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Multiple populations in globular clusters: New insights from chemical evolution and horizontal-branch models

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Abstract. In order to investigate the origin of multiple populations in globular clusters (GCs), we have constructed new chemical evolution models for proto-GCs where the supernova blast waves undergo blowout without expelling the ambient gas. Chemical enrichments in our models are then dictated by the winds of massive stars together with the asymptotic-giant-branch stars ejecta. We find that the observed Na-O anti-correlation can be reproduced when multiple episodes of starburst and enrichment are allowed to continue in proto-GCs. The "mass budget problem" is mostly resolved by our models without ad-hoc assumptions on star formation efficiency, initial mass function, and significant loss of first-generation stars. Interestingly, ages and chemical abundances predicted by this chemical evolution model are in good agreements with those independently obtained from our stellar evolution model for the horizontal-branch. We also discuss observational evidence for the GC-like multiple populations in the Milky Way bulge.

Keywords. globular clusters, multiple populations, Milky Way bulge

1. Introduction

This year, we are celebrating the 20th anniversary of the discovery of the first good evidence for the multiple populations in globular clusters (GCs) from the discrete and multiple red-giant-branches (RGBs) in ω Cen (Lee *et al.* 1999). Since that time, thanks to the hard works by many people in the globular cluster community, it is well established that most GCs host second and later generation stars (G2+) enriched in He, Na, Al, & N, together with first generation stars (G1) having normal chemical composition (Gratton *et al.* 2012; Renzini *et al.* 2015; Bastian & Lardo 2018). For G2+, O, Mg, & C are depleted in metal-poor GCs, but they show no variation in metal-rich GCs (Tang *et al.* 2017; Muñoz *et al.* 2018). As we know, this is a unique phenomenon observed only in GCs, where the chemical evolution is dictated by asymptotic-giant-branch (AGB) ejecta and winds of massive stars (WMS) with negligible contribution from supernovae (SNe).

2. Multiple populations in globular clusters

Most of the previous models assume that SN feedback would basically wipe out the ambient gas in a proto-GC (e.g. Calura *et al.* 2015), and, therefore, G2 had to form either before the SN explosion from the gas enriched by WMS or after the SN from the gas enriched by AGB. In our recent chemical evolution models (Kim & Lee 2018),

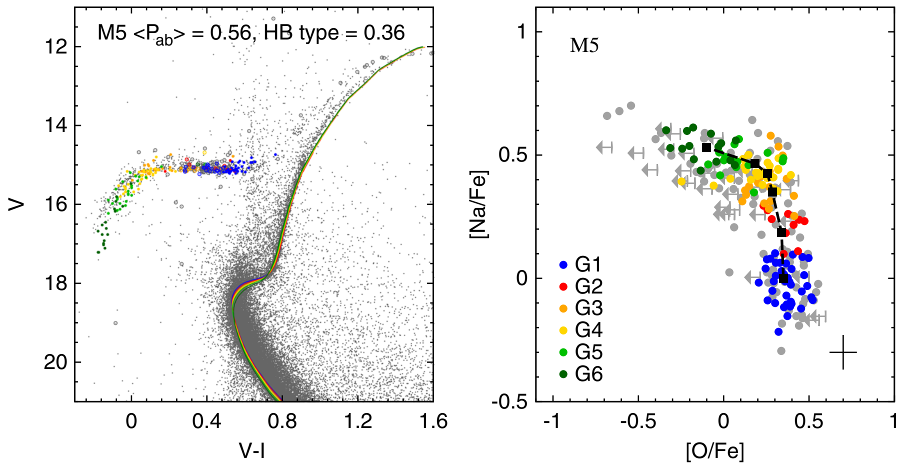

Figure 1. Combining our stellar evolution and chemical evolution models for the GC M5 (adopted from Jang *et al.* 2019). Parameters required to reproduce the Na-O anti-correlation (right panel) can simulateneously reproduce the HB morphology and mean period of type ab RR Lyrae variables (left panel).

we have released that constraint and assume that SN ejecta escape (undergo blowout) without expelling the ambient gas. This is predicted by recent hydrodynamic simulations with more realistic treatment on the proto-GC environment (Tenorio-Tagle *et al.* 2015; Silich & Tenorio-Tagle 2018), which is also supported by some observations (Turner *et al.* 2017; Oey *et al.* 2017). So in our model, chemical evolution is dictated by both WMS anf AGB. Furthermore, based on our previous experience with stellar evolution and population models including horizontal-branch (HB), star formation and enrichment beyond G2 (G3, G4...) is allowed to continue (Lee *et al.* 2005; Jang *et al.* 2014). Therefore, gas becomes more and more enriched by processed materials. Unlike previous models, no ad hoc assumptions are required on the initial mass function, star formation efficiency, and preferential loss of G1. Most importantly, the "mass budget problem" is much alleviated in our model. Of course our key assumption on the SN feedback in a proto-GC should be tested further. It is interesting to see that our models can beautifully reproduce the observed Na-O pattern in most GCs by adopting different number of subpopulations/generations and somewhat different star formation history (SFH) for each GC that lasted 0.01 - 1 Gyr. A specific form of SFH with decreasing time interval between successive generations is required, however, which may be related to the orbital decay of a proto-GC together with star formation induced by proto-bulge shocking. Now we are trying to combine these chemical evolution models with our synthetic HB models, and find that consistent results can be obtained from these two independent studies. Furthermore, a better constraint can be attained by combining these two models, simultaneously reproducing HB morphology, mean period of type ab RR Lyrae variables, and Na-O chemical pattern (Jang *et al.* 2019), see Fig. 1.

3. Multiple populations in the Milky Way bulge

During the last several years, we have been exploring the possibility that the double red clump (RC) observed in the color-magnitude diagram of the outer Milky Way bulge might be another manifestation of the multiple population phenomenion in the metal-rich population (Lee *et al.* 2015; Lee & Jang 2016; Joo *et al.* 2017). Our multiple population model with GC-origin can well reproduce the observed double RC, as is observed in the metal-rich bulge GC Terzan 5 (Ferraro *et al.* 2009; Joo *et al.* 2017). For this, we

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need a large ΔY between G2+ and G1 around solar metallicity, but this is predicted by our chemical evolution model with a strong metal-dependent He yield from WMS. With low-resolution spectroscopy, we confirmed that the bright RC stars are enhanced in CN which traces N. The difference in CN index between the bright and faint RCs is comparable to those observed in metal-rich GCs between G2+ and G1, when considering the background RGB star contamination in the RC regime (Lee *et al.* 2018). Furthermore, we also discovered the Na-bimodality, together with the unique GC-like chemical patterns displayed by Na, Al, O, and Mg, among RGB stars in the outer bulge fields (Lee *et al.* 2019). Therefore, most stars in the outer MW bulge appear to have GC-origin, which in turn suggests that massive early-type galaxies (ETGs) would be similarly dominated by G2+ and G1 originated in GCs. As noted by Lee *et al.* (2018), this is supported by the observations that massive ETGs and their GCs are also enhanced in CN and Na. In broad terms, our "GC-origin bulge" is consistent with recent cosmological hydro-N-body simulations for galaxy formation, which predict that stars from disrupted GCs would end up at the bulge of the Milky Way-like galaxy (Pfeffer *et al.* 2018). So, let's "Make GCs Great Again" with multiple populations!

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