JSPS-CAS joint program:
Exploring the early chemical evolution of the Milky Way with LAMOST and Subaru

Subaru intensive program S16A-119I:
LAMOST/Subaru study for 500 very metal-poor stars
What can we learn from metal-poor stars

• Nucleosynthesis by first stars
  → mass and evolution of first stars, and supernova explosion

• Early chemical evolution
  → constraints on galaxy formation models

• Individual nucleosynthesis processes
  big-bang nucleosynthesis (Li), heavy elements

• Evolution of low-mass stars and binary systems

Searches for metal-poor stars and follow-up high-resolution spectroscopy
LAMOST survey

- $R=1800$
- 4000 fibers
- $r<19$

Data Release 5 (DR5): 7.5 million spectra including 5.3 million AFGK stars

Target selection: random selection for a given magnitude/temperature range
cf. SDSS/SEGUE
Target selection from LAMOST sample

LAMOST medium resolution spectra

Subaru high-resolution follow-up spectroscopy

LAMOST covers relatively bright stars (V<14)

J1253+0753 [Fe/H]=-4.0 main-sequence turn-off
<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Position</th>
<th>Research Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wako Aoki 青木 和光</td>
<td>NAOJ/TMT-J</td>
<td>Associate professor</td>
<td>Stellar abundances, high-resolution spectroscopy</td>
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<td>professor</td>
<td>Galactic Archaeology</td>
</tr>
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<td>Takuma Suda 須田 拓馬</td>
<td>Univ. of Tokyo</td>
<td>Assistant professor</td>
<td>Stellar evolution Database</td>
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<td>Sokendai/NAOJ</td>
<td>PhD student</td>
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<td>ESO</td>
<td>PhD student</td>
<td>Stellar abundances, high-resolution spectroscopy</td>
</tr>
</tbody>
</table>
## NAOC team

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Research Focus</th>
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<tbody>
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<td>陳玉琴 Yuqin Chen</td>
<td>Professor</td>
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<tr>
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<td>Professor</td>
<td>Streams, moving groups</td>
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<tr>
<td>李海宁 Haining Li</td>
<td>Associate Professor</td>
<td>MP stars, target selection, observation</td>
</tr>
<tr>
<td>談克峰 Kefeng Tan</td>
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<td>Chemically peculiar &amp; super Li-rich stars</td>
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<td>邢千帆 Qianfan Xing</td>
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<td>Alpha-abnormal stars, observation</td>
</tr>
<tr>
<td>翟 萌 Meng Zhai</td>
<td>PhD. Student</td>
<td>Data analysis, observation</td>
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<tr>
<td>張世琳 Shilin Zhang</td>
<td>PhD. Student</td>
<td>Data analysis, observation</td>
</tr>
<tr>
<td>施建榮 Shi Jianron</td>
<td>professor</td>
<td>Li-rich giants / metal-poor stars in Kepler field</td>
</tr>
</tbody>
</table>

Norbert Christlieb (Heidelberg)
2016 October collaboration meeting in Beijing (北京)
Subaru intensive program: LAMOST/Subaru study for 500 very metal-poor stars

- Searches for rare but key objects:
  - signature of first stars
  - neutron-capture element-enhanced stars

- Statistics of very metal-poor stars:
  - metal-poor tail of the metalliccity distribution function
  - binary frequency from double-lined binaries
  - trend and scatter (or clustering) of elemental abundance ratios
Subaru intensive program: LAMOST/Subaru study for 500 very metal-poor stars

→ double the sample of very metal-poor stars with chemical abundance measurements by homogeneous analysis

• Main sample
  - Extremely metal-poor ([Fe/H]<-3) stars
  - Bright (V<14) very metal-poor ([Fe/H]<-2) stars
  - Li-enhanced very metal-poor stars

• Some specific topics
  - $\alpha$-rich/poor stars
  - Li-rich giants
  - Moving group members
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Large sample of metal-poor stars

Elemental abundances for >250 very metal-poor stars (including stars observed in normal programs) have been obtained

H-N. Li
Li-enhanced very metal-poor stars
Li-enhanced very metal-poor stars

Main-sequence
shallow convective layer
preserving initial Li abundance

Red giants
Surface Li diluted by the internal material due to 1st dredge-up

Initial Li

Li depleted

Li depleted

Li diluted
Li abundances along low-mass star evolution traced by globular cluster stars

Lind et al. (2009)

Li abundances in stars of globular cluster NGC6397 ([Fe/H]=-2.0)

Red Giant Branch (RGB) bump: evolutionary stage at which H-burning shell extends to the bottom of the layer mixed by the 1st dredge-up
Li-enhanced very metal-poor stars

Li-enhanced low-mass stars: Rare cases, but significant excess

• Kraft et al. (1999): a giant in the globular cluster M3
• Roederer et al. (2008): a field red giant

Kraft et al. (1999)
Li-enhanced very metal-poor stars

Super Li-rich red giant!

\[ [\text{Fe/H}] = -3.3, \ T_{\text{eff}} = 5200\text{K}, \ \log g = 2.2, \ A(\text{Li}) \sim 3.0 \]
Li-enhanced very metal-poor stars

Target selection by LAMOST spectroscopy

- \~1000 candidates for very metal-poor stars by pipeline analysis
- \~30 Li-rich star candidates by visual inspection

Li I 670.8nm
12 objects are identified with LAMOST/Subaru to be Li-rich with low metallicity ([Fe/H]<-1.7)

Comparison stars with normal Li
Abundance measurements from the two Li lines

The Li resonance line at 670.8nm is severely saturated in many cases. In such cases, the Li abundance is determined from the subordinate line at 610.36nm.

※ Spectral features show asymmetry because the lines are doublet.
Li abundances as a function of [Fe/H]

**Warm (unevolved) objects**

- \( T_{\text{eff}} > 5500\text{K} \)
- Li-rich = \( A(\text{Li}) > 3 \)

**Red giants**

- \( T_{\text{eff}} < 5500\text{K} \)
- Li-rich = \( A(\text{Li}) > 2 \)

Spite plateau

A(\text{Li})=4.5!

+ SAGA database

+ typical RGB value
Li-enhanced very metal-poor stars

Observational result on Li-rich very metal-poor stars

2. Stellar evolutionary stage

Li-rich giants (before RGB bump) are explained by dilution by 1st dredge-up

Discovery of super Li-rich subgiants
Lithium-rich very metal-poor stars discovered with LAMOST and Subaru

Summary

• 12 new Li-rich very metal-poor stars are discovered, among which 5 are warm subgiants before evolving to red giants.

• Assuming very high Li abundances ($A$(Li) > 4) as initial values, as found in one of the subgiants in our sample, the (less significant) Li-excess in red giants is explained by dilution by 1$^{st}$ dredge-up.

• The focus is to search for the mechanism to make extreme Li-excess in stars before evolving into red giants.

There is a mystery in low-mass star evolution even before the star evolves into a red giant.
New r-process enhanced (r-II) stars
New r-process enhanced (r-II) stars

SAGA database (Suda et al. 2008; 2017)
(Carbon-enhanced stars are excluded)
New r-process enhanced (r-II) stars

Bright r-II stars!

Stars with [Fe/H]<-2.5
SAGA database (Suda et al. 2008; 2017)

[Eu/Fe]

CS31082-001

V magnitude
New r-process enhanced (r-II) stars

Detection of Th in r-II stars with low metallicity

\[
\log A(\text{Th}) = -2.74 \pm 0.15
\]

\(\frac{^{12}\text{C}}{^{13}\text{C}} = 3\) is assumed

\[
\log A(\text{Th}) = -1.64 \pm 0.15
\]

\(\frac{^{12}\text{C}}{^{13}\text{C}} = 5\) is assumed
New r-process enhanced (r-II) stars

Th/Eu abundance ratios: small scatter with some “actinide-boost” stars

Mashonkina et al. (2014)

A low Th/Eu star!? [Preliminary result (Honda et al.)]
New r-process enhanced (r-II) stars

Metal-rich r-II star!

Strong evidence of late accretion of a classical dwarf galaxy-like object!

Stars in dwarf galaxies (Fornax, Ursa Minor ...)

Preliminary result (Xing et al.)
Publications and plans

● Published
  • Aoki et al. (2017, PASJ) Post-AGB sta J1833+3138= CC Lyr
  • Li et al. (2018, ApJL) Li-enhanced very metal-poor stars

● 1st Draft ready
  • Li et al., Li-enhanced extremely metal-poor star J0705
  • Xing et al., alpha-poor/r-process-rich star
  • Zhao et al., moving group stars I
  • Aoki et al., alpha-rich CEMP star J2217
  • Liang et al., moving group stars II

● Draft in preparation
  • Honda et al., r-process-rich extremely metal-poor stars
  • Zhang et al., CEMP turn-off stars

● Main sample: Aoki, Li, Matsuno et al.
  -project summary + binary frequency
  -abundance results
  -combination with Gaia
Summary and future prospect

LAMOST is providing huge samples of metal-poor stars and other chemically/kinematically interesting objects. We are conducting follow-up spectroscopy with Subaru for 500 stars.

◆ LAMOST objects studied with Subaru are relatively bright, providing good sample for detailed abundance studies.

◆ Observing program is very successful

◆ Publications for various topics are ongoing

◆ Combining kinematics data provided by Gaia