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LITHIUM IN LATE-TYPE GIANTS. IV. THE SUBGIANT CH STARS

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ABSTRACT

We report on lithium abundances in 10 subgiant CH stars and one giant CH star. In no star was the Li I resonance doublet detected, and upper limits to the lithium abundance in the range log ϵ(Li) ≤ 0.7 to log ϵ(Li) = 1.5 [log ϵ(H) = 12.0] were determined for this sample of stars. The subgiant CH stars are on, or near, the main sequence, and as they evolve up the red giant branch, the deepening convective envelopes will dilute lithium by a factor of ~30–50. This dilution factor, along with our upper limits to the current lithium abundances, would give the subgiant CH stars when they become red giants distinctly lower Li abundances than are observed in the classical barium stars. This suggests that subgiant CH stars are not progenitors of the classical barium stars. As the subgiant CH stars do show ^{12}C and *s*-process enhancements and are all binaries with low-luminosity companions, they may represent mass transfer from a former asymptotic giant branch star (now a white dwarf) onto a main-sequence companion (now a subgiant CH star).

Subject headings: stars: abundances — stars: Ba II — stars: binaries — stars: evolution — stars: late-type

I. INTRODUCTION

Lithium, with its neighboring light elements beryllium and boron, is destroyed by protons at temperatures that leave the elements of higher atomic number unaffected. Unlike Be and B, Li is detectable spectroscopically with relative ease in cool stars. The conjunction of these nuclear and atomic properties provides Li with the nearly unique role of a tracer of material exposed to moderate temperatures, say $6 \times 10^6 > T > 2 \times 10^6$ K, and mixed into a stellar atmosphere; the Li abundance declines as a result of the mixing.

Another distinguishing mark of lithium is its production in some residents of the asymptotic giant branch (AGB): rare S stars such as T Sgr and C stars such as WZ Cas (see review by Boesgaard 1976). Nucleosynthesis of Li is attributed to the chain ^{3}He(α, γ)^{7}Be(e^-, ν)^{7}Li in a hot convective layer (Cameron and Fowler 1971).

Today, mass transfer from an AGB star to a less evolved companion in a binary system is advanced as the origin of a variety of peculiar stars, the stars created from the less evolved companion. In particular, the classical and mild barium stars and the subgiant and giant CH stars may be the products of mass transfer across a binary. Thanks to the possibility that the AGB star may have been Li-rich, measurements of the Li abundance in the barium and the other peculiar stars provide a test of the mass-transfer hypothesis. Since atmospheric Li can be destroyed and diluted in the course of stellar evolution, comparisons of the abundance in different classes of peculiar stars may provide clues to their kinship.

In this paper, we determine upper limits to the Li abundance in one giant and 10 subgiant CH stars and explore the implied constraints on the hypothesis that the CH subgiants are mass-transfer products. In particular, we examine whether these stars are related to the mild and classical barium stars, which share many of the same abundance anomalies, e.g., high ^{12}C and *s*-process abundances (see review by Lambert 1985). To illustrate one test provided by Li, consider the hypothesis that the subgiant CH stars are the progenitors of the more luminous classical barium stars, as suggested by Luck and Bond (1982). The subgiants are expected to have a shallow convective envelope, but the barium stars, being giants, have the deep convective envelope of a red giant. Then, if the subgiants evolve to barium stars, these inferred structural differences demand that the Li abundance of subgiant CH stars should be at least 50 times as great as the abundances found for barium stars; the factor of 50 is the expected mass ratio of a giant's deep convective envelope and the shallow outer zone of the subgiant in which Li survives. Our abundance analyses, the first to provide information on Li in a number of subgiant CH stars, show that Li is at or below the concentrations reported for the classical barium stars and, hence, the hypothesis must be rejected. After presenting our abundance analyses in § II, we combine the available information of Li with other evidence and explore possible evolutionary links between the subgiant CH stars and the more evolved CH giants, mild barium, and classical barium stars.

II. OBSERVATIONS AND ABUNDANCES

We obtained spectra covering the 6707 Å Li I doublet in 10 subgiant CH stars and the giant CH star HD 26. Observations were made using the McDonald Observatory's 2.7 m telescope, coudé spectrograph, and either a Digicon intensified diode array (Tull, Choisser, and Snow 1975) or a Reticon silicon diode array (Vogt, Tull, and Kelton 1978). Approximately 100 Å of spectra were recorded at a resolution of 0.2 Å. One star, HD 176021, was observed at a resolution of 0.12 Å with the coudé echelle spectrometer (Enard 1979) and the 1.5 m telescope of the European Southern Observatory. Figure 1 illustrates the Li I region in two Digicon spectra from McDonald. Note the expanded intensity scale.

In no star did we detect the Li I doublet. Upper limits to its equivalent width (W_λ) were estimated in two ways. Initially, an upper limit was established by drawing a continuum level by eye and sketching a line profile that was just larger than the noise fluctuations; we refer to this method as providing an "eye" estimate. A more reproducible, quantitative estimate was made by calculating the noise in a smooth, continuum region. Approximately 4 Å (~35 Digicon diodes) of smooth spectra were averaged and the standard deviation σ computed.

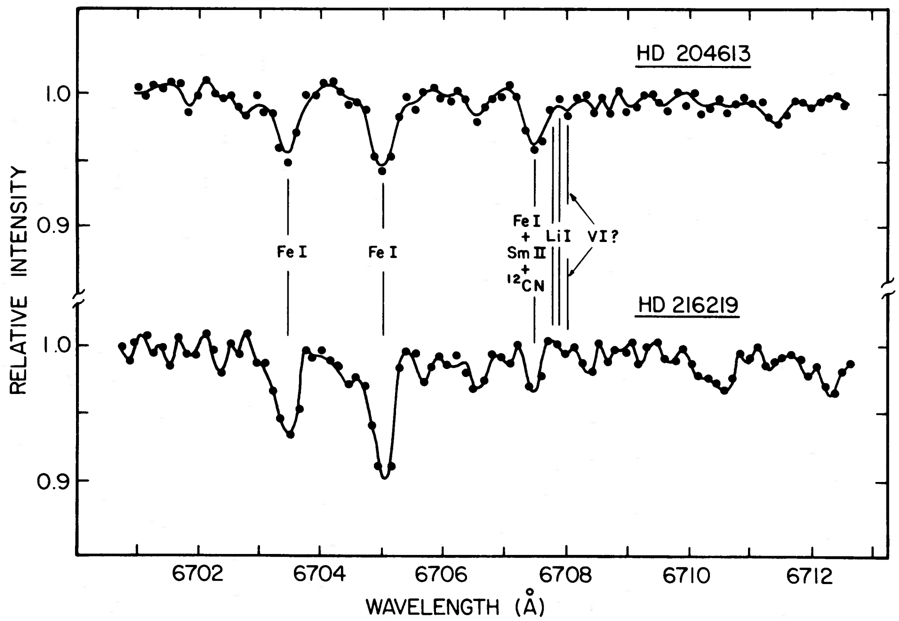

FIG. 1.—Sample McDonald Observatory Digicon spectra of the Li I doublet region in two subgiant CH stars

TABLE 1

OBSERVATIONAL INFORMATION

Star	V (mag)	Signal-to-Noise Ratio	Upper Limit to W_λ(Li I) (mÅ): 2 σ Line Depth	By Eye
HD 26	8.2	55	11	10
HD 4395	7.7	86	7	8
HD 11377	8.5	40	15	20
HD 88446	7.9	110	5	7
HD 89948	7.7	81	7	5
HD 125079	8.5	79	7	4
HD 176021	7.6	106	6	5
HD 182274	7.8	128	4	4
HD 204613	8.2	85	7	6
HD 207585	9.8	35	17	8
HD 216219	7.5	108	5	5

By identifying other weak features in the spectra, it was determined that any feature deeper than about 2 σ in depth would be readily detectable. The widths of weak lines in our spectra could be measured (typically, full width at half-depth was about 0.28 Å) and this width applied to the Li I doublet, which consists of two unresolved components for each isotope split by ~ 0.15 Å. Using a central-line depth of 2 σ, an estimated full width at half-depth, and a Gaussian approximation to the line shape, upper limits to the equivalent width were computed. In Table 1 we list the stars observed, their apparent V-magnitudes, the signal-to-noise ratio of the spectra as estimated from the computer σ's, and the upper limits to the equivalent widths of the Li I feature obtained from the 2 σ line-depth method and by eye. Note that the "eye" estimates generally agree fairly well with the more quantitative estimates.

Most stars in this sample have been studied in detail by previous observers (Sneden and Bond 1976; Luck and Bond 1982, hereafter LB; Sneden 1983; Krishnaswamy and Sneden 1985), and we have adopted their atmospheric parameters (effective temperature $T_{\rm eff}$, surface gravity g, and microturbulent velocity ξ). In Table 2 we present the adopted parameters, the metal abundance [Fe/H], and the source of this information. Sneden (1983) points out that LB's microturbulent velocities are considerably larger than values he obtained for the same stars (typically 1.5–2.0 km s^{-1} as opposed to 3.0–4.0 km s^{-1}). Since Sneden's spectra are of higher quality than LB's, we presume that his values are to be preferred, and for stars for which we use LB's values for $T_{\rm eff}$ and log g, we assume that $\xi = 1.5$ km s^{-1}. Larger values of ξ will, of course, have a negligible effect on derived Li abundances because of the very small upper limits to the Li I equivalent widths. Also in Table 2 we list values for the absolute visual magnitude, M_v, as estimated by LB from derived values of $T_{\rm eff}$, log g, and an assumed mass of 1.0 $M_\odot$ (accurate to within a factor of 2 given that these stars are old disk or even halo objects). LB estimate that these values of M_v are accurate to within ± 0.8 mag.

Two stars in our list, HD 125079 and HD 207585, have not

TABLE 2

STELLAR PARAMETERS

Star	$T_{\rm eff}$ (K)	log g (cgs)	ξ (km s^{-1})	[Fe/H]	M_V	Source[a]
HD 26	5250	2.50	2.5	−0.4	0.3	LB
HD 4395	5450	3.30	1.5	−0.3	2.1	S
HD 11377	6000	4.10	1.5[b]	−0.2	3.8	LB
HD 88446	6000	4.50	1.5[b]	−0.4	4.8	LB
HD 89948	5950	4.10	1.0	−0.5	3.8	S
HD 125079	5300	3.50	1.5[b]	−0.3	...	This study
HD 176021	6000	4.00	2.0	−0.4	3.5	SB
HD 182274	6000	4.50	1.5[b]	−0.4	4.8	LB
HD 204613	5650	3.75	2.0	−0.5	3.1	S
HD 207585	5400	3.50	1.5[b]	−0.5	...	This study
HD 216219	5600	3.25	1.0	−0.3	2.0	S

[a] SB = Sneden and Bond 1976; LB = Luck and Bond 1982; S = Sneden 1983.

[b] Assumed (see text).

TABLE 3

Atomic Line Data and Equivalent Widths

Species	λ (Å)	χ (eV)	log (gf)	Equivalent Width (mÅ) HD 26	HD 4395	HD 11377	HD 88446	HD 89948	HD 125079	HD 176021	HD 182274	HD 204613	HD 207585	HD 216219
Fe I	6703.57	2.76	−3.05	45	32	20	17	19	50	10	13	21	19	23
	6705.11	4.61	−1.12	47	40	26	24	27	52	15	21	26	26	34
Ca I	6717.69	2.70	−0.54	119	101	92	66	76	110	53	70	81	68	99
Al I	6696.03	3.14	−1.44	28	38	28	20	19	49	11	20	30	20	21
	6698.67	3.14	−1.78	21	23	16	10	10	32	6	9	13	...	10

been analyzed before, and we have estimated $T_{\rm eff}$ and log g for them. Broad-band *UBVRI* magnitudes are available for HD 207585 from Eggen (1975). Its $(B-V) = +0.70$ and the temperature calibration from Böhm-Vitense (1981) for the metallicity range $-0.5 <$ [Fe/H] < 0.0 lead to $T_{\rm eff} = 5400$–5540 K. The metal lines of the star appear quite weak, so we adopt the lower temperature of $T_{\rm eff} = 5400$ K as the more appropriate for this metal-poor star. Washington photometric magnitudes, CMT_1 T_2, for HD 125079 have been measured by one of us (V. V. S.), and the star's $(T_1 - T_2)$ color of $+0.38$ plus the temperature calibration from Harris (1980) yield $T_{\rm eff} = 5300$ K. Our spectral coverage is inadequate to yield a spectroscopic log g, so we have estimated a value for gravity by noting that other stars in this sample with $T_{\rm eff} \approx 5400$–5600 K have log $g \approx 3.2$–3.7. For both stars we assign a value of log $g = 3.5$.

Additional lines are available in this spectral region due to the species Fe I, Al I, and Ca I. Lines from these species were analyzed as checks on the atmospheric parameters and the values of [Fe/H] extracted from the literature or estimated by ourselves. In Table 3 we list the lines used along with their values of W_λ, excitation potentials, and LTE solar gf-values derived using our measured solar equivalent widths from the Liège atlas (Delbouille, Neven, and Roland 1973) and the solar atmosphere of Holweger and Müller (1974) with a microturbulent velocity of 0.8 km s^{-1}. We note that the 6717.69 Å Ca I line is slightly blended to the blue by a weak Fe I line, but the blending can be estimated, and in no case is the offending line very strong.

Synthetic equivalent widths were computed for each line using a modified version of the LTE spectrum synthesis program from Sneden (1974). Element abundances were varied until a match with the measured equivalent widths was obtained. The Li I feature was synthesized and the predicted profile integrated for an equivalent width. The gf-values for the Li I lines were taken from the recent study of Li isotopes by Andersen, Gustafsson, and Lambert (1984).

The subgiant CH stars are not very different in $T_{\rm eff}$ and log g from the Sun, so scaled solar atmospheres were generated from the Holweger and Müller (1974) solar atmosphere for the particular $T_{\rm eff}$–log g–[Fe/H] combination. The giant CH star HD 26 is the most different from the Sun, and, as a test of the appropriateness of using a scaled solar atmosphere, abundances were also determined using a model atmosphere from the grid of metal-poor giants in Bell *et al.* (1976, hereafter BEGN). The differences, in the form of log $\epsilon(X)_{\rm scaled\ solar}$ − log $\epsilon(X)_{\rm BEGN}$, were +0.11 (Fe I), +0.07 (Al I), −0.03 (Ca I), and 0.00 (Li I). These are not significant to our results, hence scaled solar atmospheres are appropriate for our purposes.

Our results are presented in Table 4 as values of [X/H] for Fe, Al, and Ca, and an absolute upper limit, based upon the scale log ϵ(H) = 12.0, for the lithium abundance. A comparison of Table 4 and Table 2 shows that our determinations of [Fe/H] are in good agreement with other investigations; of course, ours are not completely independent because we adopted published atmospheric parameters. The values of [Al/H] and [Ca/H] are also in fair agreement with [Fe/H] although there is a noticeable tendency for Al and Ca to be enhanced relative to Fe: the mean values are [Al/Fe] = +0.16 and [Ca/Fe] = +0.12. Although these results are consistent with those obtained for moderately metal-poor dwarfs (Tomkin, Lambert, and Balachandran 1985), this agreement cannot be claimed to be very significant. In each star the Ca I line was strong enough to be affected by saturation, so a careful determination of the microturbulence is required, while the Al I lines were often so weak as to be near the limits of detectability. These comparisons do indicate that our upper limits to the Li abundances are not strongly influenced by systematic effects or improper analyses.

TABLE 4

Derived Abundances

Star	[Fe/H]	[Al/H]	[Ca/H]	log ϵ(Li)
HD 26	−0.45	−0.33	−0.27	<0.8
HD 4395	−0.38	−0.10	−0.10	<0.7
HD 11377	−0.30	−0.07	0.00	<1.5
HD 88446	−0.38	−0.27	−0.46	<1.2
HD 89948	−0.31	−0.29	−0.20	<1.3
HD 125079	−0.30	−0.04	−0.27	<1.0
HD 176021	−0.61	−0.53	−0.63	<1.2
HD 182274	−0.47	−0.29	−0.40	<1.2
HD 204613	−0.54	−0.24	−0.48	<0.9
HD 207585	−0.74	−0.51	−0.71	<1.5
HD 216219	−0.39	−0.39	−0.06	<0.7

The effects of uncertainties in the model atmosphere parameters are illustrated by comparison of the abundances derived from a typical atmosphere ($T_{\rm eff} = 5800$ K, log $g = 3.5$, $\xi = 1.5$ km s^{-1}, and [Fe/H] = −0.3) with those obtained by varying each of the model parameters. Using a 60 mÅ Ca I line, a 20 mÅ Al I (6696 Å) line, a 30 mÅ Fe I (6705 Å) line, and a 5 mÅ Li I line, we obtain the differences, in Δ log ϵ(X), shown in Table 5.

III. LITHIUM AND THE MASS-TRANSFER HYPOTHESIS

When the class of subgiant CH stars was introduced by Bond (1974), these stars were considered to be Population II and to be possible progenitors of the giant CH stars (Keenan 1942). Today the subgiant CH stars may be considered a mixture of Population I and Population II stars. As the metal abundances (Tables 2 and 4) show, our selection does not include a true Population II star; note, too, that the prototypical giant CH star HD 26 is indistinguishable by metal abun-

TABLE 5

DEPENDENCE OF DERIVED ABUNDANCE ON MODEL ATMOSPHERE PARAMETERS

Species	log (W/λ)	$\Delta T_{\text{eff}} = +100$ K	$\Delta \log g = +0.5$	$\Delta\xi = +0.5$ km s^{-1}	Δ[Fe/H] $= +0.1$
Fe I	−5.35	+0.05	−0.01	−0.04	0.00
Al I	−5.52	+0.04	−0.01	−0.01	0.00
Ca I	−5.05	+0.06	−0.04	−0.08	0.00
Li I	−6.13	+0.09	−0.01	0.00	0.00

dance from the selected subgiant CH stars and many mild and classical barium stars—e.g., the mild Ba star *o* Vir has [Fe/H] $= -0.4$ (Tomkin and Lambert 1985) and the classical Ba star HR 774 has [Fe/H] $= -0.3$ (Tomkin and Lambert 1983; Smith 1984). Furthermore, the carbon and *s*-process enrichments of our subgiant CH stars span the range found for mild and classical Ba stars (see Lambert's 1985 review for discussion and references). The discovery that the Ba stars occur only in binary systems (McClure, Fletcher, and Nemec 1980; McClure 1983) and the close correspondence between the ^{12}C and *s*-process enrichments in carbon-rich and oxygen-rich AGB stars and those seen in Ba stars (Lambert 1985; Smith and Lambert 1985) encourage the hypothesis that Ba stars are formed by mass transfer across a binary from an AGB star to its companion. Since subgiant CH stars are binaries too (McClure 1985), with a composition similar to that of the Ba stars, this suggests that subgiant CH stars are also products of mass transfer. In Figure 2 we show the location of the subgiant CH stars in an H-R diagram. Representative classical and mild Ba stars from Böhm-Vitense, Nemec, and Proffitt (1984) are also shown. We do not show the two subgiant CH stars for which we do not have spectroscopically derived gravities. Theoretical models from Iben (1967*a*, *b*) are also shown; these particular models were chosen because Li depletion factors, relative to its main-sequence value, were given and are shown along the model tracks for 1.0, 1.25, and 1.5 $M_\odot$ stars.

We begin by discussing mass transfer onto a main-sequence companion (see Iben and Tutukov 1985). If transfer occurs via Roche lobe overflow at a high rate, it appears most likely that a common envelope is created around the two stars, and rapid collapse of the orbit (a "spin-down") is followed by ejection of the envelope to create a planetary nebula with the binary evolving to become a cataclysmic variable (Paczyński 1976; Meyer and Meyer-Hofmeister 1979). Discoveries of close binaries as the central objects of planetary nebulae (Bond, Liller, and Mannery 1978) support this scenario.

At a lower mass-transfer rate, the main-sequence star develops an extended envelope resembling a giant. This is the expected result for rates $\dot{M}_{\text{tr}} > M_{\text{MS}}/\tau_{\text{KH}}$, where $\dot{M}_{\text{tr}}$ is the mass-transfer rate, M_{MS} is the main-sequence star's mass, and τ_{KH} is its Kelvin-Helmholtz time; this condition is $\dot{M}_{\text{tr}} > 3 \times 10^{-8}$ $M_\odot$ yr^{-1} for a 1 $M_\odot$ star. Such transfer rates might occur as

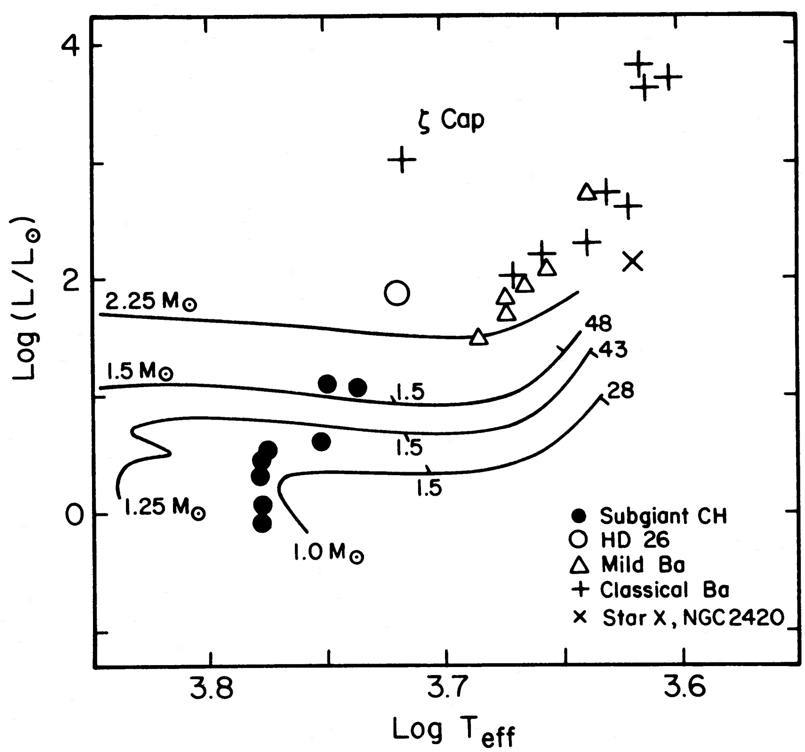

FIG. 2.—Luminosity–surface temperature diagram for the subgiant CH stars (*filled circles*) and the giant CH star HD 26 (*open circle*). Classical barium stars (*plus signs*) and mild barium stars (*open triangles*) from Böhm-Vitense, Nemec, and Proffitt (1984) are shown along with the classical barium star in the old open cluster NGC 2420 (*cross*), which has a well-determined distance, from McClure, Forrester, and Gibson (1974). Theoretical models from Iben (1967*a*, *b*) are shown with predicted Li depletions, relative to the main-sequence abundance, indicated along the model tracks.

the star accretes mass lost from the AGB star through a wind or an ejection of the envelope. On the cessation of mass transfer, the smaller envelope collapses and the secondary reassumes a main-sequence appearance, albeit now with a peculiar composition. This composition, even after some mixing between the transferred mass and the underlying layers, seems likely to resemble that of the subgiant CH stars. The collapse back to the main sequence occurs quickly (on a Kelvin-Helmholtz time scale). As Iben and Tutukov (1985) remark, this scenario cannot account for the majority of the giant Ba stars. With the collapse spanning just a fraction (10^{-4}) of the nuclear lifetime of a normal giant, the predicted frequency of Ba stars is, at most, 1 among every 10^4 normal giants, whereas the observed frequency is about 1 among 10^2 (MacConnell, Frye, and Upgren 1972). However, this scenario may account for the subgiant CH stars.

At low mass-transfer rates, $\dot{M}_{tr} < M_{MS}/\tau_{KH}$, the main-sequence companion is simply coated with mass from the AGB star. The thin convective envelope of the main-sequence star may mix the outer layers and so slightly reduce the abundance anomalies. Again, the star would be classified as a subgiant CH star.

Our working hypothesis is that our subgiant CH stars are products of mass transfer across a binary. Certainly, McClure's (1985) radial velocity survey suggests strongly that the stars belong to long-period binary systems with a low-luminosity companion. Bond (1984) describes an unsuccessful search with the *International Ultraviolet Explorer* (*IUE*) satellite for an ultraviolet excess attributable to a white dwarf in some 21 CH subgiants. He concludes that the white dwarf, if present, must have a surface temperature cooler than 12,000 K. A white dwarf can cool to this temperature in about 10^9 yr (Sweeney 1976). Bond points out that if the CH subgiants have white dwarf companions with a uniform distribution of ages over 5×10^9 yr, and if a white dwarf is detectable for 10^9 yr, some 20% of the sample, or about four stars, should have detectable white dwarf companions. However, one could argue that the CH subgiants, as a group, are older than 5×10^9 yr and closer to 10^{10} yr, in which case the above argument would predict only two detections. The lack of detections would not be a statistically significant event. In addition, Bond's argument ignores interstellar extinction, which, for a color excess of as little as a few hundredths of a magnitude in $(B-V)$, could have a significant (> 50%) effect on the ultraviolet flux near 1500 Å. *IUE* does not have the sensitivity to test thoroughly the presence, or lack thereof, of degenerate companions. A rigorous analysis must await the Space Telescope.

Another potential problem with the mass-transfer hypothesis, as pointed out by Bond (1984), concerns the rather narrow range of spectral types seen for the subgiant CH stars. If mass transfer from an AGB star onto an "innocent bystander" is the mechanism, then the Ba/CH star phenomena should be seen all along the main sequence. It is not clear, however, that low-dispersion classification would necessarily detect the hotter CH-like stars. In Abt, Morgan, and Tapscott (1968), it is noted that, at their dispersion of 125 Å mm^{-1}, the G band is first discernible at F2 V. Bond's (1974) discovery paper of the CH subgiants was based upon spectra of 108 Å mm^{-1}. A main-sequence spectral type of F2 corresponds to roughly 1.5 $M_\odot$, and some of the subgiant CH stars in this study fall quite close to 1.5 $M_\odot$ evolutionary tracks (see Fig. 2). The detection of F and earlier types of main-sequence examples of the Ba/CH stars probably requires careful, high-resolution studies of a large number of stars. Concerning late G or K dwarf CH/Ba stars, we point out that, owing to their low luminosities, such stars would be difficult to detect. Certainly, more careful surveys of dwarfs are warranted to sort out these uncertainties.

There are, of course, alternative hypotheses to mass transfer, such as the suggestion by LB that CH subgiants are stars that have undergone a violent He-core flash followed by extensive mixing of H back into the stellar core, sending the star onto or near the core hydrogen-burning main sequence. This scenario, and a similar He-core flash mechanism for the Ba/CH giants, does not directly address the problem of why such violent events occur only in wide binaries. Suggestions that the companion may somehow influence the internal structure of the Ba/CH star and cause a more violent He-core flash are not currently testable by realistic (i.e., three-dimensional, rotating core flash) models. We prefer to compare our results with a mass-transfer idea because such a hypothesis is testable with observations to true AGB stars and models of third dredge-up on the AGB. Such a picture has certainly not been proved conclusively, and further observations of large numbers of dwarf stars plus UV observations from the Space Telescope are in order.

The mass-transfer hypothesis requires that there be close similarities between the composition of AGB (probably the carbon stars) and subgiant CH stars. Qualitatively, this is correct. Both families are carbon- and *s*-process–enhanced to about the same extent (see Lambert *et al.* 1985 and Utsumi 1985 for information on carbon and the *s*-process in carbon stars, respectively, and Lambert 1985 for a review of the subgiant CH stars). For lithium the test is less exacting because good quantitative data on Li in carbon stars are unavailable. Torres-Peimbert and Wallerstein (1966) give a "Li-index" for a sample of carbon stars, while Wallerstein and Conti (1969) convert the indices to abundances and report log ϵ(Li) ~ 1.1, on average, for seven carbon stars. The very Li-rich examples, such as WZ Cas, are quite rare and are excluded from this sample. This mean value is compatible with the upper limits for the present sample of subgiant CH stars. Depletion of lithium in a main-sequence CH star would not be unexpected, since normal main-sequence stars of the same surface temperature show significant depletion; e.g., the Sun's abundance, log ϵ(Li) ~ 1.0, is a factor of 100 below the cosmic abundance. Again, the working hypothesis passes the test, but additional abundance analyses and, if possible, better spectra are required before the test may be considered stringent.

With close parallels in their compositions, subgiant CH stars would appear to be possible progenitors of the Ba giants. Our Li abundances show that this is unlikely. As the subgiant CH star evolves up the red giant branch, the convective outer envelope grows inward and the surviving Li on the surface is diluted. On the assumption that the CH star may be represented by standard theoretical models, its surface Li, at the base of the red giant branch, ranges from a factor of 28 at 1 $M_\odot$ to a factor of 48 at 1.5 $M_\odot$ (see Fig. 2) less than the abundance immediately following main-sequence evolution (Iben 1967*a*). In Figure 3 we compare the observed Li abundances for samples of subgiant CH, mild Ba, and classical Ba stars with the predicted (i.e., diluted) abundances for the CH stars when they become red giants. We use a dilution of 45 in the latter case. For the classical Ba stars we adopt the sample of 14 analyzed by Pinsonneault, Sneden, and Smith (1984). Clearly, these stars contain too much Li to be identified as descendants of subgiant CH stars. If Li abundance (and C and *s*-process) is

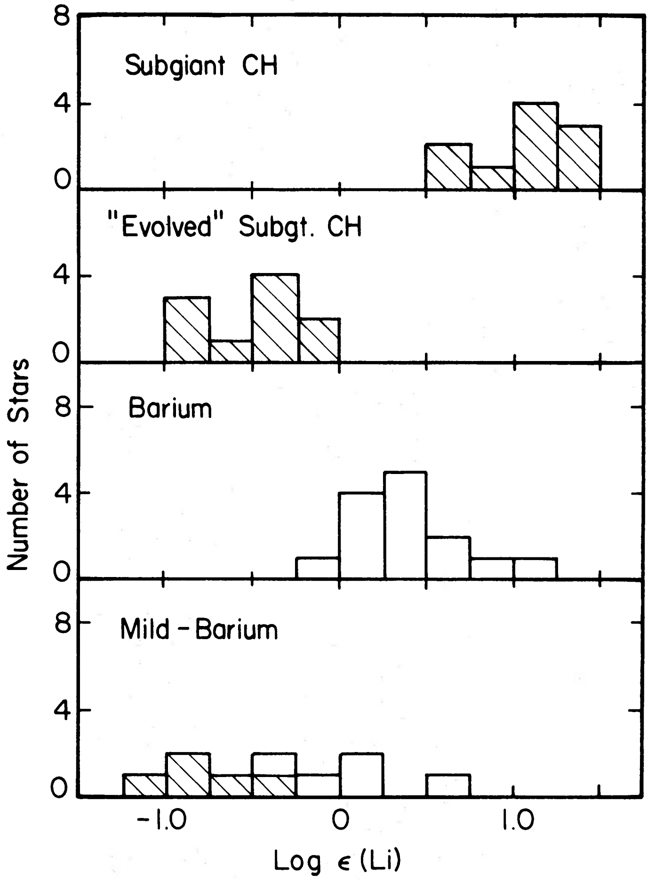

FIG. 3.—Histograms of the derived Li abundances in subgiant CH, "evolved" subgiant CH, classical barium, and mild barium stars. Cross-hatching indicates upper limits. "Evolved" subgiant CH stars are the subgiant abundances diluted by a factor of 45 (see text).

the key criterion, the CH stars could be the progenitors of some of the mild Ba stars—again the Li abundances are provided by Pinsonneault, Sneden, and Smith (1984). Such an evolutionary connection is broken by the fact that some mild Ba stars are accompanied by hot white dwarfs (Böhm-Vitense, Nemec, and Proffitt 1984; Böhm-Vitense and Johnson 1985). Böhm-Vitense *et al.* note that all mild Ba stars may have a hot white dwarf companion. If true, mild Ba stars join the classical Ba stars in having no evolutionary tie to the CH stars.

If the mass transferred to the subgiant CH star is confined to a thin layer, abundance anomalies will be reduced greatly by the giant's convective envelope which encompasses about half the stellar mass. Highly precise abundance analyses of a sample of giants might reveal such stars.

To complete discussion of mass transfer, we comment on the speculation that the classical barium stars may result from transfer onto a giant. Although Iben and Tutukov (1985) call this "the most promising scenario," they are unable to identify specific principal reasons why the companion has to be a giant rather than a main-sequence star. Rapid mass transfer by Roche lobe overflow seems likely to lead to a common envelope and finally to a close binary containing a pair of white dwarfs. Lower rates of mass transfer will lead to pollution of the giant's convective envelope. Large amounts of mass (M_{tr}) must be transferred to create the extreme Ba stars with carbon and *s*-process enhancements close to those estimated for the carbon AGB stars, say $M_{tr} \sim M_{CE} \sim 0.5\, M_*$. We speculate that the giant with its large cross section captures substantially more material than a main-sequence companion would. The latter does lack a deep convective envelope, and so little mass is required to produce marked abundance anomalies; on the other hand, the hot wind off the main-sequence star may inhibit accretion.

The observed correlation between the carbon and *s*-process abundances of mild and classical Ba stars (Lambert 1985) follows if the stars capture increasing amounts of material from the AGB star. Moreover, the composition of the extreme Ba stars is very similar to that of carbon AGB stars, although the Li abundances in Ba stars appear to be below those (uncertain) values reported for carbon stars. Another concern is the fact that the lifetimes of giants ($\sim 10^8$–10^9 yr) are shorter than the cooling time for a white dwarf. Hence, white dwarf companions ought to be seen in all cases. Dominy and Lambert (1983) reported on Ba stars for which the white dwarf, if present, was cooler than about 7000 K. This limit corresponds to about 2×10^9 yr and would seem to require that the Ba star had formed as a main-sequence star. Perhaps the addition of a substantial amount of material lengthens the giant's lifetime. If the mass transfer leaves material in and around the binary, local obscuration may result in an overestimate of the observable white dwarf's luminosity. Significantly, Ba stars do possess an infrared excess (Catchpole and Feast 1977), which may well be the signature of circum-binary dust.

One clear conclusion is provided by this paper: the subgiant CH stars are not the progenitors of the mild and classical Ba stars. This follows from the comparison of the Li abundances and the presence of hot, observable white dwarf companions with some of the giants. The true descendants of the subgiant CH stars may be giants with very small *s*-process enhancements, i.e., a subset of the mild Ba stars or giants with even smaller abundance anomalies.

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