Formation environment of Pop II stars affected by the feedbacks from Pop III stars

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Abstract

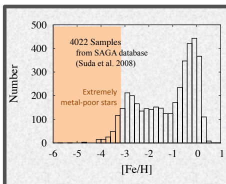
In the halo of our Galaxy and external dwarf galaxies, extremely metal-poor (EMP or Pop II) stars are observed. Their long life time and low metal abundances, they are considered to be the second- or several-generation of stars.

We in this work investigate the formation environment of EMP stars, considering the effects of radiative and kinetic feedbacks of main-sequence and supernovae (SNe) of the first-generation primordial (Pop III) stars by a series of numerical simulations.

We find that in low-mass minihalos (MHs) with M_{halo}~3×10⁵ M_*, the gas around Pop III stars with masses M_{popIII}=13-30 M_* are partly broken by their ionizing photon emission, while in a high-mass MH (M_{halo}~3×10⁶ M_*) the gas is not affected. Then, by SN explosion, a large fraction of metal is expelled to the void region while the other is mixed into the gas accreting along the filament of the large scale structure. The resulting metallicity in the recollapsing region is 10^{-4}-10^{-2} Z_*, and 10^{-6}-10^{-5} Z_* for low-mass and high-mass MHs, respectively.

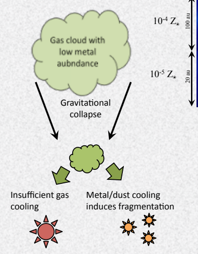
Considering that the mass range of MHs are within ~3×10⁵--3×10⁶ M_* (Hirano et al. 2015), we can conclude that the internal enrichment by Pop III SNe is one of the paths to formobserved EMP stars.

Introduction

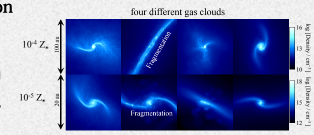


•$A(X) = 12 + \log y(X)$
•$[X/H] = \log y(X) - \log y_{\odot}(X)$
$y(X)$: number fraction of element X relative to H

Long-lived (low-mass) extremely metal-poor (EMP) stars with [Fe/H] < −3 have not so far been observed below the critical elemental abundances.
Theoreticians show that gas cooling by dust thermal emission induces the fragmentation of their parent clouds and low-mass stars are likely to form (Omukai 2000; Schneider et al. 2003; Chiaki, Tominaga, & Nozawa in prep.)



four different gas clouds



In previous work, we show that the clouds with metallicities > 10^{-5} $Z_{\odot}$ are indeed elongated and fragment by dust thermal emission by numerical simulations (Chiaki, Yoshida, & Hirano 2016).
However, in the simulasions, we unifirmly add metal and dust to pristine clouds where the first (Pop III) stars will form hosted by minihalos (MHs).
In reality, metal and dust should be distributed ununiformly by the supernova (SN) feedback of Pop III stars (Wise et al. 2012; Ritter et al. 2012; Smith et al. 2015; Chen et al. 2016).

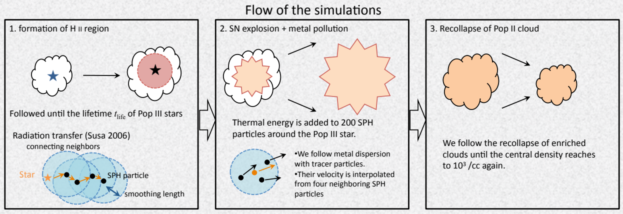
Question:
How is the distribution of metal released by Pop III SNe in Pop II star-forming regions?
Here, we focus on the internal enrichment of MHs having hosted Pop III stars.

Method

◎ GADGET-2 (Springel 2005)

- Non-eq. chemistry
  15 species
  e, H, H⁺, H_2, H⁻, H_2^+, HeH⁺, He, He⁺, He²⁺, D, D⁺, D⁻, HD, and HD⁺
  55 reactions including
  H + γ → H⁺ + e
  H_2 + γ → H + H
- Radiative cooling
  H_2, HD ro-vib. cooling
  H, He, He⁺ line, ion./rec. cooling
  Brems, & Compton
- Heating by ionizing photons

Flow of the simulations



Target halos

Halo	M_{halo}^{ini} [M⊙]	R_{halo}^{ini} [pc]	z_{form}
MH1	2.94e5	70.12	28.47
MH2	3.89e5	79.52	27.52
MH3	3.23e6	186.85	23.58

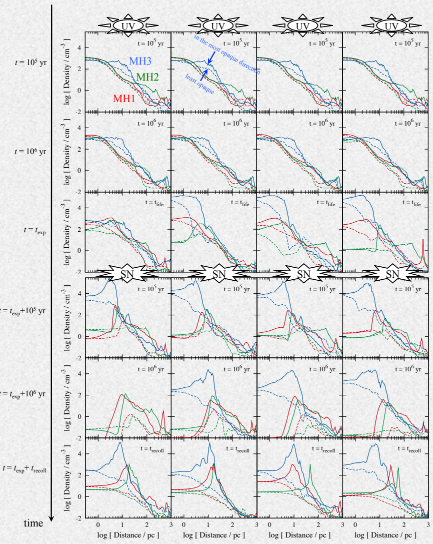
We cut out three MHs with a wide range of masses M_{halo}^{ini} from a cosmological simulation.
MH1 and MH2 have the mass of ~3×10⁵ M_*, and MH3 have ~3×10⁶ M_*, which are the respectively lowest- and highest-ends of the mass range of MHs (Hirano et al. 2015).

Pop III stars

M_{PopIII} [M⊙]	t_{life} [Myr]	Q(H) [s⁻¹]	E_{SN} [10⁵¹ erg]	M_{met} [M⊙]
13	13.7	1.33e48	1	0.746
20	8.43	4.72e48	1	2.56
25	6.46	7.58e48	1	3.82
30	5.59	1.33e49	1	7.18

Since we do not still know the mass M_{PopIII} of Pop III stars hosted by MHs, we vary it as a parameter.
The lifetime t_{life} of the stars, emission rate Q(H) of ionizing photons, and mass M_{met} of ejected metal are determined by the stellar mass (Schaerer 2002; Umeda & Nomoto 2002). We here study in the cases of core-collapse SNe (CCSNe).

Results

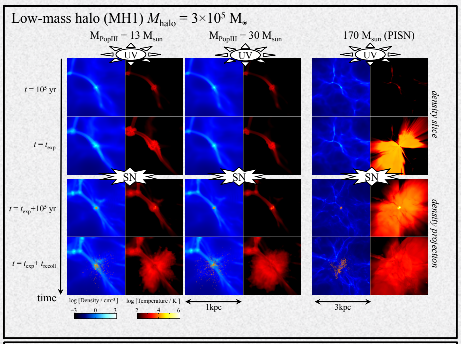


Density profile of primordial gas exposed to by ionizing photons from central Pop III stars (upper 3 rows) and shocked by SNe (lower 3 rows) after the explosion time $t_{exp} = t_{life}$. Red, green, and blue curves indicate the results for MH1, MH2, and MH3, respectively. To see the three-dimensional effect of radiative and SN feedbacks, we plot the density profile in the directions with largest (solid) and smallest (dashed) column density.

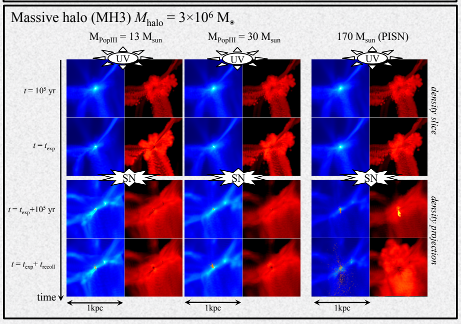
For massive halo MH3 (blue: ~3×10⁶ M_*), the gas continues to collapse because the pressure from radiation is smaller than the gravitational force.

At 10⁶ yr after the SN explosions, the gas is once rarefied. Then, at the time t_{recoll}, the gas accretes through the filament along the large scale structure and collapses again at ~1 pc distant from the Pop III remnants.

Low-mass halo (MH1) M_{halo} = 3×10⁵ $M_{\odot}$

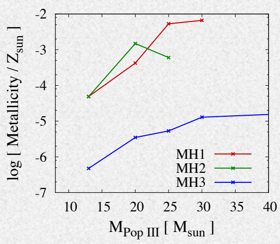


Massive halo (MH3) M_{halo} = 3×10⁶ $M_{\odot}$

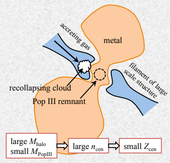


Density and temperature map around the Pop III stars/remnants from top to botom in the course of time for low-mass halo MH1 (upper) and high-mass halo MH3 (lower).

The orange dots depict the position of metal particles. A part of metal is blown away by the SN shock in cases with small M_{halo} and large M_{PopIII} (Q(H)).

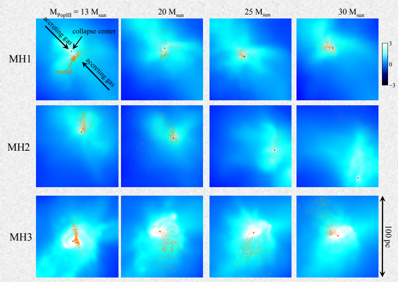


Halo	M_{PopIII} [M⊙]	n_{cen} [cm⁻³]	t_{recoll} [Myr]	Z_{cen} [Z⊙]
MH1	13	314	5.74	4.89e-5
	20	715	7.89	4.21e-4
	25	266	8.41	5.31e-3
	30	241	12.2	6.62e-3
MH2	13	83.2	11.3	4.88e-5
	20	5.90	12.4	1.49e-3
	25	50.9	22.4	6.03e-4
	30	1.39	28.8	0
MH3	13	9.02e5	0.98	4.77e-7
	20	7.88e5	1.16	3.48e-6
	25	7.32e5	1.27	5.33e-6
	30	4.77e5	1.30	1.29e-5



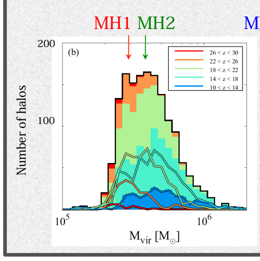
The range of metallicity z_{cen} in the recollapsing region is 10^{-4}--10^{-2} $Z_{\odot}$ for smaller-mass halos MH1 and MH2, while 10^{-6}—10^{-5} $Z_{\odot}$ for the massive halo MH3.

We might expect that the metallicity z_{cen} in the recollapsing region becomes larger with decreasing M_{PopIII}, but this is not the case. Rather, as Q(H) becomes smaller with decreasing M_{PopIII}, density n_{cen} around the stars at t_{life} increases. The gas accreting from the cosmological filament begins to collapse before the mixing with metal. Consequently, z_{cen} becomes smaller. This happens also with larger M_{halo}.



Discussion

We here consider the metal enrichment from core-collapse SNe (CCSNe). Some researchers report that the elemental abundance of hyper metal-poor (HMP) stars with metalliciteis [Fe/H] < −5 such as SDSS J1029+1729 with [Fe/H]~−5 is consistent with more energetic hypernovae (HNe) (e. g., Tominaga et al. 2014). We speculate that, with increasing explosion energy, the fraction of metal which return to recollapsing region decreases, and the abundance of HMP stars can be reproduced. Further, for pair-instability SNe (PISNe), we expect that the metallicity in the recolapsing region is below the critical metallicity, i.e., the Pop III star formation continues. This is consistent with the observations by which no EMP stars with elemental abundances of PISNe have so far been found.



Conclusion

•The range of metallicity in the region which collapses again after the radiative and kinetic feedbacks from Pop III stars and their SNe is 10^{-4}--10^{-2} Z_* for smaller-mass halos MH1 and MH2 (~3×10⁵ M_*), while 10^{-6}—10^{-5} Z_* for the massive halo MH3 (~3×10⁶ M_*).

•The mass of these halos covers the mass range of minihalos obtained by the cosmological simulations with a large box size (Hirano et al. 2015; left figure). This indicates that the metallicity range of recollapsing region is 10^{-6}—10^{-2} Z_*.

•We can conclude that the internal enrichment by Pop III SNe is one of the paths to form observed EMP stars.