Interstellar Constraints on the Cosmic Evolution of Lithium

J. Christopher Howk
University of Notre Dame

Nicolas Lehner
University of Notre Dame

Brian D. Fields
University of Illinois

Grant J. Mathews
University of Notre Dame

Fig. 9.— The temperature (TT) and temperature-polarization (TE) power spectra for the seven-year WMAP data set. The solid lines show the predicted spectrum for the best-fit flat $\Lambda$CDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance.

The model parameters are:

- $\Omega_b h^2 = 0.02260 \pm 0.00053$,
- $\Omega_c h^2 = 0.1123 \pm 0.0035$,
- $\Omega_{\Lambda} = 0.728 \pm 0.015 - 0.016$,
- $n_s = 0.963 \pm 0.012$,
- $\tau = 0.087 \pm 0.014$ and
- $\sigma_8 = 0.809 \pm 0.024$.

---

$$\eta = \frac{n_b}{n_\gamma}$$

$\eta_{10} \equiv 10^{10} \eta = 6.31 \pm 0.15$

Jarosik et al. (2010)
Fig. 9.— The temperature (TT) and temperature-polarization (TE) power spectra for the seven-year WMAP data set. The solid lines show the predicted spectrum for the best-fit flat $\Lambda$CDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance.

The model parameters are:

- $\Omega_{b}h^2 = 0.02260 \pm 0.00053$
- $\Omega_{c}h^2 = 0.1123 \pm 0.0035$
- $\Omega_{\Lambda} = 0.728 \pm 0.015 \pm 0.016$
- $n_s = 0.963 \pm 0.012$
- $\tau = 0.087 \pm 0.014$
- $\sigma_8 = 0.809 \pm 0.024$

Jarosik et al. (2010)
The lithium problem: Pop II abundances inconsistent with SBBN

![Graph showing observational and BBN+WMAP constraints for various abundances](image)

**Cyburt+ (2008)**

Hard to reconcile these estimates of the “primordial” $^7$Li abundance.
The lithium problem: Pop II abundances inconsistent with SBBN

Cyburt+ (2008)

E.g., destruction through Li(p,α)α or gravitational settling.
Non-Standard Model physics could explain the Li discrepancy

- **Decay** or **annihilation** of **dark matter** particles inject energetic Standard Model particles into BBN.
  - *Hadronic injection:* Decay products change n / p ratios or energetic decays spall $^4$He particles.
  - *Electromagnetic injection:* Excess photons photodisintegrate D or $\alpha$, providing excess $^3$He/D.

  \[
  \begin{align*}
  ^3\text{H} + ^4\text{He} &\rightarrow ^6\text{Li} + \text{n} & \quad ^3\text{He} + ^4\text{He} &\rightarrow ^6\text{Li} + \text{p} \quad \text{Enhance} \, ^6\text{Li} \\
  \text{n} + ^7\text{Be} &\rightarrow ^7\text{Li} + \text{p} & \quad ^7\text{Li} + \text{p} &\rightarrow ^4\text{He} + ^4\text{He} \quad \text{Suppress} \, ^7\text{Li}
  \end{align*}
  \]

- **Charged dark matter particles** catalyze BBN
  - *Negatively charged particles (X-)* create bound particles with baryonic nuclei, reducing Coulombic barriers.

  Suppresses $^7\text{Be}$ (and thus $^7\text{Li}$) and/or enhances $^6\text{Li}$.

(see Jedamzik & Pospelov 2009)
Interstellar Li as a probe of pre-galactic production

The idea:

Use *interstellar* Li in low metallicity environments as a probe of the contemporary Li abundance.

While the chemical evolution of Li is complex, there is no worry about time-dependent *in situ* destruction modifying the abundance of Li over time.

Significant uncertainties in the approach are *completely independent* of those affecting stellar measurements.
*This was attempted toward SN1987A using ESO telescopes (Vidal-Madjar et al. 1987; Sahu et al. 1988).
Sk 143 sight line:
* Large H I, H₂ column density
* Large columns of neutral metals
* Apparent low radiation field

The Observations:
* Sk 143 (O9.5 Ib): $V = 12.9$
* UVES @ $R \sim 74,000$
* ~1 night

MCELS: Smith+
Interstellar Li as a probe of pre-galactic production

Absorption from the SMC at $v \sim +120$ km/s

Absorption from the MW at $v \sim +0$ to $+50$ km/s
Interstellar Li as a probe of pre-galactic production

\[ \frac{^7\text{Li}}{^6\text{Li}} \approx \infty \]

\[ \frac{^7\text{Li}}{^6\text{Li}} = 8 \pm 3 \]

\[ b = 2^{1/2} \sigma \approx 0.8 \text{ km/s} \]

\[ T \approx 270 \text{ K} \]
Interstellar Li as a probe of pre-galactic production

\[ A(^{7}\text{Li})_{\text{SMC}} = 2.68 \pm 0.16 \]

\[ A(^{7}\text{Li})_{\text{MW}} \approx 2.54 \pm 0.05 \]

**Figure 2:** Estimates of the lithium abundance in the SMC interstellar medium and in several different environments.

Our best estimate for interstellar gas+dust phase abundance of \( A(^{7}\text{Li}) \) in the SMC is shown as the red circle with black core derived from the \(^{7}\text{Li} \;/ K \text{ I} \) ratio. The present day metallicity of the SMC from early-type stars is \( [\text{Fe} / \text{H}] = -0.59 \pm 0.06 \). (All uncertainties are 1\( \sigma \).) The point marked BBN and dotted horizontal line show the primordial abundance predicted by standard BBN.

The green curves show recent models for post-BBN \(^{7}\text{Li} \) nucleosynthesis due to cosmic rays (CRs) and stars. By adjusting the yields from low-mass stars, the models are forced to match the solar system meteorite abundance (see Supplementary Information). The solid and dashed lines correspond to models A and B which respectively include or not a presumed contribution to \(^{7}\text{Li} \) from core-collapse supernovae. The blue hatched area shows the range of abundances derived for Population II stars in the Galactic halo, with the “Spite plateau” in this sample at \( A(^{7}\text{Li})_{\text{PopII}} \approx 2.10 \pm 0.10 \). The violet hatched region shows the range of measurements seen in Galactic thin disk stars, where the thicker lines denote the six most Li-rich stars in a series of eight metallicity bins.

The selection of thin disk stars includes objects over a range of masses and temperatures, including stars that are expected to have destroyed a fair fraction of their Li. Thus, the upper envelope of the distribution represents the best estimate of the intrinsic ISM Li abundance at the epoch of formation for those stars, and the thicker dashed lines for the thin disk sample are most appropriate for comparison with the SMC value. The most Li-rich stars in the Milky Way thin disk within 0.1 dex of the SMC metallicity give \( A(^{7}\text{Li})_{\text{MW}} = 2.54 \pm 0.05 \), consistent with our estimate \( A(^{7}\text{Li})_{\text{SMC}} = 2.68 \pm 0.16 \).
Interstellar Li as a probe of pre-galactic production

$A(^7\text{Li})_{\text{MW}} \approx 2.54 \pm 0.05$

$A(^7\text{Li})_{\text{SMC}} = 2.68 \pm 0.16$

Figure 2: Estimates of the lithium abundance in the SMC interstellar medium and in several different environments.

Our best estimate for interstellar gas+dust phase abundance of $A(^7\text{Li})$ in the SMC is shown as the red circle with black core derived from the $^7\text{Li}$ I/$^7\text{Li}$ ratio. The present day metallicity of the SMC from early-type stars is $[\text{Fe}/\text{H}] = -0.59 \pm 0.06$. (All uncertainties are 1σ.) The point marked BBN and dotted horizontal line show the primordial abundance predicted by standard BBN.

The green curves show recent models for post-BBN $^7\text{Li}$ nucleosynthesis due to cosmic rays (CRs) and stars. By adjusting the yields from low-mass stars, the models are forced to match the solar system meteorite abundance (see Supplementary Information). The solid and dashed lines correspond to models A and B which respectively include or not a presumed contribution to $^7\text{Li}$ from core-collapse supernovae. The blue hatched area shows the range of abundances derived for Population II stars in the Galaxy, with the "Spite plateau" in this sample at $A(^7\text{Li})_{\text{PopII}} \approx 2.10 \pm 0.10$.6

The violet hatched region shows the range of measurements seen in Galactic thin disk stars, where the thicker lines denote the six most Li-rich stars in a series of eight metallicity bins. The selection of thin disk stars includes objects over a range of masses and temperatures, including stars that are expected to have destroyed a fair fraction of their Li. Thus, the upper envelope of the distribution represents the best estimate of the intrinsic ISM Li abundance at the epoch of formation for those stars, and the thicker dashed lines for the thin disk sample are most appropriate for comparison with the SMC value. The most Li-rich stars in the Milky Way thin disk within 0.1 dex of the SMC metallicity give $A(^7\text{Li})_{\text{MW}} = 2.54 \pm 0.05$, consistent with our estimate $A(^7\text{Li})_{\text{SMC}} = 2.68 \pm 0.16$.

Sources of $^7\text{Li}$:

- Big Bang nucleosynthesis
- Cosmic ray nucleosynthesis (spallation)
- Type II SNe (ν-process)
- AGB stars ("hot bottom burning")
- Novae (?)
Interstellar Li as a probe of pre-galactic production

Figure 3: Estimates of Li/Fe in the SMC interstellar medium and in several different environments. The SMC value is derived from the $^{7}\text{Li}$ I/K I ratio. At low metallicities ($[\text{Fe}/\text{H}] \lesssim -1$), stellar measurements trace the build-up of Fe with a constant Li abundance along the spike plateau. A higher metallicities, disc star abundances show a turnover to roughly constant $[\text{Li}/\text{Fe}]$ at values consistent with the solar system/meteoritic value (shown as the dash-dotted line). Our SMC estimate is consistent with the solar system and disc star abundances in this region of relatively constant $^{7}\text{Li}/\text{Fe}$ abundances, with $[\text{Li}/\text{Fe}]_{\text{SMC}} = +0.04 \pm 0.10$ for $[\text{K}/\text{Fe}]_{\text{SMC}} = 0.0 \pm 0.10$ (Supplemental Information). The most Li-rich disc stars within 0.1 dex of the SMC metallicity have a mean $\langle [\text{Li}/\text{Fe}] \rangle = -0.13 \pm 0.05$. (Assumptions are 1σ.) The green curves show the chemical evolution models as in Figure 2, while the dotted line shows the behavior of $[\text{Li}/\text{Fe}]$ for the standard BBN primordial abundance with no subsequent volatility of $^{7}\text{Li}$. The relative uniformity of the stellar $^{7}\text{Li}/\text{Fe}$ abundances at $[\text{Fe}/\text{H}] \gtrsim -1$ could be caused by a delicate balance of Li and Fe production and metallicity-dependent Li stratification (note do not give any change in mean age and mass potentially present in the sample). However, the agreement of the $[\text{Li}/\text{Fe}]$ ratio seen in these old stars (ages > 4 Gyr) and in represented interstellar medium of the SMC suggests little change in the stellar abundances for metallicities $[\text{Fe}/\text{H}] \gtrsim -0.6$ through the solar metallicity. To bring the stellar and SMC interstellar abundances into agreement with standard BBN predictions requires a delay in injection of significant $^{7}\text{Li}$ from stellar production mechanisms as well as vigorous depletion of stellar surface $^{7}\text{Li}$ abundances at metallicities just below that of the SMC.
Interstellar Li as a probe of pre-galactic production

Standard BBN and chemical evolution predict the SMC should have

\[ \frac{^6\text{Li}}{^7\text{Li}} \sim 0.01 - 0.02 \]

Non-standard models predict

\[ \frac{^6\text{Li}}{^7\text{Li}} \sim 0.05 - 0.10. \]

At S/N \sim 500, we should detect \(^6\text{Li}\) in the SMC in the latter case.
Interstellar Li in the ELT era

With 10-m class telescopes, this approach is limited to the SMC, LMC, and a single low-redshift damped Lyman-α (DLA) absorber with LMC-like metallicity.

*The planned 30 and 40-m class telescopes have the grasp to extend the search for interstellar Li to more DLAs. However, there are several issues:

1) Li will be redshifted quickly into the NIR.
2) The number of bright QSOs with quite low metal DLAs is limited.
3) The number of DLAs bearing neutral gas and/or $\text{H}_2$ is VERY limited.

*Studies of the SMC/LMC isotopic ratio and its variations should be straightforward.
Summary

• Measurements of interstellar Li I in low metallicity galaxies will allow us to probe primordial and pre-galactic production of Li (including the $^7\text{Li}/^6\text{Li}$ ratio) in a way that is independent of the systematics associated with stellar determinations.

• The first measurement of gas-phase Li in the SMC suggests a current abundance consistent with the BBN value, leaving little room for chemical enrichment. This may favor a low primordial abundance.

• The first marginal measurement of the isotopic ratio in the SMC implies that <40% of the $^7\text{Li}$ had been produced since the era of Big Bang nucleosynthesis. The $^6\text{Li}/^7\text{Li}$ ratio may represent the best test on non-standard BBN from the ISM.