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THE EARLY AND LATE EVOLUTION OF OUR GALAXY THROUGH THE LENS OF GLOBULAR CLUSTERS

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Abstract. Within the ΛCDM paradigm of hierarchical galaxy formation, reconstructing the accretion history of the Milky Way has become a central pursuit, recently boosted by Gaia data, spectroscopic surveys, and numerical simulations. Globular clusters (GCs), as ancient stellar systems mainly located in the halo, play a key role in this effort. Traditionally, accreted systems have been identified through integrals of motion, such as orbital energy and angular momentum, under the assumption that they remain conserved over time. To test this, we analysed N-body simulations of one or more satellites merging with a Milky Way-like galaxy, each bringing its own GC population. The results indicate that accreted clusters do not form distinct groupings in integrals of motion space and overlap strongly with dynamically heated in-situ clusters, questioning the reliability of purely dynamical approaches. Motivated by these findings, we focused on the chemical links between GCs, identifying the ones that are chemically similar to ω Centauri (NGC 5139) — a peculiar system long suspected to be the remnant core of an accreted dwarf galaxy, which may have contributed its own cluster population to the Milky Way. To this end, we applied a Gaussian Mixture Model to a multi-dimensional set of elemental abundances provided by APOGEE DR17. Our analysis revealed, in addition to ω Centauri itself, six globular clusters containing significant fractions of stars chemically compatible with ω Centauri. We propose that these clusters may have been introduced into the Milky Way by the progenitor galaxy of ω Centauri, referred to as *Nephele*. Because the origin and evolution of globular clusters are closely tied to those of the field stars belonging to the same parent galaxy, this result naturally motivates extending our approach to search for *Nephele* field stars dispersed into the Milky Way's field due to the tidal forces.

Keywords: Methods : N-body simulations, data analysis, Galaxy : Stellar populations, Galaxy evolution

1 Introduction

The Milky Way (MW) consists of a disc, a diffuse oblate halo, and a central bulge-bar, each hosting stellar populations with different ages, chemical abundances, and kinematics. Galactic Archaeology seeks to reconstruct how these structures assembled by examining the properties of their stars. In the framework of the ΛCDM paradigm, galaxy formation is hierarchical: small systems merge over cosmic time to build the massive galaxies observed today (White & Rees 1978). The Milky Way illustrates this process, with its stellar halo offering a unique record of its formation and assembly. Globular clusters (GCs) are particularly valuable in this respect: older than 10 Gyr, they formed in the early Universe together with their parent galaxies and thus trace the hierarchical formation of galaxies. Such accretion events can contribute both field stars and globular clusters to the Galactic system (Peñarrubia et al. 2009), implying that today's cluster population is a mixture of in-situ and accreted objects. Reconstructing past accretion events, however, remains difficult: after a few billion years, disrupted satellites disperse and lose their spatial coherence, no longer appearing as distinct stellar over-densities in the sky, unlike ongoing mergers.

Following the publication of Gaia DR2 (Gaia Collaboration et al. 2018), numerous studies have sought to distinguish between accreted and in-situ Galactic globular clusters using their distribution in kinematic spaces, most commonly the energy-angular momentum plane (E-L_z). This method assumes that accreted clusters

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preserve a degree of dynamical coherence long after accretion, appearing as groupings in kinematic space, and that each group corresponds to a different merger event (Helmi & de Zeeuw 2000). Based on this idea, clusters in separate regions of the E-L_z space have been associated with different progenitors (e.g. Massari et al. 2019). In Pagnini et al. (2023) we used N-body simulations of satellite mergers with a MW-like galaxy to test whether accreted globular clusters can be identified through kinematics. We found that clusters from the same progenitor do not necessarily group in the E-L_z plane, that multiple accretions mix populations, and that in-situ clusters can be heated into halo-like orbits.

To address these challenges, we shifted to a chemical approach, using recent spectroscopic data of Galactic globular clusters to search for shared signatures in abundance space, based on the principle that stars and clusters inherit the chemistry of their birth environment. We initiated this investigation with one of the Galaxy's most enigmatic clusters, NGC 5139 better known as ω Centauri. More details about this work can be found in Pagnini et al. (2025).

2 Nephele: the accretion event of ω Centauri

The globular cluster ω Centauri stands out as the most massive Galactic cluster ($\sim 3.5 \times 10^6 M_\odot$), showing pronounced a peculiar kinematics (e.g. van de Ven et al. 2006; Bianchini et al. 2013; Kamann et al. 2018; Pechetti et al. 2024), and stars with wide metallicity and chemical abundance spreads (see for example Johnson & Pilachowski 2010; Pancino et al. 2011; Marino et al. 2011; Nitschai et al. 2023), as well as a possible age range (Villanova et al. 2014). These complexities suggest a formation history unlike typical clusters. It has therefore been proposed that ω Cen is the stripped nucleus of an accreted dwarf galaxy of $\sim 10^8 M_\odot$, whose envelope and dark matter halo were removed by the MW's tides (e.g. Bekki & Freeman 2003). Such a merger would have contributed significantly to the Galaxy's early mass growth and likely introduced a system of additional globular clusters, raising the question of how many of these survive today and where they are located.

2.1 Data & methods

For this study, we have made use of data from the APOGEE Value Added Catalogue (VAC) of Galactic GC stars (see Schiavon et al. 2023). The catalogue comprises a total of 7737 entries for 6422 unique stars associated with 72 Galactic GCs and contains full APOGEE DR17 information (Abdurro'uf et al. 2022) including radial velocities and abundances for up to 20 elements. As in Horta et al. (2023), among these stars, only those satisfying the following criteria have been used for this study: a signal-to-noise ratio `SNREV` > 70, temperatures in the range $3500\,\mathrm{K} < \mathrm{T_{eff}} < 5500\,\mathrm{K}$, surface gravities logg < 3.6, `APOGEE STARFLAG` and `APOGEE STARBAD` $= 0$, and stars that have, according to Vasiliev & Baumgardt (2021), a high probability of being members of the cluster (`VB_PROB` ≥ 0.9).

To assess the chemical compatibility of globular clusters with ω Cen, we applied a Gaussian Mixture Model (GMM) in an eight-dimensional abundance space defined by [Fe/H], [Mg/Fe], [Si/Fe], [Ca/Fe], [C/Fe], [Al/Fe], [K/Fe], and [Mn/Fe]. We fitted the distribution of ω Cen in this space with multiple Gaussian components and identified five as the optimal number via the Bayesian information criterion. For each cluster, we then computed the fraction of stars consistent with the ω Cen GMM distribution, repeating the procedure with 100 bootstrap realisations and Monte Carlo sampling of abundance uncertainties to estimate errors. Compatibility was defined as the fraction of stars with log-likelihood values above the 5th percentile of ω Cen's distribution, which served as our reference sample, while stars below this threshold were classified as outliers.

2.2 The globular cluster population accreted with ω Cen

Apart from ω Cen itself, our analysis allowed us to identify six GCs - namely, NGC 6752, NGC 6656, NGC 6809, NGC 6273, NGC 6205, and NGC 6254 - that have a high fraction of stars compatible with ω Cen. We suggest that these clusters have potentially been brought into the MW by the progenitor of ω Cen, referred to as *Nephele*, the mother of Centaurs. We have divided these clusters into two classes - the metal-poor (NGC 6656, NGC 6809, and NGC 6273) one and the metal-rich one (NGC 6752, NGC 6205, and NGC 6254) - as these two groups share other features in addition to the [Fe/H] range. Stars in the first group of clusters occupy regions of abundance space overlapping with the highest-density areas of ω Cen (see the example of NGC 6656 in top left and central panel of Fig. 1), indicating that they share the dominant chemical properties of its stellar population. Moreover, their MDFs all show a peak aligned with the main peak of ω Cen's MDF (see top right panel of Fig. 1). For the group of metal-rich GCs, the MDFs all peak at similar metallicities, but this feature

is not visible in the APOGEE MDF of ω Cen. Previous studies, however, have reported a secondary peak at [Fe/H] ~ -1.5 dex (e.g. Johnson & Pilachowski 2010), which may be absent in APOGEE due to limited coverage of the cluster's central regions. We therefore compare the ω Cen MDF from Johnson & Pilachowski (2010) with that of our sample of metal-rich clusters. The comparison is striking: these three GCs all have MDFs that peak at the same metallicity as the secondary maximum of the ω Cen MDF (as an example see NGC 6752 in bottom right panel of Fig. 1). The common chemical characteristics of ω Cen and the identified clusters imply that they did not evolve independently but instead share a closely connected enrichment history, tied to the chemical evolution of their progenitor galaxy, *Nephele*.

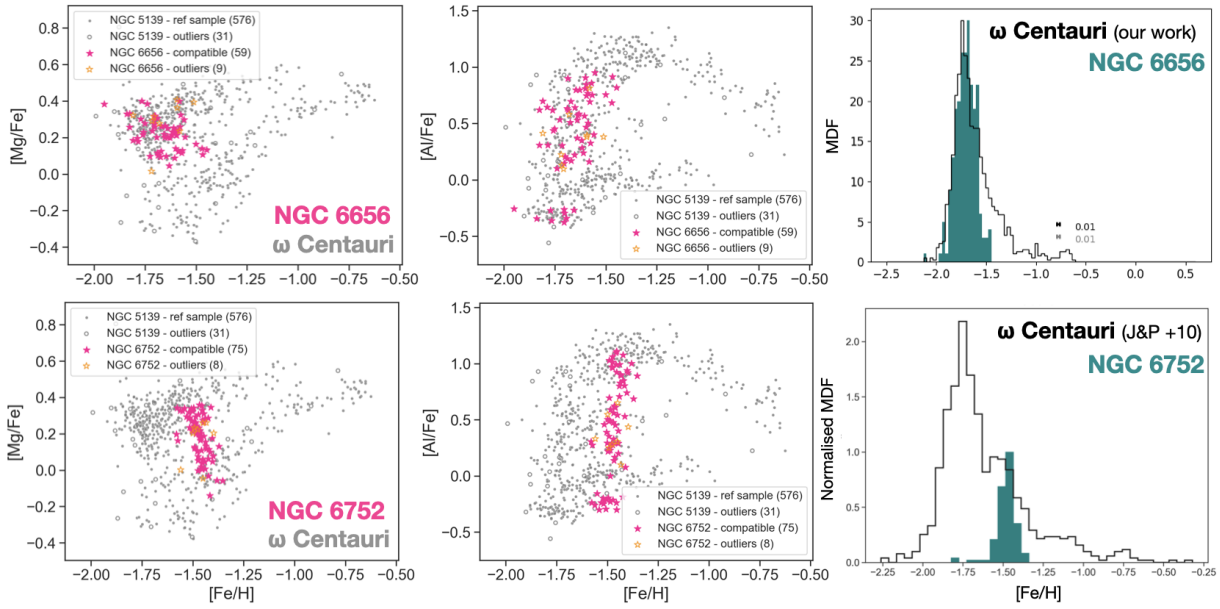

Fig. 1. [Mg/Fe], [Al/Fe] vs [Fe/H], and MDF of NGC 6656 (top row) and NGC 6752 (bottom row) compared to ω Cen.

2.3 Field stars of Nephele

Motivated by these findings, we extended our analysis searching for field stars that may be brought into the MW by the *Nephele* accretion event (Pagnini et al. to be submitted to A&A). The sample of field stars has been selected from the APOGEE catalogue as in Sect. 2.1, but this time removing the stars with `VB_PROB` ≥ 0.9 according to Vasiliev & Baumgardt (2021). After these selections, our final sample of field stars comprises 197265 stars. To assess the chemical compatibility of field stars with ω Cen, we applied the same GMM used in Pagnini et al. (2025) and described in Sect. 2.1. To account for the uncertainties in the abundances, we performed a bootstrap resampling of the data. For each star, we estimated a probability of compatibility with ω Cen by recording the fraction of bootstrap realisations in which the star satisfied the compatibility criteria. We retained only stars with probabilities greater than 0.7 as candidate members, yielding a final sample of 470 stars chemically compatible with ω Cen and the *Nephele* accretion event.

As we can see in the left panel of Fig. 2, both these stars and *Nephele*'s GCs are widely dispersed across the E-L_z space, suggesting that the accretion of ω Cen's progenitor was a relatively massive event ($\sim$ 1:10 mass ratio). To strengthen the link between these field stars and the streams of disrupted GCs, we applied a second filter by identifying stars with kinematics compatible with simulated streams of *Nephele*'s clusters. For this purpose, we used a library of simulations of Galactic GC streams*(Ferrone et al. 2023) and evaluated the compatibility through a GMM based on (E, L_z). In this way we identified 6 stars that have kinematics compatible with the stream of ω Cen, 9 with NGC 6656, 1 with NGC 6254, 2 with NGC 6089, 1 with NGC 6273, and 1 with NGC 6205 (see right panel of Fig. 2).

*`https://etidal-project.obspm.fr/`

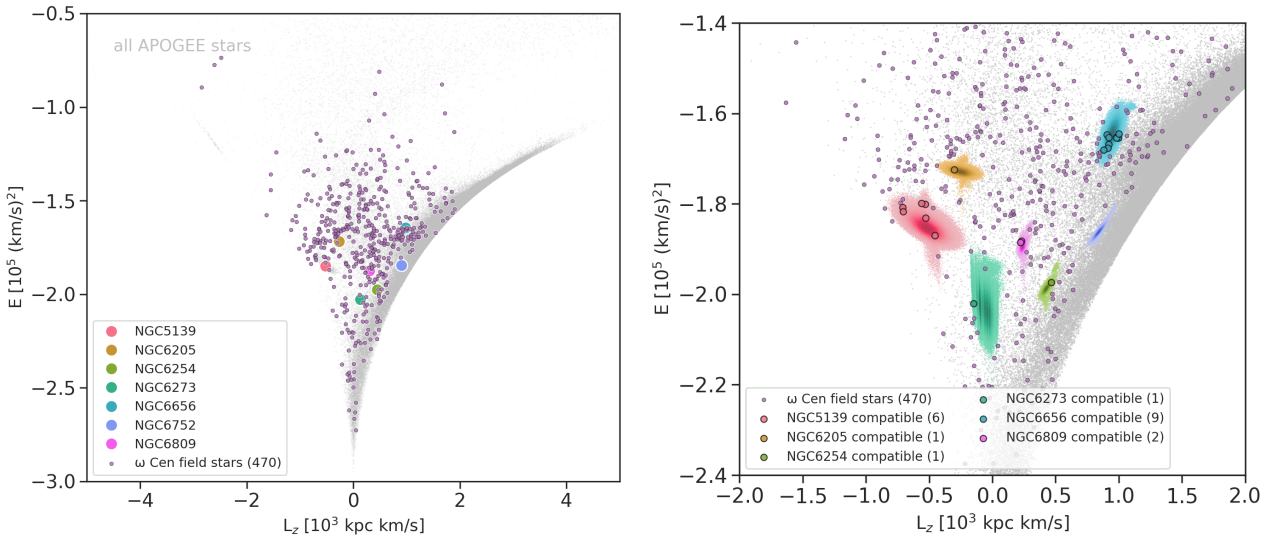

Fig. 2. Left: *Nephele*'s GCs (colour-coded) and field stars (violet) in the E-L_z space. **Right:** *Nephele*'s *simulated* GCs (coloured histograms) and field stars (violet), with kinematically compatible stars colour-coded by their associated GC.

3 Conclusions

Through a multidimensional chemical analysis, we identify six clusters as chemically compatible with ω Cen, linking them to a common disrupted progenitor galaxy *Nephele*. Applying the same method to field stars, we recover 470 *Nephele* candidates, a subset of which also displays kinematic consistency with simulated streams of its GCs, underscoring the significant imprint of this accretion event on the Milky Way.

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