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THE GALACTIC GLOBULAR CLUSTER SYSTEM AS A FOSSIL RECORD OF REIONIZATION
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ABSTRACT

We propose that structural, kinematical, and chemical properties of the Galactic globular clusters (GCs) can contain fossil information of the cosmic reionization history. We first summarize the possible observational evidence for the influence of reionization on the Galactic GC formation. We then show how structural properties of the GC system (GCS) in the Galaxy can be influenced by suppression of GC formation due to reionization during the Galaxy formation through hierarchical merging of subgalactic clumps, by using numerical simulations with and without suppression of GC formation by reionization. In particular, we show that if GC formation in dwarf galaxies that are building blocks of the Galaxy and virialized after reionization era ($z_{\text{reion}}$) are completely suppressed, the present-day radial distribution of the Galactic GCs depends strongly on $z_{\text{reion}}$. Our numerical results imply that if GC formation after $z_{\text{reion}} \sim 15$ is strongly suppressed, the origin of the observed structural properties of the Galactic GCs can be more naturally explained in the framework of the hierarchical clustering scenario.

Subject headings: galaxies: star clusters — Galaxy: abundances — Galaxy: evolution — Galaxy: halo — Galaxy: structure — globular clusters: general

Online material: color figure

1.INTRODUCTION

The globular cluster system (GCS) of the Galaxy has long been considered to contain “fossil records” on early dynamical and chemical histories of the Galaxy (e.g., Searle & Zinn 1978; Harris 1991; Mackey & Gilmore 2004). Therefore, physical properties of the globular clusters (GCs), such as the abundance gradient (e.g., Searle & Zinn 1978), radial density profile (e.g., Zinn 1985; van den Bergh 2000), kinematics (Freeman 1993), and proper motion (Dinescu et al. 1999), have been extensively discussed in the context of the Galactic formation history. Although recent numerical simulations of the Galaxy formation based on the cold dark matter (CDM) model have provided a model explaining both dynamical and chemical properties of the Galactic old stellar halo (Bekki & Chiba 2000, 2001), theoretical models trying to explain the observed structural, kinematical, and chemical properties of the Galactic GCS in a self-consistent manner have not yet been provided. This partly because physical conditions required for GC formation in low-mass dwarfs, which can be the building blocks of the Galaxy in the hierarchical clustering scenario, have not yet been completely clarified.

Recently, the effects of reionization on galaxy formation have been extensively discussed, in particular, in the context of star formation histories and old stellar populations in low-mass dwarfs (e.g., Bullock et al. 2000; Gnedin 2000; Susa & Umemura 2004; Grebel & Gallagher 2004; Bekki & Chiba 2005). These theoretical works suggested that suppression of star formation by heating and gas loss resulting from reionization can be a very important physical process for better understanding the observability and the early star formation activities in dwarfs, although Grebel & Gallagher (2004) did not find any clear fossil evidence that supports the occurrence of such suppression at the reionization era ($\sim 12.8$ Gyr) in nearby dwarf spheroidal galaxies. Although it has already been discussed whether reionization can trigger (Cen 2001) or suppress (Santos 2003) the formation of globular clusters, it remains totally unclear how reionization determines the dynamical and chemical properties of the Galactic GCs. Given the fact that data sets with an unprecedented wealth of information on the physical properties of the Galactic GCs are now available (e.g., Harris 1996; Mackey & Gilmore 2004), it is worthwhile to discuss the possible effects of reionization on the GC formation by comparing the observations with theoretical results in order to better understand the origin of the Galactic GCs.

The purpose of this Letter is to demonstrate, for the first time, that the physical properties of the Galactic GCS can be significantly influenced by reionization by comparing observational data of the Galactic GCS with numerical simulations, including possible influences of reionization on GC formation. In particular, we show how the radial profile of the number distribution of the Galactic GCs can be influenced by the suppression of GC formation by reionization by using numerical simulations of the Galaxy formation based on the CDM model. We first summarize three key observational results that can be interpreted as possible evidence of GC formation influenced by reionization in § 2, and we then describe our numerical results in §§ 3 and 4. We suggest several observable GC properties that can be used to discuss the reionization effects on GC formation for disk galaxies in § 5.

2. THREE KEY OBSERVATIONAL RESULTS

The interpretations given below for the observational results are somewhat speculative and are not unique, because there can be several alternative interpretations for each of the results. However, we suggest that the origin of the results can be closely associated with some physical processes (reionization, etc.) influencing the early Galactic GC formation. It should also be stressed that the following observations could be only three among many examples of fossil evidence for the impact of reionization on the Galactic GC formation.

The first observation is the steeper slope in the number density profile of the Galactic GCS for the outer Galactic halo (van den Bergh 2000). In Figure 1, which shows the radial profile of the cumulative number distribution of the GCS [$N_{\text{GC}}(R)$], the GC...
The second observation is the apparently clear bimodality in the metallicity distribution of the Galactic GCs (e.g., Zinn 1985; Navarro et al. 1996). These observational and theoretical results can possibly indicate that GC formation is strongly suppressed in the Galaxy compared with M31 owing to some physical processes. For the suppression of GC formation and thereby investigate how it influences the structural properties of the Galactic GCs.

3. THE NUMERICAL MODEL

We simulate the formation of a Milky Way–sized galaxy halo in a ΛCDM universe with Ω = 0.3, Λ = 0.7, H₀ = 70 km s⁻¹ Mpc⁻¹, and σ₈ = 0.9 and thereby investigate merging/accretion histories of subhalos that can contain low-mass dwarfs with GCs. The way to set up the initial conditions for the numerical simulations is essentially the same as that adopted by Katz & Gunn (1991) and Steinmetz & Müller (1995). We consider an isolated homogeneous, rigidly rotating sphere, on which small-scale fluctuations according to a CDM power spectrum are superposed. The initial total mass, the radius, the spin parameter (λ), and the initial overdensity δ of the sphere in the present model are 6.0 × 10¹¹ M⊙, 30 kpc, 0.08, and 0.26, respectively. Initial conditions similar to those adopted in the present study are demonstrated to be plausible and realistic for the formation of the Galaxy (e.g., Steinmetz & Müller 1995; Bekki & Chiba 2001).

We start the collisionless simulation at z_start (= 30) and follow it till z_end (= 1) to identify virialized subhalos with the densities larger than 170ρₗₚ(z), where ρₗₚ(z) is the critical density, at a given z. The minimum number of particles within a virialized halo (N_min) is set to be 32, corresponding to the mass resolution of 3.8 × 10⁷ M⊙. For each individual virialized subhalo with the virialized redshift of z_vir, we estimate a radius (r_vir) within which 20% of the total mass is included, and then the particles within r_vir are labeled as “baryonic” particles. Twenty percent of the outermost baryonic particles in a subhalo are labeled as “GC particles” so that the total number of GCs in the halo is 1 for the smallest halo with N_min = 32. Thus, the present simulation assumes that GCs can be formed in all low-mass subhalos.

In order to investigate the effects of the suppression of GC formation via reionization on the final structural properties of the simulated GCs, we adopt the following somewhat idealized assumption: If a subhalo is virialized after the completion of the reionization (z_reion), GC formation is totally suppressed in the halo. Therefore, GC particles in the subhalo with z_vir < z_reion are not considered at all in the estimation of the structural properties of the simulated GCs. Recent Wilkinson Microwave Anisotropy Probe observations have shown that plausible z_reion ranges from 11 to 30 (Spergel et al. 2003; Kogut et al. 2003), whereas quasar absorption-line studies can give the lower limit of 6.4 for z_reion (Fan et al. 2003). Guided by these
observations, we investigate the models with \( z_{\text{reion}} = 0 \) (no reionization), 5, 10, and 15.

Thus, the present collisionless simulation follows the dynamical evolution of GCs originating from subhalos and does not include any dissipative formation of GCs associated with starbursts during the merging/accretion of subgalactic halos. Therefore, the simulated GCs can mimic old MPCs rather than MRCs (e.g., “disk GCs” in the Galaxy). All the calculations of the Galaxy formation have been carried out on the GRAPE board (Sugimoto et al. 1990). The total number of particles used in a simulation is 508,686, and the gravitational softening length is 0.38 kpc. We consider that the final structure of the simulated GCS at \( z = 0 \) for the models with \( z_{\text{reion}} = 0 \) (dashed line), 10 (dotted line), and 15 (solid line); \( z_{\text{reion}} = 0 \) means that no suppression of GC formation by reionization is assumed. Note that the simulated profile in the model with higher \( z_{\text{reion}} (=15) \) can be much closer to the observation than those in the models with smaller \( z_{\text{reion}} (=0 \) and 10).

Figure 3 shows the final radial profile of the cumulative number distribution \( N_{\text{GC}}(R) \) of the simulated GCs in the model with \( z_{\text{reion}} = 0, 10, \) and 15. It is clear from this figure that the profiles in the models with reionization are closer to the observed one than the profile in the model without reionization \( (z_{\text{reion}} = 0) \). In particular, the profile in the model with higher \( z_{\text{reion}} (=15) \) can more closely resemble the observed one than the profile in the model with lower \( z_{\text{reion}} (=10) \). These results imply that the formation of the radial distribution of the Galactic GCs could have been influenced by reionization. Later accretion/merging of younger subhalos with GCs can add new GCs to the outer halo of the simulated Galaxy and thus flatten the density profile of the GCs. In the model with \( z_{\text{reion}} = 15 \), accretion/merging of younger subhalos cannot influence the distribution of the GCs, because they do not contain GCs owing to later virialization with \( z_{\text{vir}} < z_{\text{reion}} \) (i.e., suppression of GC formation). This is the essential reason why the model with \( z_{\text{reion}} = 15 \) can better reproduce the observation. The observed small half-number radius \( (R_{h,\text{GC}}) \) of 5.2 kpc (e.g., van den Bergh 2000) can also be better reproduced by the model with \( z_{\text{reion}} = 15 \) showing \( R_{h,\text{GC}} \) of 5.0 kpc.

The global mass profile of the simulated Galactic dark matter halo does not depend on \( z_{\text{reion}} \) in the present study. Therefore, Figure 3 also suggests that the half-number radius of a GCS \( (R_{h,\text{GC}}) \) in a model with respect to the half-mass radius \( (R_{h,\text{dm}}) \) of the dark matter halo is smaller for higher \( z_{\text{reion}} \). Given the fact that ongoing observations on kinematics of GCs in galaxies enable us to infer mass profiles of the dark matter halos (e.g., Bridges et al. 2003), this \( R_{h,\text{GC}}/R_{h,\text{dm}} \) ratio can be regarded as an important observable property that measures the influence of reionization on GC formation in galaxies. As expected from the adopted assumptions of the model, the total number of GCs \( (n_{\text{GC}}) \) depends strongly on \( z_{\text{reion}} \) in such a way that \( n_{\text{GC}} \) is larger for smaller \( z_{\text{reion}} \) (e.g., \( n_{\text{GC}} = 4986 \) and 116 for \( z_{\text{reion}} = 10 \) and 15, respectively). This result might well provide a clue to the question as to why the Galaxy has only <200 GCs. Thus, the

![Figure 2](image_url)
observed compact GC distribution with a radius-dependent slope of the distribution in the Galaxy can be better explained by the model with \( z_{\text{reion}} = 15 \).

5. DISCUSSIONS AND CONCLUSIONS

Previous theoretical studies demonstrated that the destruction of GCs is a key physical process that controls the radial profiles of GCSs in galaxies (e.g., Baumgardt 1998; Fall & Zhang 2001; Vesperini et al. 2003). In order to discuss how the simulated radial profiles of GCSs can be modified by this destruction process, we numerically investigated the orbital evolution of GCs in the model with \( z_{\text{reion}} = 15 \) and thereby estimated the orbital eccentricity \( (e) \) and pericenter \( (r_p) \) of each of the GCs formed before reionization. We found that most of the GCs have highly radial orbits \( (e \sim 0.6–0.8) \) with smaller pericenter distances \( (r_p \leq 10 \text{kpc}) \). Aguilar et al. (1988) demonstrated that GCs with highly eccentric orbits \( (e > 0.8) \) and small pericenter distances \( (r_p \leq 2 \text{kpc}) \) can be completely destroyed by the Galactic tidal field well within the Hubble time. By combining this previous result with the above one on the orbital properties of the simulated GCs, we found that about 55% of the inner GCs in the simulation can be destroyed by the Galactic tidal field. Given the fact that selective destruction of GCs with higher \( e \) and smaller \( r_p \) can result in the flattening of the radial profiles of GCSs (e.g., Vesperini et al. 2003), the above result implies that the radial density profile of the initial Galactic GCS possibly composed mostly of GCs formed before \( z_{\text{reion}} \) can be significantly steeper than that observed now. Furthermore, the kinematics of the Galactic GCS is observationally suggested to be fairly isotropic (e.g., Freeman 1993), which appears to be inconsistent of the simulated kinematics of the GCS composed mostly of GCs with highly eccentric orbits. This apparent inconsistency implies that the origin of the observed isotropic kinematics can also be closely associated with later destruction processes of GCs.

The present study neglects the influence of the local UV field from the first-generation GCs (and very massive stars) formed in subgalactic clumps at \( z > z_{\text{reion}} \) in a protogalaxy on GC formation at \( z > z_{\text{reion}} \) in the protogalaxy. The simulated GCS at \( z = 16 \) has a half-number radius of \(~50 \text{kpc} \), and an order-of-magnitude estimation implies that GC formation within the half-number radius might well be influenced by local UV effects from Population III stars even before \( z_{\text{reion}} \). Accordingly, structural and kinematical properties of the inner GCs, which can be formed well before \( z_{\text{reion}} \), could be particularly modified by this local effect. A more quantitative estimation of this local UV effect on GC formation will be done in our future numerical studies using more realistic and sophisticated models of GC formation. These future studies will also address the role of reionization in shaping the bimodal color distribution of the Galactic GCS.

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