A systematic study of Extremely Metal-Poor Stars with SDSS/Subaru

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Sextans A galaxy (Subaru Telescope)

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What can we learn from Extremely Metal-Poor (EMP) stars?

(1) Individual nucleosynthesis processes (in early generations of stars)

(2) Constraints on low-mass star formation at lowest metallicity

(3) Formation of the Milky Way halo

• Extremely Metal-Poor (EMP) stars: $[\text{Fe/H}]<-3$
• $[\text{Fe/H}] = \log(n[\text{Fe}]/n[\text{H}]) - \log(n[\text{Fe}]/n[\text{H}])_{\odot}$
What are required for observational studies of EMP stars?

• EMP stars are extremely rare around the solar system.
  → **wide-field & deep survey** is required

• Spectral lines are weak (depending on temperature).
  → **high resolution spectroscopy** is required.
Search for metal-poor stars by Sloan Digital Sky Survey (SDSS)

- SDSS spectroscopy: 
  - $R \sim 1800$
  - Covering 3900-9000Å
  - $14 < V < 20$
- Metallicity estimate from Ca II HK lines
- Standard stars in SDSS-I
- New surveys in SDSS-II (SEGUE) $\rightarrow$ 240,000 stars

The 2.5m telescope at Apache Point Observatory

Figure 7. F star metal sequence—a set of SEGUE F stars, selected to show the range of metallicities sampled by the F subdwarf, F/G, spectrophotometric standard and reddening standard categories. All 13 stars have similar effective temperatures, near 6500 K, but the strength of the Ca K line at 3933 indicates metallicities ranging from less than 0.001–1.5 times Solar.
High-resolution follow-up spectroscopy with Subaru/HDS

- $R=30,000$
- $4030-6800\text{A}$
- $S/N\sim25-30$
- $\sim150$ objects

Example: Mg triplet around $5170\text{A}$ →

High S/N spectra with $R=60,000$ for $\sim15$ selected stars have been obtained.
Metallicity ([Fe/H]) from Subaru spectra and comparison with SDSS estimates

- EMP stars are very efficiently selected from SDSS spectra
- High-res spectroscopy is required to accurately determine the metallicity for [Fe/H]<-3
- [Fe/H] estimates depend on Teff scale → a systematic error in the high-res estimate?

(estimated in 2008)
Subaru High resolution spectroscopy for EMP stars found by SDSS today's topics

- Metallicity distribution function (MDF) in the lowest metallicity range ([Fe/H]<-3)
- An r-process-enhanced cool main-sequence star with [Fe/H]=-3.4
Metallicity Distribution Function (MDF) estimated from Hamburg/ESO survey + medium-resolution (R=2000) spectroscopy (Li et al. 2010)

Selection bias

Drop at [Fe/H] = -3.5
Comparisons with chemical evolution models

Comparison with models assuming gas infall or hierarchical merging scenario by Pranzos (2003, 2008)

Comparisons with models assuming critical metallicity for low-mass star formation by Salvadori et al. (2007)

Li et al. (2010)
Metallicity distribution of the SDSS/Subaru sample

Metallicity is determined from Fe lines in high resolution spectra

![Graph showing metallicity distribution]

- **Selection bias**
- **main-sequence turn-off stars**
- **red giants**

SDSS/Subaru
Total: 115 stars
Giant: 27 stars
Homogeneity of the sample:
No trend exists for V magnitude and temperature

turn-off stars

giants (+a few cool dwarfs)
Comparison of the MDFs of the SDSS/Subaru sample with the HES result (Li et al. 2010)

Excess of $[\text{Fe/H}] < -3.2$ in our sample, or incompleteness of our sample at $[\text{Fe/H}] = -3$?
A 0.2dex metallicity offset is assumed for our sample.

Comparison of the MDFs of the SDSS/Subaru sample with the HES result (Li et al. 2010)

- SDSS/Subaru +0.2dex offset (high resolution)
- HES (turn-off stars) (medium resolution)

drop at [Fe/H] = -3.7?

Selection bias
Metallicity Distribution Function estimated from the SDSS/Subaru sample for \([\text{Fe/H}]<-3\)

- A good agreement with the HES estimates from medium resolution spectroscopy is found for \([\text{Fe/H}]>-3.5\) (after some corrections)
  - Further calibration is required between high-resolution and medium-resolution spectroscopy

- A drop of MDF is also suggested at \([\text{Fe/H}]\sim-3.7\), but that is not as sharp as found in HES estimates. The existence of stars with \([\text{Fe/H}]<-3.5\) in our sample will slightly modify the conclusions from the HES estimates.
Discovery of a cool main-sequence star with $[\text{Fe/H}]=-3.4$ and large excesses of r-process elements

[SAGA database (Suda et al.)](#)

2 stars from SDSS

*Teff*=5000K, log g~5
r-process enhancement in a cool main-sequence star with $[\text{Fe/H}]=-3.4$

SDSS 2357-0052 has $[\text{Fe/H}]=-3.4$ and $[\text{Eu/Fe}]=+1.9$ with r-process abundance pattern

Aoki et al. (in prep.)
SDSS 2357-0052 has [Fe/H]=-3.4, the lowest metallicity among extremely r-enhanced stars.
Discovery of a cool main-sequence star with [Fe/H]=-3.4 and large excesses of r-process elements

- r-process-enhanced ([Eu/Fe]>+1) stars have been found only at [Fe/H]~-3 by previous studies, but the metallicity range extends to [Fe/H]=-3.4. Constraints on the mass range of supernova progenitors related to r-process?

- There seems to be an upper bound of r-process excesses of [Eu/H]~-1.5 ([Eu/Fe]=+1.5 at [Fe/H]=-3), suggesting the existence of limits in the pollution of interstellar matter by a single r-process event.
High-resolution follow-up spectroscopy has been conducted for 150 candidates for EMP stars.

• A new estimates of metallicity distribution function is obtained for \([\text{Fe/H}]<-3\).

• Discovery of anr-process enhanced star at \([\text{Fe/H}]=-3.4\).

Further abundance studies for other elements (e.g. Mg, Ba etc.) for a large sample, and detailed abundance studies for several stars with \([\text{Fe/H}]<-3.5\) are ongoing.
Mg abundance ratios of SDSS/Subaru sample

comparisons with previous studies  
average and standard deviation
Extremely Metal-Poor stars in the Milky Way halo found by SDSS/SEGUE

Chemical abundance studies of metal-poor stars:

• survey of metal-poor stars from (low- and) medium-resolution spectroscopy
  e.g. HK survey (Beers et al. 1985)
  Hamburg/ESO survey (Christlieb et al.)
  SDSS/SEGUE (Yanny et al. 2009)

• high resolution spectroscopy of candidates for (extremely) metal-poor stars with large telescopes
Strategy of the program

Two steps of high-resolution spectroscopy with Subaru for SDSS/SEGUE objects

(1) Moderate R & S/N
- R = 30,000
- S/N ~ 30
- ~ 150 objects
→ metallicity
  - C/Fe
  - α/Fe

(2) High R & S/N
→ detailed abundance pattern
Li (turn-off stars)
Project team

- SDSS/SEGUE sample selection
  - Calibration of SDSS analysis
  - Beers, Sivarani, Carollo

- Moderate S/N survey:
  - Aoki, Honda, Hidai

- High S/N study: Li abundances, neutron-capture elements, etc.
  - Honda, Ito, Aoki, others

- Collaborations with programs with other telescopes
  - Frebel, Norris

- Interpretation: Fujimoto, Suda
Thirty Meter Telescope (TMT)

The construction site was decided to be Hawaii. The first light is planned in 2018.