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Formation of the Galactic globular clusters with He-rich stars in low-mass halos virialized at high redshift

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ABSTRACT

Recent observations have reported that the Galactic globular clusters (GCs) with unusually extended horizontal-branch (EHB) morphologies show a significantly lower velocity dispersion compared with that of the entire Galactic GC system. We consider that the observed distinctive kinematics of GCs with EHB has valuable information on the formation epochs of GCs and accordingly discuss this observational result based on cosmological N-body simulations with a model of GC formation. We assume that GCs in galaxies were initially formed in low-mass halos at high redshifts and we investigate final kinematics of GCs in their host halos at $z = 0$. We find that GCs formed in halos virialized at $z > 10$ show lower velocity dispersions on average than those formed at $z > 6$ for halos with GCs at $z = 0$. We thus suggest that the origin of the observed lower velocity dispersion for the Galactic GCs with EHBs is closely associated with earlier formation epochs ($z > 10$) of halos initially hosting the GCs in the course of the Galaxy formation. Considering that the origin of EHBs can be due to the presence of helium-enhanced second-generation stars in GCs, we discuss the longstanding second parameter problem of GCs in the context of different degrees of chemical pollution in GC-forming gas clouds within low-mass halos virialized at different redshifts.

Key words: globular clusters: general – galaxies: star clusters – galaxies: evolution – galaxies: stellar content

1 INTRODUCTION

A growing number of observational studies have recently reported that some Galactic GCs (e.g., ω Cen and NGC 2808) show a possible He abundance spread in their stellar populations (e.g., Bedin et al. 2004; D’Antona et al. 2005; Lee et al. 2007, L07; Piotto et al. 2007). L07 furthermore have reported that about 25% of Galactic GCs show very extended horizontal-branch (HB) morphologies that can be due to He-rich stars in these GCs. One intriguing observation of the Galactic GCs with extended HB morphologies (EHB) is that they show a significantly lower velocity dispersion ($93 \pm 13 \text{ km s}^{-1}$) in comparison with the rest of the halo GC system ($137 \pm 14 \text{ km s}^{-1}$, L07). Although this observation can shed new light on the Galaxy formation through hierarchical merging of low-mass building blocks (L07), the origin of the unique kinematics of the Galactic GCs with possible He-rich stars remains unclear.

Although previous one-zone chemical evolution models have discussed the observed possible star-to-star variation in He abundance in Galactic GCs (e.g., D’Antona et al. 2002; Bekki et al. 2007a), they have not discussed the origin of the observed kinematics of the GCs with EHB. Recent numerical simulations of GC formation during hierarchical galaxy formation based on a ΛCDM model have greatly improved the predictability of dynamical and chemical properties of GC systems in galaxies (Kravtsov & Gnedin 2005; Yahagi & Bekki 2005; Bekki et al. 2007b). However they have not yet discussed the origin of the observed lower velocity dispersion of Galactic GCs with EHB (hereafter these GCs are referred to as EHB GCs for convenience).

The purpose of this paper is to demonstrate, for the first time, that the observed kinematics of EHB GCs is consistent with a scenario in which they were formed in low-mass halos virialized before $z > 10$. We consider that (i) the present-day metal-poor GCs of galaxies were formed initially in low-mass...
halos virialized at \( z > 6 \) before the completion of reionization (Fan et al. 2003) and (ii) GCs were then tidally stripped from their host halos during hierarchical merging to become halo GCs in the final galaxy. The above (i) is consistent with recent hydrodynamical simulations of GC formation in low-mass halos by Bromm & Clarke (2002). Based on high-resolution cosmological N-body simulations with a model of GC formation, we investigate the kinematics of GC subpopulations originating from low-mass halos virialized at different redshifts \( (z) \). We show that the kinematical properties of GC subpopulations initially in low-mass halos virialized well before \( z > 10 \) show significantly lower velocity dispersions in comparison with GCs formed at \( z > 6 \). We discuss this result in terms of the origin of EHB GCs in the Galaxy.

## 2 THE MODEL

Since the present model of GC formation in hierarchical galaxy formation is essentially the same as those adopted in our previous works (Yahagi & Bekki 2005; Bekki et al. 2006; Bekki et al. 2007b), we briefly explain the model here. We simulate the large scale structure of GCs in a ΛCDM Universe with \( \Omega = 0.3, \Lambda = 0.7, H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \) and \( \sigma_8 = 0.9 \) by using the Adaptive Mesh Refinement N-body code developed by Yahagi (2005) and Yahagi et al. (2004), which is a vectorized and parallelized version of the code described in Yahagi & Yoshii (2001). We use 512\(^3\) collisionless dark matter (DM) particles in a simulation with the box size of 70h\(^{-1}\)Mpc and the total mass of 4.08 \times 10^{16} M_\odot. We start simulations at \( z = 41 \) and follow it till \( z = 0 \) in order to investigate physical properties of old GCs within virialized dark matter halos at \( z = 0 \). We used the COSMICS (Cosmological Initial Conditions and Microwave Anisotropy Codes), which is a package of fortran programs for generating Gaussian random initial conditions for nonlinear structure formation simulations (Bertschinger 1995, 2001).

Our method of investigating GC properties is described as follows. Firstly we select virialized dark matter subhalos at each output by using the friends-of-friends (FoF) algorithm (Davis et al. 1985) with a fixed linking length of 0.2 times the mean DM particle separation. The minimum particle number \( N_{\text{min}} \) for halos is set to be 10. For each individual virialized subhalo, the central particle is labeled as a “GC” particle. This procedure for defining GC particles is based on the assumption that energy dissipation via radiative cooling allows baryon to fall into the deepest potential well of dark-matter halos and finally to be converted into GCs. We assume that GC formation is truncated for halos virialized after \( z = z_i \) and that \( z_i = 6 \) corresponds to the epoch of the completion of reionization (e.g., Fan et al. 2003). Secondly, we follow the dynamical evolution of GC particles till \( z = 0 \) and thereby derive locations \((x, y, z)\) and velocities \((v_x, v_y, v_z)\) of GCs at \( z = 0 \). We then identify virialized halos at \( z = 0 \) with the FoF algorithm and investigate whether each GC is within a halo.

We investigate velocity dispersions \( (\sigma_{v_{<z}}) \) of GC subpopulations originating from halos virialized at redshifts \( z_v < z \) in halos at \( z = 0 \). The most important key parameter in the present study is the virialization redshift \( z_v \), and accordingly we investigate the kinematics of GC subpopulations with \( 6 \leq z_v \leq 15 \) for \( z_i = 6 \) in the GC system (GCS) in each of the simulated halos at \( z = 0 \). We particularly investigate the ratio of \( \sigma_{v_{<z}} \) of GC subpopulations to the entire GCS in each halo at \( z = 0 \), denoted as \( \sigma_{\text{all}} \). These velocity dispersion ratios are referred simply to as \( R_v \) from now on. To avoid a large error bar of \( R_v = (\sigma_{v_{<z}}/\sigma_{\text{all}}) \) for each individual halo at \( z = 0 \) resulting from the small GC number, we pick up haloes in which both the numbers of GCs originating from halos with \( z_v < z \) and \( z_v < z \leq z_v \) exceed a threshold number of \( n_{\text{th}} \). When the total number of GCs in the \( i \)-th halo is \( n_{\text{gc},i} \), this criterion corresponds to \( n_{\text{gc},i} > 2n_{\text{th}} \). We generally show the results for the models with \( n_{\text{th}} = 3 \) in which \( n_{\text{gc},i} \) in each halo is larger than \( 6 \) \((=2n_{\text{th}})\).

In order to discuss the dependences of the present results on \( n_{\text{th}} \), we also show the results of the models with \( n_{\text{th}} = 24 \). Although an error bar in \( R_v \) for each individual halo becomes significantly small in the models with \( n_{\text{th}} = 24 \), the total number of halos with \( n_{\text{th}} \geq 24 \) becomes very small.

L07 reported that the Galactic GCs with EHB has a velocity dispersion of \( 93 \pm 13 \text{ km s}^{-1} \) \((=\sigma_{\text{EHB}})\) whereas the entire GCs of the Galaxy has a dispersion of \( 124 \pm 10 \text{ km s}^{-1} \) \((=\sigma_{\text{all}})\). We compare the observed ratio \( (R_v) \) of \( \sigma_{\text{EHB}} \) to \( \sigma_{\text{all}} \) (shown in Table 1 of L07) for the Galactic GCs with our simulated one in order to determine the best value of \( z_v \) for which the observed \( R_v \) can be well reproduced. Since the observed \( \sigma_{\text{all}} \) is derived for all GCs including relatively young halo GCs (L07), \( z_i = 6 \) is regarded as a reasonable truncation epoch in deriving \( \sigma_{\text{all}} \) for the present study.

The Galactic GCs around the Galactic bulge (“bulge GCs” or “disk GCs”) could have been formed as a result of dissipative and (star-forming) major merging possibly responsible for the bulge formation at a lower redshift. The present model does not include the formation of these younger, metal-rich GCs, and accordingly \( \sigma_{\text{all}} \) is estimated only for GCs originating from halos virialized before \( z=6 \). Thus it should be stressed that the derived \( \sigma_{\text{all}} \) in the present model does not literally mean the velocity dispersion of all GCs in a galaxy. However we think that it is still reasonable to compare the derived \( \sigma_{\text{all}} \) in the simulations with the observed \( \sigma_{\text{all}} \) (based on all GCs with known HB morphologies), because the observed small number fractions of bulge/disk GCs in disk galaxies (e.g., Zinn 1985 for the Galaxy) mean that there could be only a small difference in velocity dispersions between a GCS including bulge/disk GCs and the GCS not including them for a galaxy.

## 3 RESULTS

Fig. 1 shows how \( R_v \) for GC subpopulations with \( z_v = 7, 10, \) and 13 depend on \( M_h \) in the model with \( n_{\text{th}} = 3 \) corresponding to \( n_{\text{gc},i} > 6 \). Fig. 1 demonstrates that GC subpopulations with higher \( z_v \) are more likely to show a lower \( R_v \) for a given \( M_h \), though the dispersion in \( R_v \) for a given \( M_h \) is larger for low-mass halos. This result suggests that \( R_v \) of a GC subpopulation in a galaxy can provide some information about the redshifts of virialization for low-mass halos that initially hosted the subpopulation. Fig. 1 also shows that more massive halos are more likely to show a higher \( R_v \) value for a given \( z_v \), which means that differences in velocity dispersions between GC subpopulations originating from high-\( z \) halos with different redshifts of virialization are less remarkable in more massive galaxies.
Figure 1. Velocity dispersion ratios ($R_s = \sigma_{z,v<z}/\sigma_{all}$) as a function of their host halo masses ($M_h$) for GC subpopulations with the virialization redshifts $z_v = 13$ (top), 10 (middle), and 7 (bottom). Here the ratios are derived for the $x$-components of velocity dispersion ($\sigma_x$) in halos at $z = 0$. Each small dot represents a halo with a GCS with $n_{gc,i} > 6$. Blue, filled circles represent the mean values of the ratios in five halo mass bins and the error bars are due to the number of halos ($N_h$) in each halo mass bin (i.e., $\propto 1/\sqrt{2(N_h-1)}$). For the lowest mass bin with no GCs for $z_v = 13$, $\sigma_{z,v<z}/\sigma_{all}$ is shown. For comparison, the observed ratio ($R_o$) of $\sigma_{EBHB}/\sigma_{all}$ (L07) is shown by a red, open circle for the mass model of the Galaxy (Wilkinson & Evans 1999). Note that GC subpopulations with $z_v = 10$ and $M_h \approx 10^{12}M_\odot$ show low $\sigma_{z,v<z}/\sigma_{all}$ which is best agreement to the observed one in L07.

Furthermore, Fig. 1 shows that GC subpopulations with $z_v = 10$ in galaxy-scale halos with $M_h \approx 10^{12}M_\odot$ (corresponding roughly to the total mass of the Galaxy, e.g., Wilkinson & Evans 1999) have $R_o$ very similar to the observed velocity dispersion ratio ($R_o$): The $R_o$ of GC subpopulations with $z_v = 7$ are too high to be consistent with $R_o$, whereas those of GC subpopulations with $z_v = 13$ are marginally consistent with $R_o$. These results suggest that EHB GCs in the Galaxy were initially within low-mass halos virialized at $z > 10$ and later tidally stripped during the

Figure 2. The same as Figure 1 but for $\sigma_x$ (top), $\sigma_y$ (middle), and $\sigma_z$ (bottom) of GC subpopulations with $z_v = 10$.

Figure 3. The same as Figure 1 but for GC subpopulations with $z_v = 10$ in the model with $n_{gc,i} > 24$. 
The hierarchical merging of halos to finally become the halo GCs in the Galaxy. The origin of the lower $R_h$ in GC subpopulations with $z_v = 10$ may well be closely associated with characteristic orbital properties (e.g., more eccentric orbits and smaller pericenter distances with respect to their halos’ centers).

Fig. 2 shows that lower $R_h$ values for GC subpopulations with $z_v = 10$ can be clearly seen in the three velocity components (i.e., $\sigma_x$, $\sigma_y$, and $\sigma_z$) in galaxy-scale halos with $M_h \approx 10^{12} M_\odot$, which confirms that lower $R_h$ values can be one of the kinematical properties characteristic of GC subpopulations with $z_v = 10$ in galaxy-scale halos. Fig. 2 also shows that the trend of GC subpopulations in more massive halos ($10^{13} M_\odot \leq M_h$) to have higher $R_h$ values can be clearly seen for the three velocity components. This result implies that differences of line-of-sight velocity dispersions in GC subpopulations (e.g., intra-group and intra-cluster GCs) originating from halos virialized at different redshifts are observationally difficult to detect for group-scale and cluster-scale halos.

Fig. 3 shows $R_h$ of halos in the model with $n_{th} = 12$ corresponding to $n_{gc, i} > 24$ in which only halos with significantly larger numbers of GCs with $z_v = 10$ are selected. Lower $R_h$ values in halos with $M_h \approx 10^{12} M_\odot$ can be clearly seen even in this strongly biased sample of halos at $z = 0$, though the scatter in $R_h$ become small thanks to a larger number of GCs used in deriving $R_h$. This result demonstrates that the derived lower $R_h$ values in galaxy-scale halos are not due to the parameter $n_{th}$ introduced for minimizing scatters in $R_h$ for individual halos in the present study.

4 DISCUSSION AND CONCLUSIONS

4.1 Origin of GCs with He-rich stars

Recent observations have revealed that the (line-of-sight) velocity dispersions of “ultra-compact dwarf” (UCD) galaxies are significantly smaller than those of other galaxy populations in the Fornax and the Virgo clusters of galaxies (Mieske et al. 2004; Jones et al. 2006; Gregg et al. 2007). Bekki (2007) first demonstrated that the observed lower velocity dispersion of the UCD population in the Fornax cluster is consistent with the UCDs having significantly smaller pericenter distances (with respect to the center of the Fornax) than other galaxy populations in the cluster. This result suggests that the simulated lower velocity dispersions of GCs with $z_v > 10$ in halos at $z = 0$ are due to significantly smaller pericenter distances of the GCs (with respect to the halos’ centers) in the present study. It furthermore implies that EHB GCs in the Galaxy can have smaller pericenter distances with respect to the Galactic center.

The present study has first shown that EHB GCs originate preferentially from low-mass halos that were virialized at higher redshifts ($z > 10$). Given the fact that the origin of EHB can be closely associated with the presence of He-rich second generation stars in GCs (e.g., D’Antona et al. 2002; L07; but see Choi & Yi 2007 for a different formation mechanism of He-rich stars), the above result implies that the formation of He-rich stars is much more likely to happen in GC-forming gas clouds of halos with possibly higher gas densities (due to higher $z_v$). Gas ejected from the first generation of stars of a GC can be efficiently trapped in the central regions of halos during the GC formation owing to the deep gravitational potential of the halos so that the gas can be used for the formation of the second generation with a higher helium abundance for the GC (Bekki 2006): there are two generations of stars with different helium abundances in a GC. Formation of He-rich second-generation stars therefore can proceed more efficiently in the central regions of halos with higher $z_v$ and thus deeper gravitational potentials (for a given halo mass). Therefore, formation of He-rich stars is highly likely to occur in GC-forming gas clouds located in the central regions of halos with higher $z_v$.

Although both observational and theoretical studies have discussed the origin of the second parameter(s) that can control the morphologies of HBs in GCs, it is not yet clear what the second parameter(s) is (are) in these studies (e.g., Catelan et al. 2001 and references therein). Recently, Recio-Blanco et al. (2006, R06) have discovered that HB morphologies depend on the total masses of GCs in the sense that more massive GCs tend to have more extended HBs: the masses of GCs can be one of the second parameters. They have accordingly suggested that higher fractions of He-rich stars in more massive GCs can cause EHB in the GCs and that the origin of the higher fractions can result from more efficient “self-pollution” by stars formed earlier in more massive gas clouds.

If the number fraction of He-rich stars in GCs is one of the second parameters, as suggested by R06, then the present numerical study suggests that the differences in HB morphologies in GCs are due partly to the differences in formation epochs (i.e., the redshifts of viralization) of low-mass halos initially hosting GCs. The present study furthermore suggests that if more massive GCs with He-rich stars are more likely to be formed in halos virialized at higher redshifts, then the observational results by R06 (i.e., the presence of EHB in massive GCs) and by L07 (i.e., kinematic decoupling of EHB GCs) can be self-consistently explained.

Owing to the lack of extensive theoretical studies on GC formation processes in halos with different viralization redshifts, it is however unclear whether more massive GCs can be formed in halos virialized at higher redshifts.

It remains unclear whether AGB stars (e.g., D’Antona et al. 2002; Karakas et al. 2006; Bekki et al. 2007) or massive stars (e.g., Charbonnel & Frantzos 2006; Bekki & Chiba 2007) are responsible for the origin of He-rich stars in GCs. Micocchi (2007) has recently discovered an intriguing correlation between the possible presence of intermediate-mass black holes (IMBHs) and the presence of EHB in GCs. Given the fact that recent numerical simulations (e.g., Portegies Zwart et al. 2004) have demonstrated the formation of IMBHs through runaway collisions of massive stars, the above result by Micocchi (2007) implies that massive stars rather than AGB stars could have played a major role in the formation of He-rich stars within forming GCs.

4.2 Chemo-kinematics of GC subpopulations and galaxy formation

Although previous theoretical and observational studies have focused mostly on differences in kinematical properties between metal-poor and metal-rich GCs in galaxies (e.g., Bekki et al. 2005; Brodie & Strader 2006), they have not so far investigated the kinematical differences between GCs
with different masses, abundances of He and light elements (e.g., C, N, and O), and α-abundance ratios (e.g., [Mg/Fe]). The discovery of the chemokinematical correlation in the Galactic GCs by L07, combined with the present numerical results (i.e., lower velocity dispersions of GC subpopulations originating from halos virialized at higher redshifts), provide the following three implications. Firstly, there could be kinematical differences in GCs with He-rich stars compared to those without in many galaxies. Recently, Kaviraj et al. (2007) have investigated the ultraviolet and optical properties of 38 GCs in M87 and suggested the possible presence of He-rich stars in the GCs. It is thus an interesting observational question whether the 38 GCs in M87 show a lower velocity dispersion in comparison with the entire GC population in M87.

Secondly, velocity dispersions of GC subpopulations with very high \([\alpha/Fe]\) (e.g., [Mg/Fe]) can be lower. This is mainly because star formation time scales, which determine \([\alpha/Fe]\) of stellar populations (e.g., Matteucci & François 1992; see also Nagashima et al. 2005), is shorter in halos that were formed at higher redshifts and thus have higher densities in their baryonic components. Thirdly, there can be significant kinematical differences between GC subpopulations with lower masses and those with higher masses in the sense that the latter subpopulations should show lower velocity dispersions. This is because the present simulations suggest that more massive GCs can be formed at halos virialized at higher redshifts.

The observed chemokinematical correlations in the Galactic stellar halo and the physical properties of GCs have long been discussed in the context of the time scale of the Galaxy formation (e.g., Eggen, Lynden-Bell, & Sandage 1962) and the accretion history of dwarfs with GCs (Searle & Zinn 1978). The present study suggests that the observed kinematical correlations of GCs with, and without, EHBs in the Galaxy can be considered in terms of different formation epochs of low-mass halos initially hosting GCs. We thus suggest that HB morphologies of GCs in a galaxy contain valuable information both on the formation epochs of building blocks of the galaxy and on the hierarchical merging histories of that galaxy. We also suggest that one of the second parameters governing the HB morphology is the formation (i.e., virialization) epochs of low-mass dark matter halos that initially hosted GCs at high redshifts. In other words, the environments of GCs are a key ‘second parameter’ as they determine the extent to which GC-forming gas clouds are chemically polluted by earlier generations of stars.

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