Effect of interstellar objects on metallicity of low-mass first stars formed in a cosmological model

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Substructures
- ~30 dwarf galaxies
- 91 GCs (Rproj > 25 kpc)
- Many merger remnants (Streams, shells)

Theory
- Geehan+06
- Fardal+06, +07, +08, +13
- Mori & Rich 2008
- Hammer+10, +13, +18
- Sadaun+14
- Miki+14, +16
- TK+14, +17a, +17b

Observation
- Ibata+01, +04, +07, +13
- Ferguson+02, +16
- Kalirai+06
- Guhathakurta+06
- Gilbert+07, +09, +12, +19
- Koch+08
- McConnachie+09, +18
- Tanaka+10
- Martin+13
- Lewis+13
- Conn+16
- Komiyama…, TK+18
- Preston+19
- Escala+19

$[\text{Fe/H}] \sim -2.3$
$[\text{Fe/H}] \sim -1.4$
$[\text{Fe/H}] \sim -0.7$

$R_{M31} \sim 150$ kpc
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**PAndAS survey**
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Cosmological study for sub-structures

> 24,000 substructures for 9 MW-sized halos
Population III stars

Pop. III stars were formed in smaller DM halos (minihalos: $10^{5-6} \, M_\odot$) based on the ΛCDM model.

- formed in pristine gas
- typically very massive $10 - 1000 \, M_\odot$
- SN explosions at high-z

(e.g., Tegmark+97; Omukai & Nishi 1998; Abel+02; Bromm+02; Hosokawa+11; Stacy+12)
Low-mass Pop. III stars (survivors)

- $M_* \lesssim 0.8 M_\odot$ (Lifetime $\geq$ Cosmic age)
- Born in the disks via fragmentation (e.g., Greif et al. 2012)

Distribution of pop. III survivors in the MW

Cosmological $N$-body simulation + pop. III formation model

Ishiyama+16

z=0

No Metal-free stars have been discovered so far.
Metal pollution of Pop.III survivors

- ISM (interstellar medium) accretion while wandering in the MW
  $\rightarrow [\text{Fe/H}] \sim -5$
  assuming Bondi-Hoyle accretion
  (Yoshii 1981, Komiya+15, Shen+17)

- Steller wind block the accretion
  $\rightarrow [\text{Fe/H}] < -14$
  (Tanaka+17, Suzuki 2018)

It is difficult to pollute them with ISM metal while orbiting the MW.
Interstellar objects (ISOs)

'Oumuamua
- The first ISO observed passing through the Solar System (Meech et al. 2017).
- Size: \(\sim 100\) m
- The 2nd ISO has been approaching (Jewitt+19)

Estimated cumulative number density of such ISOs (>100 m) is \(n_0 = 0.2\) au\(^{-3}\) (Do+18)
Pop. III survivors polluted by ISOs

By Tanikawa et al. 2018

ISOs (>100 m) accretion rate

\[ \dot{N}_{\text{acc},0} \sim 1.4 \times 10^{-4} \left( \frac{n_0}{0.2 \text{au}^{-3}} \right) \text{[yr}^{-1}] \]

(=f n_0 \sigma v)

ISO size distribution

\[ n = n_0 \left( \frac{D}{D_0} \right)^{-\alpha} \]
Pop. III survivors polluted by ISOs

ISOs (>100 m) accretion rate

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ISO size distribution

\[ n = n_0 \left( \frac{D}{D_0} \right)^{-\alpha} \]

\[ [\text{Fe/H}] \sim \log_{10} \left( \frac{1}{f_{\text{conv}}} \frac{M_{acc} \Delta t_{\text{pol}}}{M_* Z_\odot} \right) \]

\[ \Delta t_{\text{pol}} = 5 \text{ Gyr} \]

ISOs are the most dominant contributor of metal enrichment.

They assumed one modelled orbit for the analytical estimation.
Cosmological $N$-body simulation

$N$-body simulation (Ishiyama+16)
+ Pop. III formation model

✓ $N=2048^3$
✓ Boxsize: 8 $h^{-1}$cMpc
✓ Minimum halo mass: $2.4 \times 10^5 M_\odot$

We calculate

$$\dot{N}_{acc,0} = \frac{1}{\Delta t_{ISO}} \int_{\Delta t_{ISO}} f n_0(R(t)) \sigma |v(t) - V_{circ}(R(t))| dt$$

(\(\Delta t_{ISO} \equiv 5\text{Gyr}\))

We set the number density of ISOs $\propto \rho_*$ of the Galactic thin disk.

$\dot{N}_{acc,0} \geq 10^{-6}, 10^{-5}, 10^{-4}$
Accretion rate of ISOs

Pop. III survivors have experienced typically 5M times of ISO($>100$ m) collisions in the last 5 Gyr. The value is one order of magnitude greater than estimated in Tanikawa +18.
α=2 is suggested by observations of comets in the solar system (Fernandez & Sosa 2012).

Stellar surface metallicity ($\alpha=2$ case)

Size dist. of ISOs

\[
\left( \frac{D}{D_0} \right)^{-\alpha}
\]

- 0.80 $M_\odot$: typically polluted to $[\text{Fe/H}] \sim -2$.
- 0.70 and 0.75 $M_\odot$ stars: the typical surface metallicity are around $[\text{Fe/H}] = -6 \sim -5$. 

Number of Pop. III survivors

[Diagram showing distribution of $\text{Fe/H}$ values for different masses of stars]
Surface metallicity of Pop. III survivors

The degree of metal enrichment decreases as increasing $\alpha$. 
Metal pollution of stars in inner halo

20% of Pop. III survivors remain as metal-free stars in inner halo.

Median value of the accretion rate is comparable to the analytical estimate (Tanikawa+18).
• We investigated metal pollution onto the surface of Pop. III survivors by ISOs floating in the Galactic disk.

• ISOs are the most dominant contributor of metal pollution.

• Metal-poor stars so far discovered at solar neighborhood are possible to be metal-free Pop. III stars on birth.

• Pop. III survivors could hide in extremely metal-poor stars discovered so far.

Kirihara et al., 2019, MNRAS, 486, 5917