Early Disk-Galaxy Formation from JWST to the Milky Way
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The Curious Stellar System M22

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Abstract. In the context of hierarchical galaxy assembly, globular clusters and dwarf galaxies are indispensable probes of the formation of our Milky Way. M22 is a stellar system with chemical abundances reminiscent of an accreted dwarf galaxy such as ω Centauri but disc-like kinematics suggesting a Milky Way origin. Curiously, M22 contains a population of stars enhanced in slow neutron-capture (s-)process elements due to pollution from low-mass AGB stars. Recently, the original in-situ population stars of the Milky Way disc has been revealed to be enhanced in s-process elements. This provides a tantalizing link between the in-situ Milky Way population and the formation of M22. This talk discussed how recent high-precision chemical abundance measurements suggest that M22 may be coeval with this in-situ component, and what the formation mechanisms of this s-process population can tell us about the chemical evolution of our Galaxy before the establishment of the disc.

Keywords. (Galaxy:) globular clusters: general, stars: abundances

1. The Milky Way's childhood as traced by globular clusters

Globular clusters (GCs) are among the most captivating and enigmatic objects in our Milky Way (MW). Forged in the early Universe, these objects trace the tumultuous lives of Galaxies from their childhood to the present day. They have allowed astronomers to quantify the number of accreted systems in the MW which has far-reaching consequences for understanding the assembly and evolution of our Galaxy (e.g. Freeman & Bland-Hawthorn 2002). Accretion events such as the *Gaia*-Enceladus/Sausage system (e.g. Belokurov et al. 2018), Sequoia system (e.g. Myeong et al. 2019) or the Helmi stream (e.g. Helmi et al. 1999) each contributed their own cohort of star clusters, which have now integrated themselves into the MW own in-situ population of clusters. However, our Galaxy hosts a population of imposter globular clusters; ones that show anomalous Na-O anti-correlations and have pronounced iron and other heavy element abundance spreads. It has been hypothesised that these clusters may have originated as dwarf galaxies or as the nuclear star clusters (NSC) of these accreted structures (Da Costa 2016). Many efforts have gone into linking these structures with their NSCs (for a recent summary, see Pfeffer et al. 2021) and the study of the chemical homogeneity of heavy elements in GCs is an active field (McKenzie & Bekki 2018, 2021; Legnardi et al. 2022).

Two of the most massive star clusters in our night sky, ω Centauri and 47 Tucanae, are premiere examples of NSC and in-situ GCs, respectively. A small but growing number of Galactic GCs exhibit a star-to-star variation in the relative abundances of the heavy elements. ω Centauri is the most prominent member of this group with its stars spanning a range in metallicity from $[\mathrm{Fe/H}] \simeq -2.0$ dex to $[\mathrm{Fe/H}] \simeq -0.5$ dex for certain elements. Additionally, the abundance ratios with respect to iron exhibit considerable variations with metallicity (e.g. Johnson & Pilachowski 2010).

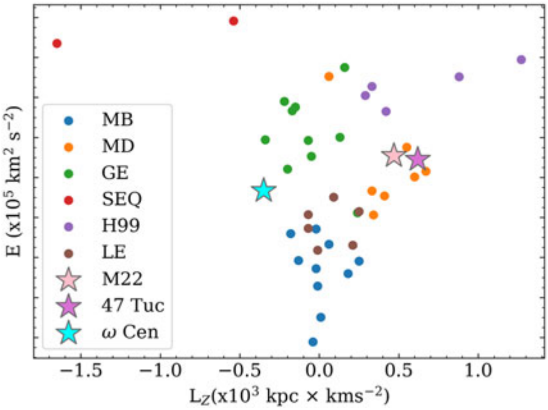

Figure 1. Orbital energy and vertical action as a function of orbital azimuthal action taken with permission from Horta et al. (2020) for the GCs in their sample. Kinematic associations are from Massari, Koppelman, & Helmi (2019) where MB is the main bulge, MD is the main disc, GE is the *Gaia* Enceladus accretion event, SEQ is the Sequoia accretion event, H99 is the Helmi stream and LE is the low energy group. M22 sits among the main disc population, in a similar space to 47 Tuc. The NSC ω Cen is among the accreted populations.

ω Centauri hosts abundance spread across all well-measured elements and its retrograde orbit is a hallmark sign of its accreted origin. In contrast, 47 Tucanae shows the stereotypical Na-O anticorrelation ubiquitous to GCs and is homogeneous across heavy elements (however, even this assumption is beginning to break down; see Legnardi et al. 2022 and references therein). Further cementing its status as a true MW GC, it has a circular, prograde orbit confined to the disc.

2. The dichotomy of a disc-like cluster with nuclear star cluster-like abundances

M22 is a wonderful contradiction of a cluster with NSC-like chemical abundances and disc-like kinematics. In the plot of orbital energy and vertical action as a function of orbital azimuthal action space in Fig. 1 from Horta et al. (2020), M22 sits in the region associated with the main disc of the MW, in a very similar location to our in-situ cluster 47 Tucanae. For comparison, the NSC ω Centauri is found on the other side of the diagram with the accreted structures.

An analysis of the metallicity distribution shows that M22 clearly contains iron abundance variations. Using data from Marino et al. (2011), the metallicity distribution function is plotted in Fig. 2. The iron abundance variation is a key characteristic shared with ω Centauri but absent in the majority of clusters (e.g. see Carretta et al. 2010), albeit with a smaller range than that found in ω Centauri (the iron abundance spread in ω Centauri' is ∼ 4 times larger than in M22).

This raises the question of whether M22 is a disc cluster like 47 Tucanae or a NSC like ω Centauri.

3. The s-process rich population

Using a technique known as differential analysis, which has proven to be incredibly successful at minimising systematic errors, McKenzie et al. (2022) verified that M22 contains a bonafide iron abundance spread, but also has the unique characteristic of containing two slow neutron capture elements (*s*-)process element groups (See Fig. 3).

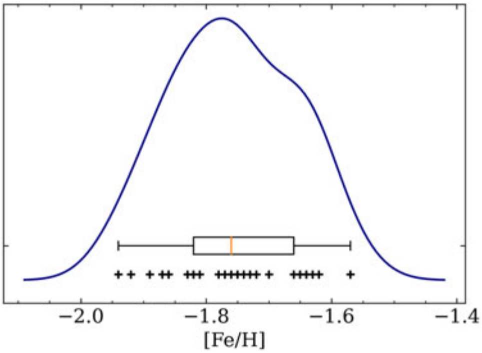

Figure 2. The metallicity ([Fe/H]) distribution function of M22 using abundances from Marino et al. 2011 and assuming an error of 0.05 dex. The actual [Fe/H] values are shown at the bottom with + markers, along with the corresponding box plot. These abundances suggest that there is almost a 0.4 dex spread in [Fe/H] in this cluster.

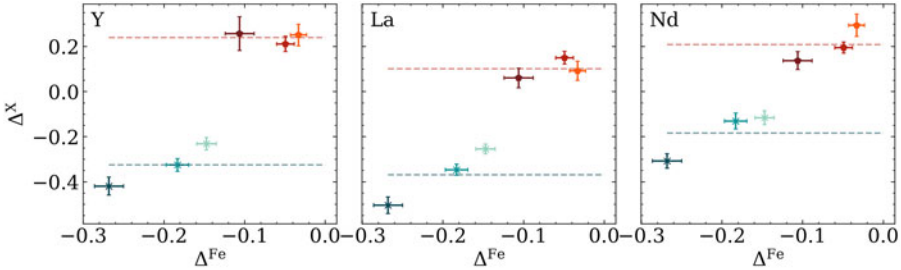

Figure 3. High precision differential abundances for the *s*-process population analysed in McKenzie et al. (2022). Δ^{Fe} notation is analogous to the square bracket notation [Fe/H] but compared to a reference star with similar stellar parameters. The blue points are from the *s*-process poor population, and the red points are from the *s*-process rich population. The dashed horizontal line denotes the average value for each population. For all elements, the abundance variations are larger than the differential errors, illustrating that this cluster harbours a genuine *s*-process element and Fe abundance spread.

Asymptotic giant branch (AGB) stars are one of the most obvious culprits for this effect, and Shingles et al. (2014) and Straniero, Cristallo, & Piersanti (2014) both concluded that the mass limits on AGB stars which generated these *s*-process abundance variations range from 3-6 $M_\odot$. Using an innovative approach, McKenzie et al. *(in prep)* utilised Magnesium isotope ratios to further constrain this mass range. It was found that only the low-mass AGB stars with ∼3 $M_\odot$ can reproduce the Mg isotopic patterns while satisfying the *s*-process difference between the two groups.

4. Is M22 a baby tooth of the Milky Way?

The creation of a disc-like cluster with NSC-like abundances lends itself to speculation about its formation scenario. Could M22 have formed through merging two individual clusters at very similar metallicities or could it have been a true NSC that was accreted onto the MW on a remarkably disc-like orbit? Or as an alternative suggestion, could M22 be the baby tooth of the MW?

To elaborate on this, we refer to the work from Belokurov & Kravtsov (2022) which introduced the discovery of the original in-situ component of the MW, dubbed Aurora. In a follow-up study, Myeong et al. (2022) analysed the *s*-process content of Aurora and found that it has a larger spread than any of the other analysed components. This spread is reminiscent of the *s*-process population in M22, with similar degrees of variation to what was recorded by McKenzie et al. (2022). Thus perhaps M22 formed alongside these original in-situ MW stars in a high-density region of the proto-MW and then like a *baby tooth*, "fell out" and survived the formation of the disc. If this scenario is correct, this implies that the *s*-process abundance enhancement in Aurora can be attributed to low-mass ∼3 $M_\odot$ AGB stars, as in M22. Future work intends to investigate this tantalising connection further by performing Mg isotopic analysis of accreted and in-situ stars to note any similarities between each population and M22. Furthermore, high-precision differential abundance measurements of Aurora stars will help uncover further similarities between Aurora and M22. Until then, M22 will continue to exist as just another enigma of our Galaxy.

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