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Li Production in the Big Bang

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Abstract. Li abundance is determined for 23 halo subdwarfs. About half of the stars show [Fe/H] < –1.4 and a space velocity V > 160 km s $^{-1}$. Li appears to be present in all our halo stars, with an abundance within about ± 0.2 dex of the value log n (Li) = 2.0 found by Spite & Spite (1982). Thus our results provide confirmation of the main conclusion of Spite & Spite.

Key words: abundances, Li—cosmology—stars, halo subdwarfs

1. Introduction

Accurate measurements of the abundance of lithium in the surface layers of 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 topic has recently been reviewed by Boesgaard & Steigman (1985). Standard models of the hot big bang (*e.g.*, Yang *et al.* 1984) predict the formation of D, ^{3}He, ^{4}He, and ^{7}Li in an epoch of primordial nucleosynthesis of a few minutes duration. If the abundances so produced can be measured, they may be used to probe the conditions of the big bang, and to place constraints on particle physics and cosmology.

The primordial abundance of ^{7}Li is last of these quantities to be probed, in large part because it seemed unlikely that primordial lithium could be detected. Li is the easiest of all elements to destroy. If subjected to temperatures in excess of 2.5×10^6 K, it is rapidly destroyed by (p,α) reactions. Such temperatures are reached at the base of the convection zones of cool stars, and the Li in these stars is continuously destroyed. The present Li abundance in the Sun is approximately 100 times less than that in the matter from which it formed.

Thus it was a surprising and extremely important discovery by Spite & Spite (1982; hereinafter SS) that Li is present in halo stars of approximately solar temperature, in quantities approximately 10 times larger than in the Sun. Surveying old disc and halo stars, SS, and Spite, Maillard & Spite (1984; hereinafter SMS) found basically that Li is present in stars which have [Fe/H] < 1.0, and log T_e = 3.74–3.80. When detected, the Li abundance was in all cases between 1.9 and 2.2, on the scale log n(H) = 12.0. The age of the stars and the uniformity of the Li abundance led SS to conclude that they were observing Li produced by the big bang and not modified since then.

The explanation of how such halo stars could presently have more Li than the Sun, despite their greater age, is apparently related to their metallicities. Calculations by Dappen (1984, personal communication) show that as metal abundance is reduced at fixed log T_e, convection zones become thinner and the temperature at their base less. The rate of Li destruction, being extremely temperature-dependent, may be greatly lessened.

What may be a related effect was first noted by Duncan (1981). In studying two phenomena associated with age in solar-type stars, chromospheric activity and Li abundance, he found that although most stars either exhibited high activity and high Li abundances, indicating youth, or low activity and low Li abundance, indicating that they were old, perhaps 15 per cent showed a discrepancy. In all cases the discrepancy was in the sense of low chromospheric activity and high Li abundance. Duncan tentatively concluded that the stars were probably in fact old, and had somehow avoided destroying their Li. 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 metal-poor.

Stimulated by the results of SS, the present authors independently set out in 1983 to examine a larger number of subdwarfs chosen to be as homogeneously old as possible. Since both temperature and metal abundance could be expected to effect Li destruction, we set out to survey a large region of the [Fe/H], log T_e plane. We have combined our data, and now have spectra of the Li I λ6707 doublet at a resolution of typically 0.2 Å for a group of 23 subdwarfs with iron abundances [Fe/H] $\leqslant -0.6$ and space velocities $\geqslant 100$ km s^{-1}. About half of these stars in fact show [Fe/H] $\leqslant -1.4$ and $V \geqslant 160$ km s^{-1}.

A very preliminary report on some of the most interesting stars is presented here.

2. Observations

A typical spectrum is presented in Fig. 1. Signal-to-noise ratios are generally 100–200. Agreement between our spectra and those of SS are very good. For eleven stars in which we both measured equivalent widths, the mean difference is 2 ± 5 mÅ. Every one of our stars which is clearly a halo object shows measurable Li λ6707.

3. Temperatures

We have paid particular attention to accurate temperature determination for the stars in our sample. Since Li I λ6707 is the resonance line of the neutral species of an atom which is almost completely ionized in these stars, it is very temperature sensitive, and accurate stellar temperatures are needed to derive accurate Li abundances. Peterson & Carney (1979, and additional data in Carney 1983) derived temperatures for most of these stars from matching spectrophotometric scans covering 5,000–8,400 Å to ATLAS6 model-atmosphere surface fluxes, and also from $R - I$ and $V - K$ colours. These three sets of determinations are independent, so random errors should be reduced by averaging them. The discussion which follows concerns differences between stars, in which random errors are the most important ones. Peterson & Carney estimate a random error of 80 K in their temperatures, and a possible 80 K systematic error or zero-point uncertainty. Intercomparison of their three sets of temperatures for each star indicates random errors of approximately 80 K in any one determination from a

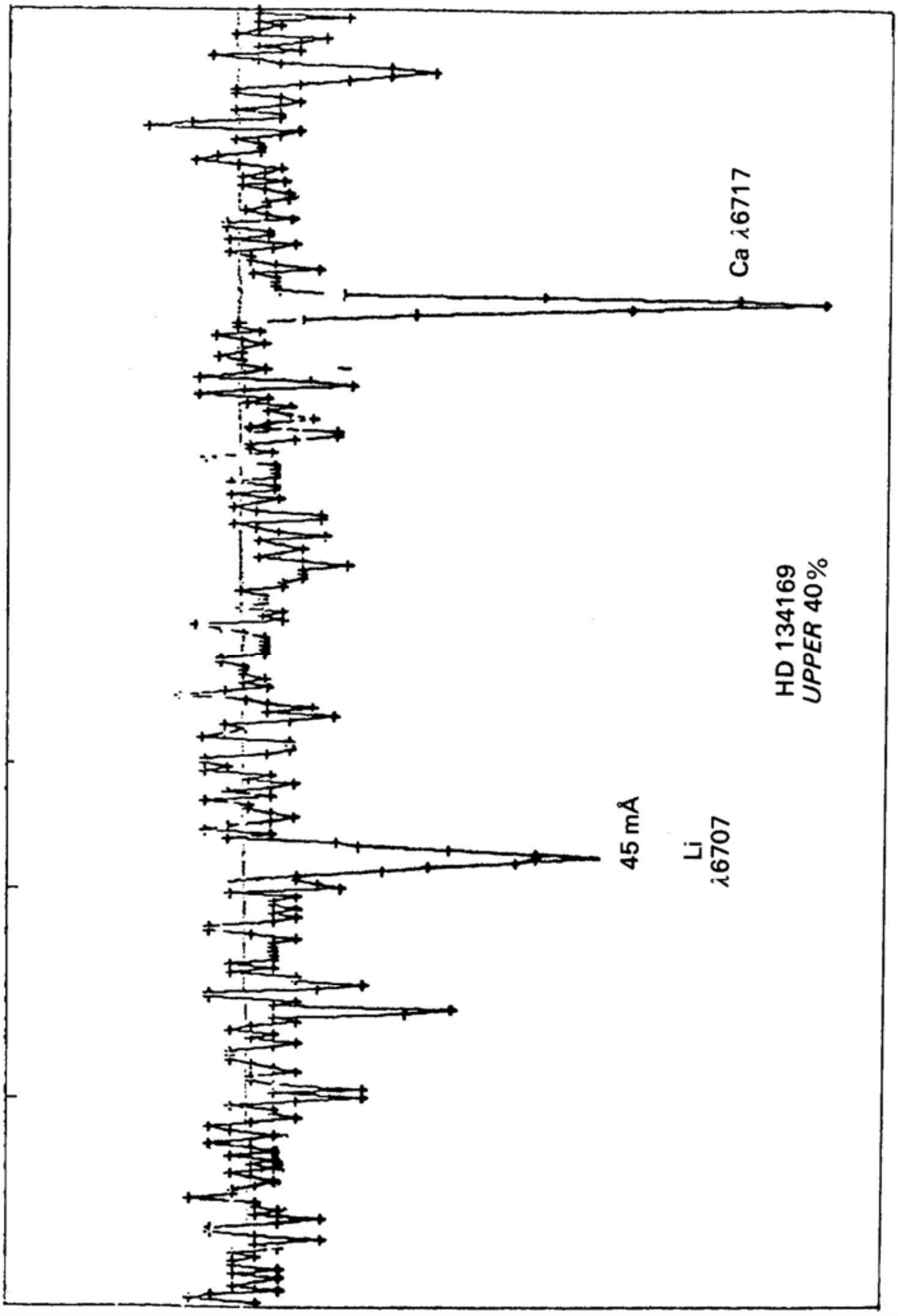

Figure 1. Spectrum of HD 134169 showing the upper 40 per cent of the flux.

colour or scan. It appears that Peterson and Carney's estimate of random errors of 80 K in the average of three measurements is conservative.

We conclude that random errors in the present temperature determinations, which are typically based on three independent sets of data, are approximately 60 K. It follows that we can estimate temperature differences between stars with a typical accuracy of about 80 K.

4. Abundances

Curves of growth for Li were computed using the program WIDTH6 (R. L. Kurucz 1983, personal communication) and model atmospheres of Bell *et al.* (1976). Computations were made for T_e =4500K, 5000K, 5500 K, and 6000 K; [Fe/H] =0, –1, and 2; log g= 4.5 and 3.75. The Li line was treated as a singlet although it is actually a close doublet since previous computations (Duncan 1981) showed this causes negligible error. Atomic parameters were the same as in Duncan (1981). Though there may be small systematic errors in the curves of growth, the dominant source of relative error is the temperature uncertainty. A typical error of 60 K in a star of temperature 5800 K and Li equivalent width 30 mÅ causes an abundance error of 0.06 dex.

5. Discussion

Li appears to be present in all our halo stars, with an abundance within about ± 0.2 dex of the value log *n*(Li) = 2.0 found by SS. Thus our results provide significant confirmation of their main conclusion, that in the halo stars one sees Li which was probably produced in the big bang.

However, we are less certain that it is an *unaltered* big bang product. Some halo stars of almost exactly the same temperature show differences in Li which may be real. Three examples are listed in Table 1. Although the stars are very similar physically, the Li abundances differ. However, since the temperature uncertainty contributes signify-cantly to the inferred Li abundance, we consider this evidence of differences to be marginal.

The abundance of Li in a wide variety of galactic locations has been found to be approximately log *n*(Li) = 3.0. These include the interstellar medium, young galactic clusters such as the Hyades (Cayrel *et al.* 1984), the T-Tauri stars, and also lunar samples (Dreibus, Spettel & Wanke 1976), and carbonaceous chondrites (Nichiporuk & Moore 1974). The Pleiades stars which show the least Li depletion (late F stars: Duncan & Jones 1982) also have the same abundance of approximately log *n*(Li) = 3.0. Thus the galactic Li abundance appears constant over at least the last 5 billion yr. The simple monotonic increase suggested by SS (Fig. 5) cannot be correct—it ignores the

Table 1. Observed and derived parameters for three stars from the sample.

HD	$R-I$	$V-K$	T_{scan}	T_{R-I}	T_{V-K}	$T_{adopted}$	[Fe/H]	W_{Li}(mÅ)
19445	0.34	1.39	5820	5770	5850	5810	-2.1	38 ± 4
201891	0.33	1.42	5810	5830	5810	5810	-1.4	27 ± 3
134169	0.33	1.46	—	5840	5780	5800	-1.3	46 ± 3

meteoritic and lunar evidence. If the primordial big bang production of Li is approximately 2.0, a substantial galactic source of Li must have raised the abundance relatively early to log n(Li) = 3.0, but not increased it over the last 5 billion yr.

It also seems possible to us that the big bang production was log n(Li) = 3.0, and that the halo stars have in fact suffered some depletion (10 ×), but not as much as the Sun (100 ×). This, of course, depends on the star-to-star differences being real. The star-to-star differences would then represent scatter about the mean depletion curve, (*cf.* the scatter in Fig. 2 of Cayrel *et al.* 1984). We suggest that the value log n(Li) = 2.0 be taken as a lower limit to the big bang production.

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