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THE LITHIUM ABUNDANCE IN HALO STARS

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ABSTRACT

Spectra of 54 stars obtained in the region of the Li I λ6707 line are reported. The primary group of stars investigated consists of 23 halo stars with space velocities $|v_{LSR}| \geq 100$ km s^{-1} and metallicities [Fe/H] ≤ -0.6. Twelve of these 23 show the more extreme properties $|v_{LSR}| \geq 160$ km s^{-1} and [Fe/H] ≤ -1.4 and should therefore constitute an especially old, homogeneous subgroup. The principal results for these 12 extreme halo stars and five similar stars observed in previous studies are that (1) a single, well-defined relation, previously discovered and discussed by Spite and Spite, exists without exception between the atmospheric Li/H ratio and T_e, and (2) at $T_e \geq 5600$ K the average lithium abundance is $\langle \text{Li/H} \rangle = 1.2 \pm 0.3 \times 10^{-10}$. The latter value constitutes a lower limit on the ^{7}Li fraction produced in primordial nucleosynthesis and thereby significantly constrains the cosmic ratio of baryons to photons. With several important exceptions, similar results are found for the larger group of 23 halo stars. The evolution and the implications of the Galactic lithium abundance are briefly rediscussed.

Subject headings: nucleosyn thesis—stars: abundances — stars: weak-line

I. INTRODUCTION

Accurate measurements of the abundance of lithium in the surface layers of both old and young stars and in the interstellar medium can increase our knowledge of stellar structure, Galactic element production, and big bang nucleosynthesis. The latter subject recently has been reviewed by Boesgaard and Steigman (1985). Observational efforts to measure the lithium abundance in stars sufficiently old to test theoretical estimates of ^{7}Li production in the prestellar universe were pioneered by Spite and Spite (1982, hereafter SS) and by Spite, Maillard, and Spite (1984, hereafter SMS). This paper presents new observations which confirm and extend their work.

In conventional theoretical models of the Sun, temperatures hot enough to destroy lithium are reached somewhat below the base of the convective envelope. Nevertheless, the present abundance of lithium in the solar atmosphere probably is at least 100 times smaller than its initial main-sequence value. This deficiency points to a mechanism, as yet not conclusively identified, which has destroyed nearly all of the lithium in the solar envelope. In stars of spectral type A and hotter, the surface convection zone vanishes, and the surface lithium may be preserved throughout the main-sequence lifetime of such stars. In these hotter stars, however, the one strong line of lithium present in the visible spectrum, Li I λ6707, is made undetectably weak by the essentially complete ionization of lithium.

The discovery by SS that lithium is present in halo stars of approximately solar temperature in amounts at least 10 times the solar value was therefore surprising and important. The great age of the halo stars and the uniformity of the Li/H ratio in such stars with $T_e \gtrsim 5600$ K led those authors to conclude that the lithium in these stars was produced in the big bang and has subsequently remained effectively unmodified. An explanation of how the lithium abundance in such halo stars can exceed the value observed in the younger Sun may be related to their lower metallicities. Calculations by Däppen (1984) and by D'Antona and Mazzitelli (1984) show that convective zones become cooler at the base and thinner, as the metal abundance is reduced at a fixed stellar effective temperature. The rate of lithium destruction, which depends strongly on temperature, may therefore be severely reduced in the halo stars.

What may be a related effect was discussed by Duncan (1981). Chromospheric activity and lithium abundance are two phenomena related to age in solar-type stars. Most such stars exhibit either high activity and high Li/H ratios, indicating youth, or low activity and low lithium abundance, indicating advanced age (Herbig 1965). About 15% show a different pattern, however. In all cases the discrepancy is in the sense of low chromospheric activity combined with a high lithium abundance. Duncan tentatively concluded that these stars are in fact old but have somehow preserved their lithium from destruction. The anomalous stars included the most metal-poor stars in Duncan's sample, but no star was more metal-poor than [Fe/H] = −0.6, and not all of the anomalous stars were of low metallicity.

Stimulated by the initial results of SS, we independently set out in 1983 to extend those results to a larger number of subdwarfs chosen to be as homogeneously old as possible. Our separate results are combined in this paper, in which measurements of the Li I λ6707 doublet at a resolution typically of 0.25 Å are reported for a primary group of 23 subdwarfs with iron abundances [Fe/H] ≤ -0.6 and space velocities $v = |v_{LSR}| \geq 100$ km s^{-1}. Twelve of these stars in fact are extreme halo stars

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which show [Fe/H] ≤ -1.4 and $v \geq 160$ km s^{-1}. Li I equivalent widths are also described for a separate, highly varied group of 31 additional stars of interest, most of them F and G dwarfs of Population I. The results meanwhile published by SMS have brought to 14 the number of λ6707 equivalent widths measured here in our primary group of 23 stars which already have been published by SS and SMS. Nevertheless, the nine new spectroscopic subdwarf abundances, the independent measurements of 14 other subdwarfs in common with SMS, and the data for 31 additional stars of interest should add usefully to the subject.

II. OBSERVATIONS AND RESULTS

a) The Stars Observed

In order to isolate a group of uniformly old stars, two criteria—one chemical, the other kinematic—were used together to select the primary sample of 23 stars listed in Table 1. First, with the two exceptions of HD 29587 and HD 201889, a previously published, apparently reliable, spectroscopic analysis of each star's abundances had yielded [Fe/H] = log $\{[n(\text{Fe})/n(\text{H})]/[n(\text{Fe})/N(\text{H})]_\odot\} \leq -0.6$. The less accurate estimates of [Fe/H] for HD 29587 and HD 201889 enclosed in parentheses in Table 1 have been derived by interpolating, from our own spectra, the strengths of a few Fe I lines and the Ca I line near λ6707 in these two respective spectra among the corresponding lines of the other stars in Table 1. The other, more accurate iron abundances in the last column of Table 1 are taken from either Carney (1979) or Peterson (1981); the prior existence of such analyses was a primary requirement which governed the course of this work. Very similar iron abundances in six of the stars have been independently derived by Tomkin, Sneden, and Lambert (1986). The second criterion for the inclusion of stars in Table 1 was that v, the magnitude of the star's space velocity with respect to the local standard of rest, must exceed 100 km s^{-1}. The values shown in column (7) of Table 1 have been calculated anew from the distances in column (6), the radial velocities and the proper motions referred to in columns (8) and (9), respectively, and the basic solar motion of Delhaye (1965). With the six exceptions enclosed in parentheses, the distances in Table 1 are derived from trigonometric parallaxes listed in the *Parallax Catalogue* (Jenkins 1952) or its *Supplement* (Jenkins 1962); or, for four of the brightest stars, in the *Bright Star Catalogue* (Hoffleit 1982) or its *Supplement* (Hoffleit, Saladyga, and Wlasuk 1983); or, for HD 157089 (= BD +1°3421), by Villki, Welty, and Cudworth (1986). In contrast, for six of the seven stars fainter than $V = 8.7$, more uncertain photometric estimates of the distances necessarily have been used, because direct parallaxes either have not been published or are little larger than their errors. The photometric distances enclosed in parentheses therefore have been calculated from absolute visual magnitudes assumed to be 0.5 mag fainter than those of Population I main-sequence stars (Blaauw 1963) with the same $(R-I)$ color. No corrections were applied for interstellar absorption or

TABLE 1

POPULATION II DWARFS

HD/BD (1)	V (2)	$B-V$ (3)	$R-I$ (4)	References (5)	d (pc) (6)	$\lvert v_{\text{LSR}}\rvert$ (km s^{-1}) (7)	RV References (8)	PM References (9)	[Fe/H] (10)
6582[a]	5.16	0.70	0.43	1	7.7	160.	3	7	−0.6
19445	8.06	0.46	0.33	1	48.	230.	3	8	−2.1
22879	6.68	0.54	0.35	1	23.	120.	3	8	−0.6
29587	7.28	0.63	0.36	2	42.	170.	3	7	(−1.0)
64090	8.27	0.61	0.41	2	26.	340.	3	8	−1.6
LP 608−62[b]	10.47	0.36	0.27	2	(170.)	430.	4	9	−2.7
84937	8.31	0.39	0.28	2	40.	160.	3	7	−2.1
94028	8.22	0.48	0.33	2	44.	120.	3	7	−1.7
103095[c]	6.45	0.75	0.45	1	9.3	330.	3	7	−1.4
106516	6.12	0.46	0.29	2	29.	140.	3	8	−0.9
108177	9.67	0.43	0.32	2	32.	170.	3	7	−1.9
+34°2476	10.05	0.40	0.29	2	(130.)	300.	3	9	−2.3
140283	7.22	0.49	0.31	1	32.	230.	3	8	−2.6
148816	7.28	0.53	0.34	2	36.	250.	3	7	−0.7
157089	7.03	0.60	0.32	1	40.	160.	3	7	−0.6
160693	8.41	0.58	0.35	2	31.	160.	3	7	−0.7
+20°3603	9.76	0.44	0.30	2	(100.)	280.	5	7	−2.3
+26°3578	9.36	0.39	0.33	2	(70.)	130.	5	7	−2.6
188510	8.83	0.59	0.37	2	(40.)	190.	6	7	−1.8
201889	8.06	0.59	0.37	2	50.	140.	3	7	(−1.4)
201891	7.37	0.51	0.33	2	24.	110.	3	7	−1.4
+17°4708	9.47	0.44	0.34	2	(70.)	330.	5	7	−2.0
219617	8.14	0.45	0.33	1	40.	240.	3	8	−1.4

[a] μ Cas.

[b] Designation in the *NLTT Catalogue* (Luyten 1979). This subdwarf appears in neither the BD nor the HD catalog; in 1950, however, the star was about 1′ southwest of the visually slightly brighter, Population I star HD 83769 = BD +1°2341 (Joy 1947; Sandage 1964). A finding chart is given in the *LHS Atlas* (Luyten and Albers 1979).

[c] Groombridge 1830.

REFERENCES.—(1) Johnson, MacArthur, and Mitchell 1968. (2) Carney 1983. (3) Wilson 1953. (4) Popper 1943. (5) Abt and Biggs 1972. (6) This work: heliocentric radial velocity = −192 ± 3 km s^{-1}. (7) *AGK 3 Catalogue*. (8) *SAO Catalogue*. (9) *NLTT Catalogue* (Luyten 1979).

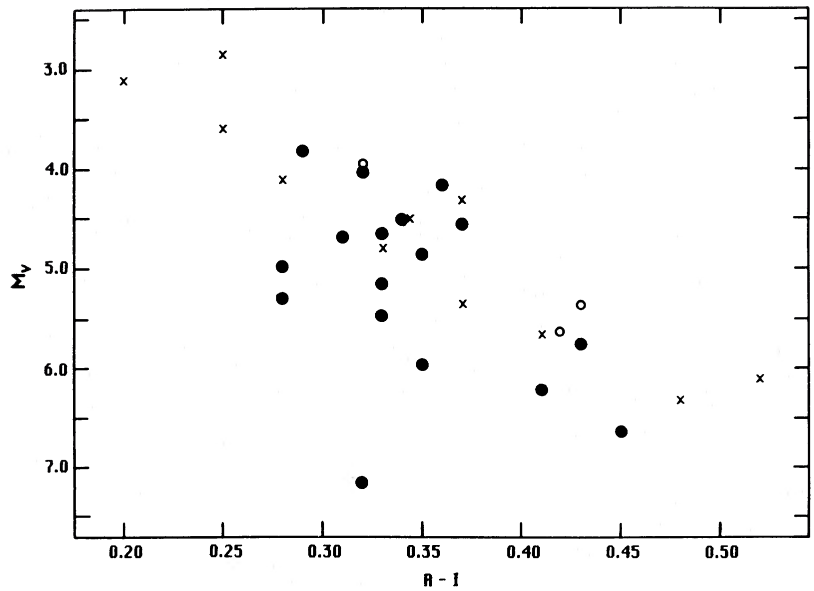

FIG. 1.—A color-magnitude diagram for 17 halo stars (Table 1) and three other stars (Table 2) which have trigonometric parallaxes. The halo stars are indicated by filled circles, and the other stars, by open circles. For comparison, the crosses show data for 11 main-sequence members of the Hyades cluster taken from Johnson, MacArthur, and Mitchell (1968); a distance modulus of 3.30 mag is assumed.

reddening, because all three stars for which $d > 70$ pc are at $|b| \geq 21°$ (Perry, Johnston, and Crawford 1982).

The resulting color-magnitude diagram shown in Figure 1 for the 17 stars with trigonometric parallaxes confirms that these stars are essentially unevolved, as well as chemically and kinematically old. The mean locus of the subdwarfs does appear to lie slightly below the Hyades main sequence, although the scatter in both sequences is fairly large. One subdwarf, HD 108177, lies well below all the other stars; its assumed distance modulus appears too small by about 2 mag, an error well outside that allowed by its nominal parallax.

While this primary program was being carried out, we also obtained comparable λ6707 observations of 31 additional, mostly brighter stars of interest which did not qualify for inclusion in the primary sample of stars. Seven of these 31 additional stars constitute the varied group listed in Table 2. BD +25°1981 and HD 122563 satisfy both the kinematic and the abundance criteria imposed in Table 1. However, the former star is a presumably younger "Population II blue straggler" with $T_e \approx 6900$ K (Carney and Peterson 1981), and the latter is an evolved Population II giant with $M_v \approx -2.1$ (Wolfram 1972). The other five stars in Table 2 satisfy one or the other, but not both, of the criteria utilized above. The format of Table 2 and the sources of the data listed there are similar to those for Table 1, except that the photometric distances to BD +25°1981 and HD 122563 are based on the absolute magnitudes $M_v = +4.0$ and $M_v = -2.1$ advocated respectively by Carney and Peterson and by Wolfram. The value [Fe/H] = −2.7 for HD 122563 also is taken from Wolfram's study. The three stars in Table 2 which have measured trigonometric parallaxes are also seen to be essentially unevolved, when they are plotted in Figure 1.

The remaining 24 stars among the additional group of 31 are a heterogeneous collection which will be loosely characterized here as "Population I dwarfs," owing to their relatively high metallicities and relatively low space velocities. They are listed in Table 3 and will be discussed separately in § IV. The distances in Table 3 are derived from trigonometric parallaxes or, in the case of the six members of the Pleiades or the Hyades, from cluster membership. When plotted in Figure 1, all of the

TABLE 2
OTHER STARS

HD/BD (1)	V (2)	$B-V$ (3)	$R-I$ (4)	References (5)	d (pc) (6)	$\lvert v_{LSR} \rvert$ (km s^{-1}) (7)	RV References (8)	PM References (9)	[Fe/H] (10)
65583	7.00	0.71	0.42	1	19.	94.	4	7	−0.6
−25°1981	9.29	0.30	0.20	2	(115.)	190.	5	7	−1.3
114762............	7.32	0.54	...	3	(25.)	79.	4	8	−0.8
122563............	6.19	0.91	0.58	1	(450.)	420.	4	7	−2.7
134169............	7.69	0.54	0.34	2	(30.)	31.	6	7	−1.6
208906............	6.96	0.50	0.32	2	40.	110.	4	7	−0.5
224930[a]	5.75[b]	0.67[b]	0.43[b]	1	12.	69.	4	7	−0.8

[a] 85 Peg AB.
[b] The combined light of the visual binary.
REFERENCES.—(1) Johnson, MacArthur, and Mitchell 1968. (2) Carney 1983. (3) Blanco *et al.* 1968. (4) Wilson 1953. (5) Abt and Biggs 1972. (6) This work: heliocentric radial velocity = -31 ± 6 km s^{-1}. (7) *AGK 3 Catalogue.* (8) *SAO Catalogue.*

TABLE 3

"POPULATION I" DWARFS

HD (1)	Name (2)	V (3)	$B-V$ (4)	$R-I$ (5)	References (6)	d (pc) (7)	$\|v_{LSR}\|$ (km s^{-1}) (8)	RV References (9)	PM References (10)	[Fe/H] (11)
4614	η Cas A	3.44[a]	0.58[a]	0.36[a]	1	5.7	23.	6	8	−0.2
10700	τ Cet	3.50	0.72	0.42	1	3.5	51.	6	9	−0.4
23194	Hz 232	8.09	0.20	0.10	2	120.	21.	6	8	0.1
23326	Hz 530	8.96	0.39	0.24	2	120.	19.	6	8	0.1
23386	Hz 739	9.48	0.63	0.36	2	120.	18.	7	10	0.1
25680	39 Tau	5.90	0.62	...	3	16.	18.	6	8	(0.0)
26462	vB 14	5.73	0.36	0.19	2	45.	34.	6	8	0.1
27962	vB 56	4.28	0.04	0.01	2	45.	28.	6	8	0.1
28406	vB 78	6.92	0.45	0.25	1	45.	30.	6	8	0.1
30649	...	6.96	0.58	0.35	1	19.	52.	6	8	−0.3
64096	9 Pup	5.16[a]	0.60[a]	0.36[a]	1	16.	39.	6	9	(−0.4)
68017	...	6.81	0.68	0.34	4	22.	73.	6	8	(−0.2)
98231	ξ UMa A	3.79[a]	0.59[a]	0.34[a]	1	7.3	20.	6	9	0.0
110379	γ Vir A	2.74[a]	0.36[a]	0.19[a]	1	10.	23.	6	11	−0.1
114710	β Com	4.26	0.58	0.30	1	8.1	44.	6	8	+0.2
115383	59 Vir	5.22	0.59	...	3	13.	28.	6	8	(0.0)
131156	ξ Boo A	4.54[a]	0.77[a]	0.43[a]	1	6.4	22.	6	8	−0.1
142373	χ Her	4.62	0.57	0.32	1	16.	73.	6	8	−0.4
154417	...	6.00	0.58	...	3	22.	30.	6	8	(−0.2)
155125	η Oph AB	2.42[a]	0.05[a]	0.01[a]	5	19.	22.	6	11	...
170153	χ Dra	3.58	0.49	0.31	1	7.8	53.	6	8	−0.3
184960	...	5.74	0.48	0.28	1	27.	31.	6	8	(−0.1)
203454	...	6.40	0.53	0.34	1	29.	36.	6	8	(−0.3)
207978	15 Peg	5.51	0.42	...	4	25.	34.	6	8	−0.5

[a] The combined light of the visual binary.

REFERENCES.—(1) Johnson, MacArthur, and Mitchell 1968. (2) Mendoza 1968. (3) Blanco *et al.* 1968. (4) Carney 1983. (5) Johnson *et al.* 1966. (6) Wilson 1953. (7) This work: heliocentric radial velocity = $+5 \pm 4$ km s^{-1}. (8) *AGK 3 Catalogue*. (9) *SAO Catalogue*. (10) Jenkins 1952. (11) Hoffleit 1982.

stars with trigonometric parallaxes in Table 3, except possibly χ Her and 15 Peg, indeed appear also to be dwarfs. With two exceptions, each star shows $v \leq 55$ km a^{-1}. Abundance analyses by Carney (1979), Peterson (1981), Hobbs (1985), or Boesgaard and Tripicco (1986*b*) which are available for 10 of the 18 field stars have all yielded [Fe/H] ≥ -0.5; all six members of the Hyades or the Pleiades presumably show [Fe/H] ≈ 0.1 (Cayrel, Cayrel de Stroebel, and Campbell 1985; Boesgaard and Tripicco 1986*a*); and the seven estimates of [Fe/H] enclosed in parentheses are approximate values derived from our own spectra, as described above. The hotter star η Oph has a spectrum which has been classified on the MK system as being normal but which apparently has not been subjected to detailed abundance analyses.

Figure 2 compares [Fe/H] with v for the 53 stars other than η Oph which are included in this investigation, in order to illuminate their division into the three distinct groups. The value [Fe/H] = 0.1 has been assumed for the six members of the Pleiades or the Hyades in Figure 2.

b) The Spectra

The spectra were acquired with three different instruments which are indicated in column (6) of Tables 4, 5, and 6. These tables correspond to Tables 1, 2, and 3, respectively. Some examples of the spectra are shown in Figures 3, 4, and 5. Observations of 42 of the 54 stars were obtained in 1983 and 1984 at an instrumental resolution (FWHM) of 0.26 Å or, for seven of these stars described below, 0.52 Å, using the Digicon detector and grating B of the coudé spectrograph at the 2.7 m reflector of McDonald Observatory. The 1200 line mm^{-1} grating is blazed at 6000 Å in first order and gave a dispersion of 0.13 Å per photodiode. The entrance slit corresponded to 0″.6 and yielded a projected slit two diodes wide. A useful spectral interval of about 120 Å was recorded in each exposure. The typical S/N ratio of 80 which was achieved corresponds to a 2 σ detection limit of about 6 mÅ. For the six stars other than LP 608−62 in Table 1 which are fainter than $V = 8.7$, and for BD +25°1981 in Table 2, a slit width of 1″.2 and a consequent resolution of 0.52 Å were chosen instead. Observations of eight stars obtained at higher resolution with the echelle grating during the same period have been described already (Hobbs 1984, 1985). Data for 16 of the 54 stars were obtained in 1983 and 1984 at a resolution of 0.3 Å with the 3.0 m reflector of Lick Observatory, using the bare Reticon detector at the coudé camera with a 40 inch (1 m) focal length. The agreement of the λ6707 equivalent widths for the five stars in common between the McDonald and the Lick observations is excellent, the average difference being 0 ± 4 mÅ. Finally, observations of five of the faintest stars in Table 4 were acquired in 1985 October at a resolution of 0.2 Å, using the TI-2 CCD and the echelle spectrograph at the 4 m Mayall reflector of Kitt Peak National Observatory.

The resulting equivalent widths of the Li I λ6707 and the Ca I λ6717 blends are given in Tables 4, 5, and 6; the upper limits are empirical 2 σ values calculated from $W_\lambda \leq (2\Delta I/I) \times \Delta\lambda$, where $\Delta I/I$ is the rms fluctuation of the residual intensities about the continuum level and $\Delta\lambda$ is the instrumental resolution. A comparison, especially between stars in Figures 3 and 5, of the strengths of the Fe I and Ca I lines in stars of similar effective temperatures vividly illustrates the differences

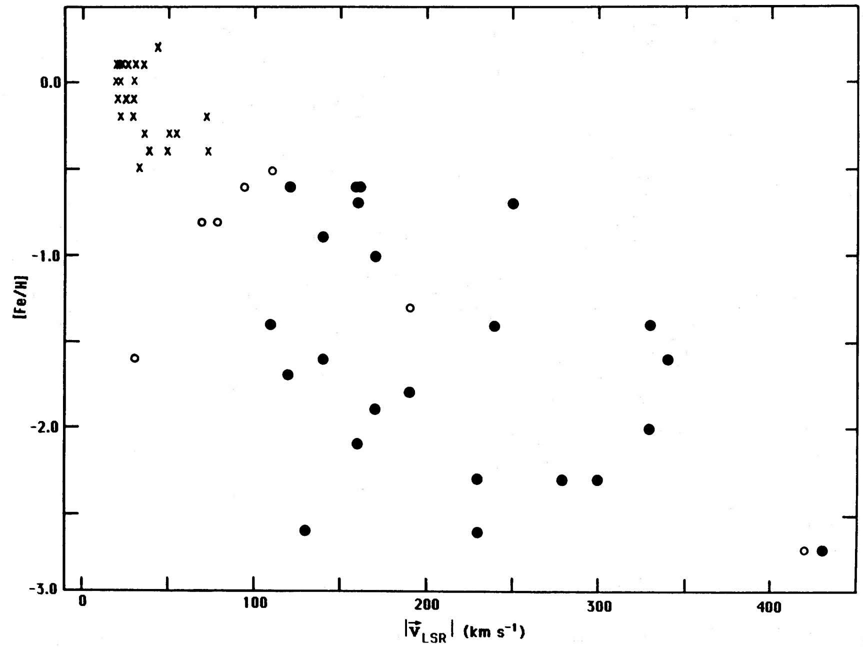

FIG. 2.—A comparison of [Fe/H] with $|v_{LSR}|$ for the stars in Tables 1 (*filled circles*), 2 (*open circles*), and 3 (*crosses*). The halo stars of Table 1 are defined by the properties [Fe/H] ≤ -0.6 and $|v_{LSR}| \geq 100$ km s^{-1}.

TABLE 4

TEMPERATURES, EQUIVALENT WIDTHS, AND ABUNDANCES

HD/BD (1)	T_e (K) (2)	Types (3)	W_λ(6707) (mÅ) (4)	W_λ(6717) (mÅ) (5)	Source[a] (6)	12 + log (Li/H) (7)	[Fe/H] (8)	Previous W_λ(6707) (9)	References (10)
6582[b]	5230	3	≤6.	111.	M	≤0.6	−0.6	≤4.	1
19445	5810	3	38. ± 4	≤13.	M	2.1	−2.1	33.	1
22879	5740	3	25. ± 10	75.	M	1.8	−0.6	...	
29587	5570	3	≤10.	62.	L	≤1.2	(−1.0)	...	
64090	5380	3	≤8.	23.	L	≤0.9	−1.6	...	
LP 608−62	6250	2	23. ± 9	≤9.	K	2.2	−2.7	...	
84937	6200	3	20. ± 6	≤6.	K, L, M	2.1	−2.1	18, 23.	1, 2
94028	5860	2	33. ± 5	31.	L, M	2.1	−1.7	35.	1
103095[c]	5010	3	≤5.	71.	M	≤0.4	−1.4	≤4.	1
106516	6110	2	≤6.	60.	L, M	≤1.5	−0.9	≤11.	3
108177	5900	2	≤24.	≤24.	M	≤1.9	−1.9	35.	4
+34°2476	6110	2	≤26.	≤26.	M	≤2.2	−2.3	...	
140283	5650	3	48. ± 6	17.	M	2.1	−2.6	45.	1
148816	5810	3	18. ± 7	65.	L	1.7	−0.7	17.	1
157089	5735	3	20. ± 5	75.	M	1.7	−0.6	25.	1
160693	5780	3	≤7.	72.	L	≤1.2	−0.7	...	
+20°3603	6040	2	27. ± 6	12.	K, M	2.1	−2.3	28.	1
+26°3578	5830	2	24. ± 3	3.	K, M	1.8	−2.6	24.	4
188510	5490	3	≤16.	20.	M	≤1.3	−1.8	18.	1
201889	5570	3	≤12.	62.	L	≤1.3	(−1.4)	...	
201891	5810	3	27. ± 3	50.	L, M	1.9	−1.4	23.	1
+17°4708	5810	3	25. ± 3	28.	K, M	1.9	−2.0	...	
219617	5820	3	43. ± 6	28.	M	2.2	−1.4	42.	1

[a] K = Kitt Peak, L = Lick, M = McDonald.
[b] μ Cas.
[c] Groombridge 1830.
REFERENCES.—(1) SS. (2) Boesgaard 1985. (3) Duncan 1981. (4) SMS.

1987ApJ...317..796H

TABLE 5

TEMPERATURES, EQUIVALENT WIDTHS, AND ABUNDANCES

HD/BD (1)	T_e (K) (2)	Types (3)	$W_\lambda(6707)$ (mÅ) (4)	$W_\lambda(6717)$ (mÅ) (5)	Source[a] (6)	12 + log (Li/H) (7)	[Fe/H] (8)	Previous $W_\lambda(6707)$ (9)	References (10)
65583	5260	1	≤9.	110.	M	≤0.9	−0.6	...	
+25°1981	6780	2	≤12.	≤18.	M	≤2.5	−1.3	...	
114762	5750	1	17. ± 8	58.	L	1.6	−0.8	...	
122563	4400	2	≤4.	7.	M	≤ −0.4	−2.7	...	
134169	5800	2	46. ± 5	48.	L	2.2	−1.6	44.	SS
208906	5900	3	43. ± 5	46.	L	2.2	−0.5	...	
224930[b]	5200	3	≤6.	114.	M	≤0.6	−0.8	≤4.	SS

[a] K = Kitt Peak, L = Lick, M = McDonald.

[b] 85 Peg AB.

in the heavy-element abundances, which range up to almost three orders of magnitude. The increasing contribution of the Fe I 6707.44 Å line to the Li I feature in progressively cooler metal-rich stars is illustrated in the high-dispersion spectra of Cayrel *et al.* (1984) and Hobbs (1985); similar information is displayed for several metal-poor stars by Maurice, Spite, and Spite (1984). For all but the few coolest metal-poor stars in Tables 4 and 5, the contamination of the Li I feature by Fe I absorption apparently should be negligible. The cited high-resolution data also show the important effects of the Fe I 6717.53 Å line which is blended with the Ca I line. The last two columns of Tables 4, 5, and 6 compare our Li I results with earlier work. In particular, the agreement of our results with the data of SS and SMS, which were recorded at generally similar resolution and better photometric accuracy, is excellent for all of the 17 stars in common except HD 108177. Even the latter discrepancy is removed if our 2 σ upper limit is replaced by a 3 σ value instead. The average difference in the Li I equivalent widths is 1 ± 3 mÅ for the 12 stars for which positive λ6707 detections were obtained in both observing programs.

The spectra of about one-third of the 54 program stars were recorded more than once. These multiple spectra were properly taken into account in determining the final equivalent widths given in Tables 4, 5, and 6. All of the spectra shown in Figures 3, 4, and 5 are individual exposures, however. For some of the stars, the uncertainties in the final equivalent widths are there-

TABLE 6

TEMPERATURES, EQUIVALENT WIDTHS, AND ABUNDANCES

Name (1)	T_e (K) (2)	MK (3)	$W_\lambda(6707)$ (mÅ) (4)	$W_\lambda(6717)$ (mÅ) (5)	Source[a] (6)	12 + log (Li/H) (7)	Previous $W_\lambda(6707)$ (8)	References (9)
η Cas A	5660	G0 V	19. ± 4	100.	M	1.6	≤24.	1
τ Cet	5260	G8 V	≤6.	138.	M	≤0.7	v.	2
Hz 232	8420	A5 V	≤9.	≤9.	M	≤3.3[b]	...	
Hz 530	7000	F2 V	71. ± 5	95.	M	3.5[b]	...	
Hz 739	5930	G0 V	181. ± 12	150.	M	3.3	215.	1, 3
39 Tau	5600	G5 V	61. ± 6	145.	M	2.2	74.	1
vB 14	6860	F4 V	52. ± 10	72.	M	3.1[b]	67.	4
vB 56	9000	A3 V	≤6.	≤6.	M	...	...	
vB 78	6400	F6 V	≤27.	83.	M	≤2.5	30.	4
HD 30649	5700	G1 V–VI	33. ± 12	125.	M	1.9	...	
9 Pup	5690	G0 V	24. ± 6	109.	M	1.8	26.	1
HD 68017	5600	G4 V	≤8.	118.	L	≤1.1	...	
ξ UMa A	5700	G0 V	54. ± 4	92.	M	2.3	49.	1, 5
γ Vir A	6940	F0 V	45. ± 3	73.	M	3.2[b]	51.	6
β Com	5980	G0 V	62. ± 5	128.	M	2.6	60.	1
59 Vir	5900	G0 V	93. ± 4	133.	M	2.8	125.	1
ξ Boo A	5300	G8 V	114. ± 18	146.	M	2.4	v.	2
χ Her	5830	F9 V	56. ± 2	70.	L, M	2.4	69.	1, 5
HD 154417	6000	F8.5 IV–V	79. ± 5	95.	L	2.8	73.	1
η Oph AB	9170	A2 V	≤3.	5.	M	...	...	
χ Dra	5920	F7 V	29. ± 5[c]	62.[c]	M	2.0	42.	7
HD 184960	6180	F7 V	45. ± 6	107.	M	2.6	83.	1
HD 203454	5750	F8 V	64. ± 4	100.	M	2.4	...	
15 Peg	5780	F6 IV–V	≤5.	51.	L	≤1.1	8.	6

[a] K = Kitt Peak, L = Lick, M = McDonald.

[b] From curves of growth of Boesgaard and Tripicco 1986*b*.

[c] This equivalent width refers only to the stronger set of lines seen in the spectrum of this double-lined spectroscopic binary and is uncorrected for blending (cf. SS).

REFERENCES.—(1) Duncan 1981. (2) Herbig 1965; v = visual intensity scale. (3) Duncan and Jones 1983. (4) Boesgaard and Tripicco 1986*a*. (5) Hobbs 1985. (6) Boesgaard and Tripicco 1986*b*. (7) SS.

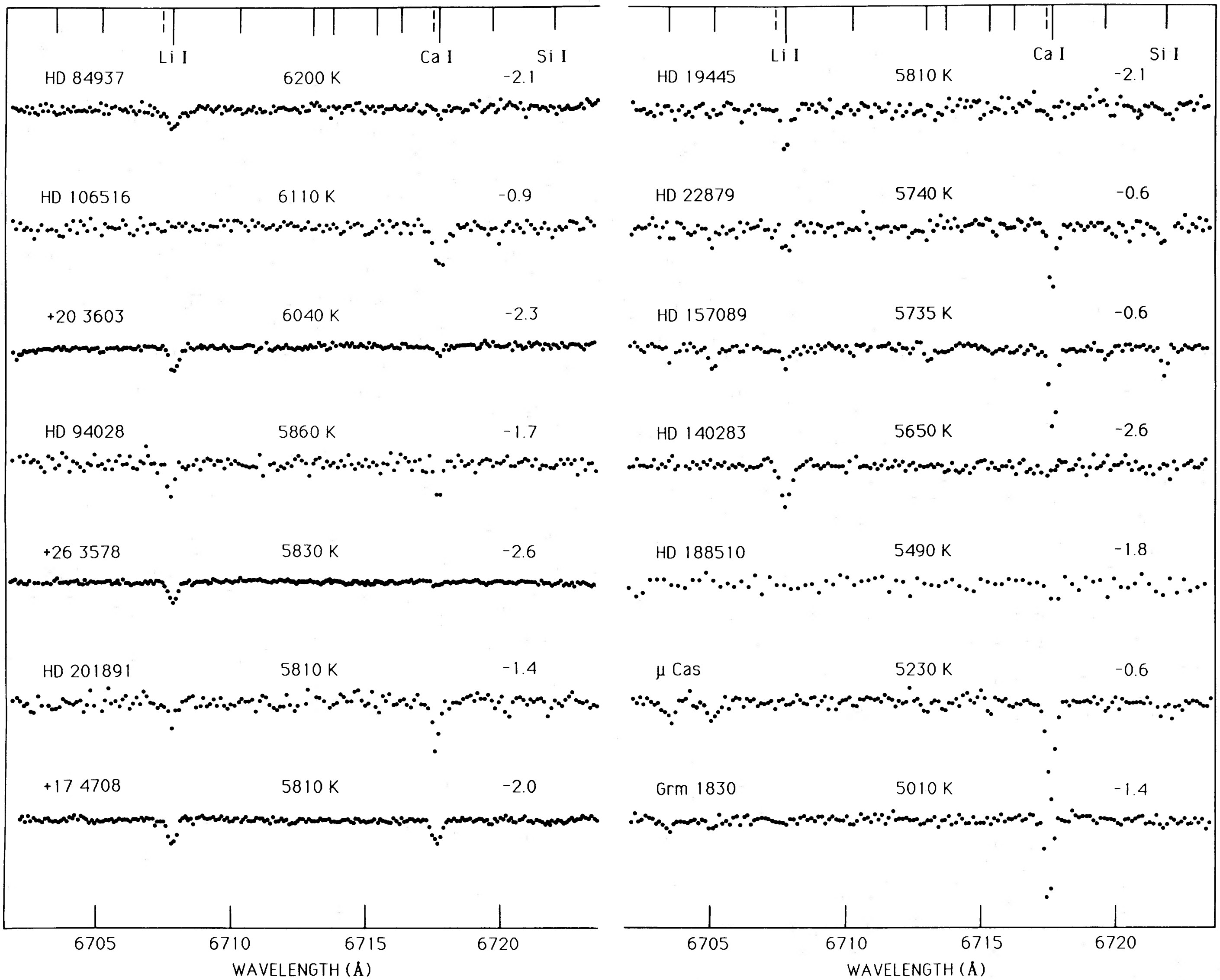

FIG. 3.—The spectra of 14 halo stars near 6707 Å. Except for the Li I λ6707.8 and the Ca I λ6717.7 lines shown by the longer tick marks and for the Si I λ6721.8 and the unidentified λ6719.6 lines, all of the features indicated near the top are Fe I lines, including the two weak lines which are identified by dashed marks and which are respectively blended with the Li I and the Ca I absorption. The central residual intensity of the Li I line in the spectrum of HD 140283 is 0.88. The star's name, temperature, and metallicity [Fe/H] are given just above each spectrum.

fore smaller than is suggested by the partial data shown in the figures.

c) The Adopted Temperatures

Li I λ6707 is the resonance line of the neutral species of an atom which is almost completely ionized in these stars. The equivalent width of the line is therefore very temperature sensitive, and accurate stellar temperatures are needed in order to derive accurate lithium abundances from model atmospheres. Peterson and Carney (1979) and Carney (1983) derived temperatures for most of these stars from $R-I$ and $V-K$ colors and by matching spectrophotometric scans in the region 5000–8400 Å to surface fluxes calculated from ATLAS6 model atmospheres. From photometry available in the literature, such as the $R-I$ colors in Tables 1, 2, and 3, we have calculated temperatures anew by using their two photometric methods. The methods are accurate at $4500 \lesssim T_e \lesssim 7000$ K, a range which includes all of our halo stars. After initial calibration, these three kinds of temperature determination are independent, so random errors should be reduced by averaging them. In an effort to get the best possible temperatures, one more set of colors, the Strömgren photometry tabulated by Hauck and Mermilliod (1979), was examined. In a few cases such as HD 22879 and HD 140283, in which there was disagreement by more than 100 K among the various temperatures discussed above, Strömgren colors were used to indicate which temperature is more nearly correct.

The temperature adopted for each star in Table 4 or 5 is generally the unweighted average of as many of these three respective kinds of estimates as are available. This availability is indicated in column (3) of both tables. An intercomparison of the three sets of temperatures indicates a random error of approximately 80 K in the temperature estimated from any

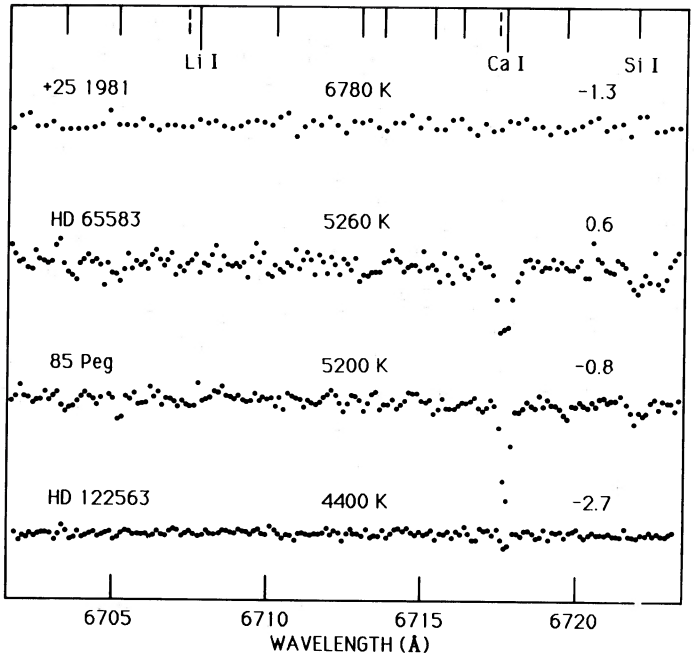

FIG. 4.—The spectra near 6707 Å of four stars from Table 2. The format, including the scale of the residual intensities, is as in Fig. 3.

color or scan, and we conclude that the random component of the standard (1 σ) error in the final temperatures adopted here is about 60 K. For a given star, Peterson and Carney similarly deduced a random error of 80 K in the temperature derived from all three methods together. They also estimated an additional systematic or zero-point error of 80 K in the absolute temperatures. For stars in common, we have further compared our adopted temperatures with those of SS and SMS, which are derived from spectroscopic analyses or $R-I$ colors. The temperature differences do not exceed 170 K except for HD 148816, for which the discrepancy is 280 K. For the other 15 Population II stars in common, the average difference in temperature is in fact 10 ± 110 K.

For most of the (approximately) Population I stars in Table 6, temperatures were calculated as above, from the $R-I$ and $V-K$ colors as available. However, the spectra of these stars can also be classified usefully on the MK system. Spectral types taken from the *Bright Star Catalogue* (Hoffleit 1964) or its *Supplement* are given in column (3) for 18 of the stars; the remaining types are those of Roman (1955), Mendoza (1956), or Morgan and Hiltner (1965). It should be noted that Mendoza identified members of the Pleiades by their Hz I numbers, while the Hz II numbers are used here. *Only* for 39 Tau, 59 Vir, ξ Boo A, HD 154417, η Oph, and the six members of the Pleiades or the Hyades were the spectral types also considered in determining the adopted temperature. Neither $R-I$ nor $V-K$ colors seem to be available for 39 Tau, 59 Vir, and HD 154417, while the photometry for ξ Boo A is affected by a dM companion and that for the Pleiades by nonnegligible interstellar reddening. An important caution is, however, that the metallicity even of some stars in Table 6 is sufficiently lower than solar to raise artificially the temperatures derived from the spectral types at a given effective temperature, owing to the associated line weakening. At a given effective temperature deduced in most cases from the colors, an unusually large scatter is in fact found in the spectral types in Table 6. The scatter probably reflects primarily this abundance effect.

d) The Derived Abundances

Curves of growth for Li I λ6707 have been computed using model atmospheres constructed by Bell (1984) and the spectrum-synthesis program WIDTH6 (Kurucz 1983). Calculations were carried out for $T_e = 4500$ K, 5000 K, 5500 K, and 6000 K, log $g = 4.5$ and 3.75, and [Fe/H] = 0, -1, and -2. Some of the results are shown in Figure 6. The method described by Duncan and Jones (1983) was used to extend the calculations to $T_e = 6500$ K as well. The atomic data used in the calculations are those of Duncan (1981). An isotope ratio ^{6}Li/^{7}Li = 0 was adopted (Maurice, Spite, and Spite 1984; Andersen, Gustafsson, and Lambert 1984; Hobbs 1985), and the small separation of the two fine-structure components of the ^{7}Li line was ignored, because the fine structure is unresolved in our observations and neglect of the splitting causes negligible errors (Duncan 1981).

The resulting abundances are given in Tables 4, 5, and 6. For a given set of model atmospheres, errors in the relative abundances from star to star arise from uncertainties in both the equivalent widths and the temperature differences. A typical random error of 60 K at $T_e = 5800$ K and $W_\lambda = 30$ mÅ causes an abundance error of $\pm 15\%$ in our results; a measurement error of $\pm 20\%$ in the equivalent width contributes a further abundance error of $\pm 20\%$. Quadratically combining these independent errors yields a total error of $\pm 25\%$, or 0.10 dex, which we take as the representative standard (1 σ) error of the *relative* abundances. Our derived abundances also can be compared directly with those of SS and SMS, who used a different set of model atmospheres. For the group of 11 Population II stars for which λ6707 is definitely detected in both sets of observations, our lithium abundances exceed those of SMS by an average factor 1.05 ± 0.33, which corresponds to a logarithmic difference of 0.02 ± 0.12 dex. Not only does the mean difference effectively vanish, but the scatter of 0.12 dex is consistent with the estimated abundance errors of about 0.1 dex in each investigation. Since the agreement between the two respective sets of equivalent widths and adopted temperatures was seen already to be generally good, this excellent agreement between the derived abundances attests to the satisfactory further agreement between the respective sets of model atmospheres adopted.

Six program stars, all found in Table 6, show $T_e > 6800$ K. The curves of growth of Boesgaard and Tripicco (1986*b*), calculated from model atmospheres of Kurucz with solar abundances, were used to determine the lithium abundances in four of these hotter stars. The abundances derived from the Bell and the Kurucz models, respectively, show satisfactory agreement at the one common temperature $T_e = 6000$ K.

III. DISCUSSION

The lithium abundances of the 23 halo stars investigated here are plotted as a function of effective temperature in Figure 7. The most important results of the present study are seen to be (1) a confirmation of the discovery by SS and SMS that lithium is present at an average abundance near $\langle \text{Li/H} \rangle = 1.1 \times 10^{-10}$ or $\langle N(\text{Li}) \rangle = \langle 12 + \log (\text{Li/H}) \rangle = 2.05$ in nearly all halo stars with $T_e \geq 5600$ K, and (2) an extension of these spectroscopic results to nine additional halo stars. The main conclusion of SS, that lithium in the halo stars

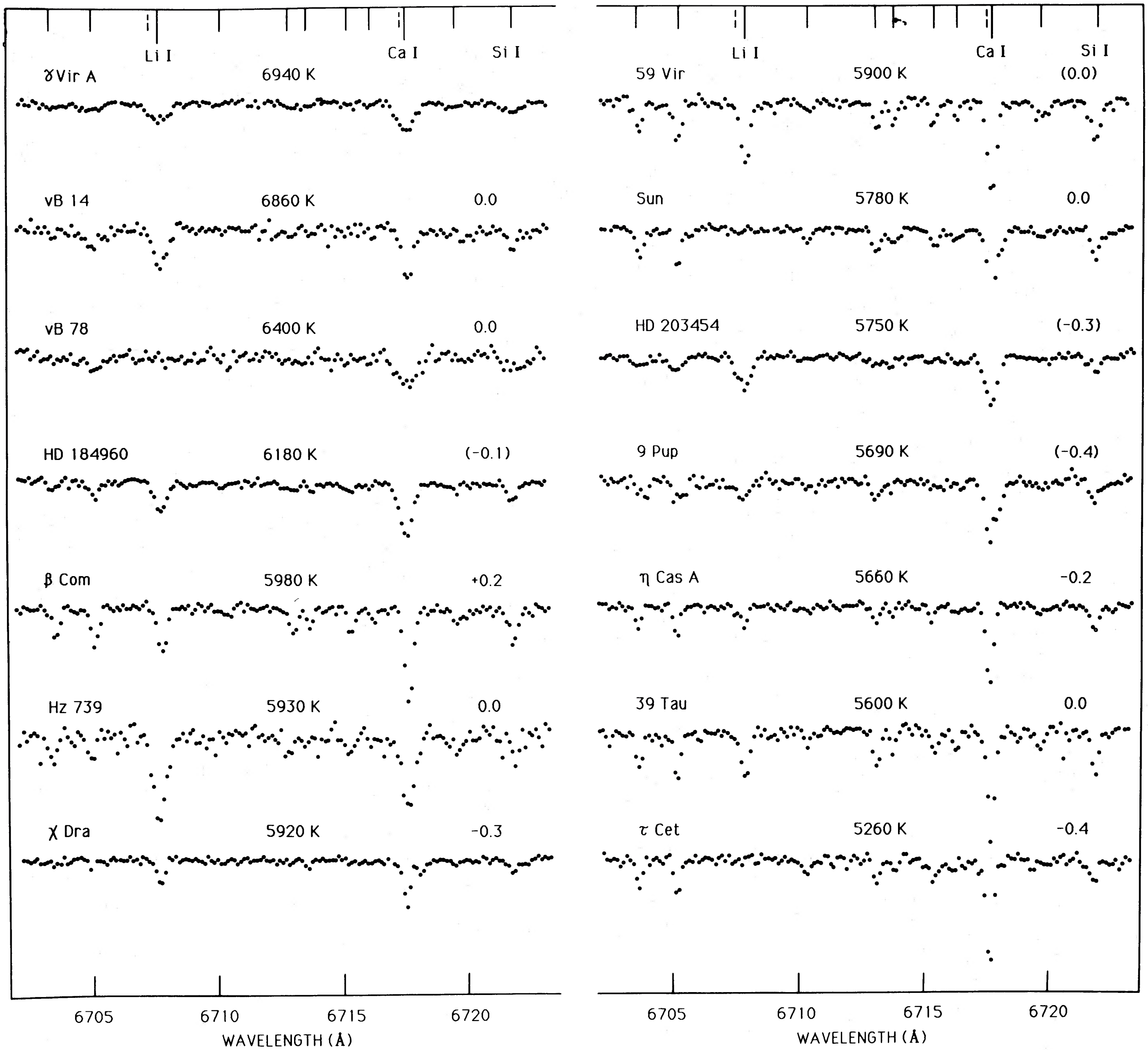

FIG. 5.—The spectra of 14 "Population I" dwarfs near 6707 Å. The format, including the scale of the residual intensities, is as in Fig. 3. The spectrum of the Sun, intentionally recorded at approximately comparable photometric accuracy, is included for comparison.

probably was produced in the big bang, is therefore immediately supported by our results.

We now further ask how certain it is that this lithium is a product of primordial nucleosynthesis alone and whether the lithium observed in the halo stars is an unmodified sample of the lithium fraction produced in the big bang.

a) The Extreme Halo Stars

Twelve of the 23 stars in Table 4 which have the properties $v \geq 160$ km s^{-1} and [Fe/H] ≤ -1.4 are indicated by filled circles in Figure 7. These 12 stars should constitute a selectively very old, homogeneous subset of the 23 halo stars observed here, and they will therefore be referred to as extreme halo stars, or extreme subdwarfs. All of the 12 except HD 64090, Groombridge 1830 (= HD 103095), and HD 188510 are relatively hot, with $T_e \geq 5600$ K. These nine relatively hot, extreme halo stars have atmospheric lithium abundances, or upper limits on the abundances, in the narrow range $1.9 \leq N(\mathrm{Li}) \leq 2.2$ (Fig. 7). The average value derived from the seven definite detections of λ6707 is $\langle N(\mathrm{Li})\rangle = 2.11 \pm 0.09$ or $\langle \mathrm{Li/H}\rangle = 1.3 \pm 0.3 \times 10^{-10}$. In contrast, the abundances of the three cooler, extreme subdwarfs are $N(\mathrm{Li}) \leq 1.3$. Five stars from the list of SMS which are not among our program stars also satisfy our definition of extreme halo stars. The three relatively hot stars, BD +21°607, HD 194598, and BD +2°4651, and the two cooler ones, HD 25329 and BD +0°4470, also exhibit lithium abundances reported by SMS which conform to the respective limits just noted. For this selectively old group of 17 extreme halo stars, we conclude that (1) a single, very well-defined relation exists *without exception* between Li/H

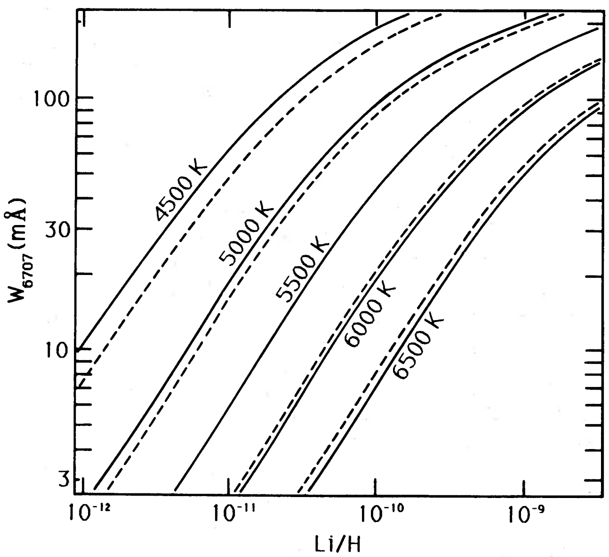

FIG. 6.—Curves of growth derived from the model atmospheres of Bell (1984). The five solid curves, which differ negligibly from the results of Duncan and Jones (1983), were calculated for effective temperatures of 4500, 5000, 5500, 6000, and 6500 K, respectively, log $g = 4.5$, and a solar metallicity [Fe/H] = 0; the five dashed curves show the corresponding results for [Fe/H] = -2. The dashed and the solid curves coincide at 5500 K. (We note that the dashed and the solid curves of Duncan and Jones for 5000 K were erroneously interchanged.) The equivalent widths are seen to be nearly independent of metallicity in the range $5300 \lesssim T_e \lesssim 6000$ K. The contribution of the Fe I 6707.44 Å line to the Li I blend has not been included.

and T_e, and (2) $\langle N(\text{Li}) \rangle = 2.07 \pm 0.11$ or $\langle \text{Li/H} \rangle = 1.2 \pm 0.3 \times 10^{-10}$ for 10 stars with $T_e \geq 5600$ K in which Li I has been definitely detected.

It is instructive to relax progressively the two somewhat arbitrary criteria which have so far been adopted here in order to isolate the oldest halo stars. If the kinematic threshold is reduced to $v \geq 100$ km s^{-1}, four additional stars in Table 4 are now included: HD 94028, BD +26°3578, HD 201889, and HD 201891. All except HD 201889 show $T_e \geq 5600$ K. Except for the insignificant difference that $N(\text{Li}) = 1.8$ for BD +26°3578, the lithium abundances of all four stars are seen in Figure 7 to satisfy the limits already found above. Similarly, the three stars now correspondingly added from the list of SMS, HD 16031, BD +23°3912, and ν Ind (= HD 211998), also satisfy the same limits. These results suggest that the exact choice of a kinematic lower limit in this general range is not of much importance. The data collected in Table 7 and plotted in Figure 8 for this larger group of 24 halo stars defined by $v \geq 100$ km s^{-1} and [Fe/H] ≤ -1.4 is the primary result of the present work. The average lithium abundance for the 16 stars in this group which show $T_e \geq 5600$ K and for which the λ6707 line was definitely detected is $\langle N(\text{Li}) \rangle = 2.06 \pm 0.12$ or $\langle \text{Li/H} \rangle = 1.15 \pm 0.3 \times 10^{-10}$, where 10 of the values used are from the present observations.

When the metallicity limit is increased to [Fe/H] ≤ -0.6, in order to include the remaining seven more metal-rich stars in Table 4, a different result is obtained, however. Among these seven added subdwarfs, the two cooler stars, μ Cas (= HD 6582) and HD 29587, indeed do display $N(\text{Li}) < 1.3$, in agreement with the lower abundances seen in other halo stars with $T_e < 5600$ K. In contrast, among the five hotter stars, only HD 22879 duplicates the pattern set by the more extreme subdwarfs. The other four, HD 106516, HD 148816, HD 157089, and HD 160693, show reduced lithium abundances $N(\text{Li}) \leq 1.7$, even at $T_e \geq 5600$ K. The effect is immediately obvious in Figures 3 and 7 for HD 106516 and in Figure 7 for HD 160693.

The λ6707 line is not detected at all in HD 106516 or HD 160693 and only relatively weakly in HD 148816 and HD 157089. Their space velocities $v \geq 140$ km s^{-1}, so these four stars are clearly halo objects on kinematic grounds. However, their metallicities of $-0.9 \leq$ [Fe/H] ≤ -0.6 are relatively high in Table 4. These stars are thus similar to HD 97916, discussed by SMS, which has $T_e = 6120$ K, $v = 120$ km s^{-1},

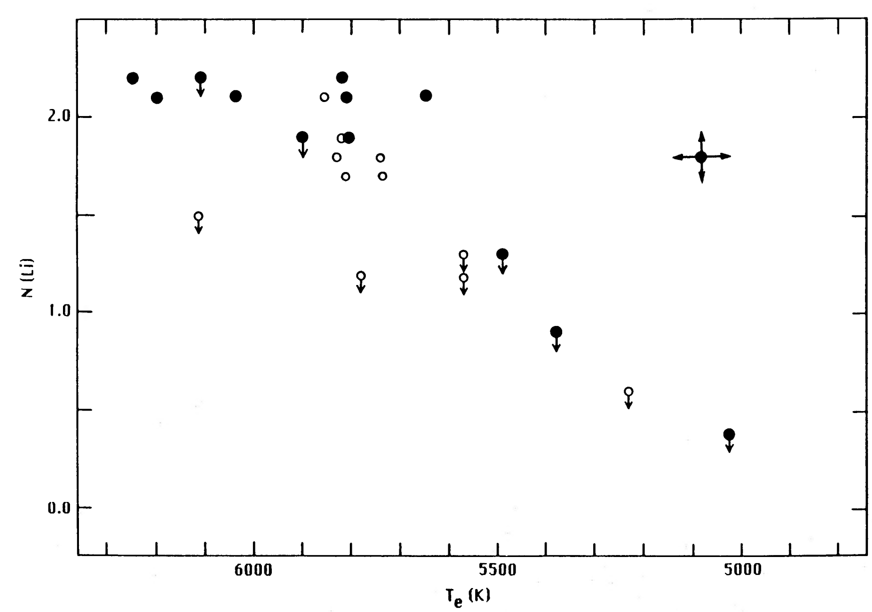

FIG. 7.—The variation of $N(\text{Li}) = 12 + \log(\text{Li/H})$ with T_e for the 23 halo stars of Table 4. The 12 extreme halo stars, defined as those with $|v_{\text{LSR}}| \geq 160$ km s^{-1} and [Fe/H] ≤ -1.4, are shown by filled circles; the other 11 stars, by open circles. Representative 1 σ errors of ± 0.10 dex in $N(\text{Li I})$ and ± 60 K in T_e are indicated in the upper right-hand corner.

TABLE 7

STARS WITH $|v_{LSR}| \geq 100$ km s^{-1} AND [Fe/H] ≤ -1.4

HD/BD (1)	$\lvert v_{LSR} \rvert$ (km s^{-1}) (2)	[Fe/H] (3)	T_e (K) (4)	N(Li) (5)	N(Li)[a] (6)
LP 608−62	430	−2.7	6250	2.2	...
84937	160	−2.1	6200	2.1	2.05
+34°2476	300	−2.3	6110	≤2.2	...
+20°3603	280	−2.3	6040	2.1	2.11
+21°607	390	−1.6	5930	...	1.98
16031	100	−2.2	5930	...	2.03
108177...........	170	−1.9	5900	≤1.9	2.09
94028	120	−1.7	5860	2.1	2.09
+26°3578	130	−2.6	5830	1.8	2.01
219617...........	240	−1.4	5820	2.2	2.04
201891...........	110	−1.4	5810	1.9	1.89
194598...........	280	−1.6	5810	...	2.00
+17°4708	330	−2.0	5810	1.9	...
19445	230	−2.1	5810	2.1	2.00
+2°4651	330	−2.3	5790	...	1.92
140283...........	230	−2.6	5650	2.1	1.98
+23°3912	130	−1.7	5600	...	2.23
201889...........	140	(−1.4)	5570	≤1.3	...
188510...........	190	−1.8	5490	≤1.3	1.43
64090	340	−1.6	5380	≤0.9	...
+0°4470	410	−1.4	5200	...	1.02
211998[b]	140	−1.5	5200	...	1.04
103095[c]	330	−1.4	5010	≤0.4	≤0.5
25329	190	−1.8	4840	...	≤0.0

[a] From SMS.
[b] ν Ind.
[c] Groombridge 1830.

[Fe/H] = −1.1, and also fails to show lithium. All five of these stars belong to the halo population both by Eggen's (1979) criteria and by the criteria for inclusion in Table 1, but their velocities and metallicities are less extreme than those of most of our halo stars. SMS argue that HD 97916 defines empirically the boundary between stars which destroy lithium and those which do not. This seems plausible because a metallicity difference probably is the major cause of the apparent difference in the lithium destruction rate. Because the age spread in the halo is a small fraction of its total age, these five stars probably are at least $\frac{2}{3}$ as old as the extreme halo stars. The main effect of the relatively enhanced metal abundance in these almost comparably old stars is to make the convection zone thicker and therefore to increase the highest temperature to which lithium is exposed (Däppen 1984; D'Antona and Mazzitelli 1984). The reaction rates for lithium destruction are extremely temperature sensitive (Audouze *et al.* 1983). A slightly changed rate, acting over 10–15 Gyr, could therefore produce a large difference in lithium abundance. However, the opposite result provided by HD 22879, which is of even higher metallicity yet has N(Li) = 1.8, demonstrates that other unidentified mechanisms, perhaps including rotation, must also play a major role, at least at [Fe/H] $\gtrsim -1$. In particular, the stars HD 22879 and HD 160693, which have nearly identical temperature and metallicities, show Li/H ratios which differ by a factor of at least 4. Among the stars studied by SMS, HD 76932 provides a similar contrast to HD 97916.

Another instructive star is HD 134169 in Table 5, which has [Fe/H] = −1.6 and a velocity $v = 31$ km s^{-1}, which is very low for a halo object. Eggen (1979) identifies a number of stars which are very metal poor but have low space velocities, like HD 134169, and concludes that they are genuine halo members. The lithium abundance of N(Li) = 2.2 in HD 134169 conforms to that of the extreme halo stars, from which this star is therefore entirely indistinguishable here except for its low space velocity. With respect to the atmospheric lithium fraction, this result still further underlines the importance of variations in metallicity and the contrasting intrinsic unimportance of variations in space velocity, a conclusion suggested independently on the general physical grounds sketched above.

b) *Variations in the Lithium Abundance*

Since the fundamental details of lithium destruction are unknown, even in the Sun, it is impossible to predict reliably

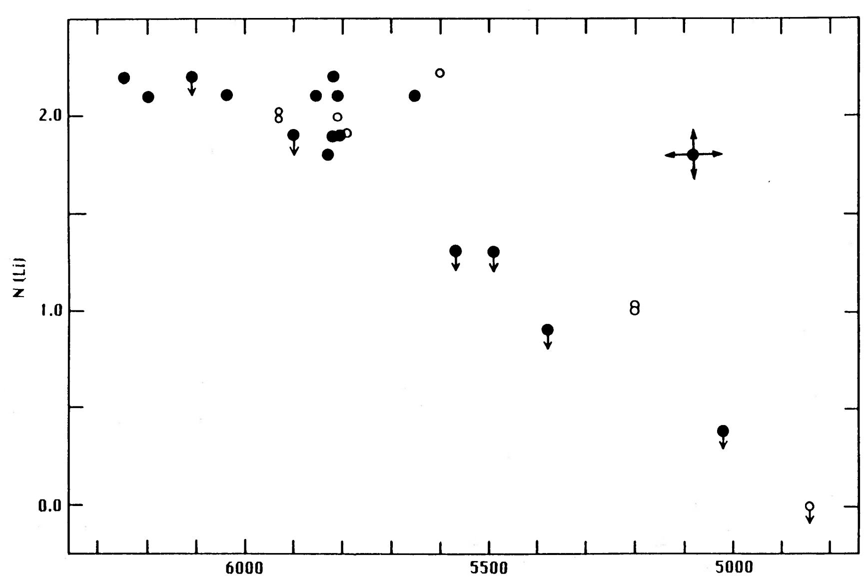

FIG. 8.—Same as Fig. 7, for 24 halo stars with $|v_{LSR}| \geq 100$ km s^{-1} and [Fe/H] ≤ -1.4 (Table 7). The 16 stars from Table 4 are indicated by filled circles; eight additional stars from SMS which were not observed here are shown by open circles.

from theory which of the observed halo stars have destroyed lithium. Michaud, Fontaine, and Beaudet (1984) postulate that some lithium destruction is likely to have occurred in all halo stars. Some sort of mild mixing or turbulence below the convecting zone may be needed in solar models to explain the destruction of lithium, since the bottom of the convection zone itself apparently is not hot enough to explain the low solar abundance. These authors' calculations argue that similar turbulence would destroy lithium in halo stars as well. Their new result is to demonstrate that, even if no mixing actually takes place below the convection zone, diffusion in a sufficiently circulation-free atmosphere will slowly reduce the lithium abundance. These arguments remain true no matter what ratio of the mixing length to the pressure scale height is chosen for the model atmosphere. Michaud, Fontaine, and Beaudet conclude that lithium destruction by at least a factor of 2 seems inescapable. Some observational support for the hypothesis that diffusion does indeed affect the lithium abundance in stars may be found in the additional calculations of Michaud (1986), who uses diffusion to explain the very low abundance of lithium discovered by Boesgaard and Tripicco (1986*a*) in Hyades F stars which have very thin convection zones, an effect also subsequently discovered in NGC 752 (Hobbs and Pilachowski 1986).

The observations may provide direct evidence as to whether the relatively hot, extreme halo stars in the present study have destroyed some of their original atmospheric lithium. These stars show a very small dispersion in lithium abundance, as emphasized above. We have performed a statistical test to determine whether this dispersion is explained by the estimated errors in the abundances, or whether it is real. The results in Table 4 for the stars HD 19445, 94028, 201891, 219617, BD $+26°3578$, and $+17°4708$ were analyzed first. All have [Fe/H] ≤ -1.4, $v \geq 100$ km s^{-1}, and fall within the narrow range of temperatures $5810 \leq T_e \leq 5860$. In agreement with the discussion above, the velocity threshold was reduced to $v \geq 100$ km s^{-1} for inclusion in this test group. Allowing this sample of six stars to determine the mean, and adopting $\sigma = 0.10$ dex as our measurement uncertainty (§ II*d*), we find a mean abundance $\langle N(\text{Li})\rangle = 2.00$ and a reduced $\chi^2 = 2.4$. For 5 degrees of freedom, the chance that χ^2 is this large due to statistical fluctuations is $p = 0.04$. In case we significantly underestimated our abundance errors, we repeated the test with $\sigma = 0.15$ dex, for which $p = 0.38$. These analyses are essentially unaltered if we include either (1) from the lists of SS and SMS, the one star, HD 194598, which satisfies the selection criteria above, or (2) from the stars observed here, the hotter stars LP 608−62, HD 84937, and BD $+20°3606$ and the cooler star HD 140283. We conclude that, while there is some evidence for real differences, the apparent star-to-star variations in lithium abundance are probably accounted for by the estimated errors of measurement.

c) *Other Sources of Lithium*

Lithium is observed in many Population I objects, such as the Hyades (Cayrel *et al.* 1984), the Pleiades (Duncan and Jones 1983), NGC 752 (Hobbs and Pilachowski 1986), early-F field stars (Boesgaard and Tripicco 1986*b*), and late-F and G stars in the solar neighborhood (Duncan 1981). In all these objects, the maximum abundance observed is $N(\text{Li}) \approx 3.0$ (cf. Boesgaard and Steigman 1985, Fig. 10). In type I carbonaceous chondrites the abundance is $N(\text{Li}) \approx 3.3$, but there is some evidence of chemical enrichment (Nichiporuk and Moore 1974). Interstellar abundances are typically $2.5 \lesssim N(\text{Li}) \lesssim 3.6$ and are appreciably more uncertain than the stellar ones (Hobbs 1984; Ferlet and Dennefeld 1984). This fairly uniform upper limit to $N(\text{Li})$ makes it unlikely that the lithium fraction produced in the big bang exceeded $N(\text{Li}) \approx 3.0$.

Several sources of lithium other than the big bang have been suggested (cf. Audouze *et al.* 1983). These include novae, red giants, and spallation by Galactic cosmic rays, primarily on C, N, O nuclei. Important information can be provided in principle about such sources by the ratio of the two lithium isotopes, ^{7}Li and ^{6}Li. The observed solar system ratio is $^7\text{Li}/^6\text{Li} = 12.5$; it is difficult to detect ^{6}Li elsewhere (Ferlet and Dennefeld 1984; Maurice, Spite, and Spite 1984; Andersen, Gustafsson, and Lambert 1984; Hobbs 1985). Standard models of the big bang predict the formation of negligible amounts of ^{6}Li. Spallation produces the ratio $1.6 < {}^7\text{Li}/^6\text{Li} < 6$, depending on the cosmic ray energy spectrum. Models of cosmic ray spallation can simultaneously match the observed Galactic abundances of ^{6}Li, Be, and B but do not explain the observed large $^7\text{Li}/^6\text{Li}$ ratio (Reeves and Meyer 1978). Thus, the observed low abundance of ^{6}Li precludes spallation as the source of more than about 30% of the Population I abundance of ^{7}Li.

The bulk of ^{7}Li might be produced in novae or red giants. It seems unlikely that these objects could explain the ^{7}Li seen in the halo stars, however. If the ^{7}Li were the result of stellar processing, a relation between lithium abundance and other elements such as iron might be expected but is not observed. As [Fe/H] varies by a factor of 20 over the range −1.4 to −2.7, for the 12 stars in Table 4 with $T_e \geq 5600$ K and [Fe/H] ≤ -1.4, $N(\text{Li})$ varies by a factor of about 3 in an unrelated fashion. We conclude that the ^{7}Li in the halo stars is almost certainly primordial.

d) *Cosmological Implications*

In agreement with the discussion of Boesgaard and Steigman (1985), the two limiting possibilities appear to be that either the big bang produced an abundance $N(\text{Li}) \approx 3.0$ and all sufficiently hot halo stars have suffered lithium destruction amounting uniformly to almost an order of magnitude, or it produced an amount $N(\text{Li}) \approx 2.1$ and the halo stars have suffered little lithium destruction, as argued by SS. The extreme halo stars studied so far show no positive evidence of the destruction required by the former hypothesis, which is perhaps simpler in requiring only one significant source of ^{7}Li. In the latter case, Galactic sources not yet conclusively identified must have produced somewhat more ^{7}Li than the big bang. A definite conclusion apparently cannot yet be reliably drawn from the data now available.

In two metal-poor stars, Maurice, Spite, and Spite (1984) find an upper limit $^6\text{Li}/^7\text{Li} < 0.1$ for the isotope ratio, a result expected in any case at such an early epoch when lithium is almost entirely ^{7}Li. Ferlet and Dennefeld (1983) deduced a range $25 < {}^7\text{Li}/^6\text{Li} < 180$ in the interstellar medium toward ζ Oph. This would imply significant evolution in the isotope ratio during the last 5 Gyr and perhaps a variation in the present ISM. None of the models discussed by Audouze *et al.* for Galactic production of lithium can reproduce the result of Ferlet and Dennefeld.

Whether or not additional lithium has been produced by Galactic sources, the present investigation corroborates the conclusion of SS and SMS in indicating that the primodial production of ^{7}Li was $2.1 \lesssim N(\text{Li}) \lesssim 3.0$. Compared with standard models of light element production in the big bang (Yang *et al.* 1984; Kawano, Schramm, and Steigman 1987), which assume a neutron half-life of $t = 10.6$ minutes and the existence of three types of neutrinos, this lithium abundance restricts the baryon-to-photon ratio r essentially to $1 \times 10^{-10} < r < 10 \times 10^{-10}$. If the primordial lithium abundance was $N(\text{Li}) \approx 2.1$, the ratio of baryons to photons is rather narrowly restricted to $r \approx 3 \times 10^{-10}$. These constraints appear to be consistent with those imposed by the abundances of D, ^{3}He, and ^{4}He (SS; SMS; Boesgaard and Steigman 1985). All indicate a low baryon density, $\Omega_B \approx 0.1$.

IV. POPULATION I STARS

Lithium abundances are listed in Table 6 for 24 relatively strong-lined, low-velocity stars. Li I equivalent widths, measured in most cases at much lower resolution and accuracy, have been previously reported for 15 of these stars.

All six of the abundances $N(\text{Li}) \geq 2.8$ found in Table 6 occur at $T_e \geq 5900$ K. The strong Li I line with $W_\lambda = 45$ mÅ which is seen in the spectrum of γ Vir A (Fig. 5) is noteworthy. The λ6707 line apparently must be detectable in at least some narrow-lined late-A stars. Such data may be important in prospectively testing observationally Michaud's (1986) hypothesis that the deficiency of atmospheric lithium seen in middle-F stars in the Hyades can be explained by diffusion. The theory predicts that the surface lithium present on the high-temperature side of the gap may not rise to its true asymptotic (presumably ZAMS) value except at spectral types somewhat earlier than F0. The large abundance $N(\text{Li}) = 3.5$ or Li/H $= 3 \times 10^{-9}$ inferred here for Hz 530, an F2 V member of the Pleiades, is also of interest in this respect.

All three abundances $N(\text{Li}) \leq 1.1$ occur at $T_e \leq 5780$ K. In particular, 15 Peg displays both a temperature and a Li/H ratio nearly identical to the Sun's. The relatively high abundance $N(\text{Li}) = 2.5$ in ξ Boo A, a quite cool binary member with $T_e = 5300$ K, has been discussed by Herbig (1965).

V. CONCLUSIONS

We have principally analyzed the lithium abundances in 23 subdwarfs. The random 1 σ abundance errors are about $\pm 25\%$ or ± 0.10 dex. Lithium is present in the abundance range $1.9 \leq N(\text{Li}) \leq 2.2$ in all of the halo stars studied here and by SMS which have metallicities $[\text{Fe/H}] \leq -1.4$ and $T_e > 5600$ K. This lithium was almost certainly produced in the big bang, so that $N(\text{Li}) \approx 2.1$ is a lower limit to the primordial abundance. If all halo stars have destroyed some lithium, despite the absence of any conclusive observational (or theoretical) evidence for this process in the hotter subdwarfs, then the big bang production could have been as high as $N(\text{Li}) \approx 3.0$, the abundance of ^{7}Li seen in all Population I objects whose lithium has not been destroyed. The determination of $2.1 \lesssim N(\text{Li}) \lesssim 3.0$ as the primordial ^{7}Li fraction is a powerful constraint on standard models of the big bang, substantiating and making more precise the low ratio of baryons to photons indicated by the abundances of D, ^{3}He, and ^{4}He (SS; SMS; Boesgaard and Steigman 1985).

Note added in manuscript.—Our attention has been kindly drawn by Dr. A. Boesgaard to additional results recently published by Spite and Spite (1986). Their λ6707 equivalent widths for HD 64090, HD 108177, and BD +34°2476 constitute definite detections which probably agree, within the combined errors, with the upper limits given here for the three stars.

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