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THE LITHIUM ISOTOPE RATIO IN FIVE F OR G DWARFS

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ABSTRACT

Observations of the Li I λ6707 doublet obtained at high resolution and photometric precision are reported for two F dwarfs and three G dwarfs known to have narrow lines and strong λ6707 absorption. Adjacent lines of Ca I and Fe I are used to predetermine accurately the position and the broadening of theoretical Li I profiles fitted to the observed ones, leaving the abundances of ^{6}Li and ^{7}Li as the only adjustable parameters of the calculated profiles. Upper limits $R \equiv {}^6\text{Li}/{}^7\text{Li} < 0.1$ are obtained for four of the stars, while $R \lesssim 0.1$ for ξ UMa A. The total Li/H abundances range from 3×10^{-10} to 10×10^{-10}, with uncertainties probably not exceeding a factor of 2.

Subject heading: stars: abundances

I. INTRODUCTION

The isotope ratio ^{6}Li/^{7}Li is of considerable prospective importance in choosing among several mechanisms advanced to explain the origin of galactic lithium (Reeves 1974; Duncan 1981; Spite and Spite 1982; Audouze *et al.* 1983). Despite observations of the Li I λ6707 doublet in many stars (e.g., Herbig 1964; Feast 1970; Cohen 1972; Maurice, Spite, and Spite 1984) and in the interstellar medium (Vanden Bout *et al.* 1978), no convincing detection of the isotopically shifted ^{6}Li lines apparently has been yet achieved because the shift of 0.16 Å and the ratio $^6\text{Li}/^7\text{Li} \lesssim 0.1$ are both small. Improved spectrographs and detectors now make new observations of Li I at higher resolution and photometric precision feasible. This paper reports such measurements for five solarlike, northern stars. After the present observations were completed, a similar but independent study of nine southern stars came to the author's attention (Andersen, Gustafsson, and Lambert 1984).

II. OBSERVATIONS

The program stars are listed in Table 1, where the observed stellar data in columns (2), (4), and (6) are taken from *The Bright Star Catalogue* (Hoffleit 1982). The magnitude of the space velocity with respect to the local standard of rest, which is given in column (3), has been calculated from the proper motions and the radial velocities in the same reference, with allowance for the standard solar motion (Delhaye 1965). The MK spectral types in column (7) are taken from Hoffleit (1964), the projected rotational velocities in column (8) from Soderblom (1982), and the $R-I$ color indices in column (9) from Johnson, MacArthur, and Mitchell (1968). The values of $B-V$ and $R-I$ entered for ξ UMa A are actually those for the combined light of the binary, which consists of two similar but probably not identical components (Soderblom 1983).

All five program stars are known to show strong λ6707 absorption (Herbig 1964), sharp lines, and relatively large trigonometric parallaxes. With respect to the main sequence of the Hyades' color-magnitude diagram, the V and $(B-V)$ photometry of Table 1 place the three G dwarfs on the main sequence and the two F dwarfs somewhat above it, but sufficiently close to corroborate the luminosity class V of all five MK types. The five stars also have annual proper motions in excess of 0″.15; however, with the exception of the high-velocity star χ Her, their LSR space velocities do not differ by as much as 10 km s^{-1} from the solar value of 20 km s^{-1}. In addition to observationally suitable Li I lines, the program stars—with the possible exception of χ Her (Carney 1979)—may therefore be expected to have abundances and atmospheric structures sufficiently similar to those of the Sun to allow reliable calculation of theoretical λ6707 line profiles for analysis of the observations.

The spectra were obtained with the coudé spectrograph of the 2.7 m telescope at McDonald Observatory, using the echelle grating and the dual-array Digicon detector. An instrumental resolution (FWHM) of 0.61 Å, or 38% of the isotope shift, was set by choosing a slit width of 0″.6 on the sky, which also resulted in a spectral sampling of two detector photodiodes per resolution element. Each exposure covered the region extending approximately from 6695 Å to 6721 Å. Comparison spectra from both Li/Ne and Th/A hollow-cathode lamps were obtained before and after each stellar spectrum to confirm that no detectable wavelength shifts of the instrumental system occurred during the stellar exposures and to estab-

TABLE 1
THE STARS OBSERVED

Star (1)	π (2)	$\lvert v_{LSR} \rvert$ (km s^{-1}) (3)	V (4)	M_v (5)	$B-V$ (6)	MK (7)	$v \sin i$ (km s^{-1}) (8)	$R-I$ (9)
ξ UMa A	0″.137	17	4.41	5.09	0.59	G0 V	1.4 ± 0.7	0.34
HD 130948	0.069	28	5.85	5.04	0.56	G2 V	...	...
χ Her	0.062	73	4.62	3.58	0.56	F9 V	2.2 ± 1.0	0.32
ι Peg	0.082	11	3.76	3.33	0.44	F5 V	6.5 ± 0.8	0.25
53 Aqr A	0.057	12	6.35	5.13	0.61	G2 V	9.5 ± 0.8	...

TABLE 2

OBSERVED EQUIVALENT WIDTHS (mÅ)

Star	Fe I λ6703.57	Fe I λ6705.12	Li I λ6707.8	Ca I λ6717.69[a]
ξ UMa A	22	29	60	99
HD 130948	33	43	96	125
χ Her	16	22	56	86
ι Peg	10	23	70	82
53 Aqr A	38	45	129	95

[a] Includes weak, blended Fe I λ6717.56.

lish accurate wavelength scales. An empirically determined signal-to-noise (S/N) ratio of at least 100 was achieved for all of the stars except 53 Aqr A, for which S/N ≈ 45, in observing times which ranged from 23 minutes for ι Peg to 87 minutes for HD 130948 in roughly average seeing. The resulting equivalent widths of four stellar lines are given in Table 2, where the observational uncertainties typically are ±3 mÅ, except for 53 Aqr A where they are perhaps ±5 mÅ. Except for ι Peg, for which Duncan (1981) reported $W_\lambda(6707) = 47$ mÅ, the Li I equivalent widths in Table 2 probably show acceptable agreement with those measured at low resolution by Duncan for the same stars when uncertainties in both sets of data are included.

Portions of the five spectra are shown in Figure 1. The asymmetry of the Li I line is immediately evident for ξ UMa A and χ Her, the two stars with the narrowest lines; the asymmetry arises almost entirely from the presence of the two fine-structure components of the ^{7}Li resonance doublet, which are split by 0.151 Å, rather than from the presence of a shifted ^{6}Li doublet (Table 3). The weak Fe I 6717.56 Å line in the short-wavelength wing of the Ca I line is similarly evident for all stars, except perhaps ι Peg. In addition, a very weak line near 6707.45 Å, which is probably an Fe I line and is reasonably well resolved from the Li I absorption, can be seen in the spectra of χ Her, ξ UMa A, and perhaps HD 130948, the three cooler stars with spectra showing S/N ≥ 100.

III. ANALYSIS

Theoretical line profiles were calculated from model stellar atmospheres to determine both the ^{6}Li/^{7}Li ratios and, secondarily, the Li/H abundance ratios. The basic method employed was first to use the adjacent Fe I λ6705.117 and Ca I lines to determine in advance both the position and the nonthermal contributions to the broadening of the theoretical Li I profile, and then to secure the best agreement with the observed Li I profile by adjusting only the ^{7}Li and ^{6}Li abundances as free parameters of the theoretical profiles. In the first step, the Fe I λ6703.57 line also was used in predicting the expected position of the Li I lines. The wavelengths and transition probabilities adopted are given in Table 3; except for the *f*-values for the Fe I lines, all are obtained from laboratory measurements. It should be noted that, for these sharp-lined program stars, the major contribution to the width of the λ6707 line components is made by thermal broadening.

The calculations were carried out using the University of

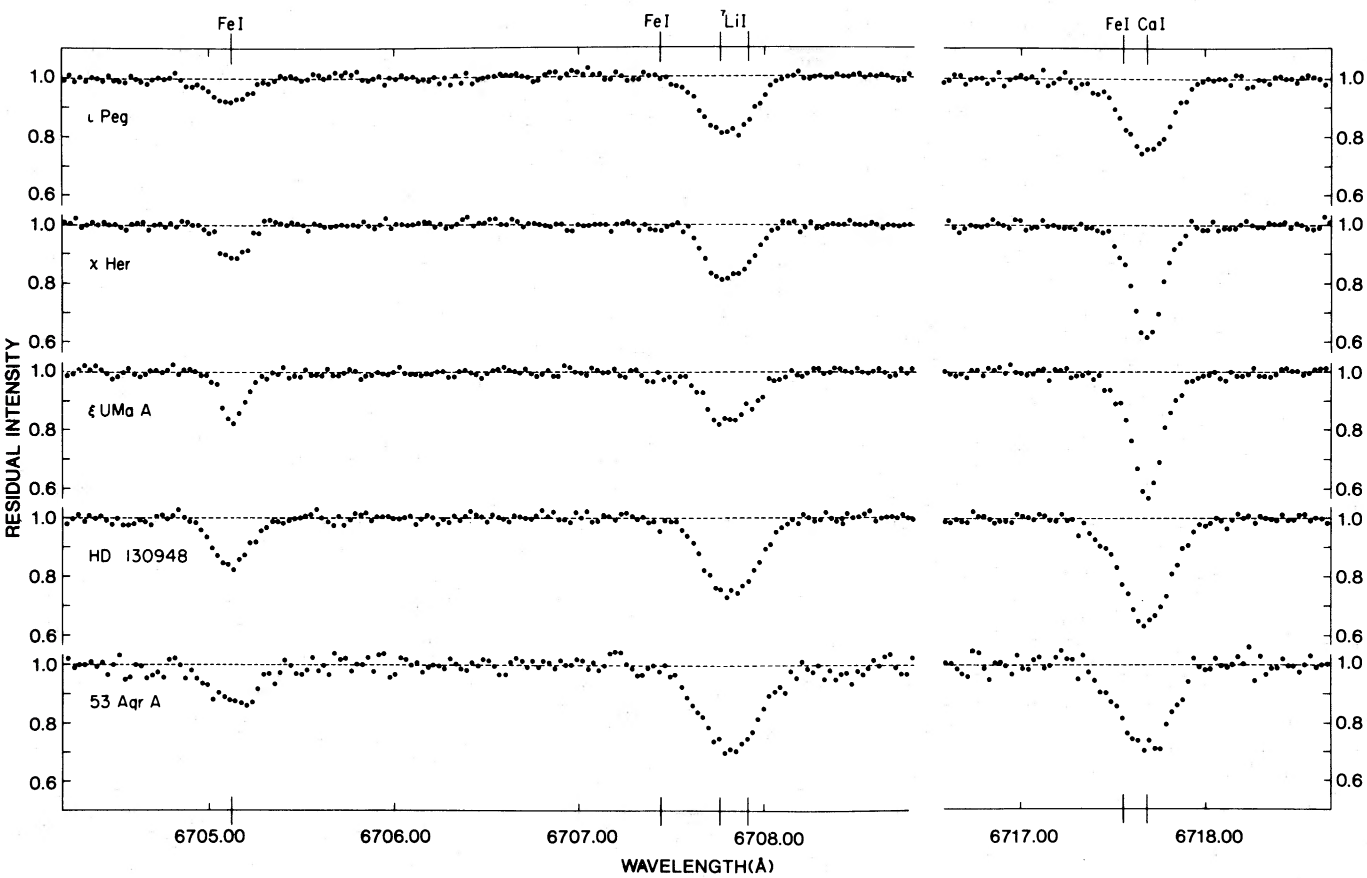

FIG. 1.—The spectra of five stars, from 6704.2 Å to 6708.8 Å and from 6716.6 Å to 6718.7 Å. The line positions and identifications are shown at the top. The stars are shown in order of decreasing temperature.

TABLE 3

ATOMIC DATA

Atom	λ(Å)	Reference[a]	Excitation Potential (eV)	gf	Reference[b]
Fe I	6705.117	1	4.61	0.050	1
^{7}Li I	6707.761	2	0.00	0.988	2
^{7}Li I	6707.912	2	0.00	0.494	2
^{6}Li I	6707.921	2, 3	0.00	0.988	2
^{6}Li I	6708.072	2, 3	0.00	0.494	2
Fe I	6717.556	1	4.61	0.015	1
Ca I	6717.685	1	2.71	0.245	3

[a] (1) Harrison 1969; (2) Meissner, Mundie, and Stelson 1948; (3) Hughes 1955.

[b] (1) Andersen, Gustafsson, and Lambert 1984; (2) Gaupp, Kuske, and Andrä 1982; (3) Wiese, Smith, and Miles 1969.

TABLE 4

MODEL ATMOSPHERES AND ABUNDANCES

Star	T_e(K)	v_2 (km s^{-1})	[Ca/H]	[Fe/H]	10^{10} × Li/H[a]
ξ UMa A	5800	2.5	0.2	0.0	3.2
HD 130948	5700	4.2	0.5	+0.2	4.9
χ Her	5900	2.5	−0.1	−0.2	3.6
ι Peg	6300	5.0	0.2	+0.1	9.7
53 Aqr A	5700	5.3	0.0	+0.3	7.8

[a] Assuming ^{6}Li/^{7}Li = 0.

Texas spectrum-synthesis program kindly made available by Dr. David Lambert. The model atmospheres used are scaled solar models which are in hydrostatic equilibrium and LTE with plane-parallel geometry. The abundances adopted are the solar values, including $(\mathrm{Fe/H})_\odot = 3.2 \times 10^{-5}$ and $(\mathrm{Ca/H})_\odot = 2.2 \times 10^{-6}$, of Ross and Aller (1976), as modified for CNO by Lambert (1978). For all five stars, a surface gravity log g = log $g_\odot = 4.44$ and a microturbulent velocity $v_1 = 1.0$ km s^{-1} were adopted. The respective effective temperatures T_e chosen are listed in Table 4; they were estimated by taking into account the spectral types as well as the $(B-V)$ and $(R-I)$ color indices, with the calibration of Johnson, MacArthur, and Mitchell (1968) for the latter. The ^{6}Li/^{7}Li abundance ratios which are of primary interest here are quite insensitive to the exact choices of T_e, g, and v_1. Furthermore, it will be seen below that, with these adopted parameters, the absolute Ca/H and Fe/H abundances which are derived for all five stars agree with the solar values to within a factor of 2, with one exception.

Profile fitting of the Ca I λ6717 line yielded both the nonthermal contribution to the broadening of all lines, expressed as a velocity v_2 characterizing a Gaussian distribution of macroturbulent velocities, and the Ca abundance [Ca/H] ≡ log [(Ca/H)/(Ca/H)$_\odot$]. The results are shown in Table 4 and are illustrated for ξ UMa A in Figure 2. Within the uncertainties, the derived values of v_2 are indeed ordered in the same sequence as the values of v sin i in Table 1, and, except for HD 130948 but including the high-velocity star χ Her (see Carney 1979), the calcium abundances are solar to within ±70%, a

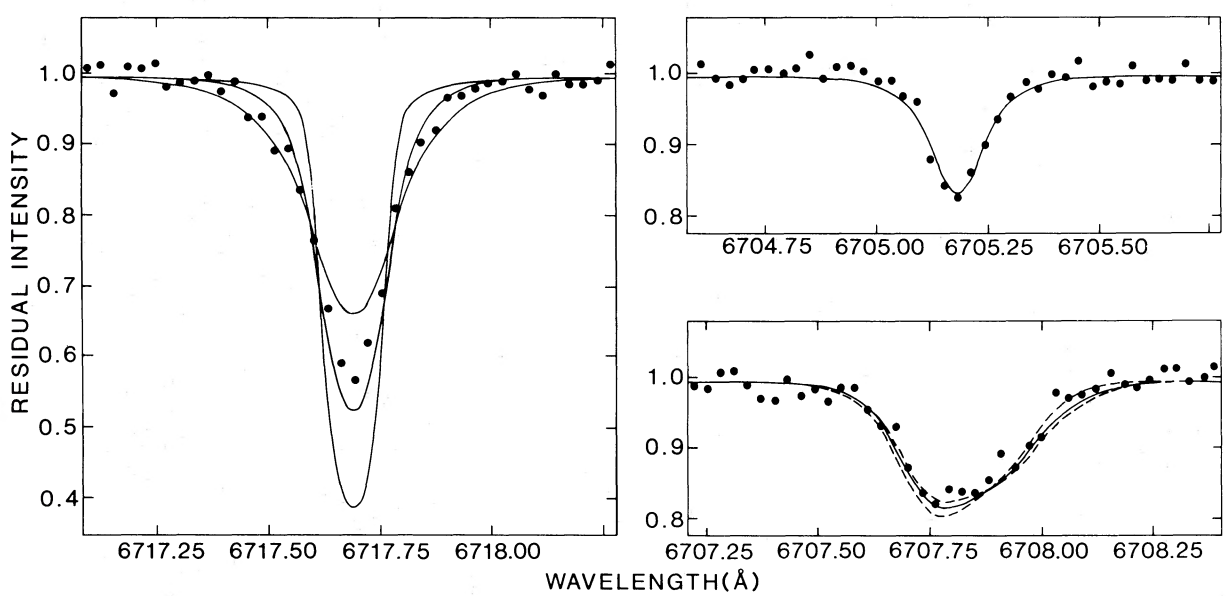

FIG. 2.—Profile fitting for ξ UMa A. The curves show theoretical line profiles for the Ca I 6717.685 Å, Fe I 6705.117 Å, and Li I 6707.8 Å lines. The observations are given by the filled circles, for which two dot diameters correspond to about ±1% in residual intensity, or approximately to the 1 σ photometric fluctuations. The three theoretical Ca I profiles correspond to macroturbulent velocities v_2 of 0, 2, and 4 km s^{-1}, respectively, in order of increasing central residual intensity. The theoretical Ca I profiles shown do not include the effects of the blended Fe I 6717.556 Å line. The three theoretical Li I profiles correspond to isotope ratios $R \equiv {}^6\mathrm{Li}/{}^7\mathrm{Li}$ of 0, 0.1, and 0.2, respectively; the solid curve applies for R = 0.1, and the dashed curve with the lowest minimum residual intensity obtains for R = 0.

difference probably smaller than the overall uncertainty in these values. As a further check, similar fitting of the Fe I λ6705 line was carried out with predetermined values of v_2 while allowing only the Fe abundance to vary. The results are again shown in Table 4 and illustrated in Figure 2; all of the resulting iron abundances are solar to within a factor of 2. Finally, the results of the Li I fitting for the three values 0, 0.1, and 0.2 of the ^{6}Li/^{7}Li ratio are shown in Table 4 and in Figures 2 and 3. As in the Ca I and Fe I profile fitting, each theoretical profile (and associated abundance) was determined by requiring specifically that its equivalent width match that of the corresponding observed line. The observational uncertainty allowed in the expected position for the theoretical Li I profile, which was deduced from the adjacent stellar lines in Table 2 as noted above, ranged from 6 to 14 mÅ for the five stars. The uncertain difference, if any, between the convective blueshifts of the Li I lines and of the higher excitation Ca I and Fe I lines, used here to determine the wavelength scale, should not exceed a few mÅ (Dravins, Lindegren, and Nordlund 1981); no such difference has been incorporated here in order to isolate the Li abundance as the only adjustable parameter in the Li I profile fitting. The hyperfine-structure splittings of both members of the ^{7}Li doublet amount to about 12 mÅ, or 20% of the instrumental resolution and 8% of the fine-structure splitting, while those of the ^{6}Li line components are still smaller by a factor exceeding 3. These small hyperfine-structure splittings also have not been explicitly included in calculating the theoretical λ6707 profiles shown in Figures 2 and 3, because their effects are small compared to the uncertainties introduced by the finite photometric precision achieved.

IV. RESULTS

The principal results evident in Figures 2 and 3 are that the ^{6}Li/^{7}Li ratios are small and that no ^{6}Li is definitely detected. In all cases except ξ UMa A, the value $R = {}^6\text{Li}/{}^7\text{Li} = 0$ yields a measurably better fit than does $R = 0.1$ or 0.2. A conservative estimate is that $R < 0.1$ for these four stars, a conclusion also reached previously for nine southern stars by Andersen, Gustafsson, and Lambert (1984) and, at somewhat lower resolution and photometric accuracy, for fourteen other stars, including χ Her, by Cohen (1972). Such conclusions would be expected if the initial main-sequence isotopic ratio in the surface layers of these stars assumed the terrestrial value of 0.08 and then declined thereafter, owing to the much faster destruction of ^{6}Li than of ^{7}Li by (p, α)-reactions (Fowler, Caughlan, and Zimmerman 1975; Audouze *et al.* 1983). In the case of ξ UMa A, an isotope ratio near 10% provides the best fit in Figure 2 among the three choices, but still higher photometric accuracy must be achieved to yield a conclusive detection of ^{6}Li. Cohen (1972) previously reported $R < 0.1$ for ξ UMa A.

The total Li/H abundances listed in Table 4, which are those determined for the case $R = 0$ but which depend very weakly on the isotopic ratio for $R \leq 0.1$, range from about 3×10^{-10} to 10×10^{-10}. Unlike the isotopic ratios, these abundances depend somewhat sensitively on the values of g and, especially, T_e adopted for the model atmospheres. As judged from the dispersion in the corresponding Ca and Fe abundances, the Li/H abundances may be accurate to within a factor of $\sim$2. In addition, three of the five Li abundances in Table 4 exceed by factors less than 1.6 those obtained for the same stars by Duncan (1981) from different observations and analysis; for the remaining two stars in common, this ratio is less than 2.9. On the basis of four detections and eight upper limits, the abundance of Li in the interstellar gas seems to be uniform near Li/H $\approx 3 \times 10^{-9}$, a value which is probably uncertain to a factor of at least 3, owing to the uncertain corrections required for the interstellar ionization balance of Li (Hobbs 1984). Therefore, among the stars which were selected for study here partly on the basis of their strong λ6707 lines, only ξ UMa A and χ Her appear to show a convincing deficiency of Li with respect to the present interstellar value. In the former case, the

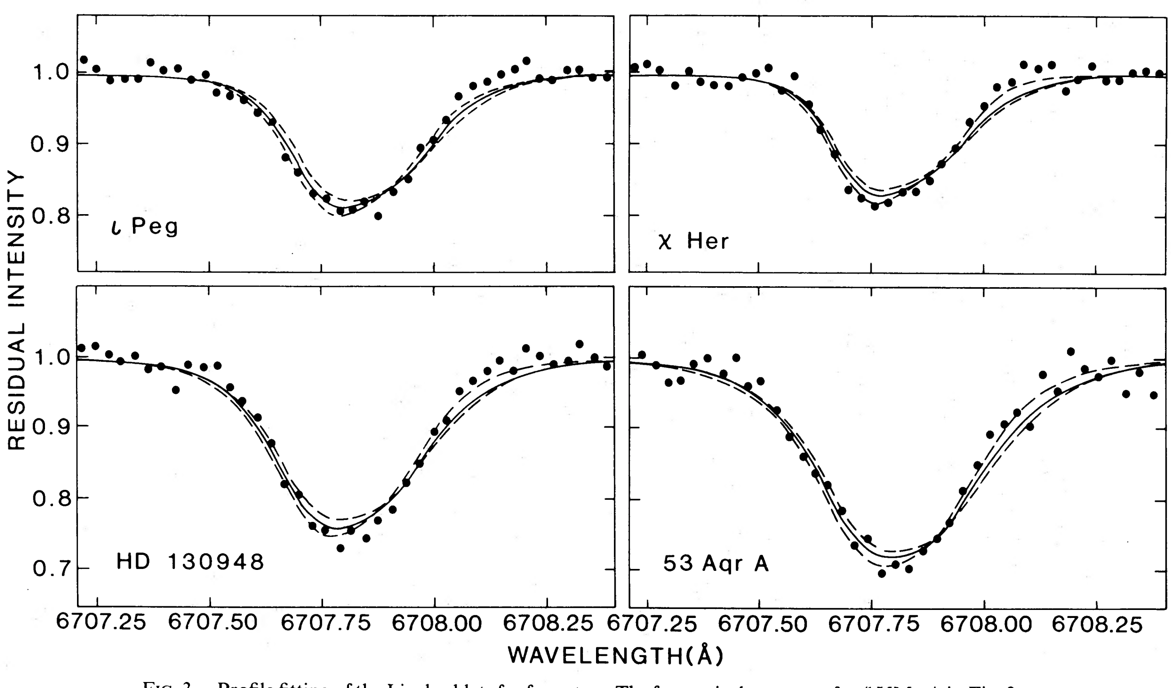

FIG. 3.—Profile fitting of the Li I doublets for four stars. The format is the same as for ξ UMa A in Fig. 2.

value of T_e adopted in Table 4 may deserve upward revision by as much as 250 K, depending on how different the binary components actually are (§ II); such a change would increase the derived lithium abundance by a factor of ~ 2, thereby leaving only χ Her with a lithium abundance clearly below the interstellar value.

I am grateful to David Lambert for generously making available both the spectrum-synthesis program used here and a preprint of the work by Andersen, Gustafsson, and Lambert, as well as for helpful discussions; to Jocelyn Tompkin for very lucid instruction in the use of the spectrum-synthesis program and for helpful discussions; to David Soderblom for useful comments; to Dan Welty, for exploratory, approximate estimates of the isotopic ratios; to the staff of McDonald Observatory for their usual kind hospitality; and to the National Aeronautics and Space Administration for partial financial support of the work through grant NGR 14-001-147.

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