PRIMORDIAL NUCLEOSYNTHESIS OF ^{7}Li

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ABSTRACT. We have observed 23 halo stars with space velocities $|\vec{v}_{LSR}| \geq 100$ km s^{-1} and metallicities [Fe/H] ≤ -0.6. Twelve of these 23 show the more extreme properties $|\vec{v}_{LSR}| \geq 160$ 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 5 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 $\langle Li/H \rangle = 1.2 \pm 0.3 \times 10^{-10}$. 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.

1. 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 pre-stellar universe were pioneered by Spite and Spite (1982; hereinafter SS) and by Spite, Maillard, and Spite (1984; hereinafter 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. The present abundance of lithium in the solar atmosphere is about 100 times smaller than its initial main-sequence value. The discovery by SS that lithium is present in halo stars of approximately solar temperature in amounts at least ten times the solar value was therefore surprising and important. An explanation of

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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.

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 here, where measurements of the Li I λ6707 doublet at a resolution typically of 0.25Å are reported for a primary group of 23 subdwarfs with iron abundances [Fe/H] ≤ -0.6 and space velocities $v = |\vec{v}_{LSR}| \geq 100$ km s^{-1}. Twelve of these stars in fact are extreme halo stars which show [Fe/H] ≤ -1/4 and v ≥ 160 km s^{-1}.

2. OBSERVATIONS AND RESULTS

2.1. The Spectra

Spectra of 16 of the stars were obtained at an instrumental resolution (FWHM) of 0.26 Å, using the Digicon detector and grating B of the coude spectrograph at the 2.7 m reflector of McDonald Observatory. The entrance slit corresponded to 0.6 arcsec 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 a few of the fainter stars a slit width of 1.2 arcsec and a consequent resolution of 0.52 Å were chosen instead. Data for 9 of the 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 coude camera with a 40-inch focal length. The agreement of the λ6707 equivalent widths for the five stars in common between McDonald and the Lick observations is excellent, the average difference being 0 ± 4 mÅ. Finally, observations of five of the faintest stars were acquired in October 1985 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 agreement of our results with the data of SS and SMS, which were recorded at generally similar resolution and slightly better photometric accuracy, is generally excellent. 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.

2.2. 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 to 8400 Å to surface fluxes calculated from ATLAS6 model atmospheres. From photometry available in the literature, 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 Stromgren photometry tabulated by Hauck and Mermilliod (1979), was also examined. In a few cases where there was disagreement by more than 100 K among the various temperatures discussed above, the Stromgren colors were used to indicate which temperature is more nearly correct. An intercomparison of the three sets of temperatures indicates a random error of approximately 80 K in the temperature estimated from any 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.

2.3. The Derived Abundances

Curves of growth for Li I λ6707 were 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. The method described by Duncan and Jones (1983) was used to extend the calculations to T_e = 6500 K as well. An isotope ratio ^{6}Li/^{7}Li = 0 was adopted. 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_λ = 30 mÅ causes an abundance error of ±15% in our results; a measurement error of ±20% in the equivalent width contributes a further abundance error of ±20%. Quadratically combining these independent errors yields a total error of ±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 11 stars in which λ6707 is definitely detected in both sets of observations the mean logarithmic difference is 0.02 ± 0.12 dex.

3. DISCUSSION

The lithium abundances of the 23 halo stars investigated here are plotted as a function of effective temperature in the Figure. 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 <N(Li)> = <12 + log (Li/H)> = 2.05 in nearly

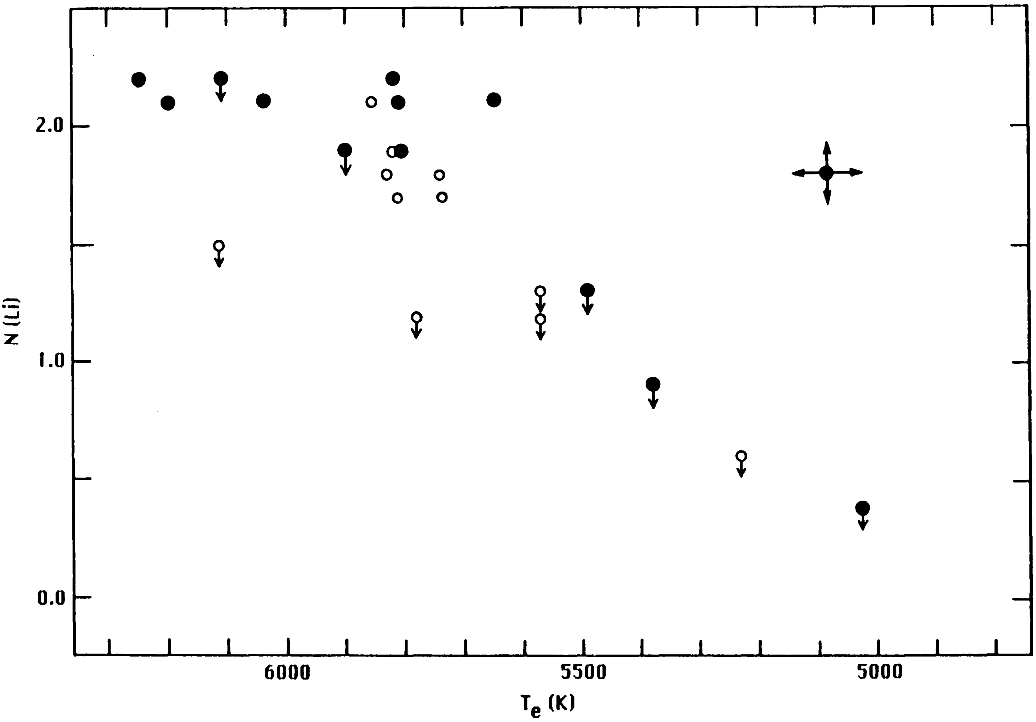

Figure. The variation of N(Li) = 12 + log(Li/H) with T_e for the 23 halo stars of Table 4. The 12 extreme halo stars, defined as those with $|\vec{v}_{LSR}| \geq 160$ km s^{-1} and [Fe/H] ≤ −1.4, are shown by filled circles; the other 11 stars, by open circles. Representative 1 σ errors of ±0.10 dex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

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 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.

3.1. The Extreme Halo Stars

Twelve of the 23 stars which have the properties $v \geq 160$ km s^{-1} and [Fe/H] ≤ -1.4 are indicated by filled circles in the Figure. 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. The nine hotter extreme halo stars have atmospheric lithium abundances, or upper limits on the abundances, in the narrow range $1.9 \leq N(\text{Li}) \leq 2.2$. The average value derived from the seven definite detections of λ6707 is $\langle N(\text{Li})\rangle = 2.11 \pm 0.09$. In contrast, the abundances of the three cooler, extreme subdwarfs are $N(\text{Li}) \leq 1.3$. Five stars from the list of SMS which are not among our program stars also 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 and T_e, and (2) $\langle N(\text{Li})\rangle = 2.07 \pm 0.11$ for 10 stars with $T_e \geq 5600$ K in which the Li I has been definitely detected.

3.2. Variations in the Lithium Abundance

Since the fundamental details of lithium destruction are unknown, even in the sun, it is impossible to predict reliably from theory which of the observed halo stars have destroyed lithium. Michaud, Fontaine, and Beaudet (1984) suggest that some lithium destruction is likely to have occurred in all halo stars.

Our 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 chi-square tests to determine whether the dispersion is explained by the estimated errors in the abundances, or whether it is real. We conclude that, while there is slight evidence for real differences, the apparent star-to-star variations in lithium abundance are probably accounted for by the estimated errors of measurement.

3.3. 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 Tripioco 1986b), and late-F and G stars in the solar neighborhood

(Duncan 1981). In all these objects, the maximum abundance observed is N(Li) ≈ 3.0 (cf. Boesgaard and Steigman 1985, Figure 10). In type I carbonaceous chondrites the abundance is N(Li) ≈ 3.3, but there is some evidence of chemical enrichment (Nichiporuk and Moore 1974). Interstellar abundances are typically $2.5 \lesssim N(Li) \lesssim 3.6$ and are appreciably more uncertain than the stellar ones (Hobbs 1984; Ferlet and Dennefeld 1984). This fairly uniform upper limit to N(Li) makes it unlikely that the lithium fraction produced in the Big Bang exceeded N(Li) ≈ 3.0.

Several sources of lithium other than the Big Bang have been suggested, such as novae or red giants (cf. Audouze *et al.* 1983). 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 about 13 over the range −1.4 to −2.5, N(Li) varies by a factor of about 3 in an unrelated fashion. We conclude that the ^{7}Li in the halo stars in almost certainly primordial.

3.4. 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(Li) ≈ 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(Li) ≈ 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 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.

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 primordial production of ^{7}Li was $2.1 \lesssim N(Li) \lesssim 3.0$. Compared with standard models of light element production in the Big Bang (Yang *et al.* 1984), 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(Li) ≈ 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, $\Omega_B \approx 0.1$.

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DISCUSSION

AUDOUZE: If the resulting primordial lithium abundance is higher than what is presently quoted by F. and M. Spite, I claim that it would favour lower values of baryonic density and not higher ones in order to agree with the present limits on the ^{4}He abundances. This would strengthen the conclusion raised by Delbourgo-Salvador et al. 1985 according to whom the baryonic density parameter Ω_N should be low.

DUNCAN: I agree that this is a possibility. It would increase the agreement with ^{4}He results, at the expense of those from D and ^{3}He, and the latter two are less certain.

FILIPPENKO: Since even your most metal-poor stars contain a substantial quantity of metals, they are probably not Population III objects. The gas they contain has presumably been processed by supernovae. Could these supernovae have significantly depleted the ^{7}Li abundance? After all, their internal temperatures are extremely high. Alternatively, could the supernovae have ejected some "extra" ^{7}Li into the interstellar medium from which your stars formed?

DUNCAN: The strongest argument that supernovae have not significantly increased or decreased the primordial ^{7}Li abundances is that the metal abundances of our true halo stars range over about two orders of magnitude, and the ^{7}Li abundances show no correlation with metallicity over that range.