LITHIUM ABUNDANCES

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^{7}Li in Metal-Poor Stars: The Spread of the Li Plateau

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Abstract. A highly homogeneous study of 23 halo field dwarf stars
has achieved a Li abundance accuracy of 0.033 dex per star. The work
shows that the intrinsic spread of the Li abundances of these stars *at a
given metallicity* is $<$ 0.02 dex, and consistent with zero. That is, the
Spite Li plateau for halo field dwarfs is incredibly thin. The thinness
rules out depletion by more than 0.1 dex by a rotational-induced extra-
mixing mechanism. Despite the thinness of the plateau, an increase of Li
with [Fe/H] is seen, interpreted as evidence of Galactic chemical evolu-
tion (GCE) of Li, primarily due to Galactic cosmic ray (GCR) spallation
reactions in the era of halo formation. The rate of Li evolution is con-
cordant with: (1) observations of spallative ^{6}Li in halo dwarfs; (2) GCE
models; and (3) data on Li in higher metallicity halo stars. New data
have also revealed four new ultra-Li-deficient halo dwarfs, doubling the
number known. Based on their propensity to cluster at the halo main
sequence turnoff *and also* to exist redward of the turnoff, we hypothesise
that they are the products of binary mergers that ultimately will become
blue stragglers. We explain their low Li abundances by normal pre-main-
sequence (and possibly main-sequence) destruction in the low mass stars
prior to their merging. If this explanation is correct, then such stars need
no longer be considered an embarrassment to the existence of negligible
Li destruction in the majority of field halo dwarfs.

1. Introduction

The first indication that the old stars of the Galaxy exhibited an almost uni-
form Li abundance emerged at IAU Coll. 68, when Spite & Spite (1981, 1982)
presented their first observations of warm halo dwarfs. Almost two decades
later, IAU Symp. 198 met to consider progress in studies of this and other light
elements.

Studies by many workers in the decade following the Spite & Spite discover-
ies resulted in mounting evidence that the warm halo dwarfs exhibited a unique
Li abundance (e.g. Rebolo, Molaro, & Beckman 1988). The interpretation of this
abundance as the primordial one reflecting big bang nucleosynthesis, at worst
"hardly altered" (Spite & Spite 1982), hinged on the importance of possible de-
pletion of Li from a higher initial abundance. While ample evidence existed of Li
destruction in some stars, the lack of a significant spread in halo dwarf Li abun-
dances provided empirical evidence that destruction may have been minimal in

these objects. (See Boesgaard & Steigman 1985 for a review of that period.) Classical stellar evolution models (e.g. Deliyannis, Demarque, & Kawaler 1990) fitted this interpretation, showing that Li destruction in metal-deficient dwarfs with shallow surface convective zones would be minimal ($\lesssim 0.05$ dex). However, this same class of stellar models failed to explain numerous Population I star observations, and an alternative class of models invoking extra mixing implied that considerable Li depletion (as high as 1 dex; Pinsonneault, Deliyannis, & Demarque 1992) could have occurred in the halo stars.

In the next decade, several dissenting voices were heard. Deliyannis, Pinsonneault, & Duncan (1993) argued that there was a non-negligible spread in the Li abundances of the halo dwarfs that would not be consistent with a perfectly primordial composition. Depending on the sample selected, they found a Li spread of $\sigma \geq 0.04$ dex. Thorburn (1994) found an even greater intrinsic spread $\sigma \simeq 0.10$ dex, and moreover claimed, as did Norris, Ryan, & Stringfellow (1994), that the abundances depended on both T_{eff} and [Fe/H]. Such dependences were contrary to the notion of a unique Li abundance in the halo stars, and thus undermined the association of the observed Li abundance(s) with the primordial one. The efforts of Ryan et al. (1996) to bring all previous observations onto a uniform temperature and abundance scale did not eliminate the cited dependences.

One of the largest uncertainties in abundance analyses is errors in the effective temperature scales. Spite & Spite (1993) and Bonifacio & Molaro (1997) discussed the possible role of such errors in distorting an otherwise uniform Li abundance, the latter work finding the previously reported trends to become insignificant when a more recent temperature calibration based on the infra-red flux method (IRFM) was applied. Although the IRFM scale might be expected to provide better systematics, the large individual uncertainties attached to each temperature determination by this method limit the scale's ability to distinguish between effects at the level of those claimed for Li. The existence of some large errors even in the metallicity estimates for program stars also hampers the efforts. In particular, the literature data utilised by Bonifacio & Molaro (1997) includes several poorly determined values which, in hindsight, frustrated their analysis by smearing out the data (Ryan, Norris, & Beers 1999, §7.3.3).

2.   The Intrinsic Spread of ^{7}Li

In an effort to avoid the impact of undesirable errors, Ryan, Norris, & Beers (1999) set out to obtain a highly homogeneous data set on a sample occupying only a narrow range of T_{eff}, [Fe/H], and evolutionary type. Restricting their sample to 6000 K $\lesssim T_{\text{eff}} \lesssim$ 6400 K and $-3.5 \lesssim$ [Fe/H] $\lesssim -2.5$, applying double-blind data analysis techniques, obtaining multiple high-resolution, high-S/N observations of the targets, and using multiple temperatures indicators to minimise random errors, they achieved a formal abundance error as low as $\sigma_{\text{err}} = 0.033$ dex per star. These results are at considerably higher precision than most previous Li measurements (typically having $\sigma_{\text{err}} \simeq 0.06 - 0.08$ dex).

The sample was known to contain one previously known ultra-Li-deficient star, G186-26, which was excluded from the analysis. Remaining objects exhibited a total observed spread $\sigma_{\text{obs}} = 0.053$ dex, considerably less than that
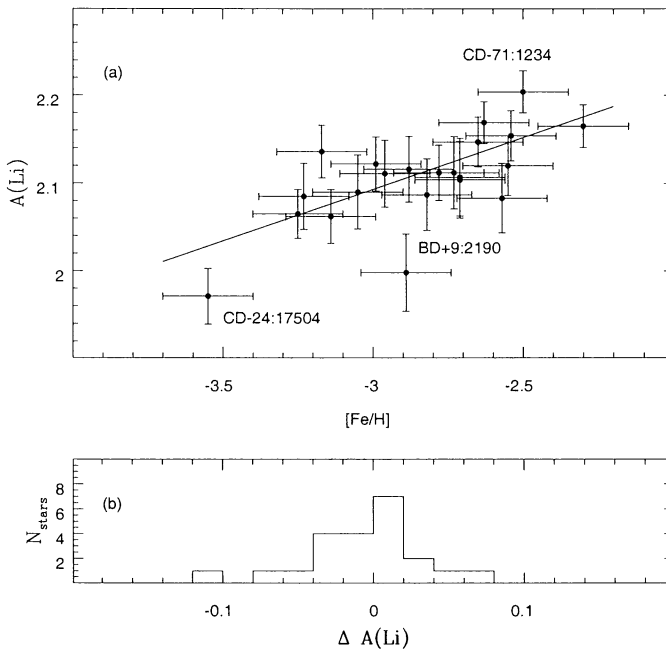
Figure 1. Metallicity-dependence of turnoff Li abundances, and residual observed spread with $\sigma_{obs} = 0.031$ dex.

found by Thorburn (1994). However, this 0.053 dex was found to be dominated by an underlying metallicity dependence, and the spread of the Li abundances about this trend is a mere $\sigma_{obs} = 0.031$ dex (see Figure 1), and Gaussian in form. This corresponds to the spread in Li abundance at a given metallicity. Comparing this with the formal measurement errors of $\sigma_{err} = 0.033$ dex leads to the conclusion that the intrinsic spread in the stars must be negligible. We state a generous upper-limit on the intrinsic spread as being $\sigma_{int} < 0.02$ dex.

An important consequence of the very narrow spread of Li abundances is its ability to constrain the impact of possible extra-mixing in so far as extra-mixing models predict a spread in the final Li abundances of a population of stars. The rotationally-induced mixing models of Pinsonneault et al. (1993) suggested that Li depletion by as much as an order of magnitude could have occurred in halo turnoff dwarfs. The more recent work of Pinsonneault et al. (1999), in concert with the observational data of Thorburn (1994), revised downward the depletion level to $\simeq 0.2 - 0.4$ dex. As Figure 2 shows, the data from Ryan et al. (1999) with their narrower spread (at a given metallicity) rule out rotationally-induced mixing models that exhibit even 0.1 dex median depletion. Considering the size of the observed sample and the absence of stars in the tail of the theoretical distribution, Poisson statistics provide only 10% chance that the observed and theoretical curves are compatible, or 90% probability that the median depletion is less than 0.1 dex. Other statistical tests discriminate the models even more significantly.

We seek now to explain previous results that yielded contrary conclusions. Thorburn's (1994) data reduction process explicitly excluded sky background
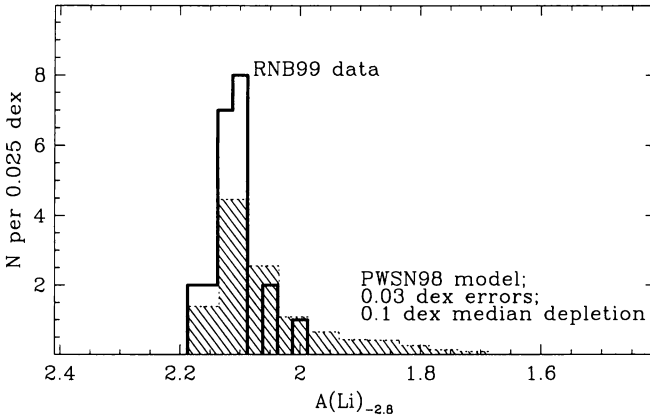
Figure 2.   Spread in observations (at a given metallicity after compensation for the [Fe/H] dependence of Li), compared with predictions for a rotationally-induced mixing model exhibiting a median depletion of 0.1 dex.

and scattered light subtractions, but this shortcut was not reflected in the formal error estimates. Incorporation of the errors introduced by this procedure are enough, on average, to inflate the error estimates to the size required by the observed scatter. That is, the scatter observed by Thorburn is almost certainly consistent with that resulting from data acquisition and analysis. Bonifacio & Molaro (1997) found no significant metallicity dependence in their analysis, but as discussed above, certain metallicities they adopted from the literature were found subsequently to be unreliable. This, and the large random errors inherent in the IRFM temperature scale, resulted in the weak Li evolution being washed out. (See Ryan et al. 1999, §7.3.3, for a detailed analysis.) Finally, we note that the small spread of abundances found by Deliyannis et al. (1993) is consistent with the observed spread in our sample if the underlying metallicity trend is overlooked. In fact, the Deliyannis et al. study pre-dated any claims of a metallicity dependence, and their result was probably driven by the large metallicity range in their sample.

3.   The Underlying Li vs [Fe/H] Trend

Although Li GCE during the halo-forming era has often been ignored, we should not be surprised that it exists. If recent detections of ^{6}Li in halo stars (Smith, Lambert, & Nissen 1993,1998; Hobbs & Thorburn 1994,1997; Cayrel et al. 1999, Deliyannis & Ryan 2000) are correct, then we would be surprised *not* to see ^{7}Li GCE. With the measurement precision attainable using modern CCDs and large aperture telescopes, even small levels of ^{7}Li enrichment can be measured, and it is consistent with the measured ^{6}Li abundances.

      To see whether the observed trend was compatible with GCE, Ryan et al. (2000a) examined the Fields & Olive (1999a,b) model. For halo stars, the ν-
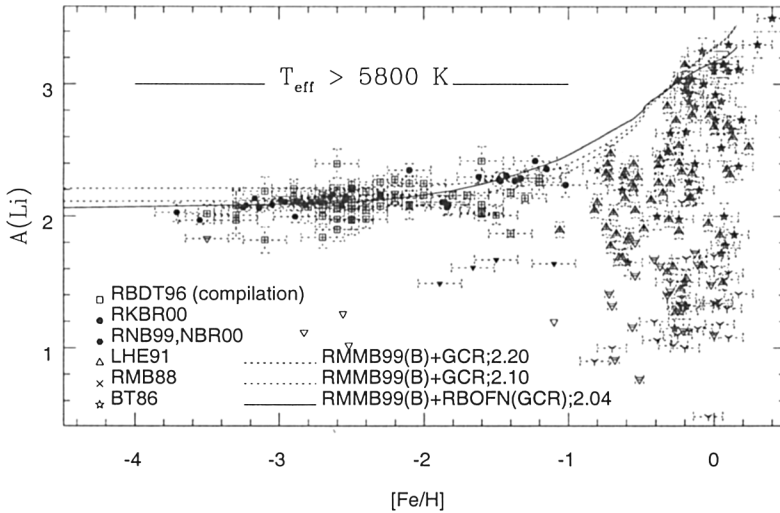
Figure 3. Evolution of Li with metallicity. Observations are for halo stars having $T_{\rm eff} > 5800$ K, to avoid lower-mass stars with Li depletion and to reduce the heterogeneity of the sample, and Population I stars from sources indicated. Models are (dashed curves) from Romano et al. (1999) for two different primordial values ($A(\mathrm{Li})_p = 2.10$ and 2.20), and (solid curve) a hybrid model using the GCR contribution of Fields & Olive (1999a,b; Ryan et al. 2000a) with Population I evolution from Romano et al.

process and GCR spallation are the most likely sources of ^{7}Li. The Fields & Olive model normalises the GCR contribution to meteoritic Be and ^{6}Li abundances, and normalises the ν-process to the otherwise unaccounted for ^{11}B. The model does not include stellar ^{7}Li sources acting in the later stages of Galactic evolution, and hence does not model the Population I abundance. The models of Romano et al. (1999) incorporate many Population I sources (primarily the ν-process, AGB stars, and novae). Figure 3 shows two variants of Romano et al's models and a hybrid using the GCR predictions of Fields & Olive from Ryan et al. (2000a). The model reproduces not only the halo star Li evolution discussed above, but also fits new data around [Fe/H] ~ -1.5 (Ryan et al. 2000b; see below) and the lowest metallicity datum at [Fe/H] $= -3.7$ (Norris, Beers, & Ryan 2000) which were added *after* the Fields & Olive model was produced.

Ryan et al. (1996) indicated that a selection bias existed in the Li data available in the literature, in that most studies centred on more-metal-poor objects. Few more-metal-rich halo stars had been examined, and those which had were on the whole cooler than the metal-poor ones. Given the difficulties with temperature scales for stars, the comparing of warmer metal-poor stars with cooler metal-rich stars was clearly undesirable. In an effort to address this bias, Ryan et al. (2000b) obtained data on 18 more-metal-rich halo stars, with $-2.0 \lesssim$ [Fe/H] $\lesssim -1.0$, but in the warm temperature range $T_{\rm eff} \gtrsim 6000$ K as for the most metal-poor samples. The sample was found to contain four ultra-Li-deficient halo stars, which will be discussed separately in the next section. The remaining stars, shown as solid circles in Figure 3, were found to sit exactly

where the Fields & Olive model predicts. We emphasise that the model was completed prior to the reduction and analysis of the metal-rich halo sample, so the agreement between the two is a genuine accomplishment, not something achieved artificially in the model. This is viewed as additional evidence that the trend of Li with [Fe/H] evidenced in Figure 1 is a result of natural GCE of the element during formation of the Galactic halo.

4.   The Primordial Li Abundance and Uncertainties

We combine these measurements in Table 1 to present a new accounting for the primordial Li abundance. Beginning with the observed abundance at the mean metallicity of our sample, we apply corrections for the inferred GCE contribution (with uncertainties) and for stellar depletion. For the latter we take the value implied by classical models, but in the uncertainties allow for additional depletion up to the 0.1 dex limit of the rotationally-induced mixing models. Temperature scale uncertainties remain one of the largest sources of error, and in this analysis we apply an offset of 0.08 dex to the Li abundance, corresponding to a change from the temperature scale adopted in our original analysis (based on the Bell & Oke (1986) and Magain (1987) b-y scales) to the systematically hotter IRFM scale of Alonso, Arribas, & Martínez–Roger (1996). However, we associate an uncertainty of ± 0.08 dex with this process, in recognition of the remaining difficulties in the temperature scales for halo dwarfs. These and the other affects tabulated lead us to infer a primordial abundance $A(\text{Li})_p = 2.09\ ^{+0.19}_{-0.13}$ dex, where the uncertainties resemble 2σ limits (Ryan et al. 2000a).

Table 1.   Transforming the observed halo Li abundance into the primordial abundance, accounting for random and systematic errors.

Systematic Effects Influencing Inferred Primordial Lithium Abundance		
Observed:		
$\langle A(\text{Li})_{-2.8}\rangle =$	2.12	± 0.02
Corrections to apply:		
GCE/GCR	-0.11	$^{+0.07}_{-0.09}$
Stellar depletion	$+0.02$	$^{+0.08}_{-0.02}$
T_{eff} scale zeropoint	$+0.08$	± 0.08
1-D atmosphere models	$+0.00$	$^{+0.10}_{-0.00}$
Model temperature gradient	$+0.00$	$^{+0.08}_{-0.00}$
NLTE	-0.02	± 0.01
gf-values	$+0.00$	± 0.04
Anomalous/pathological objects	$+0.00$	± 0.01
Total	-0.03	$^{+0.19}_{-0.13}$
Inferred:		
$A(\text{Li})_p =$	2.09	$^{+0.19}_{-0.13}$

5.   The Ultra-Li-Deficient Halo Dwarfs: Blue Stragglers After All?

Boesgaard & Tripicco (1986a) showed that Hyades stars with 6400 K $<$ T_{eff} $<$ 6900 K exhibit extremely low surface Li abundances. These and similar stars in other Population I clusters became known as "Li-dip stars". They showed that a second mechanism, besides convection on the pre-main sequence (and possibly main sequence) for lower mass stars, could greatly deplete surface Li abundances. Lambert, Heath, & Edvardsson (1991) showed that *most* of the strongly Li-depleted Population I field stars, shown for example in Figure 3, could be explained as either having evolved from the Li dip or being low mass convectively-depleted stars. However, they also noted that a small number of stars did not share these histories, and proposed that perhaps 10% of stars had experienced additional severe Li depletion through unknown causes. This work preceded the discovery of halo dwarfs whose temperatures and metallicities coincided with the Spite plateau but which were ultra-Li-deficient by more than an order of magnitude or so (Hobbs, Welty & Thorburn 1991; Thorburn 1992; Spite et al. 1993). The halo examples have been estimated at perhaps 3–5% of the Population, and may result from the same process as the Population I class proposed by Lambert et al. The nature of the process resulting in their Li-depletion has remained unclear, and our inability to explain them has been given as a reason to mistrust the entire Population II interpretation (e.g. Thorburn 1994). Whether or not such a view is held (cf. Ryan et al. 1999), they identify an embarrassing deficit in our knowledge of stellar processing of this important element. Efforts to identify common chemical signatures other than Li deficiency proved impossible; instead considerable diversity and heterogeneity was found amongst the complete sample (four) known at the end of 1998 (Norris et al. 1997; Ryan, Norris, & Beers 1998).

The study of 18 more-metal-rich halo stars by Ryan et al. (2000b) discussed above resulted in the discovery of four new ultra-Li-deficient halo stars; see Figure 4 (Ryan et al. 2000c). The discovery rate in that study, 22%, contrasts greatly with the previous Population estimate of 3–5%, and indicates that they are preferentially clustered in the stellar parameter range singled out in that investigation, namely warm, more-metal-rich halo stars. The stars are therefore seen to be grouped preferentially towards the main sequence turnoff of the halo, but not exclusively so. The clustering near the turnoff is reminiscent of blue stragglers, but the hypothesis that they were redward-evolving blue stragglers had already been ruled out for the previously known examples (Thorburn 1994; Norris et al. 1997). However, the discovery of four more such stars preferentially close to the main sequence turnoff resulted in the re-examination of the blue-straggler hypothesis, with the distinction that main-sequence blue-stragglers-to-be are now considered. Halo stars initially cooler than about 5700 K, corresponding to a mass of $\sim$ 0.7 $M_{\odot}$, deplete their surface Li during their pre-main-sequence evolution. When two low-mass stars merge to become a single object higher up the main sequence near the halo turnoff with a total mass around 0.7-0.85 $M_{\odot}$, they will in most cases form from stars which have already destroyed their Li. They will appear, then, as normal halo main-sequence stars *except* with respect to two parameters: (1) their Li abundances will be extremely low and hence appear abnormal, and (2) their main sequence lifetimes will be extended due to the delayed onset of nuclear burning
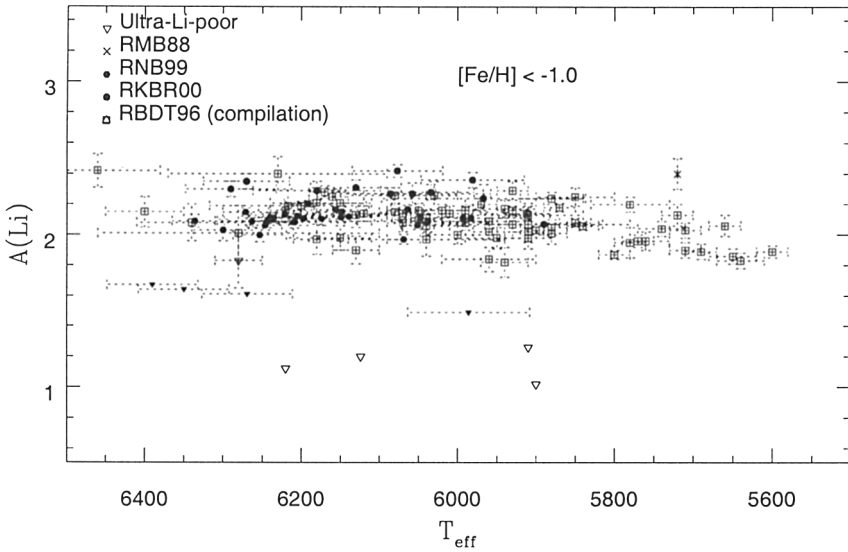
Figure 4.   Recent observations doubling the number of known ultra-Li-deficient halo stars. Their location close to the main sequence turnoff leads us to the hypothesis that they are the progeny of low-mass binary-star mergers, destined to become blue-stragglers.

at a rate expected of stars of their (combined) mass. The stars we now observe as ultra-Li-deficient halo stars, preferentially but not uniquely clustered towards the turnoff, may indeed be the progeny of such mergers and the progenitors of future blue-stragglers. Indeed, extreme Li deficiency may be the only common signal of future Pop II blue-stragglers-to-be.

If this hypothesis is correct, then we may finally remove such stars with confidence from discussions of the spread about the Spite plateau, and consider them as a truly distinct class of stars whose evolutionary history explains their abnormal Li abundances. Whether this mechanism can also explain the heterogeneity found for the abundances of their other elements remains to be seen.

6.   Differences Between Halo Field and Globular Cluster Stars?

Although the halo field stars discussed above have minimal intrinsic spread about the Li Spite plateau (at a given abundance), data for globular cluster samples show a different picture. Figure 5 compares the very metal-poor field turnoff dwarf data for stars spanning a dex in [Fe/H] with observations of subgiants in M92 (Boesgaard et al. 1998). The two groups exhibit quite different Li characteristics! The considerable spread in the globular cluster sample prompted Boesgaard et al. to favour a mechanism in which a higher pre-stellar abundance has been depleted by varying degrees in the stars, possibly by the rotationally-induced mixing mechanism discussed earlier. Why this mechanism should differ for the globular cluster and field star samples is unclear. Differences in angular momentum evolution in the two environments may be responsible, but the
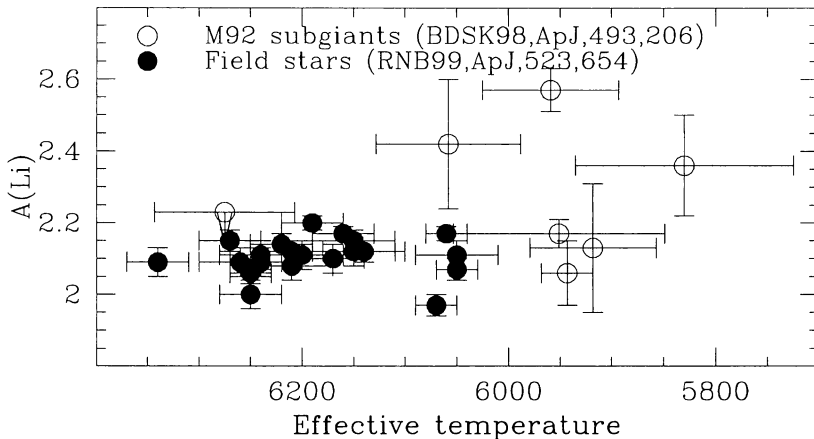
Figure 5.   Contrast between the tight distribution of Li for halo field dwarfs (having a range of [Fe/H]), compared with the broad spread in globular cluster subgiants. See text for discussion.

details have yet to be proposed. Other examples of differences in the mixing of stellar envelopes in field star and globular cluster samples has been forthcoming in recent years (e.g. Hanson et al. 1998), adding to previous evidence of field-vs-cluster differences in CNO element ratios.

Until the cause of the difference is understood, one must choose whether to use the field star or the globular cluster data to interpret GCE. I would argue that the large Galactic volume sampled by field stars in contrast to the small total volume of globular clusters, and the greatly increased possibility of star-to-star interactions in the high stellar densities of the latter, would render field star samples more representative of the evolution of the Galaxy as a whole. Of course, this in no way reduces the importance of understanding the globular cluster element abundance patterns for what they may tell us about the evolution of the Galaxy and stellar processes in dense environments.

References

Alonso, A., Arribas, S., & Martínez–Roger, C. 1996, A&AS, 117, 227

Bell, R. A. & Oke, J. B. 1986, ApJ, 307, 253

Boesgaard, A. M., Deliyannis, C. P., Stephens, A., & King, J. R. 1998, ApJ, 493, 206

Boesgaard, A. M. & Steigman, G. 1985, ARAA, 23, 319

Boesgaard, A. M. & Tripicco, M. J. 1986a, ApJ, 302, L49

Boesgaard, A. M. & Tripicco, M. J. 1986b, ApJ, 303, 724

Bonifacio, P. & Molaro, P. 1997, MNRAS, 285, 847

Cayrel, R., Spite, M., Spite, F., Vangioni-Flam, E., Cassé, M., & Audouze, J. 1999, A&A, 343, 923

Deliyannis, C. P., Demarque, P., & Kawaler, S. D. 1990, ApJS, 73, 21

Deliyannis, C. P., Pinsonneault, M. H., & Duncan, D. K. 1993, ApJ, 414, 740

Deliyannis, C. P. & Ryan, S. G. 2000, in prep

Fields, B. D. & Olive, K. A. 1999, New Astronomy, 4, 255

Fields, B. D. & Olive, K. A. 1999, ApJ, 516, 797

Hanson, R. B., Sneden, C., Kraft, R. P., & Fulbright, J. 1998, AJ, 116, 1286

Hobbs, L. M., & Thorburn, J. A. 1994, ApJ, 428, L25-L28

Hobbs, L. M., Welty, D. E., & Thorburn, J. A. 1991, ApJ, 373, L47

Magain, P. 1987, A&A, 181, 323

Hobbs, L. M. & Thorburn, J. A. 1997, ApJ, 491, 772

Lambert, D. L., Heath, J. E., & Edvardsson, B. 1991, MNRAS, 253, 610

Norris, J. E., Ryan, S. G., & Stringfellow, G. S. 1994, ApJ, 423, 386

Norris, J. E., Ryan, S. G., Beers, T. C., & Deliyannis, C. P. 1997, ApJ, 485, 370

Pinsonneault, M. H., Deliyannis, C. P., and Demarque, P. 1992, ApJS, 78, 179

Pinsonneault, M. H., Walker, T. P., Steigman, G., & Narayanan, V. K. 1999, ApJ, 527, 180

Rebolo, R., Molaro, P., & Beckman, J. E. 1988, A&A, 192, 192

Romano, D., Matteucci, F., Molaro, P., & Bonifacio, P. 1999, A&A, in press

Ryan, S. G., Beers, T. C., Deliyannis, C. P., & Thorburn, J. A. 1996, ApJ, 458, 543

Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D., & Norris, J. E. 2000a, ApJL, in press

Ryan, S. G., Beers, T. C., Kajino, T., & Rosolankova, K. 2000c, in prep

Ryan, S. G., Kajino, T., Beers, T. C., Suzuki, T., Rosolankova, K., & Romano, D. 2000b, in prep

Ryan, S. G., Norris, J. E., & Beers, T. C. 1998, ApJ, 506, 892

Ryan, S. G., Norris, J. E., & Beers, T. C. 1999, ApJ, 523, 654

Smith, V. V., Lambert, D. L., & Nissen, P.-E. 1993, ApJ, 408, 262

Smith, V. V., Lambert, D. L., & Nissen, P. E. 1998, ApJ, 506, 405

Spite, F. & Spite, M. 1982, A&A, 115, 357

Spite, F. & Spite, M. 1993, A&A, 279, L9

Spite, M., Molaro, P., Francois, P., & Spite, F. 1993, A&A, 271, L1

Spite, M., & Spite, F. 1981, IAU Coll. 68, Astrophysical Parameters for Globular Clusters, A. G. David Phillip & D. S. Haynes eds (Kluwer, Dordrecht)

Thorburn, J. A. 1992, ApJ, 399, L83

Thorburn, J. A. 1994, ApJ, 421, 318