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（氏名は必ず自署すること）

海外特別研究員としての派遣期間を終了しましたので、下記のとおり報告いたします。
なお、下記及び別紙記載の内容については相違ありません。

記

1. 用務地（派遣先国名）用務地：　アトランタ　（国名：　アメリカ　）

2. 研究課題名（和文）※研究課題名は申請時のものと違わないように記載すること。
初代銀河形成の数値シミュレーション

3. 派遣期間：平成　31　年　4　月　1　日　～　令和　3　年　2　月　28　日

4. 受入機関名及び部局名
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部局名：　School of Physics

5. 所期の目的の遂行状況及び成果…書式任意　**書式任意（A4 判相当 3 ページ以上、英語で記入も可）**

（研究・調査実施状況及びその成果の発表・関係学会への参加状況等）

（注）「6. 研究発表」以降については様式 10－別紙 1～4 に記入の上、併せて提出すること。

1. Introduction

My research aim of this JSPS Overseas Research Fellowship program is to investigate the evolution of stellar mass and the process of chemical enrichment in the first galaxies. In this program, I have researched for the formation of the second generation of stars. These stars are observed as extremely metal-poor (EMP) stars with metallicities [Fe/H] < -3 in Galactic halo or local group dwarf galaxies and considered to form in gas clouds enriched with elements heavier than helium (metals) and dust grains produced by one or several supernova (SN) events of the first generation of (Population III; Pop III) stars (Ryan et al. 1996). While no metal-free stars have been observed so far, several hundreds of EMP stars have been identified by large survey campaigns and spectroscopic follow-up measurements (e.g. Beers et al. 1985, 1992). This indicates that, while Pop III stars are massive (~10-1000 $M_{\odot}$), EMP stars are low-mass (< 0.8 $M_{\odot}$) so that they can survive for the cosmic time. Numerical studies have revealed that metal-free clouds collapse stably without fragmentation because of the lack of efficient coolants in their parent clouds (Bromm et al. 1999; Hirano et al. 2014). As semi-analytic studies have shown, dust grains are the main coolant that induces cloud fragmentation (Omukai 2000; Schneider et al. 2002). However, their formation process and mass scales are poorly understood.

2. Research

2.1 Star formation in metal-poor gas clouds

The critical conditions for the formation of low-mass stars are important to understand the stellar initial mass function in the early Universe. As discussed in Section 1, metallicity or dust-to-gas mass ratio in gas clouds may affect their thermal evolution and the mass scale of stars that finally form (Omukai 2000; Schneider et al. 2002). Several authors have investigated the gravitational collapse of low-metallicity gas clouds (Dopcke et al. 2011; Smith et al. 2015). However, they assume that elemental fraction and dust-to-gas mass ratio in the present day interstellar medium (ISM). Dust grains are mainly supplied by SNe in the early Universe, but grains are partly destroyed by reverse shocks. Therefore, dust-to-gas mass ratio is smaller than in the local ISM by a factor of 5-10 (Nozawa et al. 2007; Bianchi & Schneider 2007). On the other hand, grains can grow by accreting gas-phase metal molecules in molecular clouds, which can enhance the cooling rate and induce *cloud fragmentation* (Chiaki et al. 2015). We should also consider another mode of fragmentation: *disk fragmentation* as pointed out in my previous work (Chiaki et al. 2016). After a cloud center becomes optically thick, a hydrostatic core forms, and the gas with finite angular momentum form accretion disk around the core (Larson 1969). The disk can fragment through gravitational instability. So far disk fragmentation in metal-free clouds has been investigated by several authors (Hosokawa et al. 2016; Sugimura et al. 2020), but the evolution of accretion disk in metal-poor clouds are still unknown. In this work, I follow the evolution of collapsing clouds and accretion disk with various metallicities (0-10^{-3} $Z_{\odot}$), including all relevant chemical reactions as well as grain growth with realistic elemental abundance and dust-to-gas mass ratio in the early Universe.

I cut out two halos with a mass ~10^5 $M_{\odot}$ (minihalos; MHs), called Halo A and B, forming at redshifts 15-20 from a cosmological simulation (Hirano et al. 2014). I uniformly add metals and grains with metallicities 0, 10^{-6}, 10^{-5}, 10^{-4}, and 10^{-3} $Z_{\odot}$. The abundances of heavy elements and grain species and dust size distribution are taken from a Pop III SN model with a progenitor mass $M_{\rm PopIII}$ = 30 $M_{\odot}$ (Umeda & Nomoto 2002; Nozawa et al. 2007). I am developing a chemistry/cooling library GRACKLE (Smith et al. 2017), including the formation/destruction of metal molecules and the growth of 10 grain species. With this library, I solve a non-equilibrium chemical network of 100 reactions for 48 species. After the cloud center becomes optically thick, I follow the evolution of an accretion disk for 100-400 years. The gas accretion should cease ~10^5 year due to the photoevaporation of the disk. However, it is difficult to follow its entire evolution because the numerical timestep is limited by the Courant condition of the dense protostellar cores. Authors often utilize a sink particle technique, where the dense regions are masked and replaced with Lagrangian particles. However, since this technique requires some modeling to consider the separation and merger of sinks, I make use of another technique, imposing stiff equation of state in regions with densities > 10^{16} cm^{-3}.

We find that cloud fragmentation does not occur for all metallicities for the two MHs although dust cooling becomes dominant at densities ~10^{12}-10^{14} cm^{-3} above metallicities 10^{-5}-10^{-4} $Z_{\odot}$ (Fig. 1). This is because rapid gas heating occurs at lower densities ~10^8 cm^{-3}, where hydrogen molecules form through three-body reactions, $H + H + H \rightarrow H_2 + H$, and the binding energy is converted to the thermal energy (Fig. 2). The timescale for cloud deformation, precursor of the fragmentation, is longer than the dynamical

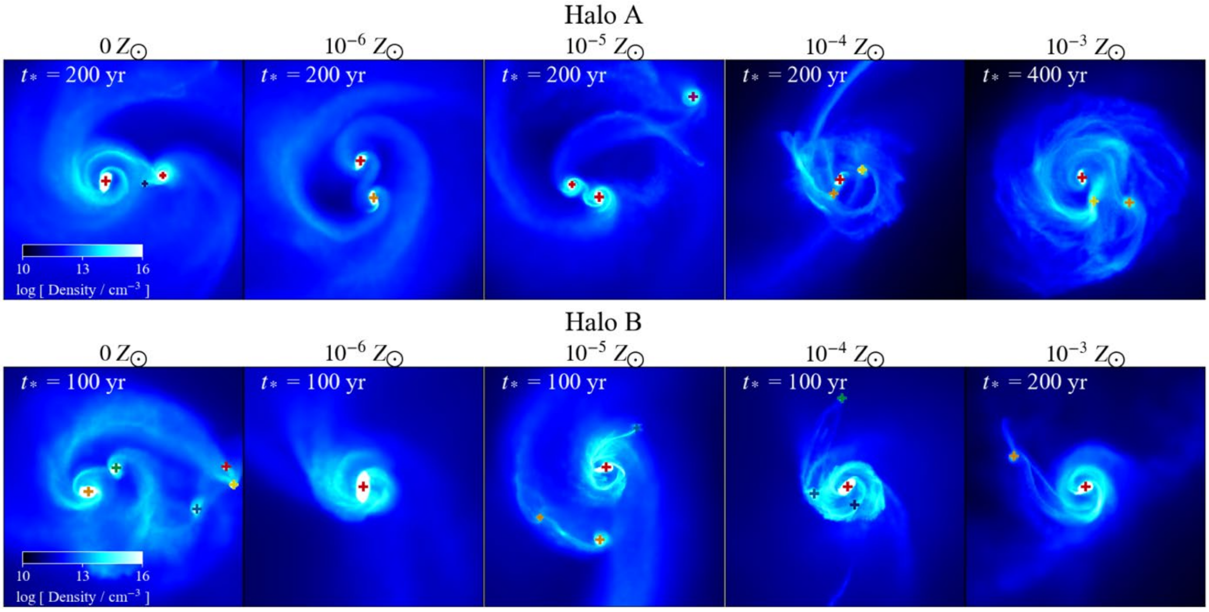

Fig. 1 Density projections of accretion disks for Halo A and B with metallicities 0-10^{-3} $\mathbf{Z_\odot}$ from left to right. The cross symbols depict the center-of-mass of protostars.

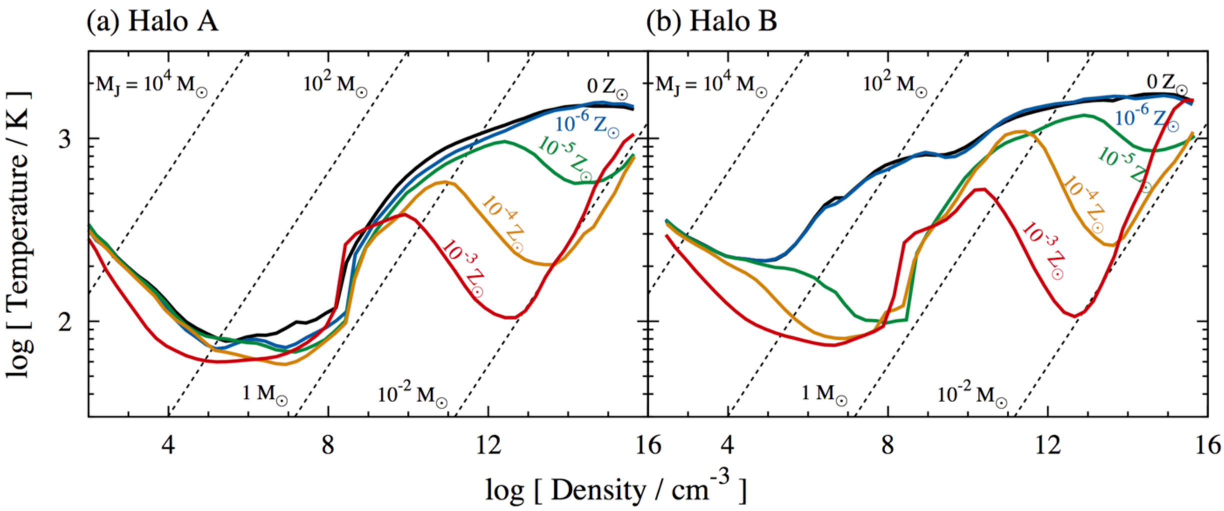

Fig. 2 Temperature as a function of density of cloud center for (a) Halo A and (b) B with metallicities 0-10^{-3} $\mathbf{Z_\odot}$. The black dotted lines show the Jeans mass at each state.

timescale of the cloud through dust cooling. This result indicates that low-mass stars would not form through cloud fragmentation in general with metallicities < 10^{-3} $Z_\odot$. This is consistent with the observational results that few stars with iron abundances [Fe/H] < -3 have been observed (~100 out of 10^6 stars in entire survey programs). We also find that disk fragmentation occurs for all our models except for a metallicity 10^{-6} $Z_\odot$ for Halo B. For 100-400 years, at most 26 protostars form through the fission of rapidly rotating protostars or interaction of spiral arms in the accretion disk. Most of them merge with each other, and finally 3-5 protostars survive. This result suggests that multiple EMP stellar systems generally form as observational studies find binary stars with metallicities [Fe/H] ~ -4 (Arentsen et al. 2019).

I present this result in domestic and international conferences [4, 6, 7], and submitted a paper [1].

2.2 Formation of CEMP stars from faint SNe

Large observation campaigns have revealed that EMP stars are classified into carbon-normal and carbon enhanced metal-poor (CEMP) stars below and above [C/Fe] = 0.7, respectively (Beers & Christlieb 2005; Aoki et al. 2007). Researchers have presented several scenarios of the formation of CEMP stars (Suda et al. 2004; Meynet et al. 2006). In this work, we focus on a scenario where their parent clouds are enriched by a specific type of SNe. Just before a SN explosion, a stellar core is stratified, and if its iron-rich inner layers fall back into the central compact remnant, only carbon-rich gas is ejected into ISM (mixing-fallback scenario). This type of SNe is called faint SNe. The scenario can explain the *relative*

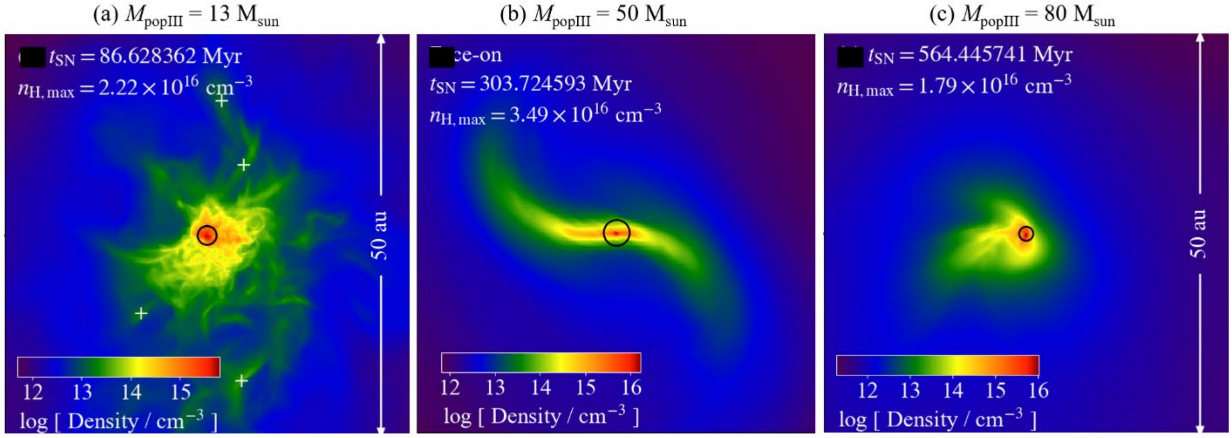

Fig. 3 Density projections of the center of clouds enriched by faint SNe with progenitor masses (a) 13 $M_{\rm sun}$, (b) 50 $M_{\rm sun}$, and (c) 80 $M_{\rm sun}$ from left to right. The circles and plus symbols depict the primary and secondary protostars, respectively.

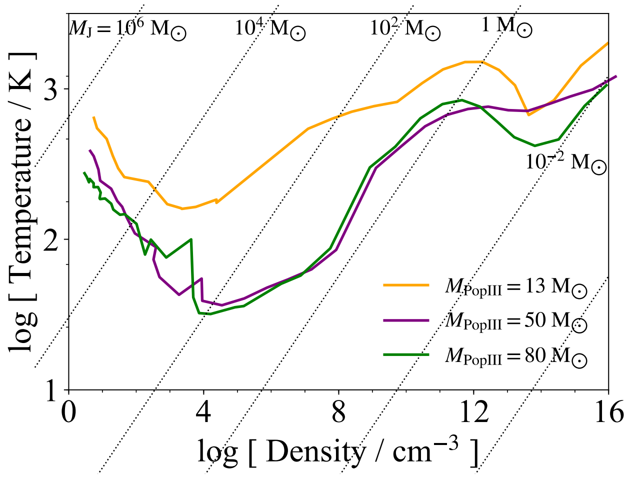

Fig. 4 Temperature evolution of clouds enriched by faint SNe with progenitor masses 13 (orange), 50 (purple) and 80 **M**$_\odot$ (green).

elemental abundance ratios of observed CEMP stars (Umeda & Nomoto 2003). However, it is still unclear whether clouds enriched by faint SNe have sufficient elemental abundances consistent with observed CEMP stars (A(C) ~ 6) because the mass of ejected metals is depleted by the fallback process.

In this work, I perform a series of numerical simulations from a SN explosion of a faint SN to CEMP star formation through the enrichment of its hosting MH with a mass ~10^6 M$_\odot$ at a redshift 12.1. The abundances of heavy elements and grain species and dust size distribution are taken from faint SN models with progenitor masses $M_{\rm PopIII}$ = 13, 50, and 80 M$_\odot$ (Marassi et al. 2014). For each progenitor mass, model parameters such as explosion energy and ^{56}Ni mass are chosen to best fit with the elemental abundance ratio of a CEMP star SMSS J0313-6708 with [C/Fe] ~ 5 (Keller et al. 2014). I solve chemical reactions and radiative cooling with GRACKLE (see Section 2.1). Then, I follow the gravitational collapse of a cloud enriched by the SN to see whether cloud fragmentation occurs through dust cooling.

I find that a SN shell returns to the Pop III hosting MH and the cloud collapses again for all progenitor models. The dispersion of metals is interrupted in the dense contact surfaces between the shell and cosmic filaments, and a fraction of metals (0.4% for 13 M$_\odot$ and 0.1% for 50 and 80 M$_\odot$) returns. The carbon abundance of the cloud is A(C) = 3.80, 5.06 and 4.90 for $M_{\rm PopIII}$ = 13, 50, and 80 M$_\odot$, respectively, which is smaller than that of observed CEMP stars (A(C) ~ 6). For 13 M$_\odot$, the mass of carbon ejected from the SN is smaller (0.08 M$_\odot$) than normal core-collapse SNe (~0.5 M$_\odot$) due to the fallback (Chiaki & Wise 2019). For 50 and 80 M$_\odot$, although carbon mass is larger (~ 1 M$_\odot$), the distance of the contact surfaces is larger because nearby dense regions have been photoevaporated through the copious emission of ultraviolet photons from these massive progenitors before the SN explosion. The solid angle of the dense contact surfaces which can interrupt the dispersion of metals is small, and thus the fraction of carbon mass which returns to the MH is reduced. To explain the formation of observed CEMP stars, enrichment by 10-100 faint SNe is required.

I also find that the fragmentation of the enriched cloud occurs for 13 M$_\odot$ even with the smallest carbon abundance (A(C) = 3.80) while fragmentation does not occur for 50 and 80 M$_\odot$ (Fig. 3). For all progenitor models, gas cooling from mainly carbonaceous grains is dominant at densities ~10^{12} cm^{-3}. For 50 and 80 M$_\odot$, gas heating along with molecular hydrogen formation stabilizes the clouds at ~10^8 cm^{-3}. This occurs because the temperature is smaller (~70 K) just before H_2 formation heating occurs than for 13 M$_\odot$ (~700 K). Since carbon and oxygen abundances are larger, OH/H_2O cooling is more efficient at densities ~10^4-10^7 cm^{-3} (Fig. 4). Whether fragmentation occurs depends on the multiple cooling/heating processes, not only dust cooling but also H_2 formation heating and metal molecular cooling. I can follow the entire thermal processes and fragmentation property of the clouds with our detailed chemistry/cooling models. Although I do not follow the accretion process of the protostellar system (see Section 2.1), the mass of the most massive protostar is 0.04 $M_{\odot}$ for 13 $M_{\odot}$. This result suggests that low-mass stars would form even with an extremely small carbon abundance (A(C) ~ 4). So far, CEMP stars with A(C) < 6 have not been observed, but these stars might be found with future observations such as Subaru/PFS (Takada et al. 2014) and TMT (Skidmore et al. 2015).

I present this result in domestic and international conferences [5, 8] and published a paper [3].

2.3 Effects of the structure of SN ejecta on the abundances of EMP stars

The mass of Pop III stars is traced back from the abundances of EMP stars. This reverse engineering often assumes that the ejecta of Pop III SNe are uniformly mixed and the averaged abundances of the ejecta are compared with the stellar abundances. However, stellar cores should be stratified at the beginning of SN explosions. If the ejecta maintains its stratified structure, it may affect the elemental abundances of enriched clouds (Ritter et al. 2015; Sluder et al. 2016). I perform numerical simulations of metal enrichment from Pop III SNe with stratified ejecta structure. From a cosmological simulation, I pick up a MH with a mass 3×10^5 $M_{\odot}$ at redshift 28.5. In the center of the MH, I inject SN explosion energy and metals. I remap the radial distribution of heavy elements (B-Ge) calculated with stellar evolution and SN nucleosynthesis models (Tominaga et al. 2014) to compare with the elemental abundances of cloud enriched by uniform SN ejecta. With a fixed progenitor mass 25 $M_{\odot}$, I run a series of simulations with four different explosion energies, E_{SN} = 0.7, 1, 5, and 10 B (1B = 10^{51} erg).

For all progenitor models, metals return to the Pop III hosting MH. A cloud enriched by the SN collapses again, which means that internal enrichment (IE) occurs. I find that the difference of the elemental abundance ratios between stratified and uniform ejecta is only within Δ[M/Fe] ± 0.4 dex for any elements M for all progenitor models (Fig. 5). The difference of the lighter element to heavier element abundance ratio is Δ[C/Fe] = 0.36, 0.33, −0.33, and −0.09 for E_{SN} = 0.7, 1, 5, and 10 B, respectively. This result suggests the negligible effect of the stratified structure of SN ejecta on the elemental abundances of EMP stars. For the highest E_{SN} model (10 B), metals reach the neighboring halos at distance ~400 pc from the central MH. Initially, only the surfaces of the halos are enriched, and then the metals penetrate into the cloud center through halo merger, i.e., external enrichment (EE) occurs. Since only the outer layers of ejecta containing lighter elements than Ca reache the halos, the enriched cloud have C-enhanced abundance feature ([C/Fe] = 1.49). This suggests that CEMP stars can form from the normal CCSN with an average abundance ratio [C/Fe] = −0.65, and EE is the new formation path of CEMP star formation.

I present this result in domestic and international conferences [7] and published a paper [4].

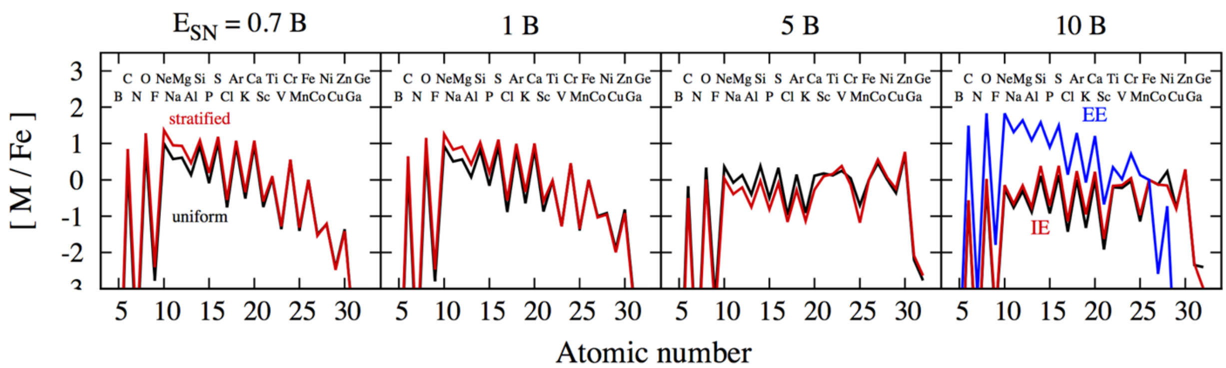

Fig. 5 Elemental abundances of collapsing clouds internally enriched by SNe with explosion energies 0.7 B, 1 B, 5 B, and 10 B from left to right for a stratified (red) and uniform (black) ejecta. The blue curve shows the results for externally enriched clouds for 10 B.