Chemical abundances of the Milky Way thick disk and stellar halo with Subaru/HDS

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The Milky Way Galaxy
A laboratory of galaxy formation

- Cosmological simulation: formation of large galaxies via accretions of smaller-mass sub halos
  - How star formation begins, proceeds or suppressed within such sub halos?
  - How they have assembled to build up larger systems
- The local group is one of the best place to examine this issues by resolved stellar populations
- Recent surveys (e.g. 2MASS, SDSS, S-Cam) revealed important signatures
What chemical abundance tell us?

- Elemental abundances are conserved in the surface of unevolved stars over long timescales (e.g. age > 10 Gyrs).
- Detailed chemical abundance patterns of metal-poor stars provide insights about past chemical enrichments at the star's birth place.
- Formation sites for individual elements:
  - Core regions of stars
  - Envelop of evolved stars (e.g. AGB phase)
  - Supernovae (Type II: massive stars, Type Ia: low-mass stars)

What kind of nucleosynthesis happen? how efficiently the enriched material mixed? How easily enriched material can escape from the system?
Formation sites of chemical elements

- α-elements (O, Mg, etc.)
  Type II SNe ($\tau \approx 10^{6-7}$)
- Fe-peak elements (Fe, Ni, etc)
  Type Ia SNe ($\tau \approx 10^{8-10}$)
- Neutron-capture elements
  - s-process: AGB stars
  - r-process: Type II SNe, neutron-star mergers, etc

Ratios of different elements (e.g. $[\text{Mg}/\text{Fe}]$):
Fractional contribution of different mechanisms (e.g. Type II / Ia SNe) to the system’s past chemical evolution
Star formation history of dwarf galaxies Fornax and Sculptor dSphs

Kirby et al. 2011

- Bursty and/or inhomogeneous SF
- Very rapid initial metal enrichment

- Low star formation efficiency
- Low initial gas mass
Subaru/HDS study on chemical abundances of the thick disk and halo stars

- **Sample:** 97 metal-poor dwarfs and giants
  - Nearby ($d<2$ kpc). Bright stars ($V<14$)
  - Wide ranges of metallicity and orbital parameters

- **Orbital parameters**
  Recalculated based on the latest proper motion, RV (from this work) and distances estimates (Chiba & Beers, 2000)

- **Membership probability ($P$)**
  - Thick disk ($P_{TD}>0.9$): 11 stars
  - Inner halo ($P_{IH}>0.9$): 35 stars
  - Outer halo ($P_{OH}>0.9$): 37 stars
  - ~15 stars with the intermediate kinematics

### Graph
- Scatter plot showing $V_R^2 + V_z^2)^{1/2}$ vs. $V_\phi$ (km/s)
Observation and analysis

- Subaru/HDS observation during 2003-2010
  - Exp. time ~ 300 - 3600 sec
  - 4000-6800 Å, R~50000
- Kurucz (“NEWODF”) model atmosphere ([α/Fe]=0.4) + a 1-D LTE abundance analysis code (Aoki et al. 2009)
- $T_{\text{eff}}$ from V-K color, logg from FeI/II ionization equilibrium, $\xi$ from Fe I EWs
Mg, Si, Ca --- α elements

Tracer of rapid chemical enrichments through Type II SNe of massive stars

- **Thick disk stars:**
  - High \([\alpha/Fe]\) ratio
  - Very small scatter \((\sigma < 0.07 \text{ dex})\)

- **The inner/outer halo stars:**
  - Lower abundance ratios
  - Larger scatter \((\sigma \approx 0.13 \text{ dex})\)
  - Enhanced \([\alpha/Fe]\) for \([Fe/H]<-1.5\)

Nissen & Schuster 2010
Na, Sc and V --- odd-Z elements

- Na: hydrostatic carbon burning of massive stars, Sc and V: explosive burning of SNe

- Higher [Na/Fe] for the thick disk stars than the halo stars
- Increasing trend with [Fe/H]

Type II SNe
Different typical metallicity of the progenitor stars?
Mn, Ni, Zn --- Fe-peak elements

EXPLOSIVE BURNING IN TYPE II/IA SNE, DEPENDING ON DETAILED CONDITIONS AT SNE

- Small scatter (e.g. Ni)
- The halo stars have lower [Zn/Fe] than the thick disk stars

\[ \text{x: Thick disk, \bullet: Inner halo, \▲: Outer halo} \]
\[ \text{O: thick/inner, \△: inner/outer} \]

Nissen & Schuster 2011
Ba and Eu --- Neutron-capture elements

- s-process: AGB stars, r-process: Type II SNe, neutron star mergers, etc.

- High [Eu/Fe] for the halo stars

→ If the Eu is synthesized with similar process as Mg, [Eu/Fe] would also show similarly low values
Implications

- Formation of the thick disk
  - Accretions of dwarf galaxies
  - Dynamical heating of pre-existing thin disk
  - Early gas-rich major merger
    - High $[\alpha/\text{Fe}]$, $[\text{Na/Fe}]$ and $[\text{Zn/Fe}]$ for the thick disk stars: Rapid chemical enrichments primarily through Type II SNe

- Formation of the stellar halos
  - Rapid collapse of gaseous materials on to the central region of the MW
  - Formed within dwarf galaxies later accreted and disrupted
    - Wide range of $[\alpha/\text{Fe}]$ and $[\text{Na/Fe}]$ for the inner/outer halo stars: both of these scenarios may have contributed to the current stellar halo

- Origin of r-process elements
  - $[\text{Eu/Fe}]$ of the halo stars do not show the trend seen in $[\text{Mg/Fe}]$
    - Difference in progenitor mass of the Type II SNe?
  - Examination of detailed abundance patterns of neutron capture elements are now underway.
Comparison with dSphs

- Higher $[\alpha/\text{Fe}]$ than the Sculptor dSphs

Star formation of progenitors of the stellar halo have stopped much earlier than Sculptor

$\rightarrow$ Large fraction of the halo stars have already accreted before $\sim 10$ Gyr

Age of halo stars are older than 10 Gyrs

Schuster et al. 2011
Future prospects: Go beyond the solar neighborhood

- Spatial/kinematical substructures are expected to be more abundant in the outer stellar halo
- Less contamination from the disk stars
- Photometric and astrometric data from the HSC and Gaia can be used to estimate star’s atmospheric parameters ($T_{\text{eff}}$, $\log g$), kinematics and age → Full phase-space, abundance-space and age information will be available up to $V < 21.5$ for a certain region of the sky