Star Clusters: From the Milky Way to the Early Universe
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A deep view into the nucleus of the Sagittarius dwarf spheroidal galaxy: M54

M. Alfaro-Cuello[1], N. Kacharov[1], N. Neumayer[1], A. Mastrobuono-Battisti[1], N. Lützgendorf[2], Anil C. Seth[3], T. Böker[2], S. Kamann[4], R. Leaman[1], G. van de Ven[5], P. Bianchini[6], L. L. Watkins[5,7] and M. Lyubenova[7]

[1]Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[2]European Space Agency, c/o STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA
[3]University of Utah, Salt Lake City, UT 84112, USA
[4]Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, United Kingdom
[5]University of Vienna, Türkenschanzstrasse 17, 1180 Wien, Austria
[6]Observatoire Astronomique de Strasbourg, CNRS, UMR 7550, F-67000 Strasbourg, France
[7]European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
email: alfaro@mpia.de

Abstract. Nuclear star clusters hosted by dwarf galaxies exhibit similar characteristics to high-mass, metal complex globular clusters. This type of globular clusters could, therefore, be former nuclei from accreted galaxies. M54 resides in the photometric center of the Sagittarius dwarf galaxy, at a distance where resolving stars is possible. M54 offers the opportunity to study a nucleus before the stripping of their host by the tidal field effects of the Milky Way. We use a MUSE data set to perform a detailed analysis of over 6600 stars. We characterize the stars by metallicity, age, and kinematics, identifying the presence of three stellar populations: a young metal-rich (YMR), an intermediate-age metal-rich (IMR), and an old metal-poor (OMP). The evidence suggests that the OMP population is the result of accretion of globular clusters in the center of the host, while the YMR population was born in-situ in the center of the OMP population.

Keywords. M56 (NGC 6751)

1. Introduction

Nuclear star clusters (NSCs) are the densest stellar systems in the Universe, with masses between $10^5 - 10^8$ $M_\odot$ and half-light radii of $1 - 10$ pc (e.g., Georgiev *et al.* 2016). They reside at the centers of over 70% of galaxies across the entire Hubble sequence (e.g., Georgiev *et al.* 2016). NSCs of galaxies in the low-mass regime present similar characteristics to high-mass, metal-complex globular clusters (GCs). Thus, the most massive GCs are possibly former nuclei from tidally disrupted dwarf galaxies (Böker 2008; e.g., ω Centauri, which is presumed to be the remaining nucleus of a now accreted galaxy, Bekki & Freeman 2003). In this context, M54, the nucleus of the Sagittarius dwarf galaxy (Sgr dSph) presents a unique opportunity to study this connection and to understand nucleation in low-mass galaxies.

M54 is the closest extragalactic NSC, at a distance where we can resolve individual stars. It still resides in the center of its host, offering insights on NSCs before their host is tidally stripped. Previous studies, with which we found consistent results, have identified stars in two metallicity regimes via photometric and spectroscopic analysis

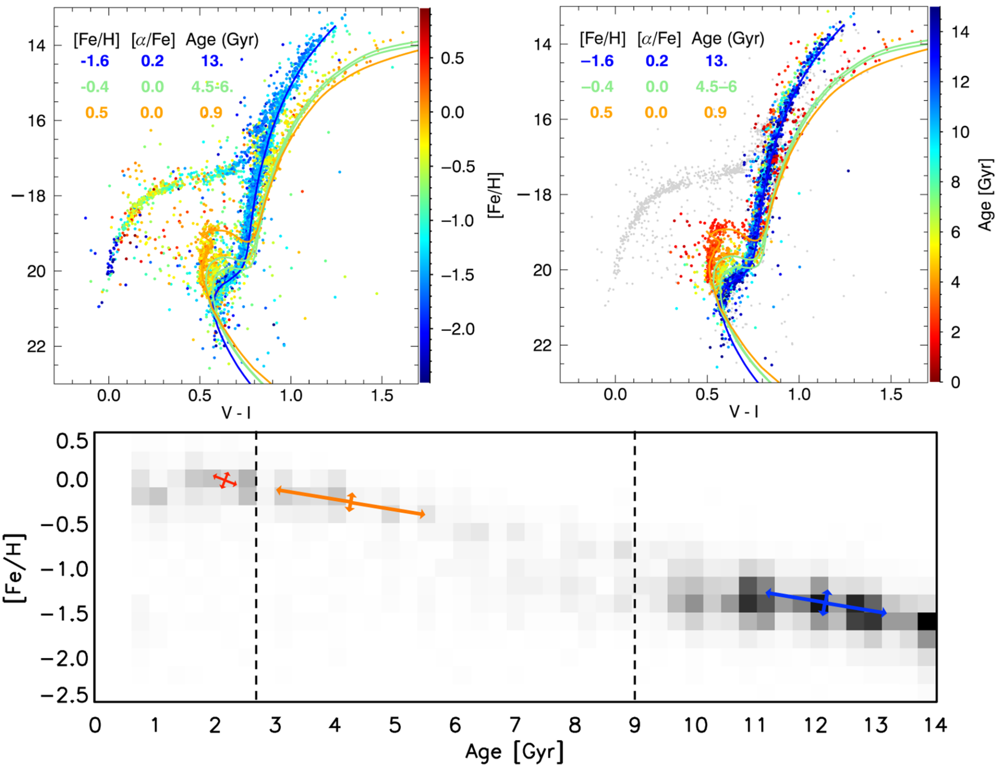

Figure 1. Top panels: Color-magnitude diagram of M54 member stars color-coded by metallicity (left) and age (right). Bottom panel: Density plot of the age-metallicity relation. The crosses show the intrinsic spread of the different stellar populations in both age and metallicity: YMR in red, IMR in orange, and OMP in blue ©AAS. Figure from Alfaro-Cuello *et al.* 2019.

pointing toward the complexity of this cluster (e.g., Monaco *et al.* 2005a,b; Siegel *et al.* 2007; Bellazzini *et al.* 2008; Carretta *et al.* 2010a,b; Mucciarelli *et al.* 2017).

2. Stellar population characterization

We extracted individual stellar spectra of more than 6 600 member stars from a large Multi-Unit Spectroscopic Explorer (MUSE) data set, which covers out to ~ 2.5 times the effective radius of M54; $R_{HL} = 0.82'$ (Harris 1996, 2010 updated) ~ 6.38 pc at a distance of 26.7 kpc (Sollima *et al.* 2010). We measured the spectroscopic metallicities, which we used together with *HST* photometry to derive the ages of the stars via isochrone fitting. In the top panels of Fig. 1 we present the color-magnitude diagrams color-coded by metallicity (left) and age (right). In the bottom panel of Fig. 1, we present the density plot of the age-metallicity relation from which we disentangled the presence of (at least) three stellar populations. The three populations have significant spreads in metallicity and age: young metal rich (YMR; 2.2 Gyr, [Fe/H]$= -0.04$); intermediate age metal rich (IMR; 4.3 Gyr, [Fe/H]$= -0.29$); and old metal poor (OMP; 12.2 Gyr, [Fe/H]$= -1.41$).

Additionally, we found that the YMR population is the most centrally concentrated, followed by the OMP. The IMR is the least concentrated population but it is still centrally peaked. We estimated the ellipticities of the populations, finding that the YMR is the most flattened one, followed by the OMP.

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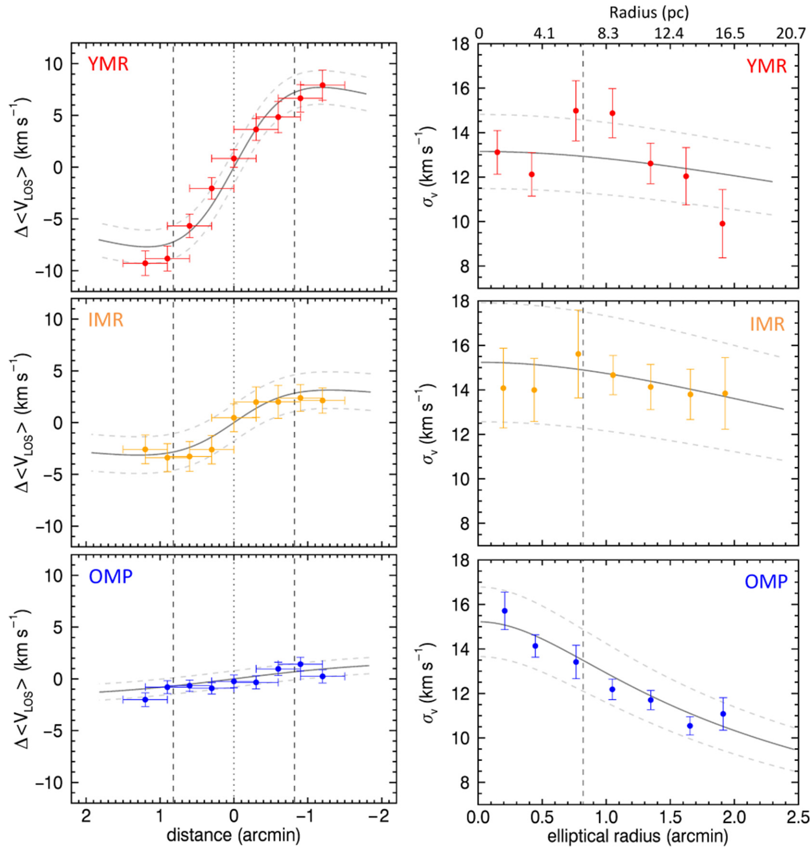

Figure 2. Rotation (left) and velocity dispersion (right) profiles for the three populations: YMR (top), IMR (middle), and OMP (bottom). Solid and dashed lines show the median of the best fit models and the $\pm 1\sigma$ uncertainty, respectively.

3. Kinematics

We measured the kinematics of the three stellar populations. The three populations have consistent line-of-sight velocities of ~ 141 km s^{-1}, supporting the idea they are in spatial coincidence (see also Bellazzini *et al.* 2008). We measure the rotation and dispersion properties simultaneously for each of the populations, using a discrete Bayesian approach similar as described in Cordero *et al.* (2017) and Koch *et al.* (2018). In Fig. 2 we present the rotation (left) and velocity dispersion (right) profiles of the YMR (top), IMR (middle), and OMP (bottom) populations separately. While we detect only a weak signal of rotation for the stars of the OMP population (< 1 km s^{-1}), the YMR population shows a very high amount of rotation (~ 7 km s^{-1}), followed by the IMR population, which also rotates but with a lower velocity. The velocity dispersion profile of the OMP population drops rapidly with radius, as observed for GCs. The YMR and IMR populations follow nearly flat velocity dispersion profiles (see also Bellazzini *et al.* 2008).

The OMP population seems to rotate slower than other GCs with similar degree of flattening (e.g., ω Cen). We performed N-body simulations emulating the OMP-YMR system in M54. We find that after 2 Gyr of evolution, the in-situ formed, rotating and flattened YMR population loses part of its angular momentum, which is then acquired by the OMP, thus increasing its degree of flattening. The observations in the OMP population might be due to the result of a merger of GCs (to explain the large spread

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in both metallicity and age), and/or the effects from the formation and evolution of the embedded YMR population. Further and more detailed simulations are needed to confirm these effects.

4. Conclusion and outlook

The different characteristics and kinematics among the three populations suggest that they do not have a common origin. Combining the stellar characterization and kinematic information of the three populations, we conclude the following:
(i) Considering the large spread in both age and metallicity, the OMP population might be the remnant of the merger of two or more GCs that spiraled into the center of the galaxy via dynamical friction. (ii) The gas retained in the potential well of M54 allowed the in-situ formation of the YMR population, resulting in a more centrally concentrated and more flattened structure as observed in the Milky Way. (iii) The IMR population is consistent with the characteristics of the Sgr dSph field stars, thus it is part of the galaxy's inner star formation history, however, we cannot discard they are dynamically bound to the other populations.

From these findings, we have observational evidence that the built-up of what we observe today as M54 took place both through: (i) the infall of two or more GCs, accreted to form a single high-mass, metal complex cluster with a significant spread in both metallicity and age (OMP), and (ii) the in-situ star formation from enriched gas (YMR).

M54 is a unique case of study, providing valuable information on low-mass galaxy nucleation, where the knowledge is limited due to the complexity and instrumental limitations to observe NSCs in dwarf galaxies.

Following up with this study, we are currently performing discrete Jeans dynamical modeling of M54. The M54 MUSE data set is being complemented with new data acquired using the MUSE narrow-field mode. This covers its innermost 3", inside the sphere of influence of the putative intermediate mass black hole in the center of M54 (10^4 $M_{\odot}$, Ibata *et al.* 2009). With the chemical information of the different stellar populations we are able to perform chemo-dynamical modeling (see Zhu *et al.* 2016a,b) to constrain the contribution of each of the populations.

References

Alfaro-Cuello, *et al.* 2019, *ApJ*, 886, 57
Bekki, K. & Freeman, K. C. 2003, *MNRAS*, 346, L11
Bellazzini, M., Ibata, R. A., Chapman, S. C., *et al.* 2008, *AJ*, 136, 1147
Böker, T. 2008, *ApJL*, 672, L111
Carretta, E., Bragaglia, A., Gratton, R. G., *et al.* 2010a, *A&A*, 520, A95
Carretta, E., Bragaglia, A., Gratton, R. G., *et al.* 2010b, *ApJL*, 714, L7
Cordero, M. J., Hénault-Brunet, V., Pilachowski, C. A., Balbinot, E., Johnson, C. I., & Varri, A. L. 2017, *MNRAS*, 465, 3515
Georgiev, I. Y., Neumayer, N., Lützgendorf, N., Böker, T., & Leigh, N. 2016, *MNRAS*, 457, 2122
Harris, W. E. 1996, *VizieR Online Data Catalog*, 7195
Ibata, R., Bellazzini, M., Chapman, S. C., Dalessandro, E., Fer, *et al.* 2009, *ApJ*, 699, L169
Koch, A., Hanke, M., & Kacharov, N. 2018, *A&A*, 616, A74
Monaco, L., Bellazzini, M., Bonifacio, P., Ferraro, F. R., Marconi, G., *et al.* 2005a, *A&A*, 441, 141
Monaco, L., Bellazzini, M., Ferraro, F. R., & Pancino, E. 2005b, *MNRAS*, 356, 1396
Mucciarelli, A., Bellazzini, M., Ibata, R., *et al.* 2017, *A&A*, 605, A46
Sollima, A., Cacciari, C., Bellazzini, M., & Colucci, S. 2010, *MNRAS*, 406, 329
Siegel, M. H., Dotter, A., Majewski, S. R., *et al.* 2007, *ApJL*, 667, L57
Zhu, L., van de Ven, G., Watkins, L. L., & Posti, L. 2016a, *MNRAS*, 463, 1117
Zhu, L., Romanowsky, A. J., van de Ven, G., *et al.* 2016b, *MNRAS*, 462, 4001

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