論文の内容の要旨

論文題目
Chemo-thermal evolution of collapsing gas clouds and the formation of metal-poor stars
（収縮ガス雲の熱化学進化と低金属量星の形成過程）

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It is under the debate how the extremely-metal poor stars (Population II or Pop II star) recently discovered in the Galactic halo can acquire such the small mass that they can survive for the cosmic time. The star SDSS J102915 + 172927 is the most metal-poor ever observed with $Z = 4.5 \times 10^{-5}$ $Z_{\odot}$ (Caffau et al. 2011). Their peculiar abundance pattern supports the idea that they are the very second-generation stars born from the cloud enriched by metal-free massive stars (Pop III stars). The Pop III stars are considered to be predominantly massive (from 20 to even 1000 $M_{\odot}$) as suggested by the metal abundance of the observed Pop II stars (Caffau et al. 2011; Keller et al. 2014; Aoki et al. 2014). Some numerical studies also show that the first stars have large masses (Bromm et al. 1999; Abel et al. 2002; Hirano et al. 2014).

The additional cooling by metal and dust is considered to trigger the gas fragmentation into low-mass clumps during cloud collapse (Bromm et al. 2001). The linear analysis of the bar-mode perturbations on a spherical cloud shows that the cloud elongation is promoted/halted when the gas is cooled/heated (Hanawa & Matsumoto 2000; Lai 2000). When cooling is dominant, the gas is elongated to form a filamentary structure. After the amplitude of perturbations on the filament exceeds the density where the cooling becomes insufficient, the cores are stabilized to collapse spherically separately.

Recent studies reveals that gas cooling by the dust thermal emission can successfully explain the cloud fragmentation into low-mass prestellar core even in an extremely metal-poor environment (Omukai et al. 2005; Safranek-Shrader et al. 2014). This cooling becomes effective only after the thermal coupling between gas and dust becomes efficient at $n_{\rm H} \sim 10^{14}$ cm^{-3}, corresponding to the Jeans mass of ~ 0.1 $M_{\odot}$. Several authors present that the dust cooling is effective even with $> 10^{-5}$ $M_{\odot}$,

However, the critical metallicity is determined with the present-day dust model which would be inconsistent with the dust properties in the early Universe. The dust cooling efficiency might be overestimated. The formation path of early grains is limited to Pop III supernovae (Dwek et al. 2007). The grain destruction by the reverse shocks also suppress the dust-to-metal mass ratio (Bianchi & Schneider 2007; Nozawa et al. 2007). Recent observations reveal that the dust-to-metal ratio is significantly smaller than in the present-day (Zafar et al. 2011).

First, we investigate the effect of the realistic dust models in the early Universe and grain growth. Here, we employ the semi-analytic one-zone model for contracting clouds pre-enriched by Pop III supernovae, focusing on their thermal properties. In this model, the density increases at the rate of $\sim t_{\rm ff}$, where $t_{\rm ff}$ is the free-fall time. We solve the chemical reactions to derive the cooling/heating rates which depends on the density, temperature, and chemical compositions in a time-dependent manner. As the metal and dust properties, we utilize the Pop III dust models presented by Schneider et al. (2012) and Nozawa et al. (2007). The metal content is obtained from the nucleosynthetic model of progenitor stars and their supernova explosion. The dust properties are then calculated with the hydrodynamic evolution of expanding ejecta, which is the formation site of grains. We consider a wide range of progenitor mass $M_{\rm pr}$ = 13–30 $\rm M_{\odot}$ of core-collapse supernovae (CCSNe) and 170–200 $\rm M_{\odot}$ for pair-instability supernovae (PISNe). Finally, the dust destruction by reverse shocks propagating inward is treated. The destruction efficiency is determined by the ambient gas density $n_{\rm amb}$ around the supernovae. Our model covers a range of $n_{\rm amb}$ = 0.1–10 $\rm cm^{-3}$. We utilize the Pop III model as the initial condition of the succeeding one-zone collapse calculations. Since here assume that a cloud is polluted by a progenitor, the model parameters are $M_{\rm pr}$ and $n_{\rm amb}$. We perform one-zone calculations with various metallicities to define the critical metallicity $Z_{\rm cr}$ above which dust cooling becomes effective in each Pop III model.

In some cases, grain growth occurs efficiently before the gas becomes optically thick. The dust cooling efficiency is enhanced, and consequently $Z_{\rm cr}$ becomes smaller, i.e., the smaller metal (dust) is enough to induce fragmentation than in the case without grain growth. This can be seen especially in the model with small fractions $f_{\rm dep,0}$ of metal depleted onto grains initially. It tends to mitigate the effect of initial depletion factor $f_{\rm dep,0}$ compared with the case without grain growth. Also, as we have expected, $Z_{\rm cr}$ is dependent on the Pop III models. We find that $Z_{\rm cr}$ is almost linearly related to $f_{\rm dep,0}$, one of the quantities which characterizes the dust property of each Pop III model. While $Z_{\rm cr}$ depends on $f_{\rm dep}$ reciprocally as

$$Z_{\rm cr}^{\rm (ng)} = 2.3 \times 10^{-8} f_{\rm dep,0}^{-1} \tag{1}$$

without grain growth, the dependency is mitigated into

$$\left(\frac{Z_{\rm cr}^{\rm (gg)}}{10^{-5.5}\ \rm Z_{\odot}} \right) = \left(\frac{f_{\rm dep,0}}{0.18} \right)^{-0.44} . \tag{2}$$

We can conclude that the grain growth is necessary process to determine the fragmentation condition for low-mass star formation. We also should note that the critical metallicity has the slight dependency on the Pop III model (spectral index of −0.44). This indicates that the critical condition can slightly vary for different clumps.

Dust thermal emission, even enhanced by the metal accretion phenomenon, is expected to enhance the cloud elongation and fragmentation. To confirm this explicitly, we perform three-dimensional hydrodynamic simulations. Before that, we elaborate the numerical technique used in collapse simulations. The cloud collapse is a phenomenon with a large dynamic range of the density over 20 orders of magnitude. Further, the mass (length) resolution should be sufficiently smaller than the local Jeans mass (length) to avoid the spurious fragmentation due to the numerical noise (Jeans criterion; Truelove et al. 1997). The strategy of particle splitting is frequently used: a coarse (parent) particle about to violate the Jeans criterion is replaced with the set of finer (daughter) particles. On the contrary to the adaptive mesh refinement (AMR) technique in a grid code, the distributions of daughter particles are not trivial in a Lagrangian smoothed particle hydrodynamics (SPH) code, which we in this theses utilize. The previous studies have developed simple and less-costly methods. Kitsionas & Whitworth (2002) distribute the daughters uniformly on a sphere centered at their parent. Martel et al. (2006) put them on edges of a cube. With these symmetric distribution of daughters, one might fail to capture the highly anisotropic shape of clouds such as a thin filament formed by dust cooling.

We develop the method such that the daughters are distributed uniformly within the Voronoi cell tessellated by their parents. The Voronoi cells flexibly capture the distribution of the particles. The several test simulations show that the resulting cloud shape for the run with our splitting method (hereafter, VORO) is consistent with that without the particle splitting. We perform the simulation for the primordial gas cloud cut out from a cosmological simulation. As a result, the structures of spiral arms and spheroidal core are more clearly captured in the run VORO than in the other cases. With the other methods, one or both of the aspherical structures cannot reproduced. The structures become somewhat blurred, and approach to spherical shapes. This would affect also the fragmentation condition of early clouds.

We finally perform three-dimensional simulations for low-metallicity clouds. We for the first time consider the relevant processes as grain growth as well as non-equilibrium chemical reactions, radiative cooling including metal molecular cooling, chemical heating owing to hydrogen molecular formation in our code. As Hirano et al. (2014) recently report, the thermal evolution of clouds and resulting stellar mass vary from cloud to cloud even with the fixed metallicity ($Z = 0$ in their case). In this thesis, the thermal evolution of four gas clouds is followed. One of the clouds initially has the uniform density of $n_{\rm H,ini} = 0.1\ \rm cm^{-3}$, rotation (the energy ratio of rotation to gravity 10^{-3}), and random density perturbation of 10% (called "UNI"). The other three are selected from the Pop III star-forming clouds formed in a cosmological simulation so that they cover the different type of the clouds ("MH1", "MH2", and "MH3"). We uniformly put a trace of metal and dust with metallicites 10^{-6}–10^{-3} $\rm cm^{-3}$. The metal abundance and dust properties are calculated from the Pop III model. We pick up the model with $M_{\rm pr} = 30\ \rm M_{\odot}$ and $n_{\rm amb} = 1\ \rm cm^{-3}$ as a characteristic parameters. During the cloud collapse, we follow the cloud evolution from extremely low density ($\lesssim 0.1\ \rm cm^{-3}$) to the density of the protostar $\gtrsim 10^{16}\ \rm cm^{-3}$, utilizing our Voronoi particle splitting method.

Consequently, we find that the cloud shape and fragmentation property diverges even with a given metallicity. On the contrary to the accepted knowledge that the cloud fragments when the dust cooling is effective with metallicities $\gtrsim 10^{-5}\ \rm Z_{\odot}$, only one of four clouds undergoes fragmentation even though the dust cooling is effective for almost all clouds. Figure 1 shows the result with $10^{-4}\ \rm Z_{\odot}$. Gas elongation and fragmentation are seen only for MH1 cloud. The diversity of the cloud fragmentation properties stems from the variety of the thermal evolution.

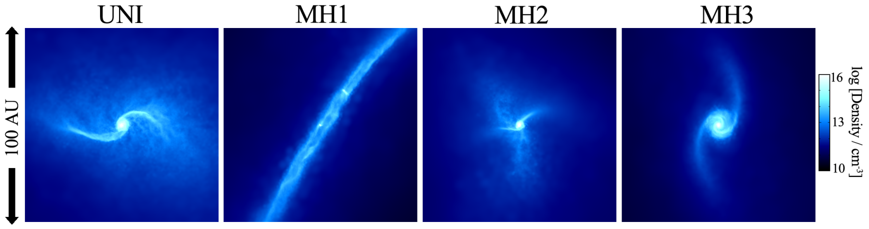

Figure 1: Density projection map of the central 100 AU region with 10^{-4} $Z_\odot$ for the clouds UNI, MH1, MH2, and MH3 from left to right.

The variation is driven by the collapse timescale $t_{\rm col}$ which varies from cloud to cloud. In a slowly collapsing cloud, the gas compressional heating rate becomes small, and thus the temperature becomes smaller throughout the collapse. The clouds with the different evolutionary paths undergo the regime where different cooling/heating processes are important. We identify the two important processes as well as dust thermal emission as follows:

- **dust cooling**
  Dust thermal emission induces the cloud elongation and fragmentation into low-mass ($\lesssim 0.1$ $M_\odot$) clumps.
- **H_2 formation heating**
  The chemical heating owing to the hydrogen molecular formation via the exothermic reactions stabilizes the gas and prevents the cloud from deforming at the intermediate density $\sim 10^8$ cm^{-3}. Actually, the cloud fragmentation via filamentary structure has a high threshold. This only occurs when the cloud ellipticity $\mathcal{E}$ becomes above the large threshold value 20–30 (called the *critical ellipticity* hereafter). If rapid gas heating leads the cloud to be sufficiently round, the timescale for the ellipticity to grow from such a small value to the critical ellipticity becomes longer than the dynamical time of the cloud. In the most of the cloud, this H_2 formation heating halt the gas elongation as the precursor of the eventual fragmentation due to dust cooling.
- **OH/H_2O cooling**
  In some cases, the clouds fragment into low-mass clumps. We find that the rapid OH or H_2O cooling is effective at $n_{\rm H} \sim 10^6$–10^8 cm^{-3} to compensate the stabilizing effect by chemical heating.

Therefore, the fragmentation condition can be written as

Fragmentation condition

(i) dust cooling is efficient to induce the cloud elongation with the ellipticity up to $\mathcal{E}_* = 20$ for clouds to fragment into low-mass clumps, and

(ii-a) H_2 formation heating is not effective to dump the bar-mode perturbation as a precursor of the further cloud elongation by dust cooling, or

(ii-b) OH cooling is efficient to enhance the cloud elongation even though H_2 formation heating is effective.

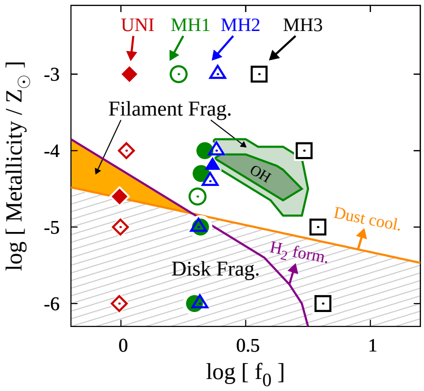

Figure 2: Regions favorable for fragmentation (orange- and green- shaded regions) and the results of our simulations. Open and close symbols indicate the models that end with and without fragments, respectively. Above orange and purple lines, dust cooling and H_2 formation heating are effective, respectively. OH or H_2O cooling is effective in the region surrounded by the green solid lines.

We define the parameter region of Z and $t_{\rm col}$ where the above criteria are satisfied. Since the collapse time varies in the corse of time according to the gas cooling/heating efficiencies, we here introduce the parameter f_0 to characterize the collapse timescale of an individual cloud. The parameter is defined as the excess of $t_{\rm col}$ relative to the self-similar solution for a cloud without rotation or dark matter halo. With the one-zone calculations, we define the parameter region as shown in Figure 2. The cloud fragmentation is favored in the shaded region. This qualitatively reproduce the results of our three-dimensional simulations (symbols) with 10^{-5}–10^{-4} $Z_\odot$.