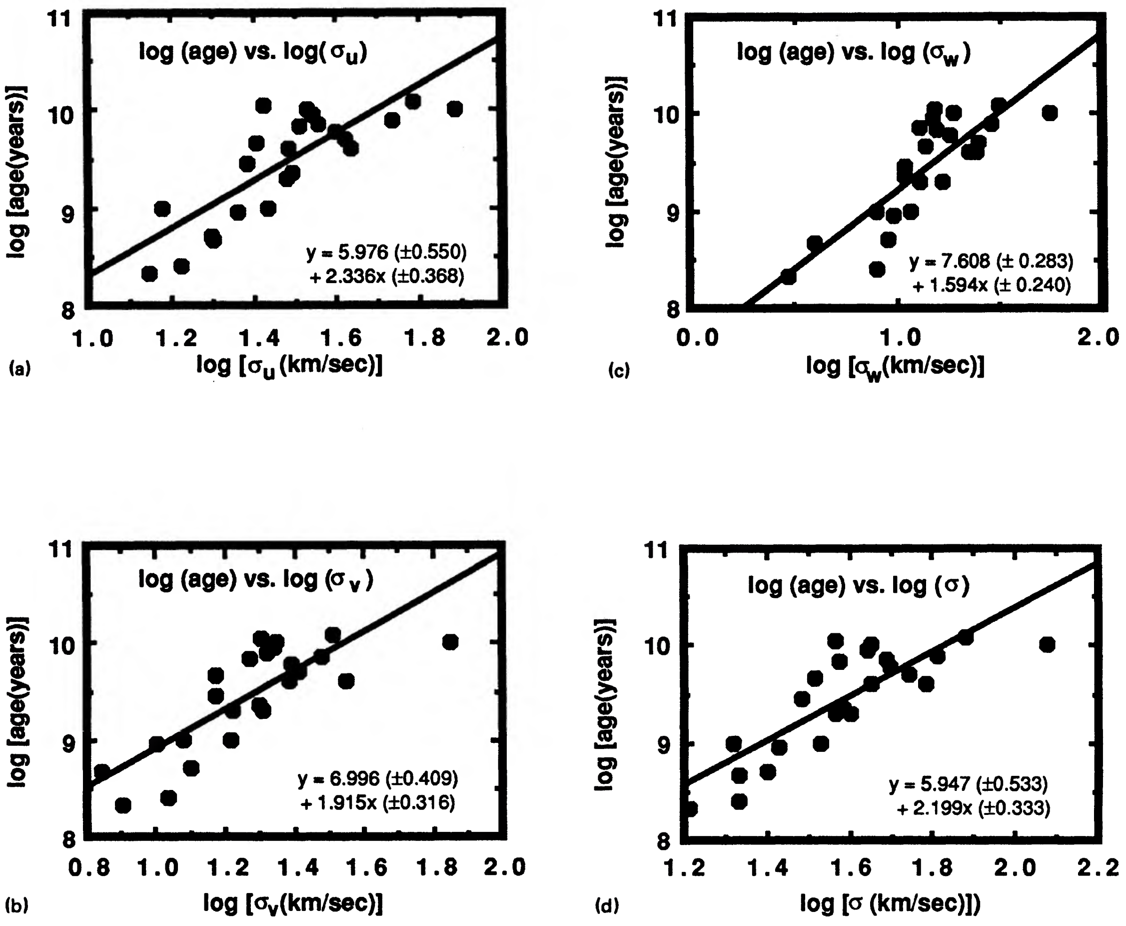

FIG. 2. Calibrations of log (age) vs log (velocity dispersion) for σ_u (a), σ_v (b), σ_w (c), and σ (d). Data points are taken from Mayor (1974), de Strobel (1974), Jahreiss and Wielen (1983), and Strömgren (1987). A least-squares fit to the data is provided for each dispersion component, assuming only random errors exist in each calibration.

as functions of age. Analysis of each component of the barium star residual velocity, as well as the overall distribution, indicates that these stars are best characterized by an age of $2.4(\pm 1.9)\times 10^9$ yr. If all barium stars evolve from stars of the same mass, then this implies (disregarding effects of mass transfer on stellar evolution) that the precursors have average masses slightly greater than 1.5 $\mathscr{M}_\odot$ (Allen 1973; Novotny 1973). However, the solution's formal error indicates that the sample could be represented by masses from 2.4 (corresponding to an age of 5×10^8 yr) to 1.2 $\mathscr{M}_\odot$ (corresponding to an age of 4.3×10^9 yr). It is unlikely that the barium stars belong to the oldest disk population (aged 5–10×10^9 yr).

If the precursors comprised a wide range of masses, then the age obtained from the velocity dispersion will be typically the age of the oldest stars in the sample (again ignoring effects of mass transfer on evolution). This is because those stars with the lowest masses dominate the sample in two ways: (1) they are generally more numerous, and (2) they are significantly older than the more massive stars. If, however, some evolutionary process favors high-mass stars over low-mass stars, then many giants in the sample should show small residual velocities indicative of a younger population. The average mass of the sample might therefore be noticeably larger than the mass inferred from kinematics. The small fraction of barium stars found relatively far outside the "A box" possibly supports this claim. The suggestion that barium stars might be made up of stars of different ages has been made previously by Catchpole *et al.* (1977).

Residual velocities of the N carbon stars are slightly larger than those of the barium stars. The values of σ_u and σ_v for N stars are found by Dahn (1964) to be $\sigma_u = 31.5$ km/s and $\sigma_v = 20.8$ km/s, while those for R0–R4 stars (excluding Miras) are found by Dean (1976) to be $\sigma_u = 36.7$ km/s and $\sigma_v = 28.5$ km/s. These values appear to indicate that the carbon stars belong to a perhaps slightly older stellar population than the barium stars, or to kinematic groups in which selection effects play significant roles.

b) Spatial Distribution and Space Density

1) The distribution perpendicular to the Galactic disk

The distribution of stars perpendicular to the Galactic plane is a good indicator of stellar age and population, corresponding to the distribution of peculiar *w* velocities. Perpendicular to the Galactic plane, stellar densities are modeled by $n = n_0 e^{-|z|/\beta}$, where the scale height β indicates the spread of galactic disk heights for stars of a particular age or spectral type.

The scale height of barium stars in the direction perpendicular to the galactic plane has been recently found by Lü (1988) to be 230 pc, and appears to be less for the marginal barium stars (in agreement with results of Catchpole *et al.* 1977). This is considerably less than the scale heights of normal G and K giants (Table III), and is much more similar to F stars than to G and K dwarfs.

However, identification of main-sequence progenitors of barium stars must be made from a class of main-sequence stars younger than that which the scale height indicates. When comparing a sample of post-main-sequence stars to their suspected main-sequence progenitors, the main-sequence progenitors (some older, some younger) are characterized by an average age that is half of their main-sequence lifetime, while the post-main-sequence stars are characterized by an age more than twice this value (as these stars have all completed their main-sequence lifetimes). Thus, the scale height of the barium stars indicates that their main-sequence progenitors belong to an intermediate-age disk population which could be slightly younger than typical F stars. If barium stars evolve from main-sequence stars with a range of masses (as discussed in Sec. II*a*), then the majority of the stars might be significantly younger than the scale height indicates.

Other peculiar-abundance disk giants have distributions perpendicular to the Galactic plane which indicate that they might belong to different stellar populations. The S stars have an average absolute distance from the galactic plane of $\langle z \rangle = 200$ pc (Yorka and Wing 1979), which is comparable to that of dwarf G stars ($\langle z \rangle = 180$ pc), and appears to identify them as being slightly older than the barium stars. While the scale height of the R0–R4 carbon stars is of the same order as the barium stars (Dean 1976), the distribution of nonvariable N stars appears to be highly concentrated to the Galactic plane (e.g., Alksne and Ikaunieks 1981), indicating that most of these stars belong to a young disk population.

TABLE III. Scale heights perpendicular to the galactic plane for some stellar samples. The values for barium stars are from Lü (1988), N carbon star values are from Dean (1976), and other values are from Mihalas and Binney (1981). From their scale height, the barium stars appear to resemble F stars more than other normal stellar types. However, the age of a post-main-sequence stellar sample is more than twice the age of its main-sequence counterpart (see the text), indicating that the barium stars should be compared to a younger sample. The barium stars appear quite similar to the N carbon stars, although these might not represent a homogeneous stellar sample.

Type of Star	Scale Height Perpendicular to the Galactic Plane (pc)
Barium Stars	230
Spiral Arm and Disk Stars	
O	50
B	60
A	120
F	190
Disk Giants	
G	400
K	300
Disk Dwarfs	
G	340
K	350
M	350
Other Peculiar-Abundance Stars	
N	226

2) The distribution within the Galactic disk and the spatial density

Most of the known barium stars have been found from objective-prism plates taken during the extensive task of reclassifying the *Henry Draper Catalogue* (Houk and Cowley 1975). As this survey was initiated in the southern hemisphere, the distribution of barium stars suffers from a peculiar selection effect: Most known barium stars are located in the southern sky. Although this biases the spatial distribution of these stars, a rough estimate of the distribution in any bounded region of galactic longitude may be arrived at using statistical arguments, yielding an estimate of the spatial distribution in the solar neighborhood. In effect, the stars in sampled regions are used to estimate the number of stars in unsampled ones.

Initially, a transformation is made from equatorial coordinates (α, δ) to galactic coordinates (l, b), and the sky is divided into regions bounded by l and b. The number of stars observed in each galactic-longitude region can be predicted by assuming only that all sampled sky regions are considered complete to some limiting apparent magnitude, and the galactic-latitude distribution of stars (by percentage) is the same for all galactic-longitude regions. The percentage in each latitude region is obtained from the sampled regions, and is applied to the unsampled regions to estimate the number of stars that should exist in each of these. The predicted number of stars in each longitude strip is then totaled, and this gives the rough spatial distribution of this stellar type in the solar neighborhood.

For this calculation, it is assumed that the barium stars have been fairly well identified south of $\delta = +10°$ (roughly the region covered by the Michigan Survey) to limiting apparent magnitude $+8.5$, where the number of stars begins to fall off with apparent magnitude (Hakkila 1986). Assuming that the barium stars have a mean absolute magnitude of $\langle M \rangle = 0.0$ and an absolute-magnitude dispersion of $\sigma = 1.2$, a spatial density of $8.9 \times 10^{-8} \pm 0.6$ barium stars/pc^3 (Hakkila 1986, 1987) is obtained from a least-squares analysis (the quoted error is only the formal error of that analysis). The sample is believed to be relatively complete out to a mean distance of $\langle r \rangle = 400$ pc, and a dominant effect in this reduction is the statistical effect of sampling luminous stars to larger distances than low-luminosity ones.

Application of the statistical analysis described above shows that the barium star distribution shows no apparent preference for the Galactic center (48%) or the Galactic anticenter (52%) directions, although they have not been sampled to an extremely large distance. The S stars are thought to prefer the direction of the Galactic anticenter (Yorka and Wing 1979), but the space distribution of Tc-poor MS and S stars has not been calculated. The N stars might prefer the Galactic anticenter and the R stars might prefer the Galactic center (e.g., Lee *et al.* 1947), but these interpretations have been disputed (e.g., Ikaunieks 1963).

When the resolution of barium star counts is increased

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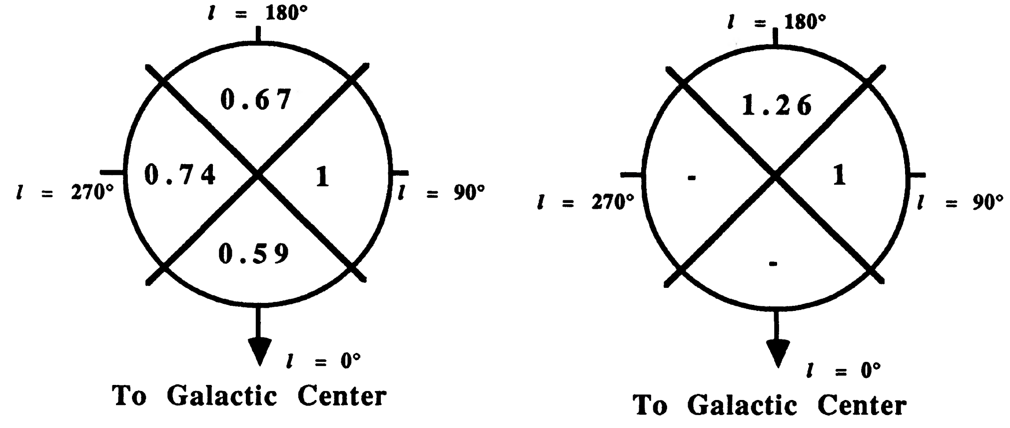
slightly to indicate the relative numbers of stars found in regions toward and away from the galactic center and toward and away from the directions of galactic rotation (Fig. 3), a smaller percentage of stars is found in the quadrant $135^\circ \leqslant l \leqslant 225^\circ$ than in the quadrant $45^\circ \leqslant l \leqslant 135^\circ$. This is more indicative of the distribution of A dwarfs than of normal K giants (McCuskey 1965), although interpretation of this result is difficult. If the technique is statistically valid, then this further suggests that the barium stars belong to an intermediate disk population.

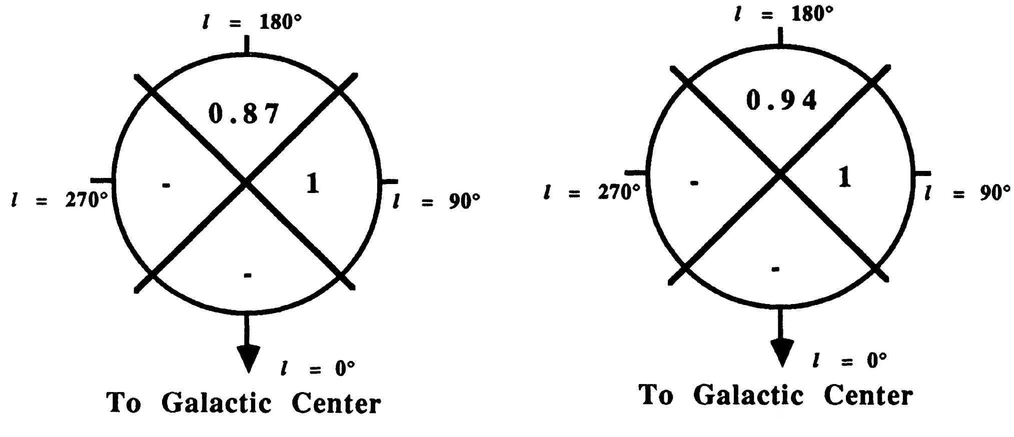
The N carbon stars show a tendency to be found in groups or clumps (e.g., Alksne and Ikaunieks 1981), whereas the barium stars, R stars, and S stars do not. This also suggests that the N carbon stars are young disk objects.

c) Results of Age Indicators

The solar motion, residual velocity distribution, and spatial distribution both in the direction of and perpendicular to the galactic plane strongly suggest that barium stars are in-



(a) Barium Stars (b) F8 to K3 Giants



(c) B8 to A0 Stars (d) A2 to A5 Stars

FIG. 3. Rough spatial distribution of (a) barium stars, (b) F8–K3 giants, (c) B8–A0 stars, and (d) A2–A5 stars in the plane of the Galactic disk within 400 pc of the sun. The relative number of stars in each quadrant is normalized to the number in the direction $45^\circ \leqslant l \leqslant 135^\circ$. Barium star values are obtained using an algorithm that estimates values for undersampled regions (and only has a quadrant resolution for this sample), while other values (incomplete in regions $225^\circ \leqslant l \leqslant 45^\circ$) are taken from McCuskey (1965). Although the method does not allow for much resolution in galactic longitude, the normalized spatial distribution of barium stars between $45^\circ \leqslant l \leqslant 225^\circ$ is less than 1, and appears more indicative of a young stellar distribution than an older one. Barium stars show no preference for the directions of either the Galactic center or the Galactic anticenter.

termediate disk objects of ages 2.4×10^9 yr (although the mean age could be as young as 5×10^8 or as old as 4.3×10^9 yr), and are younger and more massive than average field G and K giants. From this age estimate, barium star progenitors are most likely to have average masses of 1.5 $\mathscr{M}_\odot$ (although the mean could be between 1.2 and 2.4 $\mathscr{M}_\odot$), with the more massive stars possibly overrepresented (see Sec. II*a*).

These statistical values are also in agreement with detailed observations of individual systems. From careful determination of orbital characteristics (Culver and Ianna 1976, 1980; Culver, Ianna, and Franz 1977) the masses of three barium stars are found to be between 1.7 and 3.0 $\mathscr{M}_\odot$. Although this study examines only three stellar systems, the masses that are computed are indicative of intermediate disk populations, and of neither extremely young nor extremely old disk populations. The same can be said for observations of ζ Cap (Smith *et al.* 1980), which apparently has a mass of 3.6 $\mathscr{M}_\odot$ (with a factor of 2 uncertainty).

At the same time, these results do not contradict the ages of the one classical and one marginal barium star found in the old disk cluster NGC 2420. This cluster has an apparent upper age limit of 4×10^9 yr (McClure *et al.* 1974; VandenBerg 1985). The discrepancy between the masses of individual systems and the open cluster age is readily explained if barium stars evolve from stars with a range of main-sequence masses (as described in Sec. II*a*). Since this cluster provides the largest residual velocity of any barium star in Fig. 1, it might be older than most barium stars.

d) Implications for Evolutionary Relationships with Other Peculiar-Abundance Giants

Given the kinematic, spatial, and binary properties described previously, it is difficult to believe that carbon stars, barium stars, and S stars are all related via some sort of evolutionary sequence. It is possible (as described in Sec. II *b2*) that R, N, S, and barium stars prefer differing radial directions in the Galactic disk. If true, then this would certainly preclude similar evolution in all of these cases.

Although the barium stars might fit into an evolutionary sequence with either the Tc-poor MS (Smith and Lambert 1988) or perhaps a large fraction of MS and S stars (Jorissen and Mayor 1988), it is unknown whether or not this relationship extends to all MS and S stars.

The R carbon stars appear to belong to a stellar population similar to that of the barium stars, but they do not have the proper binary frequency (McClure 1989). The carbon-rich Miras most likely evolve from less massive stars than the barium stars, and their incidence of binarity is unknown.

The N carbon stars belong to a variety of stellar populations (Dean 1976), with most apparently much younger than the barium stars (as described in Sec. II). An evolution from N carbon star to white dwarf (with the secondary receiving transferred mass to become the barium star) is possible (Lambert 1988), but the incidence of binarity among these stars has also not been established. (For this model, it should be noted that the implied ages of the barium stars would place constraints on the masses and orbital separations of the precursor N carbon star systems. It is unknown whether or not the space density of stellar systems with characteristics of high-mass primary and intermediate-mass secondary is high enough to account for the space density of barium stars.)

Any search for evolutionary relationships among carbon stars, S stars, and barium stars should be limited to subsets that satisfy properties that allow for such evolution to occur (such as binarity and age). The same mechanism would not therefore appear to be responsible for the spectral peculiarities seen in all of these types of peculiar-abundance giants, although it may occur in some.

III. A SEARCH FOR MAIN-SEQUENCE PROGENITORS

The ages, masses, and binary nature of barium stars place strong constraints on what types of stars are likely progenitors. As shown in Sec. II, kinematic and spatial analyses indicate that barium stars probably evolve from main-sequence binaries of spectral types A and/or F, with younger stars perhaps being more abundant. The binary nature of the barium stars, their relatively wide orbits, true mass functions, and suspected white dwarf companions all indicate that mass transfer from the primary has taken place in their evolution. Progenitors should be binaries with closer binary orbits than barium stars, as some mass lost by the primary will likely escape the gravitational pull of the system, and mass loss with little angular-momentum loss will lead to wider orbital separations.

Not all A/F dwarfs satisfy these criteria. Many do not belong to binary systems, and many have orbits that are either too wide for mass transfer to occur or too close to account for the barium star binary characteristics. However, apparently all A4–F1 dwarfs belonging to binary systems with orbital periods between 2.5 and 100 days belong to the class of metallic-lined A stars or Am stars. These stars should be studied closely to determine the likelihood of an evolutionary relationship.

a) A Summary Description of the Am Stars

Am stars are late A and early F main-sequence stars (as summarized in reviews by Smith 1971b and Wolff 1983) whose spectral types as obtained from calcium lines are considerably earlier than those obtained from metal lines (Titus and Morgan 1940; Roman *et al.* 1948). The incidence of stars exhibiting metallic-lined characteristics (such as Fm stars) decreases at low temperature, and these stars are not observed with Strömgren colors redder than $b - y = 0.25$ (Smith 1973). A broader definition of the Am phenomenon (Conti 1970) allows inclusion of stars exhibiting marginal Am characteristics (such as Sirius and other hot stars) as well as some stars with weak calcium lines and some with strong metal lines.

Although Am stars appear to contain an excess of iron-peak elements, detailed abundance analyses indicate that the atmospheric amounts of these elements are near normal for Population I stars. Instead, the stars have enhancements of *s*-process elements and depletions of elements such as calcium and scandium (Smith 1971b; Lane and Lester 1987). An interesting feature of these stars is that their maximum observed rotational velocity is approximately 100 km/s, identifying slow rotation as a condition apparently involved in producing their peculiar spectral properties (Abt and Moyd 1973).

The majority of Am stars belong to observed binary systems (Abt 1961; Abt and Levy 1985). Although some doubt has been expressed as to whether or not all Am stars are binary (Batten 1967a,b; Conti and Barker 1973), recent evidence (Abt and Levy 1985) indicates that this is generally so. All A4–F1 binary dwarfs with 2.5 and 100 day orbital periods apparently show Am characteristics (Abt and Bidelman 1969). Rotational (tidal) braking is thought to be a major cause of the observed slow rotation, as the lack of detectable external magnetic fields makes magnetic braking an unreasonable mechanism (Conti 1970). Evidence supporting the rotational-braking model includes the massive (generally greater than 1 $\mathscr{M}_\odot$) companions found in Am systems (Abt and Levy 1985). These large mass ratios also explain why Am spectral peculiarities appear to develop in stars as young as 10^6 yr (summarized by Abt 1979). Abt and Levy (1985) also find that around 25% of Am stars are in binary systems with orbital periods greater than 1000 days. They suggest (as do Abt and Hudson 1971; Kodaira 1976; Burkhart 1979) that some other mechanism is needed to slow the rotation of the more widely separated systems, such as evolutionary expansion of the primary during its main-sequence lifetime. In summary, slow rotation appears necessary in the development of an Am star, and rotational braking between binary components appears to be the mechanism for this slow rotation in the majority of cases.

Diffusion is one mechanism (e.g., Michaud 1970, 1980) by which the Am stars are believed to remove smaller cross-section elements (such as calcium and scandium) from their surfaces while transporting elements of larger cross section outward from the interior. Slow rotation is a necessary condition for this, as rotational turbulence must be minimized for weak diffusion forces to transport significant amounts of heavy elements to the upper atmosphere.

b) Arguments for an Evolutionary Relationship between Barium and Am Stars

There are a number of stellar properties of barium and Am stars that need to be examined in detail before an evolutionary relationship between Am and barium stars can be reasonably suggested. These properties include age and binarity, kinematic and spatial properties, orbital characteristics, and elemental abundances.

1) Age and binarity

As described in the previous sections, the main arguments for suspecting that Am stars are the main-sequence precursors of the barium stars are that (1) they are of the proper age and mass, (2) they belong to binary systems, and (3) few other binary stars in the suspected mass range have orbits close enough that mass-transfer models of barium star formation could be satisfied, yet distant enough that lack of complete orbital circularization is likely.

2) Kinematic and spatial characteristics

Kinematics of Am stars have not been examined in any great detail at present, making direct comparisons difficult. However, the solar motion has been obtained (Ochsenbein and Holtzer 1985). The $v'_\odot$ and $w_\odot$ components of barium star and Am star solar motions are quite similar (Table I), whereas the $u_\odot$ component is fairly different. Spatial incompleteness in the identification of barium stars (described in Sec. II *b2*) could be responsible for this difference.

Although a rough value has been obtained for the total velocity dispersion of Am stars (by Ochsenbein and Holtzer 1985) which is similar to that of normal late A dwarfs, detailed studies that include analysis of the velocity-dispersion components and subdivision by spectral subclass (or temperature) have not yet been performed.

As described in Sec. II*b*, the space distribution of barium stars is similar to that of A and F dwarfs. The scale height of Am stars perpendicular to the Galactic plane is not identical to that of normal A stars, but appears to be slightly larger (e.g., Ochsenbein 1983). Normal kinematic interpretations would suggest that Am stars are slightly older than normal main-sequence A stars, which appears difficult to reconcile if Am stars are only peculiar based upon slow rotation. A recent theory put forth by Willson *et al.* (1987) suggests that rapid rotation in intermediate-mass stars leads to pulsational instability and early-main-sequence mass loss. Rapidly rotating main-sequence stars between 1 and 3 $\mathscr{M}_\odot$ would initially evolve down the main sequence, with early H burning significantly decreasing the star's main-sequence lifetime (Guzik 1988). Am stars, with their slow rotation, would not be expected to undergo early mass loss, and would remain on the main sequence longer than rapidly rotating "normal" A stars. If true, this might also account for any discrepant age differences between Am stars and barium stars, and suggests that an evolution is even more possible.

If barium stars evolve from Am stars, one would expect that the spatial density of barium stars would be roughly 10% that of the Am stars (as the time a star spends on the giant branch is generally a factor of 10 less than its main-sequence lifetime). A rough estimate of the spatial density of Am stars is 9×10^{-7} pc^{-3}, assuming that Am stars make up roughly 1/3 of all A stars (Smith 1971a). The spatial density of barium stars obtained previously is 9×10^{-8} pc^{-3}, which is in reasonable agreement. However, the number of barium stars has likely been underestimated due to incomplete cataloging, and classification of many marginal barium stars as well as those with weak Am characteristics is also still ongoing. Incompleteness aside, this result is still interesting.

3) Orbital characteristics

The orbital characteristics of barium and Am systems are somewhat different, as Am stars generally have shorter orbital periods than the barium stars (roughly 2/3 of the Am binary systems have orbital periods less than 100 days), and have high mass ratios (often as high as 1:1, where both components of some binaries are Am stars).

However, as mentioned earlier, it is possible that all barium stars have white dwarf companions. If a reasonable amount of mass loss is assumed to have occurred from the more massive star in its evolution to a white dwarf via slow mass loss or mass dumping, the differences in orbital periods fit an evolutionary model quite well (as mass loss with little loss of angular momentum would lead to wider orbital separations and longer periods). In fact, "typical" barium star orbital characteristics can result from evolution of "typical" Am stars upon loss of a reasonable amount of material (0.5–1 $\mathscr{M}_\odot$). Although this amount of mass is suggestive of planetary nebula formation, the true mass functions of barium stars indicate that at least some mass dumping has occurred (McClure 1989). Since most Am stars have orbital separations of intermediate distances (i.e., they are not contact binaries or semidetached systems), mass transfer and mass loss should not be expected to completely circularize the orbits. This would satisfy the barium star mass-transfer model and fit the observations of Webbink (1986).

4) Elemental abundances

So far, no mention has been made of barium and Am star elemental abundances in this suggestion of an evolutionary relationship. Both types of stars exhibit enhanced *s*-process elements. Am stars show depletions in calcium, scandium, and other light elements, while barium stars have low abundances of these as well as of many heavier iron-peak elements.

Lambert (1985) has stated that the metallicities do not suggest an evolutionary relationship, based upon three arguments: (1) Am stars show lower heavy-element overabundances than the barium stars do, (2) Am stars exhibit larger overabundances of Eu than are seen in barium stars, and (3) C abundances of Am stars are below those of barium stars. In making this comparison, Lambert compared an analysis of one barium star with one early metallicity study each of Am and δ Del stars.

There are two reasons for questioning these interpretations. The first is that metallicity studies do not easily and uniquely identify abundances for these stellar types. Recent studies of barium stars (e.g., Kovacs 1985) and Am stars (e.g., Lane and Lester 1987) indicate that Lambert's first observation is likely incorrect. If anything, the Am stars exhibit *higher* heavy-element overabundances than barium stars do. Furthermore, Lane and Lester compare their abundance analysis with those of other authors [including the study of Smith (1971b) used by Lambert] to show that many severe discrepancies exist from author to author. (Kovacs, in his paper, comments that results of other barium star analyses are also inconsistent.) To further complicate matters, abundance variations among individual stars (both barium and Am) can be exceptionally large, making it difficult to extrapolate the results obtained from one star to the whole stellar class. Although the C deficiencies and Eu overabundances of Am stars noted by Lambert could well be real, there are some Am stars with only minor C deficiencies and some barium stars with Eu/Fe ratios approaching those of Am stars. These problems make it difficult to generalize about abundance peculiarities for either stellar type.

All of this brings up the second reason for questioning these interpretations. Lambert assumes that the abundances would be the same *if the same mechanism produces abundance peculiarities in both stellar types.* Diffusion is thought to be the mechanism for the peculiar abundances seen in Am stars. The scenario leading to the atmospheric peculiarities of barium stars is thought to involve post-main-sequence evolution and mass transfer in a binary system. If barium stars evolve from Am stars, then the mechanism might involve some combination of diffusion, post-main-sequence stellar evolution, and mass loss/transfer, and it would not be expected that the barium stars and Am stars would necessarily have similar abundance peculiarities. The argument presented in this paper has been made based upon stellar population and binary properties, and not upon the expectation that a similar mechanism produces the observed spectral peculiarities.

c) Comments on Evolutionary Models

1) Evolution of Am stars to barium stars

The following model is suggested as a rough beginning in support of an evolutionary relationship between Am and barium stars: Some enriched material could be brought to the upper atmosphere of the primary (and, possibly, of the secondary as well) via the diffusion during the Am phase. Mass transfer might distribute into the secondary's atmosphere some of these heavy elements, enriched elements produced by the primary in its post-main-sequence evolution, or both. The elemental abundances formed through a combination of diffusion, normal stellar evolution, and binary system mass loss/transfer are very difficult to predict accurately due to the large number of variables that can affect the evolution.

2) Strengths of the Am/barium star evolutionary model

Barium stars must have main-sequence precursors. An evolution from Am stars is consistent with many constraints imposed by age, mass, and orbital considerations. From diffusion constraints, Am stars must have large enough masses (and therefore high enough luminosities) that radiation pressure can effectively elevate the large cross-section elements, and large enough binary mass ratios and/or small enough orbital separations (provided no other mechanism is chiefly responsible for Am characteristics) to set up significant tidal forces. These criteria are also necessary to account for both the observed barium star kinematics and any mass-transfer mechanism.

Yet evolution via this model introduces a large number of free parameters which can explain many barium star peculiarities.

Mass loss by the primary accounts for several of these free parameters; namely, orbital separation and initial masses of the primary and the secondary. Variations in these parameters from system to system, as well as the unknown effect of diffusion, could explain why barium star absolute magnitudes span such a tremendous range, classical barium star peculiar abundances vary considerably from star to star and do not appear to correlate strongly with luminosity (e.g., Lü *et al.* 1983), and a small percentage of barium stars appear to have kinematics indicative of older stars (those systems that still have low-mass companions after mass transfer is completed).

It is not necessary for this model that all Am stars evolve into classical barium stars. If a system's orbital separation is too wide, then the secondary might not receive heavy elements from the primary, would not show enhanced abundances, and would not be distinguishable from a normal giant. However, if the primary were massive enough, it could affect the secondary despite larger orbital separations. Such post-mass-transfer systems would likely exhibit weak *s*-process enhancement, have large orbital separations, and be younger than the normal barium star systems. These are all suspected characteristics of marginal barium stars.

3) Weaknesses of the Am/barium star evolutionary model

Because of the unknowns involved in the proposed evolutionary model, the evolutionary sequence from Am star to barium star might not be direct. In other words, it is not necessarily expected that all Am stars evolve into barium stars, nor is it assumed that only Am stars can evolve into barium stars.

Some Am stars have wide orbital separations and others might be single stars. These stars are thought to develop Am characteristics via evolutionary expansion (Abt and Levy 1985), and would not be expected to undergo mass transfer. Thus, not all Am stars are likely to evolve into barium stars, although Am stars in close- or intermediate-separation binary systems are stars that satisfy many criteria necessary for such an evolution.

Barium stars might not evolve only from Am stars. Not all A and early F stars in close binary systems are likely to become Am stars, particularly if current Am models are correct and if diffusion is the Am mechanism. Perhaps some barium stars evolve from normal A and F stars (such as those with orbital periods slightly greater than 100 days or perhaps some F dwarfs with temperatures too low to show metallic-lined characteristics). Perhaps a few massive (late B) stars can undergo a similar evolution as well.

Despite the problems introduced by indirect evolution, it is interesting to note how well the Am stars as a class satisfy the many criteria needed for an evolution to barium stars. Few stars of either relatively low mass or relatively high mass would appear to evolve into barium stars.

4) Problems common with other models

Lambert (1985) voices a concern that abundance peculiarities in a main-sequence star (such as an Am star) will be erased as the star expands to the giant phase. This is because the convective envelope will expand and redistribute downward any abundance peculiarities from near the surface. This presents [AV:a problem not only to any model involving Am to barium star evolution, but also to any barium star model in which the secondary was enriched by mass transfer while still a main-sequence star. It does not matter how the secondary's atmosphere was enriched while it was on the main sequence (i.e., through diffusion, mass transfer, or some other mechanism), as convective mixing during expansion should wipe out any abundance anomalies, regardless of their origin.

Another convective-mixing problem exists with mass-transfer models. Proffitt (1989) has calculated that mass accreted from an expanding giant envelope onto a $1\mathcal{M}_\odot$ main-sequence star can eliminate abundance peculiarities on a timescale shorter than the lifetime of the star, as the accretion generates turbulent motions which introduce convective mixing. A giant accreting mass from the primary would also apparently develop these turbulent instabilities.

If mass transfer in a binary system is responsible for barium star abundance peculiarities, then the convection problems described above would seem to present real difficulties with any model, and not just those involving Am stars. These problems are difficult to resolve. Perhaps mass transfer occurs via a stellar wind instead of by mass dumping (Boffin and Jorissen 1988) after the secondary has undergone post-main-sequence evolutionary expansion. This would favor systems in which the primary and secondary have very similar main-sequence lifetimes, and therefore high mass ratios (such as are found in Am systems). Or perhaps, by some as yet unknown method, convection does not destroy peculiar abundances acquired during the secondary's main-sequence lifetime or through mass dumping. If this is so, then some Am abundance peculiarities might still remain after the star has expanded to the giant phase.

d) Remaining Work

This study has led to a suggestion of an evolutionary relationship between Am and barium stars. Arguments for such a relationship are diverse, but the evidence is no more than just circumstantial. There are many places where additional work could lead to better estimates and models which could strengthen or perhaps alter many of these results and interpretations.

Full-sky identification of barium stars (particularly in the northern hemisphere) needs to be done in order to reduce selection effects that exist in the present dataset. Additionally, the kinematic results mentioned in this study are based upon only a small fraction of barium stars with measured absolute magnitudes, radial velocities, and proper motions. In order to minimize errors and obtain more accurate kinematic measurements, a larger data sample is needed.

It is assumed that all barium stars belong to binary systems, although this is still not known conclusively. Even more unknown is whether or not all barium star companions are white dwarfs. These would appear to be important questions to answer if mass transfer is indeed the mechanism behind barium star abundance peculiarities.

The kinematics of the Am stars need to be examined more fully (such a study is currently under way by the author), and should be compared to kinematics of barium stars and to those of normal A and F dwarfs.

Although diffusion is the mechanism thought by most to be responsible for the Am abundance peculiarities, many theoretical questions still remain. The same can be said for mass-transfer models of barium star formation. The effects of mass transfer via a stellar wind on convective mixing in the secondary's atmosphere have not been examined at present, but perhaps this model would not generate convective instabilities seen from mass-dumping models. Much theoretical work needs to be done in order to better understand these mechanisms.

If the N carbon stars fit into some evolutionary sequence with the barium stars, then information supportive of the N star mass-transfer scenario (such as incidence of binarity, mass ratios, orbital separations, etc.) needs to be collected. The role of the S stars in barium star evolutionary models also needs to be established in more detail.

If an evolutionary relationship exists between Am and barium stars, then the roles of the marginal Am and barium stars in this scenario need to be identified.

IV. CONCLUSIONS

Kinematic and spatial distributions suggest that barium stars belong to an intermediate disk stellar population. The binary nature of the barium stars, as well as their mass ratios and orbital characteristics, place additional constraints on which stars are their likely main-sequence progenitors. Main-sequence A and/or F dwarfs belonging to binary systems with generally close to intermediate orbital separations and low mass ratios are favored as candidates. The Am stars satisfy all of these criteria, as well as withstanding closer scrutiny concerning considerations such as space densities and additional orbital characteristics. Considerations such as metallicity do not rule out such an evolution, as the mechanism suggested to explain abundance peculiarities observed in each stellar type is not necessarily the same. It is possible that Am stars belonging to close- or intermediate-separation systems are precursors of barium stars.

Whether an evolutionary link exists or not, main-sequence precursors of barium stars must exist, and the constraints enforced by kinematics and binarity should help isolate the progenitors.

The relationship between barium stars and other peculiar-abundance giants is unknown. Kinematic and spatial characteristics suggest that barium stars might be related to S stars and possibly to some N carbon stars, but relationships with the R carbon stars and carbon-rich Miras are difficult to reconcile.

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