THE RELATIVE AND ABSOLUTE AGES OF OLD GLOBULAR CLUSTERS IN THE LCDM FRAMEWORK

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ABSTRACT

Old globular clusters (GCs) in the Milky Way have ages of about 13 Gyr, placing their formation time in the reionization epoch. We propose a novel scenario for the formation of these systems based on the merger of two or more atomic cooling halos at high redshift ($z > 6$). First-generation stars are formed as an intense burst in the center of a minihalo that grows above the threshold for hydrogen cooling (halo mass $M_h \sim 10^8 M_\odot$) by undergoing a major merger within its cooling timescale ($\sim 150$ Myr). Subsequent minor mergers and sustained gas infall bring a new supply of pristine gas to the halo center, creating conditions that can trigger new episodes of star formation. The dark-matter halo around the GC is then stripped during assembly of the host-galaxy halo. Minihalo merging is efficient only in a short redshift window, set by the ΛCDM parameters, allowing us to make a strong prediction on the age distribution for old GCs. From cosmological simulations, we derive an average merging redshift ($z = 9$) and a narrow distribution $\Delta z = 2$, implying average GC age ($t_{\text{age}} = 13.0 \pm 0.2$ Gyr including $\sim 0.2$ Gyr of star formation delay. Qualitatively, our scenario reproduces other general old GC properties (characteristic masses and number of objects, metallicity versus galactocentric radius anticorrelation, radial distribution), but unlike age, these generally depend on details of baryonic physics. In addition to improved age measurements, direct validation of the model at $z \sim 10$ may be within reach with ultradepth gravitationally lensed observations with the James Webb Space Telescope.

Key words: cosmology: theory – galaxies: general – galaxies: high-redshift – globular clusters: general

Supporting material: animation

1. INTRODUCTION

Globular clusters (GCs) are compact stellar systems with a characteristic mass of $\sim 10^5 M_\odot$ and a radius of a few parsecs (Heggie & Hut 2003). Their ubiquitous presence around galaxies and their old stellar populations make them tools to investigate early star formation, assembly history of host galaxies, and cosmological models (Katz & Ricotti 2013; Brodie et al. 2014). For example, GC ages were used to constrain the age of the universe (Jimenez et al. 1996; Krauss & Chaboyer 2003), providing early independent support for the concordance ΛCDM model (Planck Collaboration et al. 2013).

Yet, GC formation remains a debated topic with the lack of an established scenario matching all observations. Early proposals identified the high-$z$ Jeans mass ($\approx 10^9 M_\odot$) with a protoglobular cloud (Peebles & Dicke 1968). More recently, high-$z$ GC formation as been proposed within dark-matter (DM) halos of mass $M_h \lesssim 10^8 M_\odot$, with cooling driven by H$_2$ (Padoan et al. 1997), as a result of shocks induced by a reionization front (Cen 2001), or as purely baryonic systems because stream velocity displaced gas from its parent halo (Naoz & Narayan 2014). Other scenarios focus at somewhat lower redshift, ranging from cooling-induced fragmentation of (proto)galaxies (Fall & Rees 1985) to formation during galaxy merging/interactions (Ashman & Zepf 1992; Muratov & Gnedin 2010; Li & Gnedin 2014) or within high-density regions of galactic disks (Kravtsov & Gnedin 2005; Kruisjesen 2014). Analogies with today’s young massive clusters have also been proposed (e.g., Bastian et al. 2013).

The lack of consensus on GC formation may indicate multiple formation mechanisms. In fact, the oldest GCs have essentially uniform ages centered at $\sim 12.8$ Gyr and spread $\sim 5\%$ (comparable to relative age uncertainty), but a wide range of metallicities: from 1% to 1/3 the solar value with high-metallicity systems preferentially at small galactocentric radii. In contrast, younger systems show a well-defined age-metallicity anticorrelation and higher metallicity at larger galactocentric radii (Martin-Franch et al. 2009; Forbes & Bridges 2010).

In this Letter, we aim at predicting the probability distribution function of ages for the sub-population of “old” GCs starting from DM halo assembly and merging, which are fully determined (in the statistical sense) by fixing the ΛCDM parameters. Our approach parallels studies of evolution of galaxy properties with redshift, such as luminosity/stellar mass functions and clustering, all linked to halo assembly (Trenti et al. 2010b; Lacey et al. 2011; Behroozi et al. 2013; Tacchella et al. 2013).

We propose that old GCs formed via major merging of DM minihalos ($M_{\text{DM}} \sim 10^8 M_\odot$) that are gas rich (no previous star formation) and metal enriched through outflows originating from nearby (proto)galaxies. First-generation stars form during the merger-triggered burst, while subsequent gas infall through minor mergers can lead to multiple populations. Since the halo merger rate is approximately constant per unit redshift (both for major and minor events; Fakhouri et al. 2010), there is only a short window of opportunity for this mechanism. The redshift needs to be low enough ($z \lesssim 15$) so that minihalos are relatively common, but not too low ($z \gtrsim 6$); otherwise, the merger rate drops.
will collapse to the halo of mass $8 \times 10^{11} M_\odot$ shown in the right panels of Figure 4. A linear overdensity containing hundreds of collapsing/collapsed minihalos is present. Regions involved in GC formation through minihalo mergers are highlighted in red (past major merger) and yellow (future merger). (An animation of this figure is available.)

2. GC FORMATION THROUGH MINIHALO–MINIHALO MERGERS

We propose that old GCs form when a host galaxy like the MW is in the earliest stages of its assembly and lacks a well-defined disk structure. Its Lagrangian region is still a moderate linear overdensity at $z \sim 10$ containing hundreds of minihalos that are being hierarchically assembled, form stars, pollute their neighbors with metals, and merge to build up a massive system by $z = 0$ (Figure 1).

We assume that compact star clusters form during major mergers of two gas-rich and star-poor minihalos, whose gas has been previously enriched by outflows from nearby halos to $Z \gtrsim 10^{-2} Z_\odot$. The combined minihalo mass needs to exceed the threshold for HI cooling ($T_{\text{vir}} \gtrsim 10^4$ K), but if either of the progenitors was above the cooling mass threshold, it must not have started forming stars yet. Under these conditions, the merger will shock-heat and concentrate the gas, leading to efficient formation of a star cluster. Following the merger-triggered starburst, SNe II clear the gas remaining in the minihalo (escape velocity is a few tens of km s$^{-1}$), suppressing further star formation after $\sim 10$ Myr. Subsequently, slow winds from AGB stars produce chemically enriched gas (D’Ercole et al. 2008), which is retained in the potential well and diluted by infall of new pristine gas through minor mergers and/or accretion. This gas loading triggers one or more bursts of star formation, more centrally concentrated than the first generation, with merger mass ratios and timing after AGB pollution imprinting diverse chemical signatures in individual clusters, consistent with observations (Renzini 2008). The GC minihalo is eventually incorporated into the merger-tree main branch, with continued mergers and tidal interactions stripping DM and leaving a “naked” GC by $z = 0$. Qualitatively, the scenario is illustrated in Figure 2.

3. QUANTITATIVE MODELING

To evaluate the plausibility of the scenario depicted in Section 2 and compute the GC formation rate, their ages, and spatial distribution at $z = 0$, we resort to a DM-only cosmological simulation run with Gadget2 (Springel 2005), with a setup as described in Trenti et al. (2009), Trenti & Shull (2010), and Ramirez-Ruiz et al. (2015), but with a tailored volume/mass resolution and updated cosmology ($\Omega_{\Lambda,0} = 0.685$, $\Omega_{m,0} = 0.315$, $\Omega_{b,0} = 0.0462$, $\sigma_8 = 0.828$, $n_s = 0.9585$, $h = 0.673$; Planck Collaboration et al. 2013). We simulate a $10^3$ Mpc$^3$ (comoving) volume from $z = 150$ to $z = 0$ using $N = 403^3$ particles, while we run a high-resolution version of the same initial conditions to $z = 5.5$ ($t_{\text{lookback}} \sim 12.8$ Gyr) with $N = 812^3$ particles (mass resolution $8.3 \times 10^4 M_\odot$). Our multi-scale approach is based on assigning membership of high-resolution particles to $z = 0$ halos through mapping of particles IDs and studying halo assembly at higher redshift from the full resolution run, saving snapshots at uniform intervals of 10 Myr.

The high-resolution DM-only simulation is post-processed with the star formation and chemical enrichment model of Trenti et al. (2009) to flag minihalos that are in gas-rich, star-free conditions. Specifically, we follow the formation of Population III (metal-free) stars in halos above the minimum threshold for H$_2$ cooling with a time-evolving Lyman–Werner background, triggering Population III star formation when a pristine halo crosses the mass $M_{\text{min}}(z)$ shown in Figure 1 of Trenti et al. (2009). Under these conditions, a halo is flagged as enriched by Population III stars, and then starts forming Population II (metal-enriched) stars once above the hydrogen cooling limit ($T_{\text{vir}} > 10^4$ K). As a basic description of metal pollution within our DM-only framework, Population II halos, once they begin forming stars, are assumed to have outflows propagating with spherical symmetry at fixed speed $v_{\text{wind}} = 60$ km s$^{-1}$ (appropriate for dwarf-like galaxies). Halos that grow with redshift staying below $M_{\text{min}}(z)$ until $z \lesssim 13$ (the point at which $M_{\text{min}}(z)$ corresponds to atomic cooling) may either form a “late-time” Population III star or a Population II cluster/dwarf galaxy if polluted by outflows from nearby (proto)galaxies (Trenti & Shull 2010; Stiavelli & Trenti 2010).

As zeroth-order characterization of metal enrichment, we track for each minihalo the number $\xi$ of nearby halos that have metal outflows active for long enough to reach its center. We consider outflow-enriched (pollution counter $\xi \geq 1$), star-free halos with $T_{\text{vir}} \sim 10^4$ K as potential GC birth sites. The condition that needs to be satisfied in our framework to create a GC is a major merger with another smaller outflow-enriched$^4$ minihalo that increases the mass so that $T_{\text{vir}} > 10^5$ K. If either progenitor has $T_{\text{vir}} \geq 10^5$ K pre-merger, then the merger must happen before stars are formed. Otherwise, supernova feedback clears the minihalo of gas. Assuming a typical cooling time of $(1-2) \times 10^8$ years (Tegmark et al. 1997), we define a timescale $\Delta t = 150$ Myr from crossing of the cooling

$^4$ This guarantees that GC minihalos are well resolved with $N \geq 500$ particles, sufficient to characterize their properties (Trenti et al. 2010a).

$^5$ Mergers between a metal-enriched and a metal-free, star-free minihalo would also satisfy these requirements, but such configurations are rare since pairs of merging minihalos have strongly correlated $\xi$. 
threshold \( (T_{\text{vir}} \geq 10^4 \, \text{K}) \). After such time, we no longer consider a GC as the outcome of a major minihalo merger. Furthermore, we define the minimum mass ratio between progenitor halos as \( M_2/M_1 > 1/4 \).

Finally, we save IDs for all particles involved in GC formation to track halo membership, check for subsequent mergers, and characterize their spatial distribution at \( z = 0 \) through ID re-mapping into the lower-resolution run.

Our simplified gas treatment from DM-only simulations ignores the relative velocity difference between baryons and cold dark matter imprinted at recombination time, which can significantly impact formation of high-\( z \) halos with \( 10^3 \, \text{K} \lesssim T_{\text{vir}} \lesssim 10^4 \, \text{K} \), suppressing the halo mass function (Tseliakhovich & Hirata 2010; Naoz et al. 2011) and the gas fraction (Naoz et al. 2013). Quantifying the impact of stream velocity for GC formation is difficult without a hydrodynamic simulation because of competing effects. Gas-rich minihalo mergers require progenitors where Population III star formation is suppressed. In our framework, this happens because of \( \text{H}_2 \) photodissociation, but stream velocity works as well. In addition, the halo bias would be higher (Tseliakhovich & Hirata 2010), enhancing the merger probability. Overall, the number of gas-rich minihalo mergers may be only moderately suppressed, or possibly even enhanced, in contrast to the \( \sim 50\% \) suppression of star formation inferred for the general population of minihalos (Bovy & Dvorkin 2013). We expect our estimate on the GC birth rate to be accurate within a factor two or better compared to a full treatment of stream velocity.

### 3.1. Merger Rate and Age Probability Distribution

Figure 3 shows predictions for the GC formation rate in the most massive simulated halo \( (M_h = 4.9 \times 10^{12} \, M_\sun \), selected for best statistics). At \( z > 5.5 \) (universe age <1 Gyr), there are...
279 minihalo–minihalo mergers fulfilling the conditions for GC formation. The average merger redshift is \((z) = 9.3\) (\(t_{\text{lookback}} = 13.2\) Gyr) with dispersion \(\Delta z = 1.88\) (age spread \(\sim 200\) Myr). Minihalo–minihalo merging is strongly peaked with redshift because of competing processes. At \(z > 12\), atomic cooling halos are rare, and there is not sufficient time for chemical pollution by outflows originating in nearby star-forming sites. Later, as the redshift decreases, so does the merger rate (Fakhouri et al. 2010), and at \(z \lesssim 8\), structure formation starts shifting toward larger scales. This is qualitatively similar to the circumstances leading to the “Gamov peak” in nuclear astrophysics.

Figure 3 is representative of the average GC formation rate, albeit with significant halo-to-halo scatter. Its bottom panel illustrates the cumulative GC number for the five most massive halos in the box comprising a mass range of \((0.8–4.9) \times 10^{12} M_\odot\), as well as the box average. The number of GCs is normalized by the comoving volume of each halo in the initial conditions (proportional to halo mass). The box-average normalization is the simulation volume. Figure 3 depicts halo-to-halo variations of a factor two. Furthermore, it shows that more massive halos (the blue and red lines) have slightly older GCs compared to less massive halos (the box-average line) by about 100 Myr. This is a consequence of the earlier chemical enrichment and biased halo mass function that is found in overdense environments.

With an average time delay of \(\sim 250\) Myr, the large majority of the products of minihalo–minihalo mergers has a minor merger (progenitor mass ratio \(\gtrsim 1/10\)) or receives a mass infall \(\geq 10^7 M_\odot\) between two snapshots (10 Myr temporal spacing). Major mergers are also frequent: \(\sim 25\%\) of the first-generation clusters has one. More generally, from Extended Press–Schechter modeling (see Trenti et al. 2008), we derive that a halo with \(M_h = 10^8 M_\odot\) at \(z = 10\) will evolve into a descendant that 500 Myr later (by \(z = 5.8\)) has doubled in mass at \(\gtrsim 98\%\) confidence. Therefore, the high accretion rate on the minihalos suggests that there is sufficient gas to mix, dilute chemically the AGB ejecta from first-generation stars, and concentrate them at the halo center. These conditions can lead to formation of multiple stellar populations (Carretta et al. 2009), widely observed in galactic GCs (Piotto et al. 2007). However, detailed modeling requires hydrodynamic simulations and is beyond the scope of this initial work, focused on making predictions on the robust (parameter-free) probability distribution of GC ages.

Our simulation does not include halos especially representative of the MW/local group because of its small volume. Nevertheless, since minihalo mergers are a universal process, we can rescale the results to estimate the number of old galactic GCs. The MW halo mass is debated, ranging from \(\sim 8 \times 10^{11} M_\odot\) to \(\sim 4 \times 10^{12} M_\odot\) at 95% (e.g., van der Marel et al. 2012; Phelps et al. 2013; Kafle et al. 2014), almost encompassing the halos shown in Figure 3. In these halos, there are 279 to 32 old GCs, suggesting full consistency between observed frequency and predictions in our framework (old GCs in the MW are about 50% of the total population, that is, \(N \sim 80\)). Overall, our theoretical estimate of the old GC number is accurate within a factor of two, comparable to halo-to-halo variations. For improved estimates, GC survival to \(z = 0\) is also important, as well as detailed modeling of the hydrodynamics (stream velocity, impact of progenitor mass ratio, and cooling timescale \(\Delta t\)).

However, to a first approximation all these baryonic processes, including stream velocity, do not affect the predicted age distribution, which is the key observable that can falsify our model. In this respect, we note that the GC “formation epoch” shown Figure 3 is that of the minihalo–minihalo merger, and thus an upper limit. Stars form in the following \(\sim 10^8\) years (first generation), and possibly a few hundred Myr later when further gas accretion triggers subsequent generations. Assuming \(2 \times 10^8\) years as the typical delay for the
average stellar age since the merger, our best estimate of the absolute age of old GCs is $\sim 13.0$ Gyr with a $1\sigma$ spread of $\sim 0.2$ Gyr. This is in full agreement with the current determination of ages for the old GC population $t_{\text{age}} = 12.8 \pm 0.6$ Gyr (Marín-Franch et al. 2009). We predict that, if old GCs formed through minihalo mergers, improvements in absolute and relative age calibrations should converge toward GC formation during the epoch of reionization and age scatter as small as $\Delta t_{\text{age}} \sim 0.2$ Gyr.

### 3.2. GC Masses, Galactocentric Distribution, and Tidal Stripping

Our model quantitatively predicts the age distribution of GCs formed through minihalo mergers and produces the correct order of magnitude of objects (Section 3.1). To further establish its plausibility, we investigate the expected GC masses, galactocentric distribution, and efficiency of tidal stripping in removing DM around GCs by $z = 0$.

A typical star formation efficiency used in studies of high-redshift objects is $\epsilon_* = 0.03$ (stellar to baryonic mass ratio; Alvarez et al. 2012). This gives for a minihalo with $M_h \sim 10^8 M_\odot$ a stellar mass $M_\ast \sim 4 \times 10^5 M_\odot$, consistent with the average GC mass $\sim 10^5 M_\odot$ (Heggie & Hut 2003), even if there is a diffuse stellar component formed during the merger (and later stripped). Furthermore, our model has a cutoff scale given by the HI cooling mass, naturally predicting a distribution of masses peaked around a characteristic value (log-normal type), as observed for GCs in both the Milky Way and external galaxies (e.g., Harris 1991; Parmentier & Gilmore 2005). Thus, the model has no need to invoke the preferential disruption of lower-mass star clusters (e.g., Fall & Zhang 2001).

Finally, we discuss model predictions for galactocentric GC distribution and efficiency of tidal stripping of the DM envelope. We tag in the $z = 0$ snapshot the particles associated with GC formation in the high-resolution, high-$z$ run. Results are shown in Figure 4: tagged particles (middle panel) have
higher galactocentric concentration compared to all particles (top panel). The $z = 0$ radial density profile of GC particles is shown in Figure 5 for a typical non-interacting halo, demonstrating that it follows the slope $\rho(r) \sim r^{-3.5}$ observed in the distribution of MW GCs. This is not surprising since minihalo mergers are $\lesssim 2\sigma$ DM peaks at $z \sim 9$, which Moore et al. (2006) found to be distributed with a $\rho(r) \sim r^{-3.5}$ profile by $z = 0$. The middle panels of Figure 4 also show a diffuse distribution of particles involved in minihalo mergers. This supports our proposal that tidal interactions during the merger process strip GCs of their initial DM halos, although the results need to be confirmed by a full high-resolution simulation to $z = 0$. Last, through particle tagging, we derive the correlation between $z = 0$ galactocentric distance and chemical enrichment (Figure 4, bottom panels). As observed by Marín-Franch et al. (2009), we qualitatively obtain a negative correlation between galactocentric radius and metallicity, with GCs located centrally enriched by up to $\xi = 15$ polluters, and those in the outskirts having $\xi = 1 - 2$.

4. CONCLUSIONS

The observed age–metallicity distribution of galactic GCs shows a bimodal population, with about half the objects residing along an “old” branch with an age of $12.8 \pm 0.6$ Gyr and spread comparable to the relative age error (Marín-Franch et al. 2009; Forbes & Bridges 2010). Here, we explored a novel idea to form these old GCs at the center of DM minihalos with virial temperature $T_{\text{vir}} \gtrsim 10^4$ K ($M_{\text{h}} \sim 10^8 M_\odot$) and with the following additional constraints.

1. Enrichment by metal outflows from nearby Population II halos rather than by their own Population III star formation.

2. Major merger with a similar metal-enriched but star-free minihalo within a time $\Delta t \sim 150$ Myr from the crossing of the cooling threshold ($T_{\text{vir}} \gtrsim 10^4$ K).

The minihalo–minihalo merger is the key new ingredient to creating a compact star cluster. While the details of star formation depend on complex baryonic physics that will be explored in future investigations, we make robust and falsifiable predictions on the probability distribution of the minihalo mergers (age of GCs), which are discussed in Section 3.1. We obtain $(t_{\text{age}}) = 13.0$ Gyr and $\Delta t_{\text{age}} \sim 0.2$ Gyr, in agreement with current observations.

Improvements in GC age measurements can uncontrovertibly falsify the minihalo merger scenario. Also, model predictions may be within reach of direct observations with the James Webb Space Telescope (JWST). In fact, the number density of compact star clusters at $z > 7$ is sufficiently high ($1.5 \times 10^4$ arcmin$^{-2}$) that JWST can identify some of them if highly magnified ($\mu \sim 100$) to $M_{\text{AB}} \sim -17$ by a foreground galaxy cluster. However, we note that it will be challenging to discriminate against other compact high-$z$ objects such as Population III clusters (e.g., Zackrisson et al. 2012).

Besides GC ages, other aspects of the framework such as multiple stellar population formation triggered by minor mergers (Section 2) are more speculative since they depend on a complex interplay between baryonic and DM physics. We presented consistency checks in Section 3.2 to characterize qualitatively the distribution of GCs, their metallicity, and stripping of the DM halo envelope, but further work is required. In addition to detailed investigation of DM stripping, perhaps one interesting aspect to follow up is the connection between GCs and dwarf galaxies. While earlier studies considered them as two distinct classes in the luminosity–size plane, recent work unveiled the existence of ultracompact dwarf galaxies with intermediate properties (e.g., Jennings et al. 2014). Indeed, our framework predicts a continuum between classical dwarf galaxies (no major mergers at formation, DM dominated) and old GCs (major merger, DM envelope stripped by $z = 0$). Overall, minihalo mergers appear to provide a promising scenario for exploring the formation of the oldest GCs observed in today’s galaxies. It is our pleasure to thank Duncan Forbes, Diederik Krijsens and Sasha Muratov for useful discussions on an earlier version of the manuscript and an anonymous referee for helpful comments.

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Figure 5. Density profile vs. galactocentric radius at $z = 0$ for the halo shown in the right panels of Figure 4. The DM density (solid black line) is well represented by an NFW profile (dashed blue line), while particles associated with minihalo–minihalo mergers have a steeper profile (solid red), consistent with $\rho \sim r^{-3.5}$ observed in the distribution of Galactic GCs (dotted magenta). Profiles have been normalized at $r = 10$ kpc h$^{-1}$.
