Lithium Abundances in Extremely Metal-Poor stars

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in collaboration with W. Aoki et al.
Matsuno et al. (2017a, PASJ; 2018b, AJ)
Formation of metal-poor stars

Big Bang - D, $^3$He, $^4$He, $^7$Li - CMB radiation

First Stars (z~20) - Massive - First metal enrichment

Second generation - Can be low mass (e.g., <0.8 $M_{\text{sun}}$)
Information from metal-poor stars

- Chemical composition of ISM reflects nucleosyntheses by Big Bang and by first stars.
- Star hardly changes its surface abundance during the evolution.

Second generation
- Can be low mass (e.g., \(<0.8 \, M_\odot\))
- Metal poor star at \(z=0\)

⇒ BBN (This talk)

First stars
(e.g., Ishigaki et al. 2014; 2018)
From Metal-Poor Stars to Big Bang

**Obs. CMB obs.**

0.5 dex

A(Li)

low Li due to evolution

Charbonnel+05

\[ A(X) = \log \frac{N_X}{N_H} + 12 \]

\[ [X/Y] = \log \frac{N_X}{N_H} - \log \left( \frac{N_X}{N_H} \right)_\odot \]

Spite plateau almost constant → primordial

Constraints on Baryon density

**BBN models**

primordial \(^{7}\)Li/H

Baryon-to-photon ratio \(\eta\)

Cyburt+16

CMB observation

WMAP(2001-10), Planck (2009-13)
Is the standard BBN model wrong?

- Uncertain reaction rates precise enough

Cyburt+16
Is the standard BBN model wrong?

- **Uncertain reaction rates** precise enough

- **Unknown channel** *(Chakraborty et al., 2011)* mostly ruled out by experiments *(e.g., Kirsebom & Davids, 2011; O'Malley et al., 2011)*
Is the standard BBN model wrong?

- Uncertain reaction rates
  precise enough

- **Unknown channel** (Chakraborty et al., 2011)
  mostly ruled out by experiments
  (e.g., Kirsebom & Davids, 2011; O'Malley et al., 2011)

- New physics
  e.g., Tsallis statistics (e.g., Kusakabe+18)

  *Only* Li shows discrepancy

Does the Li abundance observation really reflect BBN?
Fragility of Lithium

Li destruction at $2.5 \times 10^6$ K ($^7\text{Li}+p \rightarrow ^4\text{He}+^4\text{He}$)

Li abundance decreases when material from stellar interior pollutes the surface
e.g., red giants

Li in a globular cluster (Lind+09)
Suggestions to the Li problem

Proposed epoch of Li depletion

- **Before the formation of metal-poor stars** (Piau+06)
  - Mixing of the primordial ISM with Li-free ejecta from first stars

- **Pre main-sequence phase** (Fu+15)
  - Complete Li destruction during pre-MS + ISM accretion

- **Main sequence phase** (Richard+05)
  - Atomic diffusion + turbulent mixing during MS-phase

How to decrease Li abundance while keeping the small star-to-star scatter in Li abundance
Plateau doesn’t extend to lowest metallicity

[Fe/H]~ -3: Large scatter
[Fe/H] <- 4: Low Li in all stars

Indicative of Li depletion in some of metal-poor stars

Related to the discrepancy between CMB and Spite plateau?

Require larger sample to clearly understand the nature of the breakdown
Goal

Observationally clarify the nature of the breakdown of Spite plateau

Observations of EMP TO stars

Extremely Metal-Poor ([Fe/H] < -3.0)
Turn-Off (Teff > 5500 K)
Abundance determination

Lithium abundances at [Fe/H] < -3.5
  EMP stars from SDSS/SEGUE

Lithium in relation to Carbon
  Lithium abundances in CEMP-no stars
Abundance determination
Procedure of Abundance Analysis

Step 1. Measure the equivalent widths
Fitting absorption lines with Gaussian

Step 2. Estimate atmospheric params \((T_{\text{eff}}, \log g)\)
To determine evolutionary status
To calculate abundance from equivalent widths (Step 3)

Step 3. Abundance calculation
Calculate abundance from equivalent widths
Step 1. Measure the equivalent widths

Fitting absorption lines with Gaussian

Step 2. Estimate atmospheric params ($T_{\text{eff}}, \log g$)

to determine evolutionary status

to calculate abundance from equivalent widths (Step 3)

Step 3. Abundance calculation

Calculate abundance from equivalent widths
Due to asymmetry, Li absorption line can not be fit with Gaussian

-> Directly fit spectra with synthesized ones varying the abundance
Procedure of Abundance Analysis

Step 1. Measure the equivalent widths
Fitting absorption lines with Gaussian

Step 2. Estimate atmospheric parameters
To determine evolutionary status
To calculate abundance (Step 3)

Other methods:
- Colors (for Teff)
- Pipelines of low-resolution spectroscopic survey
- Fe lines analysis
- Distance (log g)
- etc.

Balmer lines analysis
- Hβ
  - best fit
  - ΔT = ±100 K
- Hα
  - best fit
  - Δlogg = 0.3
Comparison of stellar parameters

Difference from Balmer lines analysis
Step 1. Measure the equivalent widths

Step 2. Estimate atmospheric parameters ($T_{\text{eff}}, \log g$) to determine evolutionary status and calculate abundance from equivalent widths (Step 3)

Step 3. Abundance calculation

Calculate abundance from equivalent widths
Lithium abundances at $[\text{Fe/H}]<-3.5$

(Extremely metal-poor turn-off stars from SDSS/SEGUE)

Matsuno, T. et al. (2017b, AJ, 154, 52)
Previous measurements

Before 2008
Previous measurements

Before 2013
Previous measurements

Before 2016
Eight stars with $[\text{Fe/H}] < -3.0$

In particular, we focus on $[\text{Fe/H}] < -3.5$

**Aoki et al. 2013**

Subaru/HDS observations ($R \sim 36,000$, $S/N \sim 20-30$)
for 137 metal-poor stars found in SDSS/SEGUE survey

**Further follow-up observation**

Higher quality data ($R \sim 60,000$, $S/N \geq 50$)

$\rightarrow$ This work
### Results: Metallicity

7 out of 8 stars are $[\text{Fe/H}] < -3.5$

<table>
<thead>
<tr>
<th>Object</th>
<th>[Fe/H]</th>
</tr>
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<tbody>
<tr>
<td>SDSS J1424+5615</td>
<td>-3.10</td>
</tr>
<tr>
<td>SDSS J1640+3709</td>
<td>-3.54</td>
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<tr>
<td>SDSS J1036+1212</td>
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<td>SDSS J1522+3055</td>
<td>-3.94</td>
</tr>
<tr>
<td>SDSS J2309+2308</td>
<td>-3.96</td>
</tr>
</tbody>
</table>
Differential Analysis

Source of uncertainty in abundance analysis

Approximations in model atmosphere
(local thermodynamical equilibrium, 1D plane parallel)
Uncertainty in atomic data

\[ A \approx -\log(gf) - \log \lambda + \chi \theta + \log \left( \frac{EW}{\lambda} \right) + \text{const.,} \]

where \( \theta = \frac{5040}{T_{\text{eff}}} \).

Cancels out deviation from the approximations
Particularly effective between stars with similar stellar params.
Lithium abundance at $[\text{Fe/H}] < -3.5$

All stars with $[\text{Fe/H}] < -3.5$ have Li abundance lower than the plateau.

No significant scatter in Li abundance ($\sigma_{A(\text{Li})} \sim 0.10 \text{ dex}$)
Li is independent from Teff or log g

-> Li abundance is not relevant to stellar evolution nor mass
Lithium Abundance at $[\text{Fe/H}] < -3.5$

- All stars have low Li abundance at $[\text{Fe/H}] < -3.5$
- No significant scatter in Li abundance
- Li abundance does not correlate with any properties

Li abundance seems to only correlate with metallicity
Lithium in relation to Carbon

(Lithium in CEMP-no stars)

Based on Matsuno et al. (2017a, PASJ, 69(2), 24)
Carbon Enhanced Metal-Poor Stars (CEMP)

Carbon-Enhanced Metal-Poor stars ([C/Fe]>0.7)
Many metal-poor stars show carbon enhancements

CEMP-no
without s-process excess
[Ba/Fe]<0.0
C-excess is likely due to first stars
>80% at [Fe/H]<-4

CEMP-s
with s-process excess
[Ba/Fe]>1.0
As a result of mass transfer from evolved companion

>80% at [Fe/H]<-4
Many metal-poor stars show carbon enhancements (CEMPs) with $\text{[Ba/Fe]} > 1.0$ as a result of mass transfer from evolved companions. CEMP-no without $\text{[Ba/Fe]} < 0.0$ is likely due to first stars. >80% at $\text{[Fe/H]} < -4$. All stars show low – Li abundance.
Most of stars are CEMP-no
All stars show low Li abundance

Speculation on a connection between the two results

- Breakdown ([Fe/H] ≲ -2.5) might be due to increasing fraction of CEMP-no

**Li measurements in CEMP-no stars**

Frebel+08, Bonifacio+15 etc. -> low Li

However, most of them are [Fe/H] < -4

Which of low metallicity or CEMP-no nature is the fundamental cause of low Li abundances?
-3.5 < [Fe/H] < -2.0
- Many C-rich stars and C-normal stars
- Plateau breaks down at this metallicity

Target
2 CEMP-no stars
with [Fe/H] ~ -3, Teff ~ 6000 K

Observations
Subaru HDS
R ~ 60000, S/N ~ 100
Both of the 2 objects are C-rich, Ba-poor → CEMP-no
Lithium in CEMP-no Stars

As a result of mass transfer from evolved stars (Masseron+12)

Li abundance of CEMP-no stars are similar to that of C-normal stars
Do CEMP-no stars necessarily show low Li abundance?

No.

Li abundance of CEMP-no stars are similar to that of C-normal stars at $[\text{Fe/H}] \sim -3$

$\Rightarrow$ Breakdown $([\text{Fe/H}] \sim -3)$ is not related to the large fraction of CEMP-no

$\Rightarrow$ C-excess and low-Li at $[\text{Fe/H}] < -4$ are caused independently
Results and Models

Results of the present study

[Fe/H]<-3.5: Average Li abundance is lower than plateau

[Fe/H]<-3.5: Scatter is insignificant ($\sigma_{A(Li)} \sim 0.10$ dex)

[Fe/H]<-2.5: Breakdown is unrelated to CEMP-no fraction

Li abundance only correlate with stellar metallicity

Constraints on models

- Before the formation of metal-poor stars (first stars; Piau+06)
- Pre main-sequence phase (Fu+15)
- Main-sequence phase (Richard+05)

All need fine-tuning of a parameter

-> Need to understand the physical origin of the parameter as well as application/tuning to lowest metallicity
Discovery of normal Li stars at $[\text{Fe/H}] \sim -4$?

Bonifacio+18
Precise abundance is hardly available at [Fe/H]<-3.0

-> **Find out bright extremely metal-poor stars!**

**LAMOST-Subaru study for 400 metal-poor stars**

cf. LAMOST sample: 12-15 mag, SDSS/SEGUE: 14-16 mag

Observation has finished! (Li, H.N., Aoki, W., Matsuno,T. et al.)

e.g., More CEMP-no stars with normal Li (Zhang+ in prep.)
Li-rich stars found by LAMOST/Subaru

About 10 objects are identified with LAMOST/Subaru to be Li-rich (A(Li)>2) with low metallicity ([Fe/H]<-2).

The Li would be produced by Cameron-Fowler mechanism, but the mixing between the surface and internal layers of stars is unknown. Large sample of Li-rich stars could provide a hint to solve the mystery.

(c) Aoki, W. Lind et al. (2009)
Li-rich stars

Li abundance of Li-rich stars evolves similarly to normal stars

> Li-enrichment during main-sequence
What’s next?

Li abundance of red giants as an independent probe (Mucciarelli+12)

Let’s make use of another plateau of red giants

We have to put all the stars at the same distance
Gaia measures **distance** and **magnitude** of stars (the second data release happened on 25 April 2018)

Gaia is also important to study stellar motions in the Galaxy (this is the main reason for me to come here!)
Li abundance of red giants

Main sequence

Lower A(Li) at low [Fe/H]

Similar trend??
Summary

- **Observational understanding of the breakdown**
  - Li abundance at \([\text{Fe/H}]<-3.5\) is uniformly low
  - Breakdown is not related to a large fraction of CEMP-no

**Li abundance correlates only with metallicity**

- **Constraints on models**
  Require model understanding and application for low metallicity stars

- **Futures**
  Our ongoing project and Gaia will provide new insights
Li Depletion Models

All models are suggested to explain the discrepancy between the Big Bang and the Spite plateau

Before the formation of metal-poor stars (Piau+06)
MP stars are formed from the mixture of Li-free ejecta from first stars and ISM with BBN composition

Pre-MS stage of metal-poor stars (Fu+15)
Complete Li-destruction during pre-MS phase and later recovery by ISM accretion

During MS phase of metal-poor stars (Richard+05)
Atomic diffusion + additional mixing (see also Korn+06,07, Gruyters+13)