Lithium Trail Leads Back to the Big Bang

Sean G. Ryan (Dept. of Physics and Astronomy, The Open University)

Studies of lithium with the high resolution spectrographs UES and UCLES on the WHT and AAT have revealed a slow but steady rise in the Galactic lithium abundance from the earliest stars in the halo of the Galaxy up until the epoch at which the old disk population formed. After this period, prolific Li nucleosynthesis is apparent. Long-standing uncertainties over the contributions of galactic chemical evolution and the destruction of Li can now be addressed, and the primordial lithium abundance and ultimately the universal baryon density Ω_B can be inferred more reliably. The observations may also help clarify the roles of AGB stars and novae in more recent periods of galactic chemical enrichment.

Introduction

Studies by many workers following Spite & Spite's (1981, 1982) discoveries of an almost uniform Li abundance in the old stars of the Galaxy (e.g. Rebolo, Molaro, & Beckman, 1988) supported the interpretation of this abundance as the primordial one, at worst "hardly altered" (Spite & Spite, 1982). This interpretation required that any depletion of the stellar surface Li from a higher initial abundance be minimal. While ample evidence existed of Li destruction in *some* stars, the lack of a spread in halo dwarf Li abundances provided empirical evidence that destruction may have been minimal in these objects (e.g. Boesgaard & Steigman, 1985).

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, the same models failed to explain numerous Population I star observations, and an alternative class of models possessing extra mixing implied that considerable Li depletion as high as 1 dex could have occurred in the halo stars. Other 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. 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 $T_{\rm eff}$ 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 Intrinsic Spread of ^{7}Li

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

Excluding one previously known ultra-Li-deficient star, the objects exhibited a total observed spread $\sigma_{\rm obs} = 0.053$ dex, considerably less than that 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 $\sigma_{\rm obs} = 0.031$ dex, and Gaussian in form. This corresponds to the spread in Li abundance *at a given metallicity*. Comparing this with the formal measurement errors of $\sigma_{\rm err} = 0.033$ dex leads to the conclusion that the intrinsic spread in the stars must be negligible.

The very narrow spread of Li abundances constrains the impact of 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. (1999) suggested that Li depletion by ~0.2–0.4 dex existed. As Figure 1 shows, the new data with their narrower spread (at a given metallicity) rule out rotationally-induced mixing models that exhibit even 0.1 dex median depletion. Previous results that gave contrary conclusions can be understood as arising from a mixture of stars having different metallicities and by poorer quality data.

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. With modern CCDs and large aperture telescopes, even small levels of ^{7}Li enrichment can be measured. Moreover, it is consistent with recently measured ^{6}Li abundances (Smith, Lambert, & Nissen, 1993,1998; Hobbs & Thorburn, 1997; Cayrel et al., 1999, Deliyannis & Ryan, 2000).

To examine Li GCE, Ryan et al. (2000b) obtained UES and UCLES data on 18 halo stars with

$-2.0 \lesssim [\mathrm{Fe/H}] \lesssim -1.0$, in the same temperature range as the metal-poor sample, and compared the abundances with several GCE models. The Fields & Olive (1999a, b) model includes the most likely Population II sources of Li, the ν-process in supernovae and GCR spallation, and the models of Romano et al. (1999) incorporate many Population I sources, primarily the ν-process, AGB stars, and novae. Figure 2 shows the hybrid; it provides a reasonable fit to the data over the history of the Galaxy from [Fe/H] = −3.5 to −0.6. Mismatches at the highest metallicities may be due to the exclusion of the newly studied cool bottom processing of Li, and/or to sizeable uncertainties in the theoretical Li yields of novae.

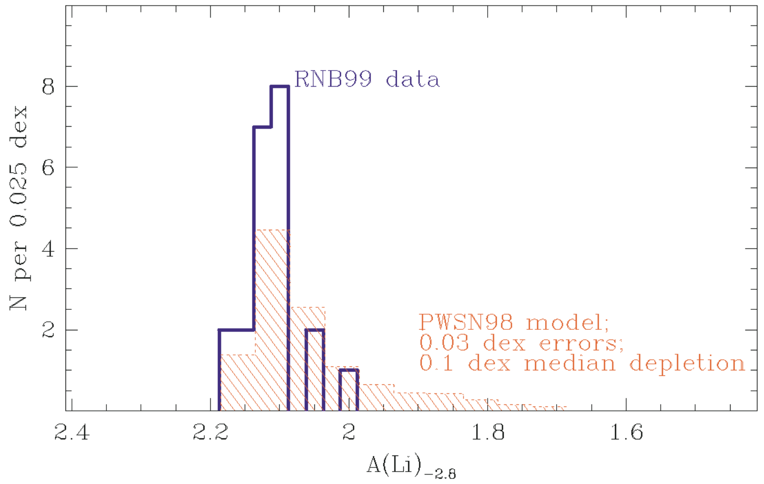

Figure 1. Spread in Li abundance A(Li) (at a given metallicity [Fe/H] = −2.8 after compensation for the [Fe/H] dependence of Li), compared with predictions for a rotationally-induced mixing model exhibiting a median depletion of 0.1 dex. The absence of stars in the tail of the theoretical distribution indicates that this particular model overestimates Li destruction.

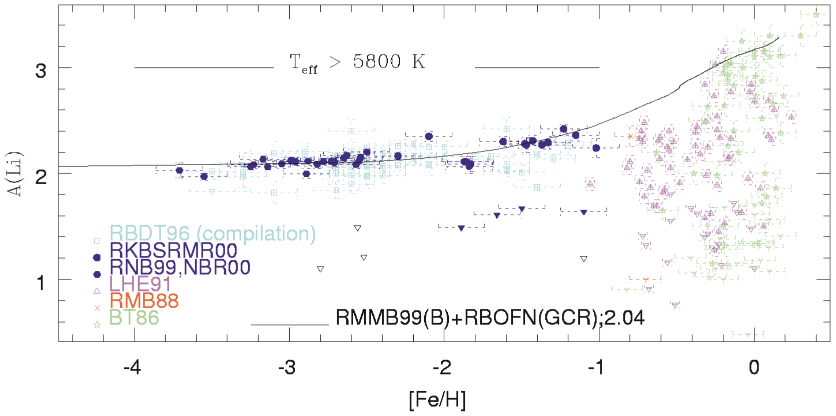

Figure 2. Evolution of Li with metallicity. Observations are for halo stars having T_{eff} > 5800 K, to avoid lower-mass stars with Li depletion and to reduce the heterogeneity of the sample, and Population I stars from sources indicated. The model (solid curve) is a hybrid using the Population II contribution of Fields & Olive (1999a, b; Ryan et al., 2000a) with Population I evolution from Romano et al. (1999).

The Primordial Li Abundance and Uncertainties

The new constraints on the stellar destruction of Li and its production over Galactic history permit a new calculation of the primordial Li abundance taking into account a wide range of random and systematic uncertainties. Beginning with the observed abundance for the most metal-poor stars, we apply corrections for the inferred GCE contribution (with uncertainties) and for stellar depletion. Uncertainties in the stellar temperature scales remain one of the largest sources of error, and in this analysis we adopt the zero-point of the IRFM scale of Alonso, Arribas, & Martínez-Roger (1996). We associate an uncertainty of ±0.08 dex with this choice, in recognition of the remaining difficulties in the temperature scales for halo dwarfs. These and the other effects lead us to infer a primordial abundance $\mathrm{A(Li)}_p = 2.09^{+0.19}_{-0.13}$ dex, where the uncertainties resemble 2σ limits (Ryan et al., 2000a). The baryon-to-photon ratios corresponding to this range are in excellent agreement with those inferred from estimates of the primordial He abundance, but the range of deuterium measurements published in recent years present more of a challenge. Disfavoured high D/H values ($\sim 20\times10^{-5}$) are compatible with the He and Li values, whereas the lowest values ($\sim 3.4\times10^{-5}$) are barely so. However, even slightly larger D/H values around $\sim 5\times10^{-5}$ are in tolerable agreement with the ^{7}Li and ^{4}He values (Ryan et al., 2000a). In any event, the inferred baryon density range,

$$\Omega_B = \frac{0.02-0.04}{(H_0/63\ \mathrm{kms^{-1}\,Mpc^{-1}})^2},$$

continues to lie 10 times below the value of Ω_M inferred from recent cosmological studies (e.g. Efstathiou et al., 1999).

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Sean Ryan (S.G.Ryan@open.ac.uk)

Photometric Redshifts: A Comparison of Methods

Dan Batcheldor* (ING and University of Hertfordshire) and Nic Walton (ING)

**: Daniel Batcheldor is currently undertaking a placement year at the ING from the University of Hertfordshire. He is studying for an Honors degree in Astronomy and is due to graduate at the end of 2001.*

The advantages of being able to accurately extract red-shifts from photometric data is of great importance when wanting to complete large scale surveys of the night sky. In an exposure of minutes, rather than the hours needed for spectroscopy, we are able to gain colour data from a great number of astronomical sources at once. This is especially apparent with the advent of large format panoramic cameras such as the INT WFC, MegaCam at the Canada-France-Hawaii Telescope (CFHT) and, in the future, VISTA (Visible & Infrared Survey Telescope for Astronomy). If this data can then be used to accurately calculate the distribution of galaxies with red-shift, the large scale structure of the universe can be more readily determined.

Views of large scale structure have revolved around the 'Swiss cheese' analogy. Geller and Huchra (1989) showed that clusters of galaxies themselves tend to form in bubbled patterns enclosing empty regions measuring hundreds of millions of parsecs across (see Figure 1). The Swiss cheese model has also been explored by Moore et al. (1992), but consists of a 'meat-ball' distribution in a void background (see Figure 2).

There are two techniques that can be used when wanting to carry out red-shift calculations from photometric data; template fitting and the use of a training set. The first technique was initiated by Baum (1962) and later developed by Koo (1985) and Loh & Spillar (1986b). More recently Bolzonella et al. (2000) have published a very flexible method using the standard Spectral Energy Distribution fitting technique, which has been made into the publicly available code *hyperz*, (see *http://webast.ast.obs-mip.fr/hyperz/*). The second method has been developed by Connolly et al. (1995) by training a relation between galaxy colours and red-shifts via linear regression. Plotting the results of broadband photometry against red-shift showed a strong correlation of red-shift with UBRI colours up to approximately $z = 0.6$. Figure 3 depicts red-shift data as a function of three broadband colours. Blue dots correspond to zero red-shift galaxies, and red to a red-shift of 0.5. Each colour distinguishes red-shift intervals of approximately $\Delta z = 0.1$.

Before we continue to use photometric red-shift methods for further investigations we will compare the two techniques. In order to do this we have selected a $9\,\mathrm{deg}^2$ area in the Elais N1 region. The data has been collected as part of the ING's Wide Field Survey (WFS) campaign in the Ug'r'i'z band-passes and reduced via the ING/CASU WFS pipelines (see *http://www.ast.cam.ac.uk/~wfcsur/pipeline.html*). Object catalogs have