Implications of the Non-Observation of $^6$Li in Halo Stars for the Primordial $^7$Li Problem

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Abstract. The primordial Lithium Problem is intimately connected to the assumption that $^7$Li observed in the atmospheres of metal-poor halo stars in fact retains its primordial abundance, which lies significantly below the predictions of standard big-bang nucleosynthesis. Two key lines of evidence have argued that these stars have not significantly depleted their initial (mostly primordial) $^7$Li: i) the lack of dispersion in Li abundance measurements at low metallicity (and high surface temperature); and ii) the detection of the more fragile $^6$Li isotope in at least two halo stars. The purported $^6$Li detections were in good agreement with predictions from cosmic-ray nucleosynthesis which is responsible for the origin of $^6$Li. This concordance left little room for $^6$Li depletion, and the apparent $^6$Li survival implied that $^7$Li largely evaded destruction, because stellar interiors destroy $^6$Li more vigorously than $^7$Li. Recent (re)-observations of halo stars challenge the evidence against $^7$Li depletion: i) lithium elemental abundances now show significant dispersion, and ii) sensitive $^6$Li searches now yield no definitive detections, revealing only firm upper limits to the $^6$Li/$^7$Li ratio. We discuss the consequences of these $^6$Li non-detections on the primordial $^7$Li Problem, Galactic cosmic-ray nucleosynthesis, and the question of differential depletion of Li in stars. The tight new $^6$Li upper limits generally fall far below the predictions of cosmic-ray nucleosynthesis, implying that substantial $^6$Li depletion has occurred—by factors up to 50. We show that in stars with
$^6$Li limits and thus lower bounds on $^6$Li depletion, an equal amount of $^7$Li depletion is more than sufficient to resolve the primordial $^7$Li Problem. In fact, this picture is consistent with stellar models in which $^7$Li is less depleted than $^6$Li, and strengthen the case that the Lithium Problem has an astrophysical solution. We conclude by suggesting future observations that could test these ideas.
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1 Introduction

There was a great deal of excitement when the first observations of lithium in low metallicity halo stars appeared. The Li abundances were uniform and independent of metallicity\(^1\) for \([\text{Fe}/\text{H}] < -1.5\) \([1]\), implying a pre-stellar origin for Li. Indeed, the observed abundance coincided well with the prediction of standard Big Bang Nucleosynthesis (BBN) \([2]\). Subsequently, there have been many observations of Li in stars with \(-3 < [\text{Fe}/\text{H}] < -1.5\) \([3–7]\) defining what is commonly known as the Spite plateau. Furthermore, the only dispersion seen in this plateau seemed consistent with observational uncertainty \([3]\). Only the primordial species \(^3\)He, \(^4\)He, and \(^7\)Li produced in BBN are expected to show little or no variation at very low metallicity, potentially justifying the association of the \(^7\)Li in the plateau with the primordial abundance of \(^7\)Li.

So long as the uncertainties in the baryon-to-photon ratio, \(\eta\), and primordial abundances were sufficiently large, there was concordance between light-element abundances as observed versus the predictions from BBN theory which depend on \(\eta\) \([8]\). This picture began to break down when higher precision data on D/H became available \([9]\). This D/H (confirmed with high precision by several more observations \([10]\)) indicated a relatively large baryon-to-photon ratio \(\eta \sim 6 \times 10^{-10}\) which would predict a \(^7\)Li/H abundance in excess of the plateau value (discussed in more detail below in \(\S\)2). Shortly thereafter, measurements of the cosmic microwave background (CMB) by \textit{WMAP} \([11]\) and confirmed by \textit{Planck} \([12, 13]\) resulted in a very precise determination of \(\eta = (6.12 \pm 0.04) \times 10^{-10}\), in excellent agreement with BBN calculations and the observational determination of D/H and \(^4\)He \([14–16]\) exacerbating the \(^7\)Li Problem \([17]\). The current primordial \(^7\)Li abundance from our group is \([18]\)

\[
\frac{^{7}\text{Li}}{\text{H}} \bigg|_{\text{BBN+CMB}} = (4.94 \pm 0.72) \times 10^{-10}, \tag{1.1}
\]

in good agreement with other recent work by the Paris group \([19]\) \(((5.46 \pm 0.22) \times 10^{-10})\) and Naples group \([20]\) \((4.69 \times 10^{-10})\). These abundances should be compared with the observational determination \([4, 21]\)

\[
\frac{^{7}\text{Li}}{\text{H}} \bigg|_{\text{obs}} = (1.6 \pm 0.3) \times 10^{-10}, \tag{1.2}
\]

which falls a factor \(\sim 3\) and over \(4\sigma\) below the prediction in eq. (1.1). This deficit comprises the “Primordial \(^7\)Li Problem,” or simply the Lithium Problem.

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\(^1\)Here the “metallicity” \([\text{Fe}/\text{H}] = \log_{10}(\text{Fe}/\text{H})/(\text{Fe}/\text{H})_{\odot}\) is the iron abundance expressed a log relative to its solar value.
The lack of dispersion in the $^7$Li abundance data has often been used as an argument against the \textit{in situ} depletion of $^7$Li in halo stars. For example, at higher metallicity or in stars with lower surface temperatures, convective depletion is expected and is evidenced by the significant dispersion in the $^7$Li abundance in these stars. Furthermore, any depletion in $^7$Li should coincide with at least as much depletion of $^6$Li [22]. Therefore, the initial observations of $^6$Li in two halo stars [23, 24] was particularly important, as they further confirmed the lack of significant depletion, and strengthened the case for the primordial status of the Spite plateau. Indeed the $^6$Li abundance in these two low-metallicity ([Fe/H] $\approx -$2) stars was entirely consistent with the expected $^6$Li production in Galactic cosmic-ray nucleosynthesis (GCRN) [25, 26], and therefore provided evidence against depletion in these stars.

The lithium isotopic ratio had been reportedly measured several times in HD 84937. In [23], results from the observations of two stars, HD 84937 and HD 19445 were presented. In the former (with [Fe/H] = -2.4 and $T = 6090$ K), an isotopic ratio $^6$Li/$^7$Li = 0.05 $\pm$ 0.02 was determined, whereas in the latter (with [Fe/H] = -2.2 and $T = 5820$ K) only an upper limit $^6$Li/Li < 0.02 could be established, consistent with the idea that depletion occurs in the cooler stars. Other positive determinations in HD 84937 were reported in [24, 27]. The weighted average of the available measurements yielded $^6$Li/Li = 0.054 $\pm$ 0.011 at [Fe/H] $\approx -$2.3. Subsequently, an additional positive detection in BD 26$^\circ$ 3578 with $^6$Li/Li = 0.05 $\pm$ 0.03, at about the same metallicity was reported in [24] and a weak detection in G271-161 with $^6$Li/Li = 0.02 $\pm$ 0.01 [28].

Several years after these initial measurements, there was a report of ($\geq 2\sigma$) $^6$Li detections in 9 out of 24 stars observed [29] over a metallicity range of -1.25 < [Fe/H] < -2.74. But the real surprise in this work was the uniformity of the $^6$Li/$^7$Li ratio as a function of metallicity. At these metallicities, the $^7$Li abundance is primarily of BBN origin, and so is essentially constant with [Fe/H]. $^6$Li, on the other hand, is predominantly produced in GCRN [25, 26, 30–34] and grows monotonically with [Fe/H] from its near negligible BBN abundance [26, 35, 36]. As a result, we expect that the isotopic ratio should also increase with metallicity rather than form an apparent $^6$Li ‘plateau’. Furthermore, these observational determinations imply that $^6$Li was in fact depleted at metallicities $\gtrsim$ -2, as cosmic-ray production is expected to exceed this ‘plateau’ value. Similarly, the determined abundance at lower metallicity necessitated enhanced production mechanisms such as Pop III production [37], flares [38], or late-decaying particles [39].

In a detailed study of HD 74000, it was found [40] that convective processes generate an excess of absorption in the red wing of the $^7$Li absorption spectrum that could be interpreted

\footnote{For a more complete summary of the early observations of $^6$Li, see [25].}
as the presence of $^6\text{Li}$. The existence of the $^6\text{Li}$ ‘plateau’ was called into question. Indeed, it was estimated [41] that the $^6\text{Li}/^7\text{Li}$ ratios determined in [29] should be reduced by 0.015, thus reducing the number of detections from 9 to 4 (or less). This conclusion was reaffirmed in [42] which examined 5 stars finding no significant detections. One of the stars in this study was BD 26° 3578 with an isotopic ratio of only $0.004 \pm 0.028$ (a ratio of $0.01 \pm 0.013$ was found in [29] for the same star.

The reliability of the $^6\text{Li}$ ‘plateau’ was further called into question with new analysis employing 3D NLTE modelling [43]. Four stars including HD 84937 were studied with no significant detections. The newly determined isotopic ratio in HD 84937 was found to be be $0.011 \pm 0.010 \pm 0.011$, i.e., consistent with no $^6\text{Li}$. A recent study of a very metal poor star with [Fe/H] = -3.7, also found no detectable $^6\text{Li}$, though this result might be expected in standard cosmic-ray models.

The most recent nail in the coffin for the $^6\text{Li}$ ‘plateau’ came from new observations using the VLT/ESPRESSO spectrograph [44]. Three stars including HD 84937 were observed and only upper limits to the $^6\text{Li}/^7\text{Li}$ ratio could be obtained. In the case of HD 84937, where a ratio of 0.05 is in fact quite consistent with standard cosmic-ray nucleosynthesis [25], a $2\sigma$ upper limit of 0.007 was obtained. As this result may now directly call for the stellar depletion of $^6\text{Li}$, one can also call into question the that $^7\text{Li}$ in halo stars retains its initial primordial value.

Indeed, the durability of the $^7\text{Li}$ plateau has also come into question. The first indications of a departure from a $^7\text{Li}$ plateau extending towards zero metallicity showed both a correlation of $^7\text{Li}$ with metallicity and significant dispersion in the data with metallicity [Fe/H] $\lesssim$ -2.7 [21, 45]. In another study [46], no ultra metal-poor star was found with a plateau value for $^7\text{Li}$. Significant dispersion at low metallicity is also seen in more recent work [47–51]. To wit, very recent observations [52] of metal-poor red giant branch stars indicate a plateau, but at $^7\text{Li}/\text{H} \approx 10^{-11}$, far below either the BBN abundance or even the initial Spite plateau.

It nevertheless remains true that the $^7\text{Li}$ plateau remains intact as an upper limit to the $^7\text{Li}$ abundance in metal-poor stars. But there seems to be abundant evidence for dispersion and low(er) $^7\text{Li}$ abundances when [Fe/H] $\lesssim$ -2.7. This combined with the recent lack of evidence of $^6\text{Li}$ detection, may be pointing to stellar depletion processes [53–55] as a solution to the mismatch between the BBN prediction for primordial $^7\text{Li}/\text{H}$ and the upper envelope of the the $^7\text{Li}$ observation, i.e., the $^7\text{Li}$ plateau.

In what follows, we will concentrate on the current state of the $^6\text{Li}$ observations vis a vis predictions from GCRN. Our conclusion that $^6\text{Li}$ destruction is likely to have occurred is consistent with the apparent destruction of $^7\text{Li}$ leading to the observed dispersion. To this end, we briefly review the current status of the $^7\text{Li}$ Problem in §2. In §3, we take a fresh
look at the predictions of GCRN of $^6\text{Li}$ in comparison with recent observations. We discuss the implications of the non-observation of $^6\text{Li}$ for stellar depletion and $^7\text{Li}$ in §4. Further discussion and our conclusions are given in §5.

2 The Primordial $^7\text{Li}$ Problem

Stated very simply, the $^7\text{Li}$ Problem is lack of agreement between the BBN prediction for $^7\text{Li}/\text{H}$ as given for example in Eq. (1.1), and the observationally determined value given in Eq. (1.2) [56]. The BBN prediction for $^7\text{Li}$ is a sensitive function of the baryon-to-photon ratio, $\eta$, or equivalently the present baryon density parameter $\Omega_b h^2 \propto \eta$ [2]. At relatively low values of $\eta$ ($< 3 \times 10^{-10}$), the BBN production of $^7\text{Li}$ is a decreasing function of $\eta$. However, at larger values of $\eta$, the $^3\text{He}\ (\alpha, \gamma)^7\text{Be}$ reaction dominates over $^t(\alpha, \gamma)^7\text{Li}$ and the primordial production of $^7\text{Be}$ (which later decays to $^7\text{Li}$) increases with $\eta$.

As noted earlier, as long as the uncertainty in the other BBN element abundances and $\eta$ were sufficiently large, concordance with $^7\text{Li}$ observations was possible. However, in standard BBN, this requires $\eta \lesssim 4 \times 10^{-10}$ and $\text{D/H} \gtrsim 5 \times 10^{-5}$. Both values are strongly excluded by CMB measurements and D/H observations in quasar absorption systems. As a consequence, attention was turned to 1) BBN reaction rates, 2) post-BBN processing of $^7\text{Li}$, 3) in situ depletion of $^7\text{Li}$ in stars.

Because of the strong sensitivity of the $^7\text{Li}$ abundance to the $^3\text{He}\ (\alpha, \gamma)^7\text{Be}$ rate (its log sensitivity is 0.964, i.e., it is nearly proportional to this rate [16]), attention turned to the experimental measurement of this cross-section [57]. A subsequent analysis by Cyburt and Davids [58] produced a model independent fit with significantly smaller uncertainties using a Markov Chain Monte Carlo algorithm. However, the resulting BBN $^7\text{Li}$ abundance increased when the new rates were employed [17]. In fact it is not surprising that attempts at resolving the Li Problem by re-examination of the standard BBN rates failed [36, 59, 60] as these are the same rates operating in the Sun and confirmed by solar neutrino flux observations. Other rates such as $^7\text{Be}(n, p)^7\text{Li}$ [61, 62], $^7\text{Be}(n, \alpha)^4\text{He}$ [63–66], $^7\text{Be}(d, p\alpha)^4\text{He}$ [67], $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ [68], $^7\text{Li}(d, n\alpha)^4\text{He}$ [69] have been recently been (re)measured (or re-evaluated [70]), though none of these rates make more than a marginal change in the final $^7\text{Li}$ abundance.

A potentially more interesting possibility is that a reaction thought to be unimportant could contain an undiscovered resonance which could boost its cross section enormously, analogously to the celebrated Hoyle $^{12}\text{C}$ resonance that dominates the $3\alpha \rightarrow ^{12}\text{C}$ rate [71]. Examples of possible candidate resonances include: $^7\text{Be} + d \rightarrow ^9\text{B}^*$, $^7\text{Be} + t \rightarrow ^{10}\text{B}^*$ and $^7\text{Be} + ^3\text{He} \rightarrow ^{10}\text{C}^*$, with various possible exit channels [72–74]. However, measurements in $^7\text{Be}(d, d)^7\text{Be}$ [75], $^9\text{Be}(^3\text{He}, t)^9\text{B}$ [76], and an $R$-matrix analysis of $^9\text{B}$ [77] all rule out a $^9\text{B}$
resonance. Similarly, $^{10}$C data rule out the needed resonance in $^{10}$C [78]. The “nuclear option” to the Lithium Problem is essentially excluded.

The post-BBN processing of $^7$Li generally involves physics beyond the Standard Model and is hence more speculative. The possibility that a long-lived particle decays during or after BBN, injecting electromagnetic and/or hadronic energy into the Universe altering the BBN-produced abundances has been well-studied [79–82]. However, these decays which may destroy $^7$Li (still $^7$Be at this time), generally also affect the abundances of D and $^4$He [83, 84]. For example, the disruption of $^4$He creates both D and neutrons as fragments. These neutrons, as well as nonthermal neutrons produced in the case of hadronic decays, then lead to mass-7 destruction via $^7$Be($n,p)^7$Li($p,\alpha)^4$He, driving D/H to higher values. Other non-standard model attempts include axion cooling [85] and variations of fundamental constants [86, 87]. However, the new very precise D/H measurements [10] dramatically reduce the possibility of perturbing the BBN abundances (for which there is excellent agreement with D/H observations) and severely challenge most new-physics solutions to the Lithium Problem.

3 Galactic Cosmic-Ray Nucleosynthesis

A third class of potential solutions to the $^7$Li Problem is the in situ destruction of $^7$Li in halo stars. We will argue below that an upper limit to the depletion of $^7$Li can be obtained from $^6$Li observational upper limits. To infer lithium depletion from the $^6$Li observations requires us to describe lithium isotope evolution with metallicity, which determines the initial abundance in halo stars. That is, we must have a model for the Galactic chemical evolution of the lithium isotopes. In this section we present results for a simple one-zone, closed-box model for GCRN, based on our earlier work [25, 34]. Our aim is to illustrate the procedure to infer depletion, using a typical LiBeB chemical evolution model. Other GCRN models are certainly possible; these will give different quantitative results, but our basic qualitative features and conclusions are robust.

3.1 Cosmic-Ray Production of LiBeB

The cosmic-ray production of LiBeB nuclides in the interstellar medium (ISM) includes two processes. For the low-metallicity stars of interest, the most important cosmic-ray source of lithium is the fusion of $\alpha$ particles: $^4$He$_{CR} + ^4$He$_{ISM} \rightarrow ^6$Li + \cdots. This process is selective, in that it only makes the $^6,^7$Li isotopes and not Be or B. In the young Galaxy, $\alpha + \alpha$ fusion dominates because both the target and projectile $^4$He nuclei are abundant, having arisen in BBN. Thus, from the onset of cosmic-ray acceleration in the Universe, this mechanism operates to produce lithium.
The more “democratic” mechanism for cosmic-ray nucleosynthesis is spallation—the fragmentation of interstellar target nuclei heavier than the $\ell \in (^6\text{Li}, ^7\text{Li}, ^9\text{Be}, ^{10}\text{B}, ^{11}\text{B})$ isotopes of interest. That is, reactions such as $p_\text{CR} + ^{16}\text{O}_{\text{ISM}} \rightarrow \ell + \cdots$ can produce all LiBeB species, in ratios determined by reaction branchings and cosmic-ray spectra. The same reactions with “inverse” kinematics, e.g., $^{16}\text{O}_{\text{CR}} + p_{\text{ISM}}$, are also included in our model, as are losses of the LiBeB products which have high energies and escape the Galaxy before being stopped. Our model also includes as targets $^{12}\text{C}$ and $^{14}\text{N}$. Recent work has argued for inclusion of even heavier and less abundant targets up to $^{56}\text{Fe}$ [88]; we neglect those contributions here which we expect to be small and which will not affect our conclusion.

Note that spallation reactions require the existence of heavy nuclei that must first be produced by stars. Consequently, production rates are low at early times and low Galactic metallicities, so that Li production is dominated by fusion within Spite plateau metallicities. On the other hand, spallation is the only mechanism available for cosmic-ray synthesis of Be and B, and so these have low but measurable abundances at low metallicities.

Our treatment of cosmic rays closely follows that of [34], so here we only highlight the essentials. We assume that supernovae are the engines of cosmic-ray acceleration, and we therefore scale the cosmic-ray flux proportionally with the supernova rate. We assume the cosmic-ray composition reflects that of the ISM, and thus set the abundances within cosmic rays to be that measured today at Earth, but with CNO scaled by their evolving ISM abundances. We assume the energy spectrum remains the same at acceleration, but that cosmic-ray escape can very over time. We thus adopt a source spectrum that is a power law in momentum $\propto p^{-2}$, and an escape column thickness ("grammage") that is $\Lambda_{\text{esc}} = 20$ g/cm$^2$ at 850 MeV/nucleon, and scales with kinetic energy per nucleon as $\epsilon^{-0.6}$. This escape parameter gives the best $^6\text{Li}/^9\text{Be}$ ratio, and larger by a factor of $\sim 2$ than that found in present-day cosmic rays, suggestive of the “overconfinement” scenarios that have been explored for LiBeB synthesis in the early Galaxy [30, 32].

Cosmic-ray interactions with interstellar gas produce atoms of species $\ell$ via a variety of reactions. Cosmic ray nuclei of type $i$ colliding with interstellar nuclei of type $j$ produce $\ell$ by the process $i + j \rightarrow \ell + \cdots$. The rate per target $j$ for this process is $\Phi_i \langle \sigma_{ij \rightarrow \ell} \rangle$, where $\Phi_i$ is the cosmic-ray flux of $i$, $\sigma_{ij \rightarrow \ell}$ is the cross section for this process, and the brackets indicate averaging over the cosmic-ray energy spectrum. Thus, the total rate of $\ell$ atom production is the sum over such processes: $(dN_\ell/dt)_\text{CR} = \sum_i \langle \Phi_i \sigma_{ij \rightarrow \ell} \rangle \mathcal{N}_j$, with the number of interstellar target atoms is given by $\mathcal{N}_j = X_j M_{\text{gas}}/A_j m_u$, and where $A_j$ is the atomic mass of the target and $m_u$ is the atomic mass unit. The rate of mass production of $\ell$ is given by
\[ Q_{\ell,\text{CR}} \equiv (dM_\ell/dt)_{\text{CR}} = A_\ell m_u (dN_\ell/dt)_{\text{CR}}, \text{ which is} \]

\[ Q_{\ell,\text{CR}} \equiv \Gamma_{\ell,\text{CR}} M_{\text{gas}} \quad (3.1) \]

where the cosmic-ray mass production rate of \( \ell \) is

\[ \Gamma_{\ell,\text{CR}} = \Phi_p \sum_{ij} \frac{A_\ell}{A_j} y_j X_j \langle \sigma_{ij \rightarrow \ell} \rangle. \quad (3.2) \]

Here \( \Phi_p \) is the cosmic-ray proton flux, which we scale with the core-collapse supernova rate measured as the massive star explosion rate: \( \Phi_p \propto R_{\text{CC}} \). Eq. (3.2) shows that the mass production rate is weighted by the cosmic-ray “projectile” abundances \( y_i = \Phi_i/\Phi_p \), the ISM “target” mass fraction \( X_j \), the relevant mass numbers \( A \).

### 3.2 Modelling Galactic Chemical Evolution

We describe chemical evolution in our Galaxy with the straightforward one-zone model used in [34]. This follows the cycling of Galactic gas in and out of stars, given a prescription for star formation, as well as stellar and cosmic-ray nucleosynthesis yields. For the star-formation rate \( \psi = dM_\star/dt \), we choose a form proportional to the gas mass: \( \psi = \nu M_{\text{gas}} \) with \( \nu = 0.25 \text{ Gyr}^{-1} \). For the initial mass function \( \phi(m) \propto dN_\star/dm \), we take the power-law form \( \phi(m) \propto m^{-2.65} \).

If we consider a closed-box model (both open and closed-box models were considered in [34]), the total mass of the Galaxy remains fixed. The net rate of gas sequestration into stars is

\[ \frac{d}{dt} M_{\text{gas}} = -\psi + E \quad (3.3) \]

where the stellar gas ejection rate \( E = \int m_{\text{ej}}(m) \psi(t - \tau_m) \phi(m) \ dm \) is lagged from the birth rate by the lifetime \( \tau_m \) of stars at mass \( m \).

For each nucleosynthesis species \( i \), an expression similar to eq. (3.3) holds for the mass \( M_{\text{gas},i} \) in that species, and the associated mass fraction \( X_i = M_{\text{gas},i}/M_{\text{gas}} \). For a LiBeB species \( \ell \), we include cosmic-ray production from eq. (3.1) and arrive at

\[ \frac{d}{dt} X_\ell = \frac{E_\ell - X_\ell E}{M_{\text{gas}}} + \Gamma_{\ell,\text{CR}} = -\frac{E}{M_{\text{gas}}} \left( X_\ell - X_{\ell}^{\text{ej}} \right) + \Gamma_{\ell,\text{CR}} \quad (3.4) \]

where \( E_\ell = \int m_{\text{ej},\ell}(m) \psi(t - \tau_m) \phi(m) \ dm \) is the rate of mass ejection in species \( \ell \), and where \( X_{\ell}^{\text{ej}} = E_\ell/E \) is the mass fraction of \( \ell \) in the ejected gas, and we use the ejection rate \( E \) in Eq. (3.3).

We see that the first term in eq. (3.4) accounts for stellar production: it acts to drive \( X_\ell \) to \( X_{\ell}^{\text{ej}} \), i.e., towards the stellar yields of this species. These occurs over a timescale
that is the characteristic time for a large portion of the galaxy’s gas to be converted into stars. Because stars produce ‘metals’ like CNO and Fe, their abundances grow with time. On the other hand, stars destroy $^6\text{Li}$, $^9\text{Be}$, and $^{11}\text{B}$, so for these species $E_\ell = 0 = X_{ej}$, and stellar processing leads to their destruction (astration).

The second term in eq. (3.4), $\Gamma_{\ell,\text{CR}}$, accounts for cosmic-ray nucleosynthesis. It is nonzero for LiBeB, while for CNO and Fe this term vanishes. The net effect for LiBeB is production at early times, which reaches a peak at late times when the effects astration become important.

Finally, we comment on the normalization of the GCRN rate which should in principle be fixed by the present cosmic ray total flux. Keeping in mind the uncertainty in the flux, we normalize the cosmic-ray yields so that $^9\text{Be}$ attains its solar abundance at $[\text{Fe/H}] = 0$; this fixes the GCRN contribution for $^6,^7\text{Li}$ and $^{10,11}\text{B}$ [34, 89]. For $^7\text{Li}$ and $^{11}\text{B}$, there is an additional source from the $\nu$-process that makes these isotopes via neutrino spallation events in supernovae [90].

Due to the model uncertainties in the $\nu$-process, we scale that contribution [89, 91, 93] so that $^{11}\text{B}/^{10}\text{B}$ at $[\text{Fe/H}] = 0$ is equal to the observed ratio, 4.05±0.16 [94]. Of course $^7\text{Li}$ receives its problematic primordial abundance from BBN, as well as other sources at higher metallicity. For completeness we also include the primordial $^6\text{Li}/\text{H} \sim 10^{-14}$ abundance, but this is too low to have any effect on our results.

We show in Figs. 1 and 2 the evolution of the LiBeB element abundances as a function of $[\text{Fe/H}]$. Here, we will restrict our attention to a relatively simple closed-box model. As our primary purpose is the implications for Li depletion, we have only normalized to the solar values of Be in Fig. 1, and we do not attempt here to fit the evolutionary behavior of these isotopes though as one can see from the comparison with the data taken from [95–108] for Be and [109–111] for B, the model reproduces the data quite well.

In particular, we do not here consider additional cosmic-ray sources of the LiBeB elements [33, 93, 113–116] which tend to yield primary BeB, i.e., a linear trend with the spallation target oxygen: $\log(\text{BeB}/\text{H}) = [\text{O}/\text{H}] + \text{const}$. This contrasts with standard GCRN which yields secondary BeB having $\log(\text{BeB}/\text{H}) = 2[\text{O}/\text{H}] + \text{const}$. Observations of BeB as a function of the metallicity tracer $[\text{Fe/H}]$ point to a mixture of primary and secondary components versus iron. However, as argued in [34, 117], a better tracer for the production of BeB is oxygen rather than iron. If $[\text{O}/\text{Fe}]$ is constant, then a mixture of primary and secondary BeB would
Figure 1: Cosmic-ray production of Be and B evolution vs [Fe/H]. Solar abundances are also shown. Top panel: $^9$Be/H; the model is normalized to reproduce the solar value, which fixes all of the cosmic-ray production of LiBeB. Data are taken from [95–108]. Bottom panel: the boron isotopes, including $^{11}$B production from the $\nu$-process. Data are taken from [109–111].

require nucleosynthesis beyond standard GCRN. Data indicate [104, 118] that [O/Fe] in fact varies with [Fe/H] leaving open the possibility that the simplest GCRN models can explain the evolution the BeB isotopes. In any case, this is not of particular concern here, as this issue bears little on the question of the Galactic production of lithium and its depletion in metal-poor stars, which is dominated by the primary $\alpha + \alpha$ fusion process.

In Fig. 2, we show the evolution of the Li isotopes. At very low metallicity, the evolution
Figure 2: Cosmic-ray prediction for lithium isotope evolution versus [Fe/H]. Curves show our cosmic-ray model predictions, which include GCR nucleosynthesis for both isotopes, and $\nu$-process production for $^7$Li. In addition, for $^7$Li, primordial BBN production is also included.

**Top panel:** The BBN/GCRN $^7$Li/H abundance is contrasted with elemental Li/H abundance data compiled from [5, 21, 29, 45–48, 51, 120–129]; stars shown have $T_{\text{eff}} > 6000$ K. **Bottom panel:** The GCRN $^6$Li/H abundance contrasted with data (upper limits) compiled from [42–44, 120].

of $^7$Li/H is very flat, as it is dominated by its BBN primordial value. Slowly, as GCRN production (and the $\nu$-process) becomes effective, the abundance of $^7$Li/H begins to rise. Note that we do not include any late time production (such as novae [119]) and thus the
present $^7\text{Li}/\text{H}$ abundance falls short of the solar value. In contrast, the primordial $^6\text{Li}/\text{H}$ abundance is very low ($\approx 10^{-14}$) and the GCRN production of $^6\text{Li}$ is seen at low metallicity monotonically rising with [Fe/H]. Note that the $^6\text{Li}$ vs [Fe/H] results largely follow scaling for a primary process, so that many of the model details are not essential. A model parameter that does have a significant impact is the [O/Fe] slope, which anticorrelates with the $^6\text{Li}$-Fe slope at low metallicity. We adopt $[\text{O}/\text{Fe}] = \omega_{O/\text{Fe}}[\text{Fe}/\text{H}]$, with $\omega_{O/\text{Fe}} = -0.35$, as suggested by observations. The $^6\text{Li}$ slope then follows as $\log(^6\text{Li}/\text{H}) = (1 + \omega_{O/\text{Fe}})[\text{Fe}/\text{H}]$. A $\omega_{O/\text{Fe}}$ value closer to zero leads to a steeper $^6\text{Li}$ slope, and thus less expected $^6\text{Li}$ at low metallicities.

The data for $^6\text{Li}$ and $^7\text{Li}$ in Fig. 2 come from many sources. For $^6\text{Li}$, we use data giving only upper limits from [42–44, 120], and for $^7\text{Li}$ there has been a substantial amount of new data as discussed above [5, 21, 29, 45–48, 51, 120–129]. Because lithium destruction is known to be a sensitive function of effective temperature (which correlates with the depth of the convective zone), we follow the standard practice of only showing abundances for hot stars, with $T_{\text{eff}} > 6000$ K.

The contrast between predictions and observations in Fig. 2 is illuminating for both lithium isotopes. For $^7\text{Li}$ we see the familiar deficit in the observed abundances versus the BBN+CMB predicted primordial value. We further see that some recent data indicate a “meltdown” of the Spite plateau, implying that some depletion has occurred, particularly for stars at very low metallicity. For $^6\text{Li}$, we see that the predicted evolution exceeds most of the observed upper limits, often by a large factor. Indeed, only one $^6\text{Li}$ limit lies well above our predictions! Here we see the power of the new $^6\text{Li}$ limits, which now imply significant destruction has occurred from the initial cosmic-ray-produced abundances. This $^6\text{Li}$ depletion will be accompanied by $^7\text{Li}$ depletion, with consequences for the primordial Lithium Problem, as we now see.

4 Consequences of the non-Observation of $^6\text{Li}$

The initial observations [23, 24] of $^6\text{Li}$ in a few metal-poor stars with [Fe/H] $\approx -2$, were in good agreement with expectations from cosmic-ray nucleosynthesis [25, 26]. At the same time, these observations put pressure on stellar models where the depletion of $^6\text{Li}$ in particular was expected [130]. The relative amount of depletion between $^6\text{Li}$ and $^7\text{Li}$ is model-dependent, but

\footnote{In fact, the data plotted in the top panel of Fig. 2 are elemental lithium abundances that sum the isotopes: $\text{Li}/\text{H} = (^6\text{Li} + ^7\text{Li})/\text{H}$. The low limits on $^6\text{Li}$ demonstrate that in practice the elemental abundances measure $^7\text{Li}$.}

\footnote{These claimed $^6\text{Li}$ detections are not shown in Fig. 2.}
Li depletion should be no more than that of ⁶Li due basic considerations of nuclear physics: ⁶Li is more weakly bound than ⁷Li and so its destruction is favored [22].

It is convenient to define the lithium depletion factor as the ratio of the initial stellar abundance to the observed abundance, so that for isotope \( i \in (6, 7) \):

\[
D_i \equiv \frac{i\text{Li}_{\text{init}}}{i\text{Li}_{\text{obs}}} \geq 1 .
\]  

With this definition, the case of no depletion is \( D_i = 1 \), while progressively more depletion means progressively larger \( D_i \). In the limit of pure dilution, the depletions are equal: \( D_7 = D_6 \), and so a measure of ⁶Li destruction also gives that of ⁷Li. On the other hand, nuclear burning depletes ⁶Li more due to its lower binding energy, and its smaller mass and hence smaller Coulomb penetration suppression. Thus, in cases where destruction is incomplete we expect \( D_7 < D_6 \), and thus ⁶Li depletion sets an upper limit to ⁷Li depletion\(^7\); this differential depletion has been studied in detailed models [54].

Because ⁶Li is not detected with certainty in any stars, we can only put a \textit{lower} limit \( D_6 > D_{6,\text{lim}} \). That is, \( D_{6,\text{lim}} \) is determined by the GCRN-predicted abundance of ⁶Li at a given value of [Fe/H] relative to the observed value (or upper limit). Our approach is to use this limit to estimate the ⁷Li depletion, by assuming that

\[
D_7 = D_{6,\text{lim}} .
\]  

In the limit of pure dilution, our lower limits on ⁶Li depletion translate to lower limits on the true ⁷Li destruction: \( D_7 > D_{6,\text{lim}} \). However, in the case of differential depletion, our ⁷Li depletion estimate could be larger or smaller than the true ⁷Li destruction. Despite this uncertainty, we will see that the approach embodied in eq. (4.2) gives illuminating results.

We now use our GCRN model to infer ⁶Li depletion and to estimate ⁷Li depletion in metal-poor stars. For each star with an observed ⁶Li limit in Fig. 2, we compute a lower limit to the depletion:

\[
D_{6,\text{lim}} = \frac{6\text{Li}_{\text{GCRN}}}{6\text{Li}_{\text{obs,lim}}} .
\]  

We then estimate the ⁷Li depletion by assuming it is the same at our limit for ⁶Li: \( D_7 = D_{6,\text{lim}} \). We then infer the initial ⁷Li abundance in the same star via

\[
\left( \frac{7\text{Li}}{\text{H}} \right)_\text{init} = D_7 \left( \frac{7\text{Li}}{\text{H}} \right)_\text{obs} \approx D_{6,\text{lim}} \left( \frac{7\text{Li}}{\text{H}} \right)_\text{obs} .
\]  

Thus the larger the ⁶Li deficit with respect to the GCRN model, the larger the correction to ⁷Li.\(^7\) However, the pre-main sequence destruction of ⁶Li could be substantial in contrast to that of ⁷Li.

\(^7\)However, the pre-main sequence destruction of ⁶Li could be substantial in contrast to that of ⁷Li.
Results appear in Fig. 3. In the lower panel we see that the depletions are in many cases very large, up to a factor $> 50$. This leads to large corrections to the $^7$Li abundances, which appear in the upper panel. There we see that the corrected $^7$Li/H in most cases easily accommodates the expected primordial abundance.

We thus see that the combination of the strong limits on $^6$Li in halo stars, along with cosmic-ray nucleosynthesis, together imply that substantial lithium destruction of both $^6$Li and $^7$Li may have occurred in these stars. This conclusion is independent of stellar models for lithium depletion, but is consistent with and supports many such models. Indeed, the observed upper limits to the observed $^6$Li abundance in halo stars, and the implied depletion when comparing these limits to the abundances predicted in GCRN, together strengthen the case that stellar depletion is the culprit in the primordial Lithium Problem. These results in turn imply that standard BBN is working well and are not in conflict the observations when similar depletion factors for $^6$Li and $^7$Li are factored in.

It is important to recall that there are is significant model dependencies to GCRN predictions. Other reasonable models would give somewhat different $^6$Li evolution trends versus metallicity, and thus lead to different $^6$Li and $^7$Li depletions. It would be useful to explore these uncertainties thoroughly in future work. However, we note that the basic primary nature of $^6$Li evolution at early times sharply limits the range of possible viable models for this isotope. Moreover, we recall that the $^6$Li depletions we find are only lower limits, and many imply a $^7$Li depletion far in excess of what is needed to resolve the Lithium Problem. Thus, our main qualitative result should be robust in that substantial lithium depletion is required.

Indeed, we can use our model to help discern the nature of lithium depletion in halo stars. We note that for most stars with $^6$Li limits, the corrected $^7$Li/H substantially exceeds the expected primordial abundance. The most straightforward interpretation is that we have overestimated the $^7$Li destruction, which we assumed to be the same as for $^6$Li. That is, fitting $^7$Li to the required primordial abundance implies this $D_7 < D_6$. This indicates differential destruction of the lithium isotopes, and thus supports stellar evolution models that have this property.

5 Discussion and Conclusions

Predictions from standard BBN for the $^7$Li abundance exceed the abundance level seen in Population II stars. This is the crux of the Lithium Problem. In fact, when one folds in the fact that some of the observed lithium is most likely cosmic-ray produced (beryllium and lithium are observed in many of the same stars and beryllium is most certainly produced in cosmic-ray collisions), the $^7$Li Problem is accentuated [131].
Stellar depletion has always offered a mechanism to solve the Lithium Problem. But standard stellar models predict $^7$Li depletion with significant dispersion [132, 133] and the initial observations of the $^7$Li plateau [1] put severe constraints on these models [134]. Considerable effort went into refining stellar models to limit the amount of dispersion. Recent work [55] now attempts to explain the meltdown at low metallicity.

Figure 3: Implications of $^6$Li depletion. Bottom Panel: $^6$Li depletion factors $D_6 \geq 1$ inferred from the mismatches between observations and model predictions in Fig. 2. Top Panel: Elemental lithium abundances Li/H = ($^6$Li + $^7$Li)/H. Points show observed values as well as corrected abundances based on depletions in the lower panel. Curves are primordial $^7$Li abundance (eq. 1.1) and our model curve for BBN+CMB evolution.
However the lack of dispersion was not the only argument against depletion. The perceived presence $^6$Li in halo stars reaffirmed the primordial nature of $^7$Li. Confidence in the early observations was strengthened by the fact that reported abundance of $^6$Li matched expectations from simple GCRN models such as that described here. The apparent lack of $^6$Li depletion implied the lack of $^7$Li depletion [22].

It is now apparent that halo stars not only show Li dispersion, but also that $^6$Li has yet to be definitely observed in any of the hot metal poor halo stars under consideration. This revised observational outlook calls for a revised assessment of lithium depletion. Indeed to some, it may not be a surprise that the $^6$Li non-observation complements the lithium dispersion, both pointing to $^7$Li depletion.

We have argued that the lack of firm $^6$Li observations, with limits far below the levels predicted by GCRN models, implies that $^6$Li was indeed depleted. Since $^6$Li is only made by cosmic rays, we can relatively simply model its evolution to infer the undepleted $^6$Li at any metallicity, then use the observed abundance to infer the $^6$Li depletion. This in turn provides and estimate of the $^7$Li depletion. An equal amount of $^7$Li depletion (expected if the primary source of depletion is dilution), exceeds the ratio of BBN $^7$Li to the original Spite plateau abundance. Therefore, not only has the evidence against Li depletion disappeared, but its necessity (to explain $^6$Li) may well suggest the absence of a primordial $^7$Li Problem.

Future searches for $^6$Li remain of prime importance to more sharply probe stellar lithium processing as well as cosmic-ray nucleosynthesis. Additional $^6$Li limits can be illuminating. Searches for $^6$Li all along the Spite plateau region, will allow for a fuller quantitative picture of the allowed depletion. Moreover, if $^6$Li could be detected in some stars, then cosmic-ray models will allow for a measurement of the $^6$Li depletion and thereby will probe $^7$Li depletion as well. In all cases, the higher metallicity end of the plateau, say [Fe/H] $\sim$ $-2$ to $-1$ offers the highest expected $^6$Li, and thus potentially offer the strongest constraints on Li destruction. Even $^6$Li measurements at still higher metallicity would be useful to establish the level of depletion in less primitive stars.

In addition to stellar measurements of lithium, interstellar observations of lithium in extragalactic low-metallicity systems could hold great promise. These environments have very different systematics compared to halo stars, most importantly because there is no in situ lithium destruction in ISM gas. Elemental lithium has been measured in the ISM of Small Magellanic Cloud, at a level similar to that in Milky Way disk (Population I) stellar abundances at the same metallicity [135]. This suggests that there is not large depletion in these stars. But our work here predicts that at lower metallicities, the ISM levels of Li should be higher than in corresponding halo stars. Moreover, in interstellar spectra, the Li isotopes can be better distinguished and thus easier to measure than in halo stars. The challenges to
overcome for such observations include finding suitable target systems with sufficiently bright background sources, and avoiding regions where Li is highly ionized. The payoff would be that such measurements would offer a new probe of lithium evolution, complementary to that of stellar abundances.

In closing, we note that a stellar astrophysics solution to the Primordial Lithium Problem clearly would have profound consequences. It would remove a cloud of lingering concern about standard BBN, and strengthen its role in cosmology and particle physics. Indeed, nonstandard BBN scenarios have already been increasingly challenged by the high-precision of D/H abundances that agree with the BBN+CMB predictions, and the tight correlation between D and $^7$Li perturbations in new physics scenarios. Also, inferring the observed primordial lithium abundance would now require the use of detailed stellar and cosmic-ray nucleosynthesis models. So for the near term, $^7$Li would seem unlikely to be a reliable independent probe of BBN—a situation similar to the current status of primordial $^3$He determinations [137]. It remains to be seen whether future observations can chart a new way to measure primordial $^7$Li unambiguously and precisely, but we remain ever optimistic.

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