

Revealing the Origins of Galactic Globular Clusters via Their Mg-Al Abundances

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ABSTRACT

Many Galactic globular clusters (GCs) originated in diverse host galaxies before being subsequently incorporated into the Milky Way through hierarchical galaxy assembly. Identifying their origins is crucial for revealing galaxy properties at early times. Traditional classification methods relying on dynamical properties face inherent uncertainties stemming from the evolving Galactic potential and complex merger histories. Chemically driven classification confronts a distinct obstacle: multiple populations — abundance variations in light elements of GC members. In this Letter, we identify primordial populations exhibiting lower [Al/Fe] as reliable tracers of their birth environments’ chemical evolution. A clear chemical dichotomy emerges between in-situ and accreted GC populations at [Fe/H] > −1.5, particularly in the [Mg/Fe]-[Al/Fe] plane, indicating that their progenitor galaxies have experienced fundamentally different enrichment histories. While our chemically driven classification demonstrates general consistency with dynamically driven classifications, notable discrepancies emerge: NGC 288 and M4 are reclassified as in-situ, and Terzan 9 as accreted. This chemically driven GC classification provides promising application for Galactic archaeology.

Keywords: Galaxies (573) — Globular star clusters (656) — Chemical abundances (224)

1. INTRODUCTION

According to the Lambda cold dark matter model, galaxies in our Universe formed hierarchically. Our Milky Way (MW) aligns with this cosmological framework, having undergone successive mergers and accretions of smaller dwarf galaxies (R. A. Ibata et al. 1994; M. Unavane et al. 1996). Globular clusters (GCs), among the oldest stellar systems in galaxies, exhibit ages comparable to their host galaxies (M. A. Beasley et al. 2002; J. P. Brodie & J. Strader 2006). While dwarf galaxies were predominantly disrupted during merger events, their high-density GCs could survive these interactions. Consequently, the present-day Galactic GC system consists of clusters originating from various progenitor galaxies. (D. A. Forbes & T. Bridges 2010; D.

Massari et al. 2019; Y. Chen & O. Y. Gnedin 2024). These ancient stellar systems therefore serve as valuable tracers for reconstructing galactic evolution and merger histories.

If the progenitor galaxy of each GC can be identified, we can decode the detailed evolution of individual progenitor galaxies through their age-metallicity relation (e.g., D. R. Law & S. R. Majewski 2010), or chemical evolution. Thanks to the precise proper motions of GCs provided by the *Gaia* mission, the clustering in their orbital parameter space links present-day Galactic GCs to their possible progenitor galaxies (e.g., T. M. Callingham et al. 2022). In a recent update of D. Massari et al. (2019) based on *Gaia* eDR3 data (hereafter MKH), Galactic GCs are linked to 10 progenitors: main bulge, main disk, Sagittarius (Sag), Helmi stream (H99), *Gaia*-Enceladus (GE), Sequoia (Seq), Low-energy group, Elqui, Cetus, and High-energy group. Only the first

two groups are considered in-situ, while other groups are classified as accreted.

However, the assumption of invariant orbital parameters becomes tenuous when considering the Galaxy’s complex merger history and long-term dynamical evolution. Simulations that include realistic ISM prescriptions also suggest that dynamical criteria alone may be problematic (e.g., [G. Pagnini et al. 2023](#)). For instance, based on chemical similarities to other in-situ GCs, [E. Ceccarelli et al. \(2025\)](#) argued that NGC 288 formed within the Galactic proto-disk, and was later dynamically heated during the GE merger. Unlike dynamical properties, chemical abundances remain largely unaffected by galaxy evolution or merger events. Consequently, they serve as robust tracers for identifying the origins of Galactic field stars. The $[\text{Mg}/\text{Mn}]-[\text{Al}/\text{Fe}]$ plane is widely used for this purpose (e.g., [K. Hawkins et al. 2015](#); [P. Das et al. 2020](#)), particularly as [D. Horta et al. \(2021\)](#) demonstrated distinct evolutionary tracks for MW-like and GE-like galaxies within it, providing a theoretical basis for empirical division lines. However, categorizing early formed metal-poor stars remains challenging, as they predominantly occupy overlapping regions (specifically the upper left) in this plane.

Chemically tagging the origins of Galactic GCs faces a further complication: multiple populations (MPs). MPs alter light-element abundances (e.g., C, N, O, Na, Mg, Al, Si) within metal-poor/compact stellar systems ([E. Carretta et al. 2009](#); [B. Tang et al. 2017](#); [S. Mészáros et al. 2020](#); [R. Huang et al. 2024](#)). A GC forms from a natal cloud inheriting its parent galaxy’s chemistry. However, after massive stars ($\sim 8 - 1 \times 10^4 M_\odot$) are born, their strong winds eject processed material. This enriched gas mixes with primordial gas, altering the composition of subsequently formed stars. Retaining this enriched gas against expulsion by stellar feedback requires a compact gas/stellar environment ([M. G. H. Krause et al. 2016](#); [R. Huang et al. 2024](#)). To mitigate MP effects when chemically tagging the Galactic GCs, studies typically employ average chemical abundances. For example, [D. Horta et al. \(2020\)](#) distinguished in-situ from accreted origins among relatively metal-rich GCs ($[\text{Fe}/\text{H}] > -1.5$) using mean $[\text{Si}/\text{Fe}]$. Conversely, [V. Belokurov & A. Kravtsov \(2024\)](#) showed that the mean $[\text{Mg}/\text{Fe}]-[\text{Al}/\text{Fe}]$ plane fails to clearly separate in-situ and accreted GCs defined by their $E - L_z$ (orbital energy vs. vertical angular momentum) location. This difficulty arises because Mg, Al, and Si exhibit significant variations within individual GCs (e.g., [B. Tang et al. 2018](#); [A. P. Milone & A. F. Marino 2022](#)), complicating classification in certain cases.

In this Letter, we aim to disentangle the distinct chemical abundance contributions from a GC’s progenitor galaxy and its internal MP enrichment. Crucially, primordial populations genuinely reflect the progenitor galaxy’s chemistry, enabling a *bona fide*, chemically driven classification of GCs. This Letter is structured as follows. Section 2 details our selection criteria for GC member stars. Section 3 presents our GC classification results based on their locations in the $[\text{Al}/\text{Fe}]-[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{Fe}]-[\text{Al}/\text{Fe}]$ planes. In Section 4, we discuss the physics behind and robustness of this classification; we further expand our GC sample to the latest data release. Section 5 provides a brief summary and outlines future perspectives.

2. DATA

The Apache Point Observatory Galactic Evolution Experiment (APOGEE, [S. R. Majewski et al. 2017](#)) delivers high-resolution ($R \sim 22,500$) H -band spectra ($\lambda = 1.51 - 1.69 \mu\text{m}$) from both the SDSS 2.5 m telescope at Apache Point Observatory ([J. E. Gunn et al. 2006](#)) and the 2.5 m du Pont telescope at Las Campanas Observatory ([I. S. Bowen & J. Vaughan 1973](#)). APOGEE data reduction software was applied to reduce multiple 3D raw data cubes into calibrated, well-sampled, combined 1D spectra ([D. L. Nidever et al. 2015](#)). When observing GC stars, targets were selected and prioritized using a combination of preexisting information (i.e., stellar parameters, abundances, radial velocities, proper motions, and location in the color-magnitude diagram) and observing constraints imposed by APOGEE magnitude and fiber collision limits ([G. Zasowski et al. 2017](#)). Such target selection is insensitive to MP. Given the typically weaker spectral lines at low metallicity (e.g., $[\text{Fe}/\text{H}] = -2$) and possible large variations of elemental feature lines (e.g., Al) in GC members, a line-by-line analysis for individual chemical species is preferred (e.g., Brussels Automatic Code for Characterizing High-accuracy Spectra, BACCHUS, [T. Masseron et al. 2016](#)) over abundance analysis based on a set of spectral windows (e.g., APOGEE Stellar Parameter and Chemical Abundance Pipeline, ASPCAP, [H. Jönsson et al. 2020](#)). We therefore adopt the homogeneous chemical abundances derived by [S. Mészáros et al. \(2020\)](#) using BACCHUS for 2283 red giant stars in 31 Galactic GCs. These authors select GC members based on their similarities in radial velocities, metallicities, and spatial locations (i.e., inside the GC tidal radius). We selected accurate Fe, Mg, Al, and Si abundances meeting the following criteria: (1) spectral signal-to-noise ratio (SNR) > 70 ; (2) effective temperature (T_{eff}) $< 5500 \text{ K}$; and (3) abundance uncertainties $< 0.2 \text{ dex}$. Addition-

ally, we require clusters to have at least six member stars to ensure statistically robust separation of primordial and enriched populations in subsequent analysis. Our final sample comprises 27 Galactic GCs with 2,142 stars (Table 1).

3. RESULTS

Among the elements analyzed, Al abundances exhibit the most significant variations, making them ideal for population separation. Since Al is strongly enhanced by GC enrichment, revealing the progenitor galaxy’s chemistry necessitates identifying the less Al-enhanced subpopulation. In line with the literature, we term this subpopulation “primordial populations” (or “first generation stars”), adopting slightly different definition (see Section 4.1 for more discussions). Specifically, we define them as follows. Stars within each GC are sorted by their $[\text{Al}/\text{Fe}]$ in ascending order. The primordial population is defined as the first N/n stars, where N is the sample size of the GC members (Table 1) and n is the fixed number of subpopulations assigned to each GC. We apply the same n value for all studied GCs. When N/n is non-integer, we use its floor value (greatest integer less than or equal to N/n). As n increases, both the subsample size and mean $[\text{Al}/\text{Fe}]$ value of the primordial population decrease. We adopt $n = 3$ for subsequent analysis and further discuss this choice in Section 4.1.

At $[\text{Fe}/\text{H}] > -1.5$, a clear separation emerges (at $[\text{Al}/\text{Fe}] \sim 0$) between in-situ ($[\text{Al}/\text{Fe}] > 0.04$ dex) and accreted GCs ($[\text{Al}/\text{Fe}] < 0.04$ dex) in the $[\text{Al}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ plane (Figure 1). These two groups also occupy distinct regions in the $[\text{Mg}/\text{Fe}]$ - $[\text{Al}/\text{Fe}]$ plane (Figure 2). We therefore focus our origin analysis on relatively metal-rich GCs. The metallicity limit ($[\text{Fe}/\text{H}] = -1.5$) will be further discussed in Section 4.2. To validate our classification, we compare it with the dynamically driven MKH classification. The agreement is generally good, except for NGC 288 and M4. Although classified as accreted by MKH, their primordial populations exhibit elevated $[\text{Al}/\text{Fe}]$ abundances comparable to other in-situ GCs. As noted in Section 1, E. Ceccarelli et al. (2025) proposed an in-situ origin for NGC 288, suggesting subsequent dynamical heating. Similarly, M4 was classified as in-situ based on its mean $[\text{Si}/\text{Fe}]$ (D. Horta et al. 2020). Given that chemical abundances remain unaffected by changes in the galactic potential, we conclude that our chemically based classification provides a more robust indicator of GC origin. See Section 4.2 for more discussions about their implications.

The $[\text{Mg}/\text{Fe}]$ - $[\text{Al}/\text{Fe}]$ plane is frequently used to investigate MPs in GCs (E. Pancino et al. 2017; S. Mészáros et al. 2020). In this Letter, we propose a novel frame-

work to disentangle galactic chemical enrichment from GC self-enrichment, illustrated conceptually in Figure 3. This separation is achieved by analyzing chemical abundances exclusively within GC primordial populations. We first exclude GCs exhibiting significant iron spreads, (e.g., ω Cen, which shows complex star formation histories; P. Jofré et al. 2025; A. C. Mason et al. 2025). Our analysis reveals distinct evolutionary pathways for in-situ and accreted GCs:

- **Low metallicity GCs** ($[\text{Fe}/\text{H}] < -1.5$): Both in-situ and accreted GCs occupy a similar region ($[\text{Mg}/\text{Fe}] \sim 0.3 - 0.4$ and $[\text{Al}/\text{Fe}] \sim 0.1$), indicating indistinguishable chemical evolution between the early MW and its accreted dwarf galaxies at these metallicities.
- **Accreted GCs** ($[\text{Fe}/\text{H}] > -1.5$): Progenitor galaxies show a pronounced decrease in $[\text{Mg}/\text{Fe}]$ but only a mild decrease in $[\text{Al}/\text{Fe}]$ with increasing metallicity.
- **In-situ GCs** ($[\text{Fe}/\text{H}] > -1.5$): The MW progenitor exhibits more complex evolution. Between $[\text{Fe}/\text{H}] = -1.5$ and -1.0 , $[\text{Mg}/\text{Fe}]$ remains nearly constant while $[\text{Al}/\text{Fe}]$ rises significantly to ~ 0.5 . Notably, NGC 288 and M4 within this metallicity range are chemically classified as in-situ. Above $[\text{Fe}/\text{H}] = -1.0$, both $[\text{Mg}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ decrease with metallicity.

Crucially, the chemical evolution patterns revealed by GC primordial populations align remarkably with those observed in field stars of their progenitor galaxies (e.g., B. Tang et al. 2023). The physics behind measured chemical abundances is further discussed in Section 4.2.

To illustrate the complexity of the $[\text{Mg}/\text{Fe}]$ - $[\text{Al}/\text{Fe}]$ plane for GC member stars, Figure 3 presents Mg-Al (anti-)correlations for three representative in-situ GCs (M68, NGC 3201, NGC 2808), and three accreted GCs (NGC 6397, NGC 6752, M107). These GCs range from metal poor to metal rich (Figure 1). Al variations in GCs depend on both metallicity and cluster mass (E. Pancino et al. 2017; S. Mészáros et al. 2020).

4. DISCUSSION

4.1. Primordial Population

Our definition of the primordial population differs from that based on HST photometry, which primarily relies on the UV NH molecular band (A. P. Milone & A. F. Marino 2022). We instead define it using derived Al abundances, which exhibit a continuous distribution without clear boundary between primordial

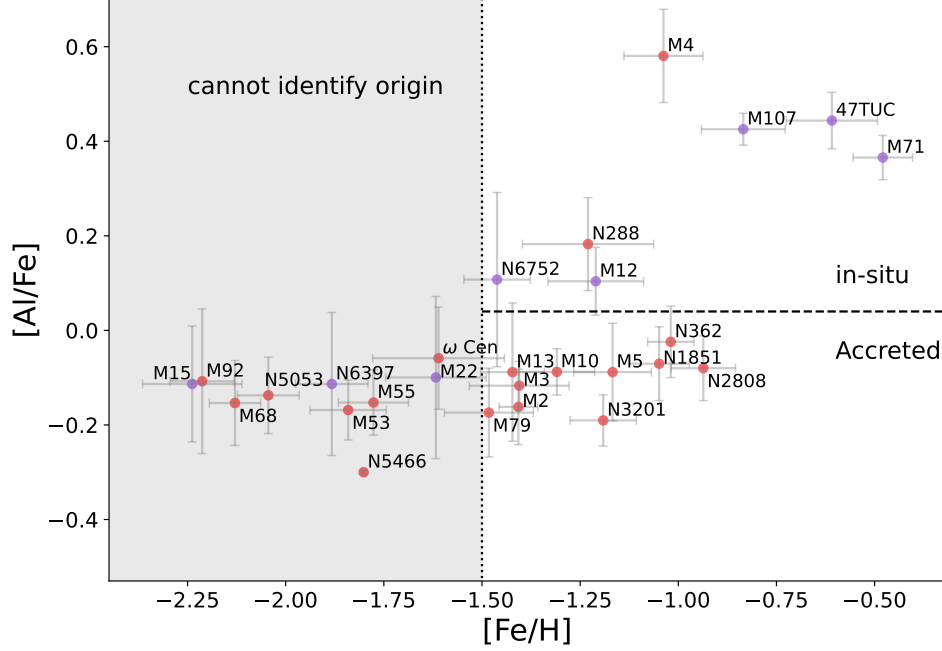


Figure 1. Mean $[\text{Al}/\text{Fe}]$ versus mean $[\text{Fe}/\text{H}]$ of primordial populations in Galactic GCs. Their associated standard deviations are shown as error bars. The black dotted line indicates the metallicity of $[\text{Fe}/\text{H}] = -1.5$. GCs with $[\text{Fe}/\text{H}] < -1.5$ are not suitable for our chemically based classification (grey region). The black dashed line separates chemically classified in-situ and accreted clusters. In comparison, MKH classification is also shown (in-situ: purple, accreted: red).

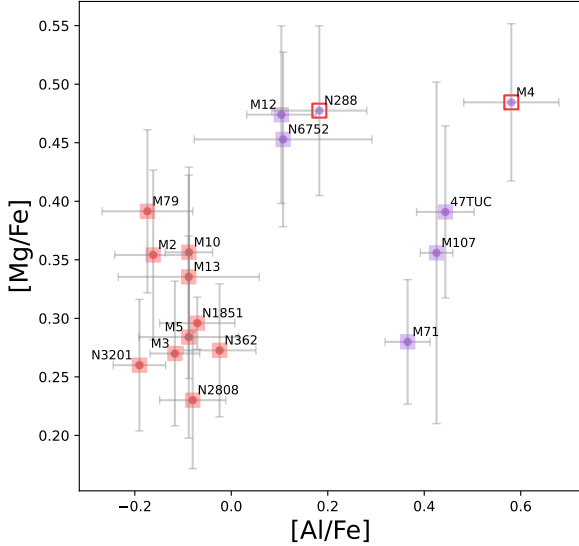


Figure 2. Mean $[\text{Mg}/\text{Fe}]$ versus mean $[\text{Al}/\text{Fe}]$ of primordial populations in Galactic GCs. Their associated standard deviations are shown as error bars. Small purple (red) dots represent the in-situ (accreted) GCs based on our classification. Filled purple (red) squares mark the in-situ (accreted) GCs based on MKH classification. Two GCs (NGC 288 and M4) with inconsistent classification between the two works are properly labeled.

and enriched populations. Consequently, our primor-

dial population refers to “stars not strongly enriched in Al by the polluters responsible for GC MP”.

The primordial population is defined as the first N/n stars with lower $[\text{Al}/\text{Fe}]$, and we adopt $n = 3$ in Section 3. In principle, a larger n yields a less Al-enhanced subpopulation, thereby better reflecting the true progenitor galaxy’s chemistry. However, smaller subsamples are prone to statistical fluctuations and are less viable for GCs with few confirmed members. Testing values of $n = 3, 4, 6, 8$ revealed that the $[\text{Al}/\text{Fe}]$ distinction between in-situ and accreted GCs at $[\text{Fe}/\text{H}] > -1.5$ is most pronounced when $n = 3$ (Figure 1). This choice also provides comparatively larger sample sizes of primordial populations, reducing statistical fluctuations in their mean abundances. We therefore adopt $n = 3$ in this Letter.

Since APOGEE targeting is insensitive to MP, one might be concerned that all observed stars in a given GC could belong to the enriched population, leaving no primordial stars. The probability (p) of this occurring is $(\frac{1}{2})^N$, where N is the number of stars observed in the GC. For Our minimum sample size ($N=6$), $p = 0.0156$. This probability quickly drops to $< 10^{-3}$ for $N \geq 10$.

$[\text{Al}/\text{Fe}] = 0.3$ has been proposed to separate primordial and enriched populations in GCs when Na lines are inaccessible (e.g., S. Mészáros et al. 2020). However, the clear distinction in primordial $[\text{Al}/\text{Fe}]$ between in-situ and accreted GCs at $[\text{Fe}/\text{H}] > -1.5$ necessitates

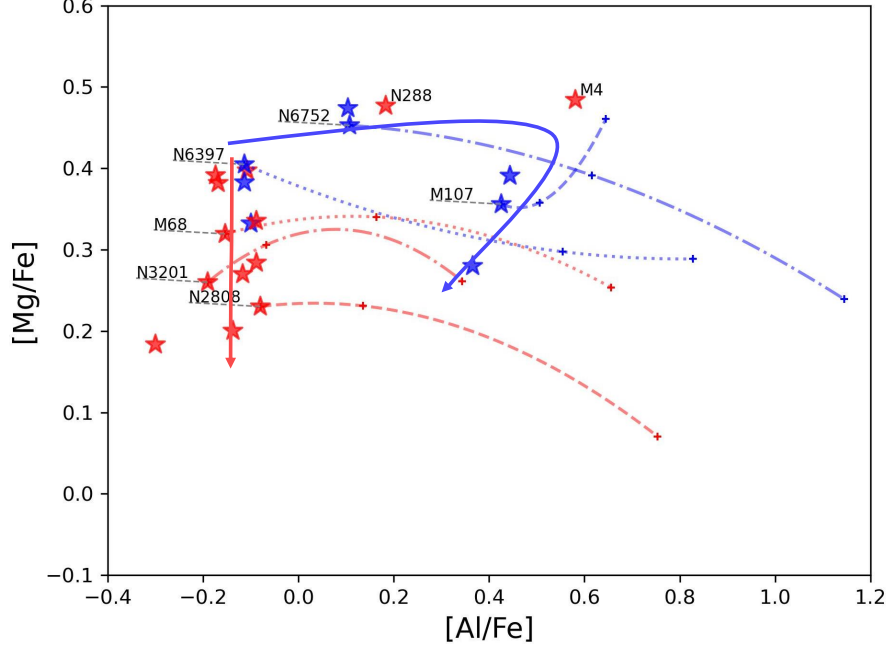


Figure 3. Our conceptual diagram showing mean $[Mg/Fe]$ versus mean $[Al/Fe]$ of primordial populations in Galactic GCs. The Blue (red) star symbols mark the in-situ (accreted) GCs classified by MKH. The blue (red) arrowed line shows the empirical evolutionary path of in-situ (accreted) GC primordial populations, with increasing metallicity. The Mg-Al (anti-)correlations of in-situ GCs are shown as: blue dotted line - NGC 6397 ($[Fe/H] = -1.88$), blue dash-dotted line - NGC 6752 ($[Fe/H] = -1.46$), blue dashed line - M107 ($[Fe/H] = -0.85$), respectively. Meanwhile, The Mg-Al (anti-)correlations of accreted GCs are shown as: red dotted line - M86 ($[Fe/H] = -2.16$), red dash-dotted line - NGC 3201 ($[Fe/H] = -1.22$), red dashed line - NGC 2808 ($[Fe/H] = -0.93$), respectively.

caution. Applying this fixed threshold risks underestimating primordial populations, particularly in in-situ systems where primordial $[Al/Fe]$ is typically higher.

4.2. Underlying Physics

Theoretical models by D. Horta et al. (2021) indicate that the chemical evolution tracks of MW-like and GE-like galaxies in the $[Mg/Mn]$ - $[Al/Fe]$ plane are clearly separated at $[Fe/H] = -0.8$ (black crosses in their Figure 2). However, these two tracks start diverging at lower metallicity, specifically during the 0.3–1 Gyr evolution phase of the GE-like system. Unfortunately, precise metallicities along these tracks cannot be robustly constrained. Based on GC’s mean $[Si/Fe]$ distribution (D. Horta et al. 2020) and primordial $[Al/Fe]$ distribution (our Figure 1), in-situ and accreted GCs are observationally indistinguishable below $[Fe/H] = -1.5$. Interestingly, such limit may also be identified in other α -elements. For example, D. Horta & M. K. Ness (2025) derive the hex ratios for Galactic GCs — ratios between hydrostatic α -elements (namely, $([Mg/Fe] + [O/Fe])/2$) and explosive α -elements (namely, $([Si/Fe] + [Ca/Fe] + [Ti/Fe])/3$). In-situ and accreted GCs are also indistinguishable below $[Fe/H] = -1.5$, but in-situ GCs generally show larger hex ratios than accreted GCs at $[Fe/H] \gtrsim -1.5$ (their Figure 4).

Current theoretical models explain the different evolution tracks between MW (thick disk and in-situ halo) and its accreted dwarf galaxies at $[Fe/H] > -1.5$ as follows: The MW’s deep potential well draws large amounts of gas, sustaining a high star formation rate and rapid enrichment. This increases the fraction of massive stars formed (T. Jeřábková et al. 2018), which produce large yields of C, N, O, Ne, and Mg due to their massive mantles (C. Kobayashi et al. 2006). The higher fraction of massive stars is further confirmed by their hex ratios: in-situ GCs generally show larger hex ratios than accreted GCs at $[Fe/H] \gtrsim -1.5$ (Figure 4 of D. Horta & M. K. Ness 2025). Higher hex ratios indicate an initial mass function (IMF) with a larger amount of most massive stars (J. L. Carlin et al. 2018; A. McWilliam et al. 2013). As one of the odd-Z elements, Al is enhanced by the surplus of neutrons in ^{22}Ne , and ^{22}Ne is transformed from ^{14}N by the CNO cycle during He burning. Consequently, Al yield correlates with the abundances of CNO elements, making it metallicity-dependent (e.g., Fig. 5 of C. Kobayashi et al. 2006). Conversely, due to slow chemical enrichment in GE-like galaxies, Type Ia supernova (SNe Ia) — which produce substantial amounts of Fe — begin to significantly influence galactic chemical evolution at

comparatively low metallicities ($[\text{Fe}/\text{H}] \sim -1.5$). Given the distinct evolutionary pathways of Mg, Al, and Fe, we expect higher $[\text{Mg}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ ratios in MW in-situ stars than in accreted halo stars ($[\text{Fe}/\text{H}] > -1.5$), matching observations by K. Hawkins et al. (2015).

Recently, M. Xiang & H.-W. Rix (2022) suggested the MW’s old disk began forming ~ 13 Gyr ago, only 0.8 Gyr after the Big Bang. Most stars in this component formed about 11 Gyr ago. Consequently, in-situ stars and GCs born in this old (thick) disk may have experienced the “Splash” phase (V. Belokurov et al. 2020) induced by the GE merger. In this context, the two misclassified GCs — NGC 288 and M4 — may not be coincidental. More “Splash” GCs are likely to exist.

4.3. Robustness

The $[\text{Mg}/\text{Fe}]$ - $[\text{Al}/\text{Fe}]$ plane was also employed to discuss GC origins in V. Belokurov & A. Kravtsov (2024), albeit with a distinct classification methodology. They first established a boundary in $E - L_z$ space separating in-situ and accreted objects using stars with robust $[\text{Al}/\text{Fe}]$ -based classification ($-1.4 < [\text{Fe}/\text{H}] < -1.0$), then classified GCs dynamically based on their $E - L_z$ positions. Their work showed that the mean $[\text{Mg}/\text{Fe}]$ - $[\text{Al}/\text{Fe}]$ plane cannot clearly distinguish in-situ from accreted GCs, effectively constituting a *chemically informed* dynamical classification. Comparing classifications for GCs with $[\text{Fe}/\text{H}] > -1.5$, we identify four discrepancies: NGC 288 (classified accreted by Belokurov et al.) versus M13, M10, and NGC 6544 (classified in-situ). As Figure 1 shows, the primordial populations of M13, M10, and NGC 6544 exhibit low $[\text{Al}/\text{Fe}]$ — a signature typical of less massive dwarf galaxies at $[\text{Fe}/\text{H}] > -1.5$. Our classification aligns with MKH for these three GCs.

Given that Si may also vary substantially within GCs, we repeat our classification replacing Mg with Si. The classification results remain unchanged. More importantly, the primordial $[\text{Al}/\text{Fe}]$ exhibits a significantly larger difference between in-situ and accreted GCs compared to primordial $[\text{Si}/\text{Fe}]$. Specifically, $\Delta[\text{Al}/\text{Fe}]$ is ~ 0.25 dex, while $\Delta[\text{Si}/\text{Fe}]$ is only ~ 0.08 dex in the range $-1.5 < [\text{Fe}/\text{H}] < -1.0$. The $[\text{Si}/\text{Fe}]$ difference here is consistent with D. Horta et al. (2020) and D. Geisler et al. (2021). In the higher metallicity range ($-1.0 < [\text{Fe}/\text{H}] < -0.7$), $\Delta[\text{Al}/\text{Fe}]$ reaches ~ 0.5 dex compared to $\Delta[\text{Si}/\text{Fe}] \sim 0.15$ dex. These differentials align with the $\Delta[\text{Al}/\text{Fe}]$ and $\Delta[\text{Si}/\text{Fe}]$ values distinguishing in-situ halo and thick disk stars from accreted halo stars reported by K. Hawkins et al. (2015). Consequently, the enhanced discrepancy in primordial $[\text{Al}/\text{Fe}]$ provides a more robust basis for classification.

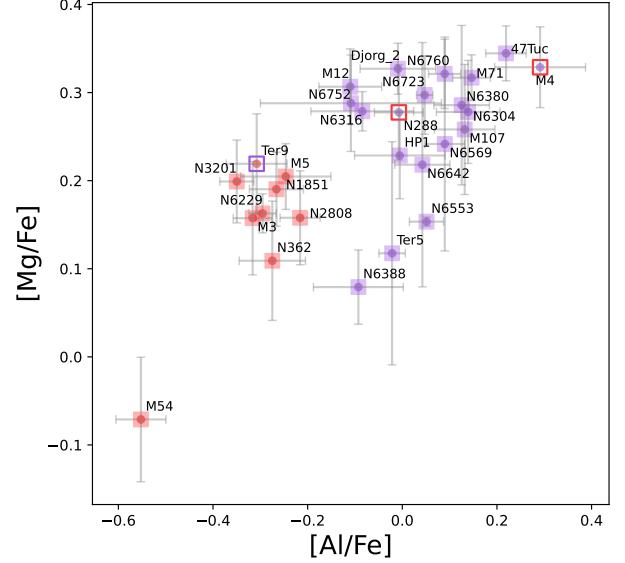


Figure 4. Mean $[\text{Mg}/\text{Fe}]$ versus mean $[\text{Al}/\text{Fe}]$ of primordial populations in APOGEE GCs. Their associated standard deviations are shown as error bars. Small purple (red) dots represent the in-situ (accreted) GCs based on our classification. Filled purple (red) squares mark the in-situ (accreted) GCs based on MKH classification. Three GCs (Terzan 9, NGC 288 and M4) with inconsistent classification between the two works are properly labeled.

4.4. Expanding the Sample

Since the homogeneous study by S. Mészáros et al. (2020), the APOGEE survey has observed additional GCs, particularly in the bulge region (D. Geisler et al. 2021; J. G. Fernández-Trincado et al. 2021). The value-added catalog by R. P. Schiavon et al. (2024) provides stellar abundances for 72 Galactic GCs derived through the APOGEE Stellar Parameter and Chemical Abundance Pipeline (ASPCAP, H. Jönsson et al. 2020). While ASPCAP may struggle with weak spectral features, it remains robust for studying Mg, Al, Si abundances in GCs with $[\text{Fe}/\text{H}] > -1.5$. We are left with 28 GCs after applying the following criteria: (1) GC mean $[\text{Fe}/\text{H}] > -1.5$; (2) no STAR.BAD flag; (3) element flags of Mg, Al, and Si equal zero; (4) sample size larger than 5 (Table 2). Figure 4 shows the primordial population abundances for these GCs alongside two classification schemes. Our chemically driven classification generally agrees with the MKH classification, except for NGC 288, M4 and Terzan 9. The first two GCs have been discussed in Section 3. Terzan 9, a bulge GC traditionally classified as in-situ (e.g., S. Ortolani et al. 1999, MKH), exhibits an accreted signature in the $[\text{Mg}/\text{Fe}]$ - $[\text{Al}/\text{Fe}]$ plane. This interpretation is reinforced by its Si abundances. Its 11 member stars yield mean $[\text{Fe}/\text{H}] = -1.37$ and mean $[\text{Si}/\text{Fe}] = 0.18$. For

bulge GCs with $-1.5 < [\text{Fe}/\text{H}] < -1.0$, both [D. Horta et al. \(2020\)](#) and [D. Geisler et al. \(2021\)](#) report higher mean $[\text{Si}/\text{Fe}]$ in in-situ GCs ($\sim 0.25 - 0.26$) versus accreted GCs ($\sim 0.17 - 0.18$). Terzan 9’s low mean $[\text{Si}/\text{Fe}]$ thus supports an accreted origin. Chemodynamical evidence indicates it formed ex-situ and was later accreted into the bulge. The complex dynamical evolution inside the bulge may change its orbits. In contrast, *bona fide* Bulge GCs near mean $[\text{Mg}/\text{Fe}] \sim 0.13$, $[\text{Al}/\text{Fe}] \sim 0$ (i.e., NGC 6553, Terzan 5 and NGC 6388) follow the in-situ chemical trend (blue arrow, Figure 3).

5. CONCLUSION

In this Letter, we present a novel approach to identify GC origins using their Mg-Al distributions. This work is part of our ongoing research initiative, “Scrutinizing **GA**laxy-**STaR** cluster coevoluti**ON** with chem**O**dyna**MI**cs (**GA**STRONOM**I**)”, which leverages multi-wavelength photometric and spectroscopic data to unravel the coevolutionary relationships between the MW, its satellite dwarf galaxies, and their stellar clusters. We demonstrate that the chemistry of a GC’s progenitor galaxy is encoded within its primordial population. The in-situ and accreted GCs at $[\text{Fe}/\text{H}] > -1.5$ are clearly distinguished by their primordial $[\text{Mg}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$. This chemically driven classification is robust against dynamical changes induced by Galactic po-

tential evolution and merger history. In this scheme, NGC 288 and M4 are reclassified as in-situ, while Terzan 9 as accreted. The future of this classification scheme is highly promising, as more metal-rich GCs are identified and observed spectroscopically within the bulge (e.g., [D. Minniti et al. 2017](#); [E. R. Garro et al. 2022](#)).

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APPENDIX

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Table 1. Globular Clusters selected from S. Mészáros et al. (2020)

GC name	sample size ^a	[Fe/H] _{prim} ^b	σ_{Fe}^c	[Al/Fe] _{prim} ^b	σ_{Al}^c	[Mg/Fe] _{prim} ^b	σ_{Mg}^c	MKH classification
GCs with origins that cannot be identified chemically								
M15	51(17)	-2.24	0.13	-0.11	0.12	0.38	0.09	main disk
M92	34(11)	-2.21	0.08	-0.11	0.15	0.40	0.09	GE
M68	25(8)	-2.13	0.07	-0.15	0.09	0.32	0.09	H99
NGC 5053	11(3)	-2.04	0.08	-0.14	0.08	0.20	0.09	H99
NGC 6397	94(31)	-1.88	0.09	-0.11	0.15	0.40	0.10	main disk
M53	31(10)	-1.84	0.10	-0.17	0.06	0.38	0.04	H99
NGC 5466	7(2)	-1.80	0.00	-0.30	0.00	0.18	0.02	Seq
M55	54(18)	-1.78	0.09	-0.15	0.07	0.49	0.07	Low-energy
M22	15(5)	-1.62	0.13	-0.10	0.17	0.33	0.15	main disk
ω Cen	665(221)	-1.61	0.17	-0.06	0.11	0.46	0.11	GE/Seq
accreted GCs								
M79	21(7)	-1.48	0.11	-0.17	0.09	0.39	0.07	GE
M13	60(20)	-1.42	0.08	-0.09	0.15	0.34	0.09	GE
M2	21(7)	-1.41	0.05	-0.16	0.08	0.35	0.07	GE
M3	132(44)	-1.41	0.13	-0.12	0.05	0.27	0.06	H99
M10	73(24)	-1.31	0.10	-0.09	0.05	0.36	0.07	Low-energy
NGC 3201	35(11)	-1.19	0.08	-0.19	0.05	0.26	0.06	Seq/GE
M5	180(60)	-1.17	0.10	-0.09	0.10	0.28	0.09	GE/H99
NGC 1851	27(9)	-1.05	0.08	-0.07	0.08	0.30	0.02	GE
NGC 362	37(12)	-1.02	0.06	-0.02	0.08	0.27	0.06	GE
NGC 2808	57(19)	-0.94	0.08	-0.08	0.07	0.23	0.06	GE
in-situ GCs								
NGC 6752	124(41)	-1.46	0.08	0.11	0.18	0.45	0.07	main disk
NGC 288	36(12)	-1.23	0.17	0.18	0.10	0.48	0.07	GE
M12	49(16)	-1.21	0.12	0.10	0.07	0.47	0.08	main disk
M4	123(41)	-1.04	0.10	0.58	0.10	0.48	0.07	Low-energy
M107	41(13)	-0.83	0.11	0.43	0.03	0.36	0.15	main bulge
47 Tuc	111(37)	-0.61	0.12	0.44	0.06	0.39	0.07	main disk
M71	28(9)	-0.48	0.08	0.37	0.05	0.28	0.05	main disk

NOTE—^a: total sample sizes of every GCs, and sample sizes of primordial populations in parentheses. ^b: mean abundances of primordial populations. ^c: the associated standard deviations.

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Table 2. GCs selected from ASPCAP

GC name	sample size ^a	[Fe/H] _{prim} ^b	σ_{Fe}^c	[Al/Fe] _{prim} ^b	σ_{Al}^c	[Mg/Fe] _{prim} ^b	σ_{Mg}^c	MKH classification
accreted GCs								
M3	261(87)	-1.48	0.11	-0.32	0.04	0.16	0.06	H99
NGC 3201	165(55)	-1.40	0.09	-0.35	0.04	0.20	0.05	Seq/GE
Terzan 9	11(3)	-1.37	0.10	-0.31	0.06	0.22	0.06	main bulge
NGC 6229	8(2)	-1.37	0.01	-0.30	0.03	0.16	0.02	GE
M5	216(72)	-1.25	0.09	-0.25	0.10	0.20	0.04	GE/H99
NGC 1851	49(16)	-1.16	0.05	-0.27	0.06	0.19	0.04	GE
NGC 362	65(21)	-1.14	0.07	-0.27	0.07	0.11	0.07	GE
NGC 2808	124(41)	-1.11	0.05	-0.22	0.04	0.16	0.05	GE
M54	863(287)	-0.69	0.23	-0.55	0.05	-0.07	0.07	Sag
in-situ GCs								
NGC 6752	138(46)	-1.48	0.23	-0.11	0.19	0.29	0.05	main disk
NGC 288	40(13)	-1.33	0.06	-0.01	0.05	0.28	0.05	GE
M12	78(26)	-1.32	0.06	-0.11	0.07	0.31	0.04	main disk
HP 1	12(4)	-1.24	0.06	-0.01	0.10	0.23	0.05	main bulge
Djorg 2	8(2)	-1.15	0.05	-0.01	0.08	0.33	0.03	main bulge
M4	205(68)	-1.13	0.10	0.29	0.10	0.33	0.05	Low-energy
M107	52(17)	-1.12	0.11	0.13	0.06	0.26	0.07	main bulge
NGC 6723	9(3)	-1.07	0.05	0.05	0.02	0.30	0.04	main bulge
NGC 6316	8(2)	-0.89	0.01	-0.08	0.11	0.28	0.02	main bulge
NGC 6760	9(3)	-0.78	0.02	0.09	0.03	0.32	0.04	main disk
47 Tuc	270(90)	-0.78	0.05	0.22	0.04	0.34	0.03	main disk
M71	108(36)	-0.77	0.05	0.15	0.04	0.32	0.03	main disk
NGC 6642	11(3)	-0.64	0.69	0.04	0.06	0.22	0.14	main bulge
NGC 6380	18(6)	-0.63	0.29	0.13	0.06	0.29	0.09	main bulge
NGC 6388	34(11)	-0.54	0.28	-0.09	0.09	0.08	0.04	main bulge
NGC 6569	9(3)	-0.53	0.67	0.09	0.04	0.24	0.12	main bulge
NGC 6304	13(4)	-0.51	0.09	0.14	0.07	0.28	0.06	main bulge
NGC 6553	8(2)	-0.17	0.00	0.05	0.04	0.15	0.01	main bulge
Terzan 5	9(3)	-0.09	0.47	-0.02	0.03	0.12	0.13	main bulge

NOTE—^a: total sample sizes of every GCs, and sample sizes of primordial populations in parentheses. ^b: mean abundances of primordial populations. ^c: the associated standard deviations.

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