Star Clusters: From the Milky Way to the Early Universe
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Hunting for Globular Clusters in the early universe

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Abstract. Setting the formation of globular clusters (GCs) within a cosmological context and characterising the properties of proto-GCs at high redshift is currently a major challenge. In this work, we address that challenge by exploring a suit of high-resolution cosmological simulations from the First Billion Years (FiBY) project at $z \geqslant 6$ to investigate theoretical scenarios concerning the formation of old, low-mass stellar systems with a particular focus on GCs. Two distinct groups of objects are identified in the simulations. The first group of objects, with a high baryon fraction, we associate with proto-GCs. The second group, that exhibit a high stellar fraction, could be forming ultra-faint dwarf galaxies (UFDs). The objects with high baryon fraction are promising proto-GC candidates because they have little to no dark matter (DM), have number densities consistent with predictions from the literature, are very compact and have a high stellar density. We fit and also assess the redshift-zero globular system mass - halo mass relation and find it provides a reasonable fit to our proto-GC objects, indicating that this relation is likely set at formation.

Keywords. globular clusters: general, early universe

1. Introduction

Galaxy evolution can be studied in a variety of ways, chiefly organised into two main approaches - either by means of astronomical observations or by means of numerical simulations. One way to study how a galaxy has evolved and to explore any changes that may have occurred in its environment is through analysing the system of star clusters hosted by the galaxy itself. Globular clusters (GCs) are one of these types of system. These are massive (10^4–10^6 $M_\odot$), compact, dense, spherical clusters (Harris 1996; Renaud 2018). Due to their extremely old stellar populations (∼11.5−12.5 Gyr), they are believed to have formed during or just after the epoch of reionisation (Ricotti 2002; Katz & Ricotti 2014). Hence, for this reason, studying GCs at high redshift can give insight into the processes and environments that governed star formation at that time.

Investigating the formation of GCs also allows one to constrain the dynamical and chemical environments needed in forming galaxies, and, through comparisons with local Universe observations, this can impart constraints on models relating to, for example, merger histories (e.g., see Kruijssen *et al.* 2019; Renaud 2018). However, in order to use GCs as a tool to probe the formation and evolution of galaxies, first they must be fully understood. There are a number of key questions and observational features concerning GCs that still need to be explained theoretically. These include the multiple stellar population phenomenon (Lardo *et al.* 2011; Piotto *et al.* 2015; Milone *et al.* 2017; Bastian & Lardo 2018), the split in the age-metallicity plane (Forbes & Bridges 2010;

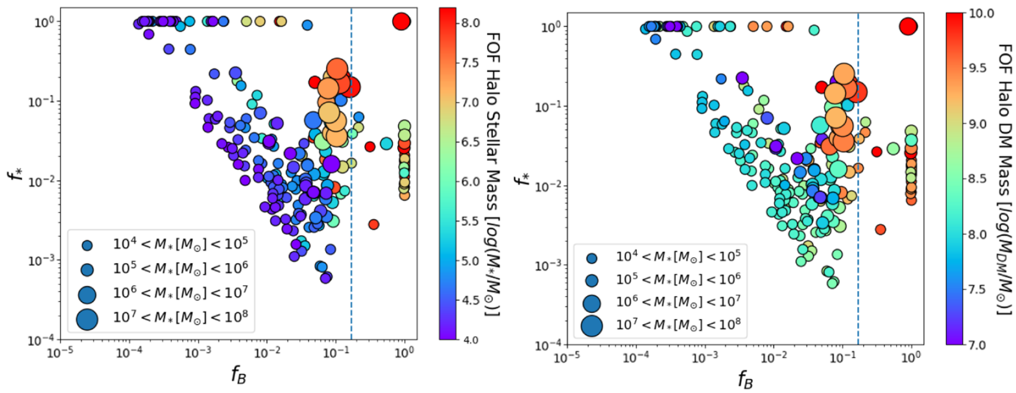

Figure 1. Stellar fraction versus baryon fraction for all substructures in the FiBY simulated 4 Mpc^3 box with stellar mass range $10^4 - 10^8$ M$_\odot$. Sizes of the symbols indicate their stellar mass. The vertical line is the universal baryon fraction. From left to right the colour bars represent: stellar mass of the parent halo, and the DM mass of the parent halo.

Leaman *et al.* 2013; Recio-Blanco 2018), the tight correlation between GC system mass and host galaxy halo mass (Spitler & Forbes 2009; Harris *et al.* 2015, 2017; Forbes *et al.* 2018) and many more. It is unclear whether these features emerge due to the epoch, environment and mechanism behind GC formation or whether they are a result of evolution.

How GCs form is still a open question, and one which is difficult to answer with observations alone. Whilst some proto-GC like objects have been detected at high-redshift (Vanzella *et al.* 2017; Bouwens *et al.* 2017, for example), these observations alone are not enough to determine the exact formation channel for GCs. In tandem with high-redshift observations, we must rely on simulations. However some of the methods employed to search for GC candidates theoretically within the simulations could be biasing the results. What is needed is a self-consistent, theoretically motivated method of selecting proto-GC candidates in cosmological simulations. In this work, we explore a suite of high-resolution cosmological simulations from the First Billion Years (FiBY) project at $z \geqslant 6$ to investigate theoretical scenarios concerning the formation of old, low-mass stellar systems with a particular focus on GCs. The aim of this study is primarily to identify and classify proto-GC like objects in a self-consistent way. We will show that two, theoretically motivated, distinct groups of objects emerge. One of which are highly likely to be forming globulars.

2. Simulations

In this work, we utilise a simulation from the First Billion Years (FiBY) project (for more details on the simulation see Johnson *et al.* 2013). These simulations were run until $z = 6$. All substructures were identified with the SUBFIND algorithm (Springel *et al.* 2001). Three particle types are tracked in these simulations: dark matter (DM), gas and stars. For the work presented here, a simulation box of volume 4 Mpc^3 with 2×684^3 particles was used. The mass resolution of particles is 1250 and 6160 M$_\odot$ for SPH and DM particles respectively. The simulations track metal pollution for 9 elements, have a prescription for supernova feedback and formation for both Population II and III stars.

All substructures within the stellar mass range $10^4 - 10^8$ M$_\odot$ were extracted and illustrated on the plane of stellar fraction ($f_* = M_*/(M_* + M_{gas})$) versus baryon fraction

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($f_b = (M_* + M_{gas})/(M_* + M_{gas} + M_{DM})$) - see Figure 1. Surprisingly, we notice that two distinct groups of objects emerge. The first of these groups can be seen as a vertical line where $f_b = 1$, i.e. the mass of these objects is entirely in the form of baryons. These stellar systems have masses in the range of 10^4–10^6 $M_\odot$. They appear to be lying within a grouping that contains many other objects characterised by a considerable amount of stellar mass of their host halo. This can be seen via the colour bar in the left-hand panel, which indicates the stellar mass of the larger parent halo where these objects are found. Whilst these individual substructures appear to have a low concentration of DM, they lie within an extended DM halo environment (right hand panel of Figure 1). We hypothesize that this group of objects can be associated with proto-GCs.

The second distinct group of objects lie along the $f_* = 1$ line, this means all their baryonic matter is tied up within stars. However, the baryon fraction of these objects is low, indicating a large concentration of DM within them. These objects are likely to be isolated. When looking at the colour bars in Figure 1, we see that the stellar masses for most of this group is equal to the stellar mass of the parent halo, implying they are the only object within the halo. Therefore, we hypothesize that objects in this group could be akin to proto-ultra faint dwarf (UFDs).

In order to test these hypotheses, we compare the properties of these two distinct groups with a set of criteria from observational constraints from the local Universe.

3. Results

Several predictions in the literature have been made regarding the number density of proto-GCs at high redshift. Therefore, as a first step, we compare these predictions with the number densities found for our candidates within the FiBY simulation. We studied the evolution of number density with redshift for both the $f_b = 1$ and $f_* = 1$ objects. This number density was calculated by dividing the total number of objects in each group by the volume of the simulated box. We compared these values to three different predictions from literature; Boylan-Kolchin 2017, Elmegreen *et al.* 2012 and Rodriguez *et al.* 2015. The resulting values for proto-GC number density show some consistency with the predictions from the literature. However, in general, we seem to be finding lower numbers than predicted. This could be due to the size of the simulated box, or due to the methods employed in the literature to determine the number density. All the methods were based upon theories of GCs at high redshift and employed present-day observations but were developed independently of high redshift observations. Thus the results we are finding in the simulations are a good foundation for future predictions, and can be regarded as a lower limit.

We also explore the global properties of our proto-GC candidates, in direct comparison with the proto-UFD candidates. The former are more compact and dense, they show a high metallicity and have a high (average) stellar velocity dispersion. These results reinforce our preliminary identification of the objects of this class as proto-GCs.

Finally we fit a redshift-zero relation to our data. By fitting a redshift-zero relation, we can approximately determine whether formation or evolutionary processes are more important in developing GC systems. We find a good agreement between the redshift-zero relations and the simulation data for the proto-GC candidates. This reinforces the idea that the relation between proto-GCs and their host galaxies is set at formation. As the redshift-zero relations studied in this work (i.e., those proposed by Spitler & Forbes 2009 and Harris *et al.* 2017) are linear, it is likely that, as the proto-GC systems evolve, they will continue to follow this relation (within the degree of scatter reported in the observational GC system mass – halo mass relations).

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