COSMIC LITHIUM: GOING UP
OR COMING DOWN?

GARY STEIGMAN

Departments of Physics and Astronomy
The Ohio State University
174 West 18th Avenue, Columbus, OH 43210, USA
ABSTRACT

Observations of interstellar lithium provide a valuable complement to studies of lithium in Pop I and Pop II stars. Large corrections for unseen LiII and for non-gas phase lithium have provided obstacles to using interstellar data for abundance determinations. An approach to surmounting these difficulties is proposed and is applied to the Galaxy and the LMC. The key is that since potassium and lithium behave similarly regarding ionization and depletion, their observed ratio (LiII/KI) can be used to probe the abundance and evolution of lithium. For ten lines-of-sight in the interstellar medium of the Galaxy (ISM) the Li/K ratio observed \( \log(\frac{N_{Li}}{N_{K}})_{ISM} = -1.88 \pm 0.09 \) is entirely consistent with the solar system value \( \log(\frac{N_{Li}}{N_{K}})_{\odot} = -1.82 \pm 0.05 \). The absence of LiII in front of SN87A in the LMC, coupled with the observed KI, corresponds to an upper bound (at \( \gtrsim 95\% \) CL) of \( \log(\frac{N_{Li}}{N_{K}})_{LMC} < -0.3 + \log(\frac{N_{Li}}{N_{K}})_{ISM} \). This low upper bound to LMC lithium suggests that cosmic lithium is on its way up from a primordial abundance lower, by at least a factor of two, than the present Pop I value of \( [Li]_{PopI} \equiv 12 + \log(\frac{Li}{H})_{PopI} = 3.2 \pm 0.1 \).
INTRODUCTION

Cosmic lithium provides a valuable probe of stellar structure and evolution, of Galactic chemical evolution and, of cosmology. In particular its primordial abundance is of special importance for testing Big Bang Nucleosynthesis (BBN) providing, as it does, a tool for discriminating between homogeneous ("standard") BBN (e.g., Boesgaard & Steigman 1985; Walker et al. 1991; Smith, Kawano & Malaney 1993) and inhomogeneous BBN (e.g., Alcock, Fuller & Mathews 1987; Applegate, Hogan & Scherrer 1988; Malaney & Fowler 1988; Terasawa & Sato 1990; Kurki-Suonio & Matzner 1990; Thomas et al. 1994).

There are two observational approaches to primordial lithium: via stars and via the interstellar medium (ISM). Each has its assets and its liabilities. In recent years the “traditional” approach to primordial lithium has been to utilize stellar observations, especially the metal-poor ([Fe/H] <∼ −1.3), warm (T > ∼ 5700K) Pop II stars of the “Spite Plateau” (Spite & Spite 1982). The vast majority of such stars have a lithium abundance [Li]_{popII} ≡ 12 + \log([Li/H]_{popII}) = 2.1 ± 0.1 which is independent of metallicity for −3.5 <∼ [Fe/H] <∼ −1.3 (Spite, Maillard & Spite 1984; Spite & Spite 1986; Rebolo, Molaro & Beckman 1988; Hobbs & Pilachowski 1988; Thorburn 1994). This metallicity plateau is evidence for the Pop II lithium abundance having the primordial value.

However, there are some complications. It has been long known that Pop I stars ([Fe/H]_{popI} ≈ 0) of similar temperatures to those in the Spite Plateau have depleted their surface lithium, often by a very large factor. For example, although the solar system (meteoritic) abundance of lithium is [Li]_\odot = 3.31 ± 0.04 (Grevesse & Anders 1989), in the solar photosphere [Li] = 1.2 ± 0.1. Lithium is easily destroyed in stars, burning at the low temperature of ∼ 2 × 10^6 K. It will only survive on the surface of those stars
whose convective layers are sufficiently thin that the surface material is not exposed to such temperatures. The solar surface depletion is a general trend seen in the cooler Pop I stars in open clusters and the field (see, e.g., the discussion in Boesgaard & Steigman 1985 and references therein). The surprise of the Spite Plateau is that the lithium appears to survive in stars which have had much longer to burn it away. Could it be that the primordial abundance of lithium was much larger (larger, even, than the Pop I/solar values) and, the structure and evolution of the Pop II stars has conspired to destroy lithium to the level of the Spite Plateau (Mathews et al. 1990)? Standard (i.e., non-rotating) stellar models for Pop II stars in the Spite Plateau in fact predict very little lithium depletion and Chaboyer et al. (1992) conclude on the basis of such models that the primordial abundance is \([Li]_P = 2.15\). It should be noted that the very recent, extensive data set and analysis of Thorburn (1994) suggests Pop II lithium abundances which are systematically higher than earlier results by \(\sim 0.2\) dex. For diffusive models, Chaboyer et al. (1992) conclude that modest depletion (\(\lesssim 0.1\) dex) may have occurred. In contrast, for rotating models Pinsonneault, Deliyannis & Demarque (1992) find that large depletion (\(\sim 0.7-1.0\) dex) (see also, Charbonell & Vauclair 1992) is predicted. Although observations of \(^6\)Li in a few Pop II stars (Smith, Lambert & Nissen 1992; Hobbs & Thorburn 1994) would appear to argue against such large lithium destruction, the situation at present is unclear (M. Pinsonneault, Private Communication).

Another complication on the path to primordial lithium is early production in cosmic ray nucleosynthesis (Steigman & Walker 1992). Observations of \(^6\)Li, Be and B in Pop II stars (Ryan et al. 1990; Gilmore, Edvardsson & Nissen 1992; Ryan et al. 1992; Duncan, Lambert & Lemke 1992) provide evidence for cosmic ray nucleosynthesis (Steigman et al. 1993) but, there are more free/adjustable parameters than data points, making it difficult to normalize the contribution of such spallation/fusion reactions to the observed/inferred
Pop II lithium abundance.

Thus, the Pop II stellar data on lithium which is consistent with $[Li]_P = 2.2 \pm 0.2$ (Thornburn 1994), has strong assets but, a few liabilities. On the positive side, there is a very large data base ($\sim 100$ stars) of accurate lithium abundances in low metallicity stars. Looming on the negative side are the uncertain corrections for reduction of the surface lithium in such old stars and for production of lithium via cosmic ray nucleosynthesis. The flatness of the Spite Plateau (Li vs. Fe) argues against these effects being large but, does not provide rigorous proof that their contribution is negligible. It is, therefore, worthwhile to explore an alternate path to primordial lithium. Observations of (or, searches for) interstellar (gas phase) lithium in the Galaxy and in the slightly less evolved LMC ($[Fe/H]_{LMC} = -0.3 \pm 0.1$; Russell & Bessell 1989) provide an indirect alternative.

INTERSTELLAR LITHIUM

There are many obstacles on the path to lithium abundances and lithium evolution via interstellar observations which account for this road being less traveled. After reviewing the major roadblocks I will propose a detour which leads to constraints on the abundance and evolution of lithium.

The first problem is observational. The abundance of lithium is small ($Li/H \sim 10^{-10} - 10^{-9}$) and the absorption features very weak; typical equivalent widths vary from a few tenths to a few mÅ. As a result, the number of lines-of-sight with absorption observed from ISM lithium is small. With the current generation of high S/N, high resolution detectors, this obstacle can be overcome.

Even when lithium is observed in the ISM it is from LiI whereas lithium in the ISM is overwhelmingly LiII. Thus, a large – and uncertain – ionization correction must be applied
to derive Li II from the observed LiI.

\[
LiII/LiI = \Gamma_{Li}/\alpha_{Li} n_e. \quad (1)
\]

In (1), \(\Gamma_{Li}\) is the LiI photoionization rate, \(\alpha_{Li}\) is the LiII radiative recombination rate and \(n_e\) is the (unobserved) local electron density; the shorthand notation LiII/LiI stands for the ratio of column densities. To determine \(n_e\), observations of CaII and CaI are often used.

\[
CaII/CaI = \Gamma_{Ca}/\alpha_{Ca} n_e. \quad (2)
\]

However, there are problems with this approach. CaII is almost always saturated leading to a very uncertain determination of its column density, especially of that part of CaII which is coeval with the observed LiI. Furthermore, we are interested in Li/H and the HI is also saturated, rendering the HI (which belongs to the observed LiI) uncertain.

Even when the large \((\sim 10^2 - 10^3)\) ionization correction is applied, the inferred ISM abundance of lithium is found to lie well below (by 1-2 dex) the solar system value (Morton 1974; Snow 1975; Snell & VandenBout 1981; White 1986). It is then usually assumed that lithium is depleted from the gas phase of the ISM although the data alone do not distinguish between depletion and a true underabundance (perhaps the Sun – or, just the meteorites – is enhanced in lithium (Steigman 1993)). What follows, then, is a tautology: It is assumed that \((Li/H)_{ISM} = (Li/H)_{\odot}\) and, that the difference between \((Li/H)_{OBS}\) and \((Li/H)_{\odot}\) is due to depletion onto grains and/or molecules

\[
[Li/H]_{OBS} \equiv -DF(Li)_{ISM}. \quad (3)
\]

In (3), and subsequently, the notation \([X/H]_A \equiv \log(X/H)_A - \log(X/H)_{\odot}\) is used; thus, from (3), we have: \(\log(Li/H)_{ISM} = \log(Li/H)_{OBS} + DF(Li)_{ISM} = \log(Li/H)_{\odot}\).
Even if the DF(Li) could be calculated from first principles and, the ionization correction better constrained, the ISM derivations would be of limited value in exploring the evolution of lithium. The simple reason is that the ISM (of the Galaxy) is “here and now”. To study the evolution of lithium requires that we compare the ISM abundance with that at an earlier epoch and/or lower metallicity. Here (finally!) the road to primordial lithium improves. SN87A was bright enough to provide a background source to probe the interstellar gas of the LMC. Several groups (Vidal-Madjar et al. 1987; Baade & Magain 1988; Sahu, Sahu & Pottasch 1988) searched, unsuccessfully, for LiI absorption in front of SN87A. Baade et al. (1991) combined all published data in hopes of extracting a signal but, were only able to place an upper bound on the LiI column density (at the LMC velocity). This upper bound to N(LiI) contains important information on the evolution of lithium from the LMC ([Fe/H]_{LMC} ≈ −0.3±0.1; Russell & Bessell 1989) to the Galaxy ([Fe/H]_{ISM} ≈ 0). But, as outlined above, great care must be taken to avoid the potholes of uncertain ionization and depletion corrections.

THE RELATIVE ABUNDANCE OF LITHIUM

Aside from any observational difficulties, the highly uncertain ionization and depletion correction factors are a barrier to using ISM absorption data to derive the present abundance of lithium. However, if the goal of deriving the absolute abundance of lithium is deferred, the data can be utilized to learn about its relative abundance. Consider interstellar potassium. As with lithium, K in the ISM is mainly KII but, it is KI that is observed. By comparing LiI to KI, a much more accurate relative abundance Li/K can be obtained than the separate absolute (gas phase) abundances Li/H and K/H.

\[
\frac{\left(\frac{Li}{K}\right)_{OBS}}{\left(\frac{Li}{K}\right)_{OBS} (\frac{\Gamma_{Li}/\Gamma_{K}}{\alpha_{Li}/\alpha_{K}})} = \frac{(LiI/KI)_{OBS} (\Gamma_{Li}/\Gamma_{K})}{\alpha_{Li}/\alpha_{K}}.
\]

(4)
The relative ionization correction factor,

\[ \text{icf}(Li/K) \equiv \log \left( \frac{\Gamma_{Li}}{\Gamma_{K}} / \frac{\alpha_{Li}}{\alpha_{K}} \right), \] (5)

is independent of the very uncertain electron density and, insensitive to reasonable variations in the photoionizing flux distribution. Indeed, Pêquignot & Aldrovandi (1986) consider four different radiation fields and find \(5.9 \leq \Gamma_{Li}/\Gamma_{K} < 6.4\). Allowing for this variation and, for ISM (HI region) temperatures from 10K to \(10^3\)K (Pêquignot & Aldrovandi 1986),

\[ \text{icf}(Li/K) = 0.55 \pm 0.08. \] (6)

Especially significant in (6) is the small expected dispersion; aside from an offset (0.55 dex), \((Li/K)_{OBS}\) should correspond closely to \((LiI/KI)_{OBS}\).

However, until depletion is corrected for, \((Li/K)_{OBS}\) and \((Li/K)_{ISM}\) need not be the same. Unless there is independent data, or a theory, to provide the relative depletion factor,

\[ \text{DF}(Li/K) \equiv \log(Li/K)_{ISM} - \log(Li/K)_{OBS}, \] (7)

the “true” ISM relative abundance remains unknown.

To see if this path is useful, consider the data (Hobbs 1984; White 1986). There are 10 lines of sight (LOS) in the ISM where there are positive detections of both LiI and KI; the data (Hobbs 1984; White 1986) is presented in Table 1 and Figure 1.

Although the LiI and KI column densities each span an order of magnitude, the ratio has a dispersion of only 0.11 dex, which is smaller than the typical (1σ) errors. For the mean (either weighted or unweighted),

\[ \log(LiI/KI)_{OBS} = -2.43 \pm 0.04, \] (8)
where ±0.04 is the 1-sigma error in the mean. Applying the relative ionization correction (eq. 6) to (8) yields the observed (i.e., gas phase ISM) relative abundance,

$$\log(Li/K)_{OBS} = -1.88 \pm 0.09,$$

(9)

where the uncertainties in (6) and (8) have been combined in quadrature.

It is, perhaps, noteworthy that although relative column densities of NaI, CaI and KI vary by \(\sim 1-2\) dex along the lines of sight in Table 1, the LiI/KI ratio shows no statistically significant variation. Even more interesting is the comparison of \((Li/K)_{OBS}\) with \((Li/K)_{\odot}\) (Grevesse & Anders 1989).

$$[Li/K]_{OBS} = \log(Li/K)_{OBS} - \log(Li/K)_{\odot} = -0.06 \pm 0.10.$$  

(10)

Thus, unless there is a cosmic conspiracy in which the observational data and the inferred ionization correction have arranged to cancel the relative depletion, the result in (10) strongly suggests that Li and K are similarly depleted in the ISM, as anticipated in the models of Snow (1975) and Field (1974).

$$DF(Li/K)_{ISM} = [Li/K]_{ISM} + 0.06 \pm 0.10.$$  

(11)

Since \(DF(Li/K)\) depends on the physics/chemistry of the gas phase depletion while \((Li/K)_{ISM}\) depends on the stellar/galactic evolution of lithium and potassium, it would be surprising indeed that their difference is so small. Although it must be emphasized that this can’t be “proven”, it is not unreasonable to infer from (11) that \(DF(Li/K) \approx [Li/K]_{ISM} \approx 0\) so that \((Li/K)_{ISM} \approx (Li/K)_{\odot}\). Apparently, in the last 4.6 Gyr, the relative abundances of lithium and potassium have not changed much.

To recapitulate, the ratio of LiI and KI column densities along 10 LOS in the ISM is observed to be constant with a very small dispersion (0.1 dex), suggesting that, in
the local ISM, neither the relative ionization correction nor the relative depletion varies significantly from place to place. Thus, the observed ratio of column densities LiI/KI provides a robust estimator of the gas phase relative abundance Li/K. When the relative ionization correction (Péquignot & Aldrovandi 1986) is applied, it is found that the gas phase abundance \((Li/K)_{OBS}\) is very close to the solar system ratio, suggesting that \((Li/K)_{ISM} \approx (Li/K)_{OBS} \approx (Li/K)_{\odot}\). Next we turn to observations which may provide a clue to the evolution of this ratio.

**SN87A AND THE EVOLUTION OF LITHIUM**

There is no primordial contribution to the abundance of potassium so that its abundance at an earlier epoch or in a less evolved system should be lower than that at present. Thus, for the LMC it is expected that \((K/H)_{LMC} < (K/H)_{ISM}\) (ISM is used only for the Galaxy). Stellar observations (Gratton & Sneden 1987) provide support, suggesting that potassium may scale nearly linearly with metallicity \([K/H] \sim [Fe/H]\). Lithium, in contrast, does have a BBN contribution and the goal of this analysis is to use the interstellar data to learn whether lithium has started low (as suggested by the observations of stars on the Spite Plateau for which \([Li/H]_{PopII} \approx -1.1 \pm 0.2\)) and is on its way up or, as required by much of parameter space for inhomogeneous BBN, has started high (as suggested by some models for depletion in rotating stars (Pinsonneault, Deliyannis & Demarque 1991)) and is on its way down. If the primordial lithium abundance were comparable to or greater than the present (PopI) abundance, then for the LMC it would be expected that \((Li/H)_{LMC} \gtrsim (Li/H)_{ISM}\) whereas for K which scales with Fe, \((K/H)_{LMC} \lesssim (K/H)_{ISM}\). In this case we should expect to find that \((Li/K)_{LMC} > (Li/K)_{ISM}\). The former case (Li on its way up) is more complicated, depending on the relative lithium and potassium enhancements during
the course of chemical evolution. To avoid the biases of any specific model for chemical evolution and, to keep the discussion as general as possible, let us simply assume that the increase in lithium scales as a power of the potassium abundance: \( \Delta (\text{Li}/\text{H}) \sim (\text{K}/\text{H})^\alpha \).

We may then write for \( y \equiv (\text{Li}/\text{H})/(\text{Li}/\text{H})_{\text{ISM}} \) as a function of \( x \equiv (\text{K}/\text{H})/(\text{K}/\text{H})_{\text{ISM}} \),

\[
y = A + (1 - A)x^\alpha,
\]

where \( A \equiv (\text{Li}/\text{H})_P/(\text{Li}/\text{H})_{\text{ISM}} \). For \( \alpha \lesssim 1 \) the Li to K ratio \((y/x)\) increases with decreasing potassium abundance \((x)\). In contrast, if \((y/x)_{\text{LMC}}\) should prove to be \(< 1\), that would be a clear sign that lithium has started low and is rapidly on its way up.

The goal then is to compare \((\text{Li}/\text{K})_{\text{LMC}}\) to \((\text{Li}/\text{K})_{\text{ISM}}\). To this end it is **not** necessary to compute Li/K with its attendant uncertain relative ionization and depletion corrections. Rather, from the earlier discussions it follows that

\[
\log(y/x)_{\text{LMC}} = \log(\text{LiI}/\text{KI})_{\text{LMC}} - \log(\text{LiI}/\text{KI})_{\text{ISM}} + \Delta \text{icf} + \Delta \text{DF}.
\]

In (13), \( \Delta \text{icf} \) and \( \Delta \text{DF} \) are, respectively, the *difference* in the relative ionization correction and depletion factors from the LMC and the ISM \((\Delta \text{icf} = \text{icf}(\text{Li}/\text{K})_{\text{LMC}} - \text{icf}(\text{Li}/\text{K})_{\text{ISM}}; \Delta \text{DF} = \text{DF}(\text{Li}/\text{K})_{\text{LMC}} - \text{DF}(\text{Li}/\text{K})_{\text{ISM}})\). The great virtue of (13) is that we may directly utilize the observational data (LiI and KI equivalent widths) and, we need not apply relative ionization correction and depletion factors. To infer \(y/x\), or a bound to \(y/x\), only requires that the sum of the *differences* in the *relative* icfs and DFs between the LMC and the ISM is small. As mentioned earlier, Péquignot and Aldrovandi (1986) find that the relative icf is insensitive to the spectral shape of the photoionizing flux so that \( \Delta \text{icf} \approx 0 \) is quite reasonable. Unlike previous authors (e.g., Baade et al. 1991), we need not make any assumptions about the absolute depletion of lithium. Rather, our only assumption is that the *relative* depletions of Li and K in the LMC and in the ISM are similar \((\Delta \text{DF} \approx 0)\).
From the study of dust in the LMC (Fitzpatrick 1985), there is no evidence this is not a good assumption. Thus, we may adopt,

$$\log(y/x)_{LMC} \approx \log(LiI/KI)_{LMC} - \log(LiI/KI)_{ISM}.$$  \hspace{1cm} (14)

In their comprehensive reanalysis of the searches for LiI absorption in the LMC, Baade et al. (1991) also rederive the LMC KI equivalent width; their results correspond to $KI = 1.10 \times 10^{11} \text{cm}^{-2}$ or, $\log(KI) = 11.04 \pm 0.02$. Since no LiI absorption is detected at the LMC velocity, it is somewhat difficult to assign a statistical uncertainty (or confidence level) to the upper bound (Baade et al. 1991). Although the distribution of upper bounds to the LiI equivalent width is decidedly non-gaussian, Baade et al. (1991) find $W_\lambda < 2.2 \pm 1.7 \text{mÅ}$ which, at “2σ” would correspond to $W_\lambda < 5.6 \text{mÅ}$. In fact, from Fig. 4 of Baade et al. (1991), 95% of the possible $W_\lambda$ values have $W_\lambda < 5.6 \text{mÅ}$. Thus, it is reasonable to adopt a 95% CL upper bound of $W_\lambda < 5.6 \text{mÅ}$ which corresponds to a ($\sim \text{2}\sigma$) upper bound on the column density of $\log(LiI)_{LMC} < 8.28$. Since the uncertainty in the upper bound to the LMC LiI column density dominates that of the (observed) KI, we may infer a $\sim 95\% \text{ CL}$ upper bound to the difference between LMC and ISM Li/K,

$$\log(Li/K)_{LMC} < \log(Li/K)_{ISM} - 0.3.$$  \hspace{1cm} (15)

This is the key result of our analysis. The relative Li/K abundance in the LMC is smaller, by at least a factor of two, than the corresponding relative abundance in the ISM. Lithium is on its way up from a primordial value which is less than its solar system abundance.

**TOWARDS THE PRIMORDIAL ABUNDANCE OF LITHIUM**

The absence of LMC lithium absorption in the presence of LMC potassium absorption (Baade et al. 1991), when combined with the Galactic LiI and KI data, argues for a pri-mordial abundance of lithium less – by at least a factor of $\sim 2$ – than the present Pop I
lithium abundance. How much less depends on assumptions which range from eminently reasonable to speculative. Let us begin with the most reasonable—and, therefore, least constraining—assumption.

Although potassium is not observed in LMC stars, it is reasonable to assume that 
\((K/H)_{LMC} < (K/H)_{GAL}\) (i.e., \(x_{LMC} < 1\)). Therefore, \([Li]_P \leq [Li]_{LMC} < [Li]_{GAL} - 0.3\).

The solar system lithium abundance (\([Li]_\odot = 3.31 \pm 0.04\)), and the stellar abundances (\([Li]_{Pop} = 3.2 \pm 0.1\)) derived from T-Tauri stars (suitably corrected for veiling and NLTE; Magazzú, Rebolo & Pavlenko 1992) and hot stars in young open clusters (Boesgaard & Tripico 1986; Balachandran 1995) suggest a 2\(\sigma\) upper bound of \([Li]_{GAL} \leq 3.4\). Thus at > 95% CL we may infer a “zeroth order” upper bound to primordial lithium,

\[ [Li]_P^{(0)} < 3.1. \] (16)

This zeroth order bound is conservative in the sense that potassium decreases with metallicity (Gratton & Sneden 1987) and \([Fe/H]_{LMC} \sim -0.3\) (Russell & Bessell 1989). Thus, for \([K/H]_{LMC} \sim -0.3\), we may infer a more reasonable “first order” bound to primordial lithium,

\[ [Li]_P^{(1)} < 2.8. \] (17)

Finally, we may use the “generic” variation of Li vs. K described by eq. 12 to bound \([Li]_P\) (where: \([Li]_P = \log A + [Li]_{GAL} < 3.4 + \log A\)). Since \((y/x)_{LMC} \lesssim 1/2\), it follows that K must decrease with metallicity less rapidly than Li; i.e., \(\alpha > 1\) (where \(\Delta(Li/H) \sim (K/H)^\alpha\)). Indeed, for \([K/H]_{LMC} > \sim [Fe/H]_{LMC} \gtrsim -0.5, \alpha > 1.6\). An obstacle to employing eq. 12, along with \((y/x)_{LMC} \lesssim 1/2\), to infer a bound to \(A\) is that \(x_{LMC}\) is not observed directly. However, \(x_{LMC}\) is, in fact, not needed to derive an upper bound to \(A\) since, for \(\alpha > 1\),

\[ A = [(y/x)_{LMC} x_{LMC} - x_{LMC}^\alpha] / (1 - x_{LMC}^\alpha), \] (18)
is maximized for some value of $x_{\text{LMC}} < 1$. For example, for $\alpha = 2$, $A_{\text{MAX}} = 1/2[1 - (1 - (y/x)^2)^{\frac{1}{2}}]$ which, for $(y/x)_{\text{LMC}} < 1/2$, $A_{\text{MAX}} < 0.067$ (or, log $A_{\text{MAX}} < -1.2$). This leads to a very strong upper bound to primordial lithium,

$$[\text{Li}]^{(2)}_P < 2.2.$$  \hspace{1cm} (19)

Since $A_{\text{MAX}}$ increases with increasing $\alpha$, we should perhaps, regard this result (19) with some caution. In general,

$$A_{\text{MAX}} \lesssim \left( \frac{\alpha - 1}{\alpha} \right) \left( \frac{y}{x} \right)^{\frac{(\alpha - 1)}{\alpha}} (y/x)_{\text{LMC}},$$  \hspace{1cm} (20)

so that for $\alpha = 3$, $A_{\text{MAX}} \lesssim 0.24$ and

$$[\text{Li}]^{(3)}_P \lesssim 2.8.$$  \hspace{1cm} (21)

Thus, although the relatively low upper bound to $(\text{Li}/K)_{\text{LMC}}$ suggests a quite small abundance of primordial lithium (eq. 19) which, by the way, is entirely consistent with the stellar data (Molaro et al. 1995), the bounds in eqs. 17 and 21 provide a relatively firm upper bound of $[\text{Li}]_P \lesssim 2.8$. This bound is entirely consistent with the Pop II data (Thorburn 1994; Molaro et al. 1995), even allowing for stellar depletion/dilution (Chaboyer et al. 1992; Pinsonneault, Deliyannis & Demarque 1992).

SUMMARY

Observations of lithium on the surface of young (Pop I) and old (Pop II) stars provide a valuable probe of the abundance of lithium and its evolution. However, in $\sim 10 - 15$ Gyr of evolution, the oldest stars may have modified their surface abundances and, therefore, no longer offer a reliable probe of the lithium abundance in the nearly primordial gas out of which they formed. Indeed, evidence for large depletion exists for relatively cool Pop I and Pop II stars. However, the flatness of the “Spite Plateau” argues that the lithium
abundance, derived from observations of the warm (\( \gtrsim 5700K \)), metal-poor ([Fe/H] \( \lesssim -1.3 \)) stars, represents the primordial value which has been little modified by stellar depletion or early Galaxy production mechanisms. Although reasonable, this common assumption cannot be proven rigorously. Indeed, the rotating stellar models of Pinsonneault, Deliyannis & Demarque (1992) suggest that large reductions in prestellar lithium are not inconsistent with the data.

As a complement to the stellar observations, it has been suggested here that interstellar data can also provide valuable information on the evolution of lithium and, may be used to bound the primordial abundance from above. Extreme caution must be exercised in utilizing interstellar observations if practical and logical pitfalls are to be avoided. Large and possibly uncertain ionization corrections (to infer LiII from the observed LiI) must be applied, as well as unknown (even unknowable!) depletion factors (to go from the gas phase to total interstellar abundances). To avoid these traps, it was proposed here that the goal of the absolute abundance (Li/H) be replaced with the more modest target of the relative – to potassium – abundance (Li/K). Even so, to proceed from the observed LiI/KI to the derived Li/K still requires knowledge of the relative ionization correction factor (icf(Li/K)) and the relative depletion factor (DF(Li/K)). Here, this approach has been first applied to data from 10 lines-of-sight in the Galaxy. The small dispersion (\( \sim 0.1\text{dex} \)) around a mean LiI/KI ratio suggests that the relative icf and DF do not vary much – if at all – in the local ISM. And, indeed, when the theoretical relative icf (Péquignot & Aldrovandi 1986) is used, the data lead to (\( Li/K \))_{ISM} \( \approx (Li/K)_{\odot} \), suggesting that the relative depletion factor \( DF(Li/K)_{ISM} \approx 0. \)
This complementary approach of relative abundances is especially valuable for probing the evolution of lithium. SN87A provided a bright source to use – only briefly! – in studying the interstellar gas of the LMC. When comparing $(Li/K)_{LMC}$ to $(Li/K)_{GAL}$, it is only the differences in relative icfs and DFs that enter. On the reasonable assumption that $\Delta icf(Li/K) + \Delta DF(Li/K) \approx 0$, the difference between Li/K in the slightly less evolved LMC and in the Galaxy follows directly from the Li I and K I observations.

$$\frac{(Li/K)_{LMC}}{(Li/K)_{GAL}} \approx \frac{(LiI/KI)_{LMC}}{(LiI/KI)_{GAL}} < 1/2.$$ (22)

That this ratio is less than unity establishes that lithium is evolving from a primordial abundance less (by at least a factor of 2) than its present value. This qualitative constraint is nonetheless sufficient to rule out much of parameter space for models of inhomogeneous BBN (Thomas et al. 1994) and to limit the depletion/dilution of lithium in Pop II stars (Chaboyer et al. 1992; Pinsonneault, Deliyannis & Demarque 1992).

Since the abundance of lithium has a “floor” – its primordial (BBN) value – while potassium does not, the upper bound to Li/K in the less evolved LMC, permits us to derive an upper bound to primordial lithium. If it is only assumed that $(K/H)_{LMC} \leq (K/H)_{GAL}$, we have found $[Li]_{P}^{(0)} < 3.1$ As a next approximation we have used $[Fe/H]_{LMC}$ to infer $[K/H]_{LMC}$ leading to $[Li]_{P}^{(1)} < 2.8$. Finally, by a “generic” scaling of the lithium production to that of potassium ($\Delta(Li/H) \sim (K/H)^{\alpha}, \alpha \geq 2$), we have used the LMC bound to provide an even tighter constraint on primordial lithium: $[Li]_{P}^{(2)} < 2.2$ (or, $[Li]_{P}^{(3)} < 2.8$).

The relatively low upper bounds to $[Li]_{P}$ derived here from interstellar absorption data lend support to the notion that the “Spite Plateau” abundance provides a fair estimate of the primordial abundance. There is not much room for significant modification of the observed Pop II abundances by stellar surface depletion and/or cosmic ray nucleosynthesis.
For example, Thorburn’s (1994) estimate $[Li]_P = 2.22 \pm 0.20 (2\sigma)$ is entirely consistent with all the upper bounds presented above. Such a low value for primordial lithium leads to a significant upper bound to the universal abundance of nucleons ($\eta_{10} = 10^{10} (N/\gamma)$) and, hence, to the present density contributed by them ($\Omega_B = 0.015\eta_{10}h_{50}^{-2}$, $H_0 = 50h_{50}km s^{-1}Mpc^{-1}$). For example, for $[Li]_P \lesssim 2.8$, $\eta_{10} \lesssim 8$ and $\Omega_B h_{50}^2 \lesssim 0.12$.

Stellar and interstellar observations provide complementary probes of lithium and its evolution. Although subject to vastly different observational and physics uncertainties, they yield a consistent picture of primordial lithium supporting the conclusion that the warm, metal-poor Pop II stars (Spite Plateau) provide a fair estimate of the BBN abundance. It is now quite feasible, and it would be very valuable, to increase the number of lines-of-sight in the Galaxy with Li I and K I observations. Even more interesting would be to use future, bright supernovae in other galaxies to probe the evolution of lithium.

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TABLE 1

Galactic Li I and K I

| Line of Sight | log(Li I) | log (K I) | log (Li I/K I) |
|---------------|----------|----------|---------------|
| δ Sco         | 8.92 ± 0.11* | 11.40 ± 0.20 | -2.48 ± 0.23 |
| σ Sco         | 9.32 ± 0.15 | 11.53 ± 0.25 | -2.21 ± 0.29 |
| ζ Oph         | 9.37 ± 0.09 | 11.87 ± 0.12 | -2.50 ± 0.15 |
| ε Aur         | 9.41 ± 0.10 | 11.88 ± 0.20 | -2.47 ± 0.22 |
| ζ ΠPer        | 9.46 ± 0.07 | 11.90 ± 0.17 | -2.44 ± 0.18 |
| χ² Ori        | 9.70 ± 0.27 | 12.18 ± 0.13 | -2.48 ± 0.30 |
| 55 Cyg        | 9.72 ± 0.12 | 12.04 ± 0.20 | -2.32 ± 0.23 |
| ρ Oph         | 9.94 ± 0.07 | 12.23 ± 0.28 | -2.29 ± 0.29 |
| η Cep         | 9.94 ± 0.25 | 12.52 ± 0.33 | -2.58 ± 0.41 |
| HR7573        | 10.00 ± 0.21 | 12.50 ± 0.34 | -2.50 ± 0.40 |

§ Data from Hobbs (1984) and White (1986).

* The Li I and K I column densities in cm$^{-2}$.

* The 2-sigma statistical uncertainties; the errors have been combined in quadrature for LiI/KI.

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Figure Caption

Figure 1. The log of the LiI/KI column density ratios for 10 lines-of-sight in the Galaxy (from Hobbs 1984 and White 1986); the error bars are ±2σ. Also shown is the solar system (meteoritic) value (Grevesse & Anders 1989) “corrected” by the icf = 0.55 ± 0.08 and, the 2σ upper bound from the LMC (Baade et al. 1991).
