Star Clusters: From the Milky Way to the Early Universe
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Globular Cluster – Bulge connection: Population synthesis models with multiple populations

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Abstract. Recent analyses of Lee *et al.* (2018, 2019) have confirmed that Galactic bulge consists of stellar populations originated from Milky Way globular clusters (MWGCs). Motivated by this, here we present the evolutionary population synthesis (EPS) for the Galactic bulge and early-type galaxies (ETGs) with the realistic treatment of individual variations in light elements observed in the MWGCs. We have utilized our model with GC-origin populations to explain the CN spread observed in ETGs, and the results show remarkable matches with the observations. We further employ our model to estimate the age of ETGs, which are considered as good analogs for the MW bulge. We find that, without the effect of our new treatments, EPS models will almost always underestimate the true age of ETGs. Our analysis indicates that the EPS with GC-origin populations is an essential constraint in determining the ETG formation epoch and is closely related to understanding the evolution of the Universe.

Keywords. globular clusters: general — stars: abundances — Galaxy: bulge — Galaxy: formation — galaxies: elliptical and lenticular, cD — galaxies: evolution

1. Multiple Stellar Populations in the Milky Way Globular Clusters

Since the early 1980s, it has been well known that GCs are chemically inhomogeneous based on spectroscopic observations. The high precision observations of HST have revealed the multiple stellar populations in GCs showing splits in the main-sequence (MS) and red giant branch (RGB), as well as several groups of HB stars. Models with variations in He abundance explain the observed splits in MS and RGB splits, and also the various morphologies of HB stars from red to extreme blue.

2. The Origin of Bright Red Clumps in the Bulge

Most of the GCs are metal-poor. In this case, the morphology of horizontal branch (HB) stars is very sensitive to a slight change in He abundance in the sense of bluer HB types with increasing He. Interestingly, this trend does not hold anymore in the metal-rich regime, and instead the high metallicity results in the increased luminosity of HBs (Joo *et al.* 2017). If we apply this phenomenon to evolutionary population synthesis (EPS), the double red clumps (dRCs) observed in Terzan 5 are naturally reproduced (see Figure 2 of Lee *et al.* 2015). In this regard, we concluded that the stellar populations with different He abundance could also explain the dRCs found in the Galactic bulge without assuming a distance difference. As a result, two red clumps (RCs) with different brightness were reproduced without further assumption on the distance effect (see Figure 3 of Lee *et al.* 2015). The model requires two simple assumptions: first, the faint RC is following the Galactic chemical evolution of $DY/DZ = 2.0$ and second, the bright RC consists of He-rich stars observed in GCs.

As presented in Figure 3 of Lee *et al.* (2015), we have explained the magnitude difference between the two RCs with He. Since it is well established that the enhancement of He is usually accompanied by N enhancement through the chromosome map (Milone *et al.* 2017), if these two RCs are indeed originated from the GCs, there would be differences between two RCs in elements other than He. Based on this, we constructed a population synthesis model with the N-spread for the Galactic bulge, and as a result, determined the CN difference that would be observed between two RCs. We performed low-resolution spectroscopy of CN absorptions of bulge RCs, and confirmed the difference in N abundance between two RCs (Lee *et al.* 2018). Together with the recent research of Lee *et al.* (2019) reporting Na bimodality in the outer bulge, these are direct evidence of a GC-origin population in the MW bulge.

3. Similarities between MWGCs and GCs in ETG

The integrated CN strengths of MWGCs show significant deviations from the models with the assumptions of standard N abundance (Chung *et al.* 2013). Since we found the close connection between MWGCs and Galactic Bulge, if we observe the strong CN absorptions in the GCs of ETGs, we could easily deduce that the GCs in external galaxies may also be linked to their host galaxies. Interestingly, GCs in N5128 show significant deviation from standard N models (Woodley *et al.* 2010). Besides, considering the Na-O anticorrelation observed in GCs (e.g., Gratton *et al.* 2012), the substantial deviation of integrated NaD of GCs from the model with the standard abundance ratio can be understood too. Standard models without including Na enhancements are placed at the lower boundaries of the observations of MWGCs and M31 GCs (Chung *et al.* 2013).

4. GC-origin Populations in ETGs

We already have several crucial pieces of evidence of how GCs have played essential roles to form their host galaxies. These evidences are closely related to each other. Extreme HB (EHB) stars observed in GCs are hot enough to emit strong UV flux, and those UV strong GCs are found in ETGs. Using these hot populations, the UV-upturn phenomenon in ETGs can be explained (Chung *et al.* 2011), and these populations can further explain dRCs in the MW bulge (Lee *et al.* 2015). These are diverse phenomena that can be observed in various forms when these stellar systems consist of GC-origin stellar populations.

In this regards, Figure 4 of Worthey (1998) provided interesting implications for ETGs and has already hinted the presence of GC-origin populations in ETGs as well. Figure 1 shows the distribution of CN_1 and $\langle \mathrm{Fe} \rangle$. Careful looking at this figure reveals that following the metallicity sequence of GCs leads to the ETGs in the most metal-rich regime. Unfortunately, the scaled solar (N-normal) standard model of Worthey (1998) did not adequately account for the CN spread in ETGs.

Furthermore, other elements, such as Na and O, indicating GC-origin populations also show strong correlations with each other. Considering that one of the typical characteristics of GC-origin populations is the Na-O anticorrelations, it is hard to say that GCs have nothing to do with the formation of ETGs which show Na-O anticorrelations with decreasing R_{eff} (van Dokkum *et al.* 2017). In addition, if we assume that strong FUV fluxes in the old ETGs are originated from He-enhanced EHB stars, one can conclude that GC-origin stars prevail in the center of ETGs. In this respect, observations that found many galaxies with very strong Na absorption lines (Jeong *et al.* 2013) are the natural outcome of GC-origin populations. All these evidence points in the same direction of the crucial role of GCs as building blocks of ETGs.

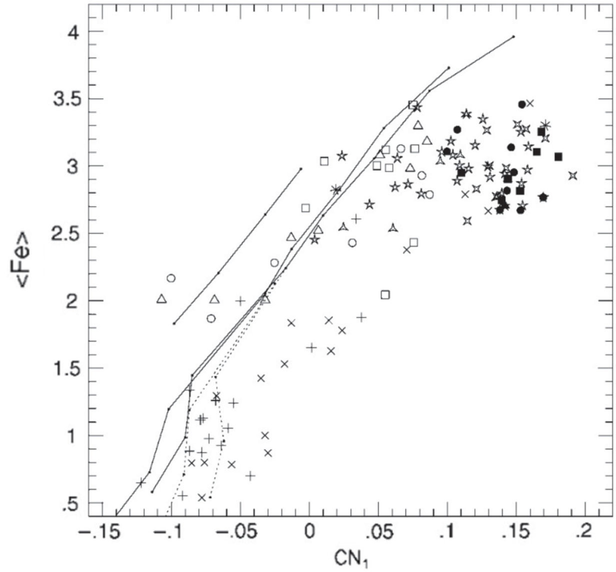

Figure 1. CN_1 spread of early-type galaxies (ETGs). This is Figure 4 of Worthey (1998). Plus signs and crosses represent GCs in the MW and M31, respectively. Other points (circles, squares, triangles, and stars) indicate ETGs with different velocity dispersions. Population models with standard abundance ratio are shown as solid and dotted lines.

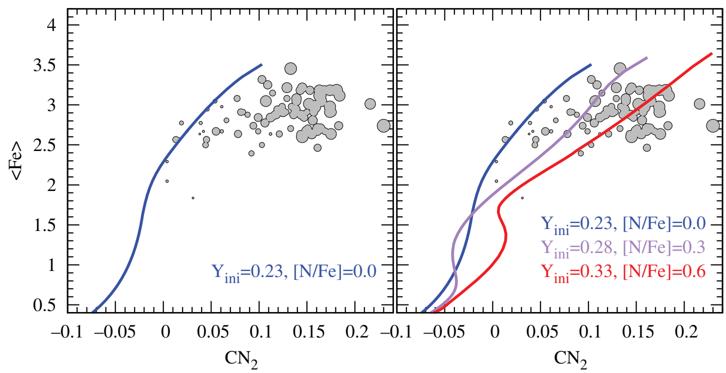

Figure 2. CN_2 spread of ETGs. Observations are from Sánchez-Blázquez *et al.* (2006). The effect of GC-origin populations on the model increases as the color changes from blue to red. The point size of the ETG differs according to the velocity dispersion.

5. Population Model with GC-origin Populations

Figure 2 shows ETGs of Sánchez-Blázquez *et al.* (2006) in CN_2 vs. $\langle Fe \rangle$ plane. Our model with normal abundance patterns cannot explain the CN_2 spread as well (left panel). However, it is possible to explain the spread of the observation naturally when enhanced He and N abundances are simultaneously applied to our model (right panel). This could be one evidence that the stellar populations originated from GCs are also found in the ETG. Based on this, it can be inferred that ETGs have experienced similar formation history with that of our Galactic bulge.

If this assumption is correct, the most problematic part would be the age-dating of ETGs that relies solely on the integrated Balmer absorption strength. Figure 3 shows ETGs and the model grids with different assumptions on the consisting populations.

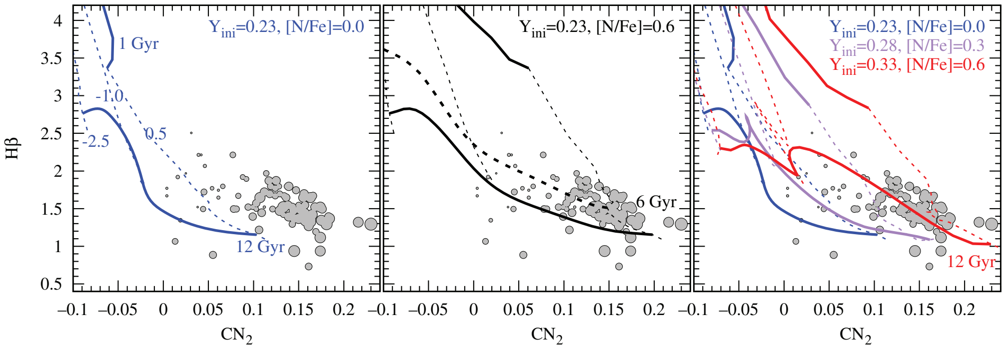

Figure 3. Age-dating of ETGs. Symbols and colors are the same as Figure 2. The model with GC-origin populations (simultaneously enhanced in He and N) predicts, on average, the age of 12 Gyr for ETGs.

In general, if the integrated Balmer absorption is strong, the age is considered to be young, and if weak, old. In the case of the normal He model (left panel), the ETG observed on this plane cannot be placed in a grid that can predict age. If we increase the N abundance only (middle panel), this grid is able to contain observations, but the age of most of ETGs would remain at 6 Gyr. However, when we apply He and N increased models, the age of these galaxies is measured as 12 Gyr. If we do not include GC-origin populations in the model, that could lead to 6 Gyr age underestimation of ETGs. This implies that the GC-origin population is an essential constraint in determining the ETG formation epoch and is also closely related to understanding the evolution of the Universe.

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