Stellar Populations as Building Blocks of Galaxies
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Extragalactic globular clusters: unraveling galaxy formation and constraining stellar evolution theories

A. Javier Cenarro[1,2,3], Michael A. Beasley[1,3], Jay Strader[3]
Jean P. Brodie[3] and Duncan A. Forbes[4]

[1]Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38200 La Laguna, Tenerife, Spain
email: cenarro@iac.es
[2]Dpto. de Física de la Tierra, Astronomía y Astrofísica II, Fac. de Ciencias Físicas, Universidad Complutense de Madrid, 28040 Madrid, Spain
[3]Lick Observatory, University of California, CA 95064, USA
[4]Centre for Astrophysics & Supercomputing, Swinburne U., Hawthorn VIC 3122, Australia

Abstract. Understanding the stellar populations of extragalactic globular cluster (GC) systems and, in particular, determining their ages, provide essential clues to constrain the star formation histories of their host galaxies. We here summarize the most relevant results derived from a detailed, spectroscopic study of 20 GCs in the E0 NGC 1407. We find most GCs are old ($\sim$ 11 Gyr), follow a tight metallicity sequence reaching values slightly above solar, and exhibit mean [α/Fe] ratios of ~ 0.3 dex. Blue horizontal branch effects are detected for 3 GCs. We also report the existence of two families of metal-rich (MR) GCs, as some of them exhibit significantly larger [Mg/Fe] *and* [C/Fe] ratios, what might be interpreted in terms of different star formation time-scales. Striking CN overabundances are found over the entire GC metallicity range. In particular, for MR GCs, N increases dramatically while C essentially saturates. This may be interpreted as a consequence of the increasing importance of the CNO cycle with increasing metallicity.

Keywords. globular clusters: general — galaxies: clusters — galaxies: formation

1. Introduction

Globular clusters (GCs) are thought to be formed during the major events of star formation in the Universe, so they constitute an essential tool to our understanding of the star formation history of their host galaxies.

The existence of bimodal color distributions in the GC systems of most galaxies has been widely interpreted as an evidence for two distinct GC subpopulations: metal-rich (MR; red) and metal-poor (MP; blue). Several GC formation scenarios have been proposed so far to explain the existence of GC bimodality, the ones in turn impose constrains on the ages of both GC subpopulations. The MP GC subpopulation is predicted to be old in all cases. In the *major merger* model (e.g. Ashman & Zepf 1992), the MR GC subpopulation is supposed to have the same age as that of the main merger driving their formation. The *in-situ/multiphase* scenario (Forbes *et al.* 1997) predicts MR GCs to be just slightly younger (by $\sim 2-3$ Gyr) than MP GCs, whereas no systematic age differences between GC subpopulations are predicted by the *accretion* picture (e.g. Côté,Marzke & West 1998), as both MP and MR GCs would originally form at high redshift in their respective host galaxies before the accretion processes take place. Trying to determine whether systematic differences in the ages of GC subpopulations exist is, therefore, a crucial test to determine the mechanism that governs the formation of the bulk of GCs in the Universe. We refer the reader to Brodie & Strader (2006) for a thorough review of the present status of extragalactic GCs and their implications for the current scenarios of galaxy formation and assembly.

As a case study, on the basis of high-quality spectroscopic data, in this paper we analyze the ages, metallicities and [α/Fe] ratios derived for 20 GCs in the massive E0 NGC1407. Full details on this work can be found in Cenarro *et al.* (2007).

2. Sample selection, observations and data reduction

GC candidates of NGC 1407 were selected from HST photometric data taken in the F435W and F814LP filters using ACS/WFC (Harris et al. 2006; Forbes *et al.* 2006).

Spectroscopic data for 20 GC candidates of NGC 1407 were taken in October 2003 at the Keck I telescope, using LRIS-B in multi-object mode with 0.8 arcsec width slits. The total exposure time for the GC candidates was 7 hours. In addition, a 15 min, long-slit spectrum along the major axis of NGC 1407 was obtained and, for calibrating purposes, 5 Lick/IDS template stars (Worthey *et al.* 1994) and spectro-photometric standard stars were observed using the same configuration. Optical spectra in the range $\sim 3400-5800$ Å were obtained for all the above targets, achieving an overall spectral resolution (full width at half maximum; FWHM) of 3.7Å.

A standard reduction procedure for spectroscopic data was carried out with $\mathrm{R_ED^{uc}_mE}$ (Cardiel 1999) to perform a parallel treatment of data and error frames throughout the whole reduction process.

3. Stellar populations and chemical enrichment of GCs in NGC 1407

Ages, metallicities, and [α/Fe] ratios have been derived for the GCs and the integrated galaxy spectrum making use of the model predictions by Maraston, Thomas & Bender (2003) and Thomas, Maraston & Korn (2004) for the Lick/IDS indices of single stellar populations.

Figure 1 presents several diagnostic diagrams involving $H\gamma_A$, Mg*b*, <Fe>, [MgFe]', and the main C and/or N dependent Lick indices: CN_2, C_24668 and G4300. Lines correspond to the above model predictions at either constant [α/Fe] (+0.3 dex; panel *a*; varying age and metallicity as given in the labels) or constant age (11 Gyr; panels $b-f$; varying metallicity and [α/Fe]). The $r_{\rm eff}/8$ central spectrum of NGC 1407 is indicated as a filled star. Asterisks correspond to the sample of 41 Galactic GCs of Schiavon *et al.* (2005) and the rest of symbols (circles and triangles) are GCs in NGC 1407: MP GCs ($B-I<1.87$; black-filled symbols) and MR GCs ($B-I>1.87$; open and grey-filled symbols).

In the light of panel *a*, all GCs studied in NGC 1407 look clearly old and follow a tight metallicity sequence that reaches values above solar. The above statement is confirmed by the old ages inferred from all the Balmer Lick indices ($\sim 11\pm2$ Gyr) for most GCs (circles), except for 3 GCs with mean, formal ages of $\sim$ 4 Gyr (triangles). However, when applying the spectral diagnostic proposed by Schiavon *et al.* (2004) to detect blue horizontal branch (BHB) effects in the integrated spectrum of GCs, we find these 3 *young* candidates to be consistent with being old GCs hosting either BHB stars or a significant population of blue-straggler stars.

As regards to element abundance ratios, in panel *b* we find GCs to pose mean [Mg/Fe] ratios of ~ 0.3 dex. There exists, however, a subset of MR GCs that exhibit higher [Mg/Fe] values (~ 0.5 dex; open circles; hereafter αGCs) as compared to the rest of MR GCs (grey-filled symbols). Interestingly, a similar systematic difference in [C/Fe] between both MR GC subsets is reported in panel *c* from C_24668. This is the first evidence for a correlation

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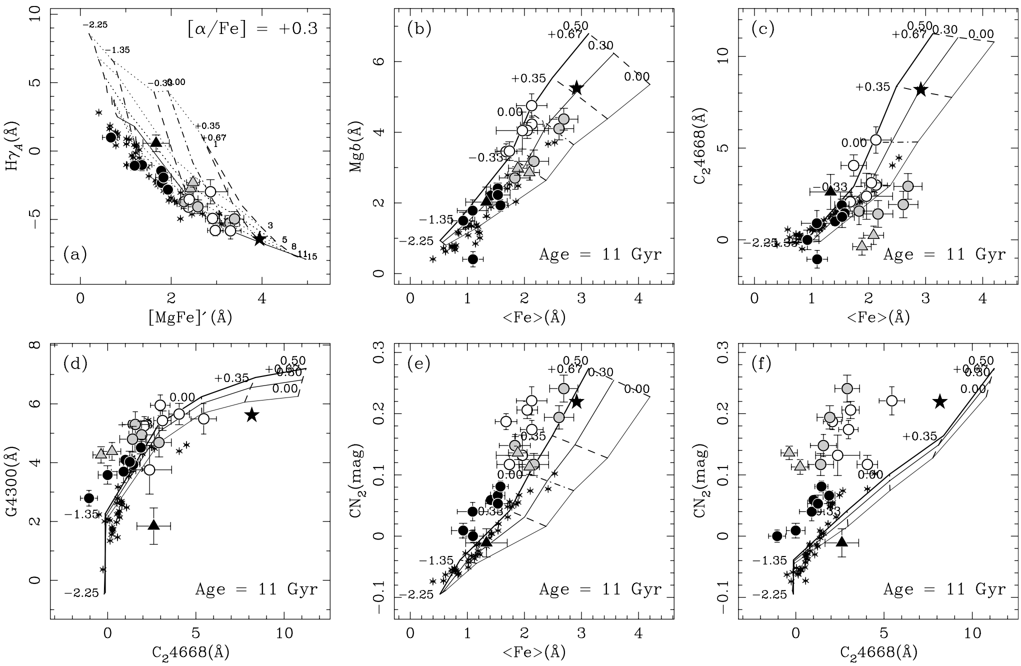

Figure 1. Some age, metallicity and element abundance ratio diagnostic diagrams constructed on the basis of Lick indices. See details in the text.

between Mg and C abundances among extragalactic GCs. Since αGCs also populate the high-metallicity regime of the C-sensitive diagram in panel d (G4300 – $C_2$4668), the possibility that such high [Mg/Fe] and [C/Fe] ratios could be just driven by a Fe depletion is ruled out. Different star-formation time-scales could be driving the dichotomy in the observed [Mg/Fe] and [C/Fe] ratios. If this were the case, a non-negligible amount of the present-day C content of MR GCs in NGC 1407 could be supplied by massive stars during relatively short star formation time-scales, although intermediate-mass stars could also be responsible for such a high C content as far as star formation in αGCs were brief enough to prevent Fe to incorporate into the newly formed stars.

On the basis of the CN bands (CN_2; panel e), which are known to be mainly driven by the N abundance, we find a striking N enhancement all over the GC metallicity range. The behavior of N and C ($C_2$4668) in MP GCs clearly departs from the one exhibited by MR GCs (panel f): for MR GCs, N increases drastically at the time that C essentialy saturates –thus becoming depleted as compared to the model predictions–, what may be interpreted as a consequence of the increasing importance of the CNO cycle with the increasing metallicity. The above observational constrains suggest that MP GCs could form from a relatively metal-free ISM with no apparent C depletion, as the CNO cycle requires the prior existence of C for it to be effective. The CNO cycle would be carried out during their evolution, thus eventually affecting the C and N of some giant stars and, more importantly, polluting the ISM with enhanced N and depleted C for subsequent star formation. MR GCs would form from such an enriched ISM that preserves the previous CNO products. Pollution during the early star formation history of the cluster could indeed contribute to the C–N anticorrelation as well as increasing the variety of [N/C] values among MR GCs.

Overall, the data presented in this work support the idea that element enrichment in MP GCs might be driven by a more standard mechanism whilst MR GCs may have undergone a wider variety of enrichment histories.

Concerning different GC formation scenarios, the old ages inferred for the GCs in NGC 1407 are consistent with the idea that both MP and MR GC subpopulations in massive Es could be formed at high redshift (Strader *et al.* 2005). Unfortunately, it is not clear whether the MR subpopulation is a few gigayears younger than the MP one, as BHB effects, different age-dating techniques, systematics of the models, and typical uncertainties in the data may blur the derived results. Larger samples of high-quality GC spectra are strongly demanded to address, from a reliable, statistical point of view, the epochs of GC formation in the Universe.

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Discussion

Trancho: It surprises me that you find a clear overabundance of α elements in your GC sample whilst, in my data of merging/interactive galaxies, most GCs h ave solar abundance ratios.

Cenarro: This is probably due to the fact that the star formation histories of merging/interactive galaxies are indeed very different to that of NGC1407. Since most GCs in your merging galaxies are young, thus associated to the merger episode, the interestellar medium out of which these GCs were formed had probably time to incorporate Fe as well as other by-products of previous type Ia supernovae. NGC1407 is, however, a massive, old, typical elliptical galaxy that presumably formed the bulk of its stars and GCs in a very short time-scale at high redshift.

Thomas: Your very high quality data sit very nicely on the SSP models in the Balmer-metal-index plane. Whenever they are below (as often the case) is most likely a problem with the data rather than the models.

Cenarro: The quality of the data set is indeed unique, with with Galactic globular clusters in the Balmer – metal index planes, so it is understanadable the agreement with your models as they are calibrated on the basis of the Milky Way globular clusters. However, I still think the models lack of a complete understanding of the old-aged regime, as there are objects like 47Tuc that cannot be normally matched by the model predictions.

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