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Physical processes for the origin of globular clusters with multiple stellar populations

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Abstract. We numerically investigate the formation processes of globular clusters (GCs) in gas-rich dwarf galaxies at high redshifts. Our particular focus is on how the first and second generations of stars can be formed from high-density gas clouds in dwarf galaxies. We find that massive stellar clumps first form from massive gas clumps that are developed from local gravitational instability in gas-rich dwarfs. These stellar clumps with masses larger than $\sim 2 \times 10^6 \mathrm{M}_{\odot}$ can finally become the first generation of stars in GCs. After supernova explosion expels the remaining gas in the clumps, stars can form from eject of AGB stars that is accreted onto the central regions of the clumps (i.e., first generation of stars). The compact clusters of these stars have much higher densities and a significant amount of internal rotation (~ 5 km s^{-1}) in comparison with the first generation and thus correspond to the second generation.

Keywords. stars: formation, globular clusters: general

1. Formation processes of originally massive GCs

A growing number of recent observational and theoretical studies on GCs with multiple stellar populations have shown that (i) most of the Galactic GCs investigated so far have characteristic anti-correlations between light elements, (ii) original GCs should be at least ~ 10 times more massive than the present ones, and (iii) physical properties of the first and second generations of stars in GCs can be significantly different (Bekki & Norris 2006, D'Ercole *et al.* 2008, Bekki 2010, Carretta *et al.* 2010, Bekki 2011, Bellazzini *et al.* 2012). Numerical simulations have shown that the second generation of stars can be formed from gas ejected from AGB stars in the first generation, if the first generation of stellar systems are as massive as $10^6 - 10^7 \mathrm{M}_{\odot}$. Furthermore, radial distributions and rotational properties are demonstrated to be significantly different between the first and second generations of stars in simulated GCs. However, it remains unclear how the first generation stellar systems of GCs can be formed owing to the lack of extensive numerical studies of GC formation.

We thus construct a new model by which we can investigate both the formation process of the first generation of stars and that of the second in a fully self-consistent manner. We consider that GCs can be formed in the very early evolution of gas-rich dwarf galaxies, which could be fundamental building blocks of luminous galaxies like the Galaxy. We use our original hydrodynamical/Nbody numerical simulations with models for star formation and chemical evolution in order to investigate the formation processes and physical properties of massive stellar objects with masses larger than $2 \times 10^6 \mathrm{M}_{\odot}$ that can correspond to masses of the first generation stellar systems. The simulations include the gas ejection processes of AGB stars and thus enable us to investigate how the second generation of stars can be formed from the AGB ejecta of the massive first generation. The total masses of baryonic and dark matter components in the initial dwarf galaxies

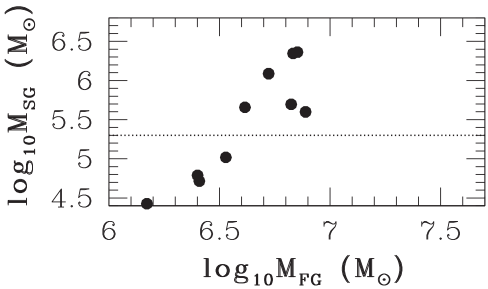

Figure 1. The dependence of the total masses of the second generations ($M_{\rm SG}$) on those of the first ($M_{\rm FG}$) in the simulated GCs of a gas-rich dwarf galaxy.The dotted line indicates the typical present GC mass ($2 \times 10^5 {\rm M}_\odot$) in the Galaxy.

are set to be $2.5 \times 10^9 {\rm M}_\odot$ and $2.5 \times 10^{10} {\rm M}_\odot$, respectively. The details of the models will be described in our forthcoming papers.

2. Two-fold GC formation process

Fig. 1 shows the total masses of the first ($M_{\rm FG}$) and second ($M_{\rm SG}$) generations of stars in the selected GC candidate. We find the following principle results on physical properties of these GCs. Firstly, the formation of massive FG with $M_{\rm FG} \geqslant 2 \times 10^6 {\rm M}_\odot$ is due to the local gravitational instability in their host dwarfs. Secondly, the AGB ejecta from FG can not be escaped from the original FG stellar systems so that it can be accumulated in the central regions and consequently converted into new stars there, which correspond to SG. Thirdly, not all of massive FG systems have $M_{\rm SG} \geqslant 2 \times 10^5 {\rm M}_\odot$, which means that only some of them can finally become the present GCs as massive as $\sim 2 \times 10^5 {\rm M}_\odot$ because most of FG stars can be lost during the long-term evolution of FG. Fourthly, SG stars clearly show rotational kinematics with the rotational amplitudes of ~ 5 km s^{-1}, which reflects the fact that SG is formed in the central regions of FG stellar systems through dissipative processes of gaseous ejecta from AGB stars. Fifthly, radial gradients of He can be clearly seen in the simulated GCs, in particular, in massive GCs ($\sim 10^7 {\rm M}_\odot$). Sixthly, formation of GCs with both FG and SG is possible only for dwarfs with higher gas mass fractions (> 0.5) and masses larger than $\sim 5 \times 10^9 {\rm M}_\odot$ (including dark halo masses). Seventhly, GC formation processes can proceed more efficiently in high-surface brightness dwarfs in comparison with low-surface brightness ones. Observational implications of these results will be discussed in our forthcoming papers.

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