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ATYPICAL MG-POOR MILKY WAY FIELD STARS WITH GLOBULAR CLUSTER SECOND-GENERATION LIKE CHEMICAL PATTERNS

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ABSTRACT

We report the peculiar chemical abundance patterns of eleven atypical Milky Way (MW) field red giant stars observed by the Apache Point Observatory Galactic Evolution Experiment (APOGEE). These atypical giants exhibit strong Al and N enhancements accompanied by C and Mg depletions, strikingly similar to those observed in the so-called second-generation (SG) stars of globular clusters (GCs). Remarkably, we find low-Mg abundances ([Mg/Fe]$<$0.0) together with strong Al and N overabundances in the majority (5/7) of the metal-rich ([Fe/H]$\gtrsim -1.0$) sample stars, which is at odds with actual observations of SG stars in Galactic CGs of similar metallicities. This chemical pattern is unique and unprecedented among MW stars, posing urgent questions about its origin. These atypical stars could be former SG stars of dissolved GCs formed with intrinsically lower abundances of Mg and enriched Al (subsequently self-polluted by massive AGB stars) or the result of exotic binary systems. We speculate that the stars Mg-deficiency as well as the orbital properties suggest that they could have an extragalactic origin. This discovery should guide future dedicated spectroscopic searches of atypical stellar chemical patterns in our Galaxy; a fundamental step forward to understand the Galactic formation and evolution.

Keywords: stars: abundances — stars: Population II — globular clusters: general — Galaxy: structure — Galaxy: formation

1. INTRODUCTION

A number of recent observational studies have revealed that a handful of MW field[1] stars may exhibit inhomogeneities in their light-element abundances (e.g., Carretta et al. 2010; Ramírez et al. 2012; Martell et al. 2016; Fernández-Trincado et al. 2016b; Schiavon et al. 2017b; Recio-Blanco et al. 2017) and neutron-capture element enhancements (e.g., Majewski et al. 2012; Hasselquist et al. 2016; Pereira et al. 2017), similar to those observed in the SG[2] population of globular clusters (e.g., Carretta et al. 2009a,b; Mészáros et al. 2015; Carretta 2016; Tang et al. 2017; Schiavon et al. 2017a; Pancino et al. 2017).

In this framework, the presence of stars with chemical anomalies in the Galactic field could be explained as the relics of tidally disrupted GCs (e.g., Majewski et al. 2012; Fernández-Trincado et al. 2016b, and references therein), indicating that dissolved GCs could have deposited these eventually unbound stars into the main components of the MW (the bulge, the disk and halo) (e.g., Carretta et al. 2010; Fernández Trincado et al. 2013; Kunder et al. 2014; Lind et al. 2015; Fernández-Trincado et al. 2015a,b, 2016a,b; Martell et al. 2016).

Despite the enormous progress that has recently been made in exploring abundance anomalies (e.g., C, N, Al) throughout the canonical components of the MW (e.g., Martell et al. 2016; Schiavon et al. 2017b), the distribution and properties of stars originally formed in GCs that are now part of the MW field are still not well understood. Therefore, the study of field stars with "polluted chemistry" opens a unique window to shed light on models that address the "mass budget" problem, stellar

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[1] Here the term "field" refers to stars distributed across all Galactic components.

[2] Here we refer to "SG" as the groups of stars in GCs that display altered (i.e., different to those of halo field stars) light-element abundances (He, C, N, O, Na, Al, and Mg).

evolution models, and the phenomenon of multiple populations (MPs) in GCs (see Bastian & Lardo 2015; Ventura et al. 2016; Schiavon et al. 2017b). Here we report the discovery of atypical MW field stars with SG-like chemical patterns from the APOGEE survey.

2. SAMPLE SELECTION

Our sample was selected from the APOGEE survey, making use of Sloan Digital Sky Survey-IV (SDSS-IV) Data Release 13 (DR13, SDSS Collaboration et al. 2016; Majewski et al. 2017). APOGEE DR13 provides chemical and kinematical information of about 150,000 Galactic stars through the analysis of high-resolution (R ∼22,500) H-band $\lambda = 1.51$ - 1.69μm spectra (Zasowski et al. 2013).

We focus our search in the low-metallicity regime ($-1.8 <$[Fe/H]< -0.7), where stars from the halo and thick disk are expected to dominate the Galactic metallicity distribution (Hawkins et al. 2015; Martell et al. 2016; Hayes et al. 2017). We impose a minimal signal-to-noise (S/N) ratio **per pixel** of 70 to ensure good quality spectra. In order to identify abundance anomalies in MW field stars, we proceed as follows:

From our initial sample (4,611 stars) we selected stars with SG-like chemical patterns in the [Mg/Fe] versus [Al/Fe] plane by means of a clustering analysis. This is done using a k-means clustering approach as described in Ivezić et al. (2014), with three different centroids in two-dimensional chemical space ([Mg/Fe], [Al/Fe]): i) the SG stars from Galactic GCs $(+0.1, +0.7)$; ii) the FG stars in Galactic GCs $(+0.15, -0.2)$; and iii) the Galactic thick disk stars $(+0.25, +0.2)$. Furthermore, we extended the limits on the Al distribution provided by the k-means analysis for SG-like stars using generous Al cuts ([Al/Fe]$\gtrsim +0.1$), and searched for SG-like stars, omitting the carbon-rich stars [C/Fe] $\gtrsim +0.15$ (Schiavon et al. 2017b), which exhibit anomalous chemical abundance patterns as observed in SG GC stellar populations. All the raw data used in this Letter are available in a public repository[3].

Figure 1a shows the locus occupied by our SG-like candidates, which are located above the dashed grey line that was derived according to the k-means algorithm. Stars from Galactic GCs of similar metallicity (Mészáros et al. 2015) and the N-rich field stars of Martell et al. (2016); Schiavon et al. (2017b) are also indicated in the figure for illustration. Indeed, ten of the N-rich stars reported by Schiavon et al. (2017b) are situated in the locus of SG-like stars found by the k-means algorithm.

After applying the criteria cited above, we have a sample of 260 stars, from which 58.5% (152/260) are known stars from clusters and other anomalous stars previously reported in the literature (Mészáros et al. 2015; Fernández-Trincado et al. 2016a; Tang et al. 2017; Schiavon et al. 2017b), and 28.5% (74/260) have no significant N overabundances (see §3) and were rejected.

To discard false positives in the remaining 34 stars, the most relevant atomic (Al, Mg, Si, and Ni) and molecular (CO, CN, and OH) spectral features in the H-band were visually inspected, to ensure that the final APOGEE spectra are of good quality (e.g., not critically affected by detector persistence, proper continuum normalization, telluric- and sky- lines correction, etc.), to provide reliable chemical abundances. We end with a final sample comprising eleven stars (Table 1).

3. CHEMICAL ABUNDANCE ANALYSIS

We have analyzed up to nine chemical elements that are typical indicators of the presence of SG stars in GCs (C, N, O, Mg, Al, Si, Ni, Na, and Fe). The APOGEE DR13 does not provide reliable N abundances for most of our potential candidates because they show very strong CN lines, falling near the high-N edge of the grid and consequently flagged as "GRIDEDGE_BAD" in DR13 (except 2M02491285+5534213 with [N/Fe]=+0.67, see Figure 1c).

In order to provide a consistent chemical analysis, we re-determine the chemical abundances by means of a line-by-line analysis. The chemical abundances have been derived assuming as input the effective temperature ($T_{\rm eff}$) and metallicity as derived by the APOGEE Stellar Parameter and Chemical Abundances Pipeline (ASPCAP; García Pérez et al. 2016). However, we do not adopt the surface gravity (log g) provided by ASPCAP, since it is affected by a systematic effect that overestimates the log g values (Holtzman et al., in preparation). We estimate surface gravity from 10 Gyr PARSEC (Bressan et al. 2012) isochrones (10 Gyr is the typical age of Galactic GCs; Harris 2010). The line list used in this work is the latest internal DR13 atomic/molecular linelist (linelist.20150714), and the line-by-line analysis was done using the 1D spectral synthesis code Turbospectrum (Alvarez & Plez 1998) and MARCS model atmospheres (Gustafsson et al. 2008). In particular, a mix of heavily CN-cycle and α-poor MARCS models were used. The same molecular lines adopted by Smith et al. (2013) and Souto et al. (2016) were employed to determine the C, N, and O abundances. Examples for a portion of the observed APOGEE spectra (spectral region covering CN, Mg, and Al lines) are shown in Figure 2 for our eleven anomalous stars. Table 1 lists the final set of atmospheric parameters and chemical abundances for each star obtained through ASPCAP DR13 (first line), and the line-by-line

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[3] `https://github.com/Fernandez-Trincado/ChemicalAnomalies/blob/master/README.md`

synthesis calculations adopting log g from theoretical isochrones and using the tools mentioned above (second line).

We find the differences in the star-to-star abundances between ASPCAP DR13 and our manual analysis to be small, Δ[Mg/Fe]$\lesssim$ +0.2, Δ[Al/Fe]$\lesssim$ +0.15, Δ[O/Fe]$\lesssim$ +0.2, Δ[Si/Fe]$\lesssim$ +0.15, and Δ[Ni/Fe]$\lesssim$ +0.15, generally overlapping with our internal errors. It is important to note that these discrepancies do not affect the main conclusion of this work, i.e., both line-to-line abundances and DR13 abundances indicate that these stars are N-rich and Al-rich. Mg abundances are usually lower in the manual analysis **compared with ASPCAP**, a result already found in similar type of **SG-like field** stars (Fernández-Trincado et al. 2016b). We note that Na abundances are more discrepant between DR13 and our manual analysis. As the Na lines are usually weak (especially in the most metal-poor stars; [Fe/H] < -1.0), the uncertainty in the Na abundance is strongly modulated by the uncertainty in the continuum location. ASPCAP uses a global fit to the continuum in three detector chips independently, while we place the pseudo-continuum in a region around the lines of interest. We believe that our manual method is more reliable, since it avoids possible shifts in the continuum location due to imperfections in the spectral subtraction along the full spectral range. This way, our manual analysis shows the Na-rich nature of the SG-like candidates.

4. ORBITAL INFORMATION

We use the galactic dynamic software *GravPot16*[4] (Model 4 in Fernández-Trincado et al. 2016b) to predict the trajectories for five stars (Table 2), from which the space velocity and position vectors can be fully resolved.

To construct the stellar orbits we employed radial velocities derived from APOGEE DR13, proper motions from UCAC-5 (Zacharias et al. 2017), and APOGEE distance estimates from Santiago et al. (2016) and Anders (2017). The orbital elements are listed in Table 2.

All five stars indeed lie on very eccentric orbits (e>0.65) passing through the Galactic bulge, reflecting a potentially unusual origin in the MW.

In particular, two stars (2M17535944+4708092 and 2M12155306+1431114) have relatively high metallicity ([Fe/H]~ -0.8) and may reach distances of up to $Z_{max} \sim 17$ kpc above the Galactic plane.

These orbital properties (together with the unusually low levels of Mg observed in the most metal-rich stars) may support our speculated scenario discussed below, in which these atypical stars may have an extragalactic origin.

5. DISCUSSION

The main finding of this work is the discovery of eleven atypical MW field red giant stars with SG GC-like abundance patterns; i.e., with strong enrichments in N, Na, Si, and Al, accompanied by decreased abundances of C, O, Ni, and Mg. Figure 1b shows that most of the new chemically anomalous stars exhibit significantly lower [Mg/Fe] ratios (at [Fe/H]$\gtrsim -1.0$) as compared to Galactic disk stars (at the same metallicity) and the N-rich halo and bulge stars (e.g., Martell et al. 2016; Schiavon et al. 2017b). This suggests that the vast majority of our stars have an unusual origin. The exceptions are the two most metal-poor stars ([Fe/H]$\lesssim -1.4$), which display higher [Mg/Fe] ratios similar to the "canonical halo". Their [Al/Fe] and [N/Fe] ratios, however, are significantly higher than those of the bulk of MW field stars (Figures 1a and 1c), indicating that they may be SG stars originally formed from material that was chemically enriched in GCs (Martell et al. 2016; Schiavon et al. 2017b). For example, the measured abundances are in nice agreement with the pollution expected by massive AGB stars at metallicity lower than [Fe/H]< -1.4 (Ventura et al. 2016, Dell'Agli et al. 2017 in prep.).

Interestingly, the most-metal rich ([Fe/H]$\gtrsim -1.2$) and atypical Mg-poor stars appear to belong to two groups, according to their Fe abundance (see Figure 1). A first group, only two stars with $-1.2 \lesssim$[Fe/H]$\lesssim -1.0$, exhibit Mg depletion more or less consistent (within the errors) with the Mg abundances typically observed in Galactic GCs of similar metallicities (Mészáros et al. 2015). The second group (7 stars), however, displays similar Mg depletion (Figure 1), but at higher metallicities ([Fe/H]$>$ -1.0). This Mg-deficiency ([Mg/Fe]$\lesssim$0) – coupled with strong N and Al enrichment ([N,Al/Fe]$\gtrsim$ +0.5) – is at odds with present observations of SG stars in Galactic GCs of similar metallicities (Figure 1)[5]. In addition, Figure 1 shows that this Mg-deficiency is not seen in the vast majority of N-rich bulge stars of similar metallicity (Schiavon et al. 2017b); only one N-rich bulge star displays a chemical pattern identical to the atypical stars reported here (Figure 1). A total of six atypical sample stars are seen to lie towards the bulge but is not clear if they could be (or not) some kind related to the latter N-rich bulge population.

Could these atypical stars be chemically tagged as mi-

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[4] `https://fernandez-trincado.github.io/GravPot16/`

[5] To our knowledge, NGC 2419 ([Fe/H]$\sim$-2.0) is the only Galactic GC where many SG stars with very low Mg have been detected (see e.g., Ventura et al. 2012). Because of NGC 2419's complex chemistry , several authors have indeed suggested that NGC 2419 has an extragalactic origin (see e.g., Cohen et al. 2010, 2011; Cohen & Kirby 2012; Mucciarelli et al. 2012).

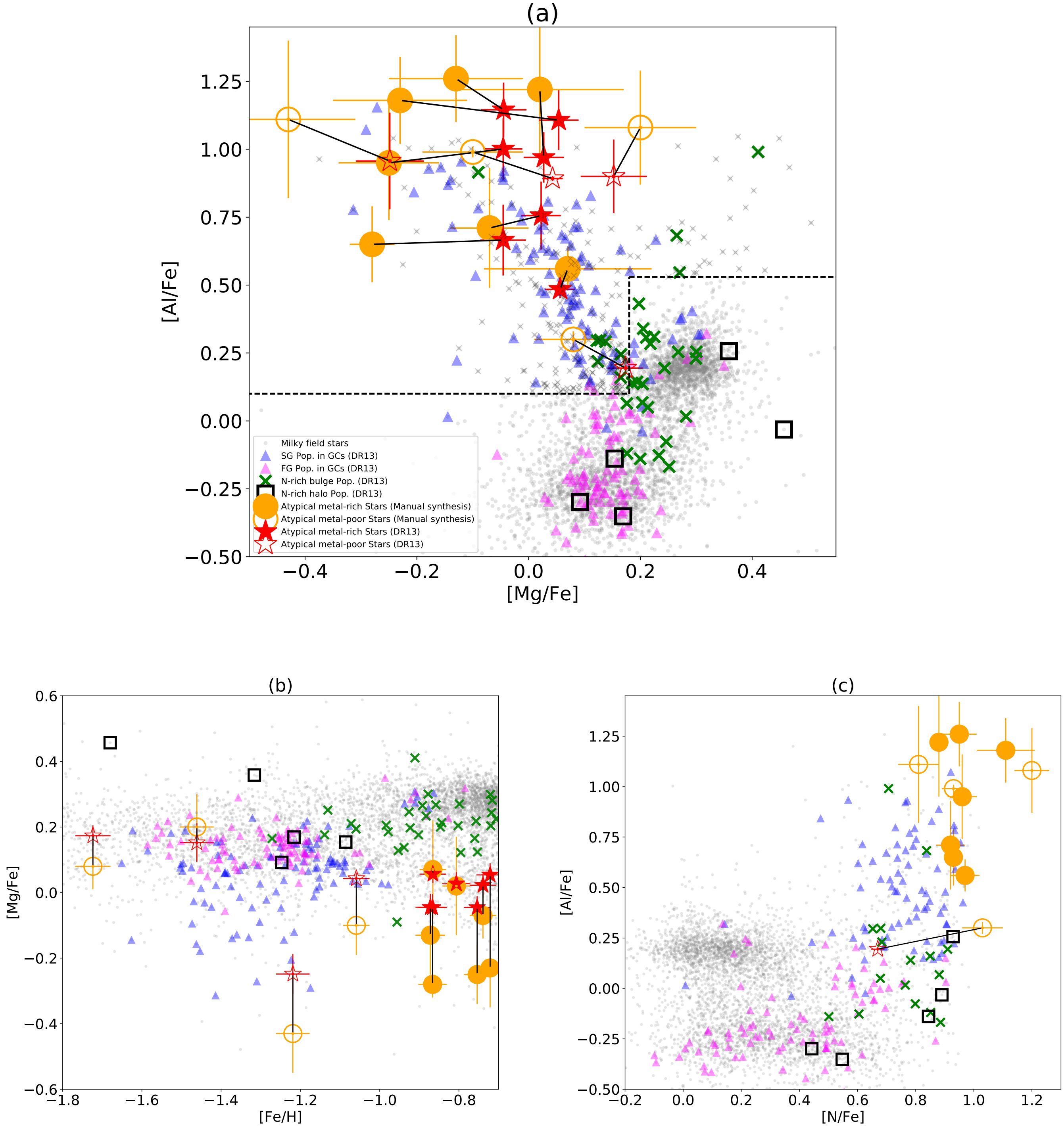

Figure 1. Abundance ratios in three different planes: (a) [Mg/Fe]-[Al/Fe], (b) [Fe/H]-[Mg/Fe], and (c) [N/Fe]-[Al/Fe], for the new field SG GC-like stars (red star symbols for DR13 abundances, orange circles for our manual analysis) overlaid with MW field stars, N-rich halo stars (Martell et al. 2016), N-rich bulge stars (Schiavon et al. 2017b), FG and SG populations in GCs M2, M3, M5, M107, M71 and M13 (Mészáros et al. 2015). Open circles indicate the SG-like candidates with [Fe/H]< -1. In (a) the grey dashed line marks the loci of the SG GC-like candidates, above [Al/Fe]$> +0.1$ ([Mg/Fe]$< +0.18$) and [Al/Fe]$> +0.53$ ([Mg/Fe]$> +0.18$), based on k-means clustering.

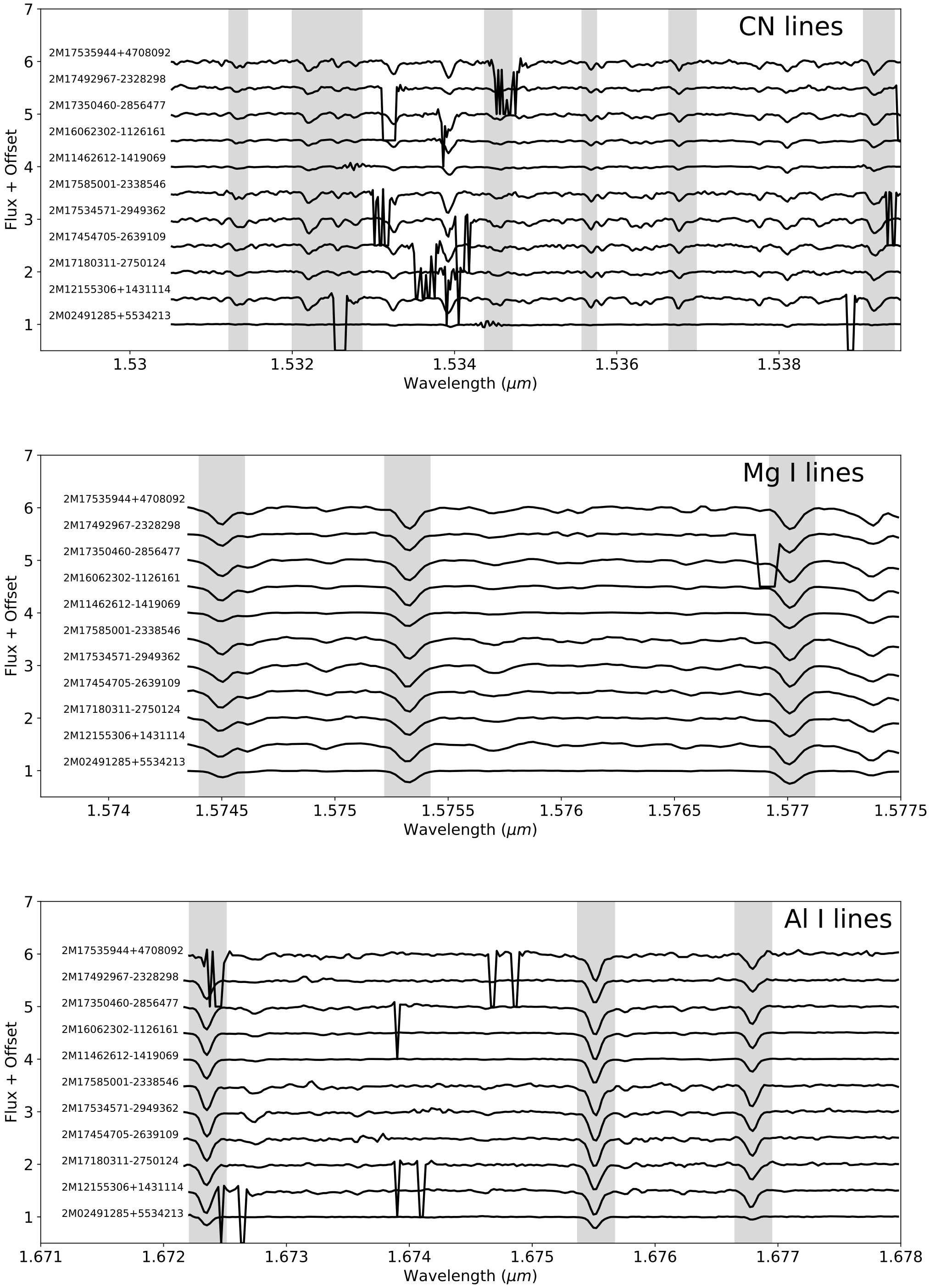

Figure 2. The H-band spectra of our atypical field stars, covering spectral regions around CN bands, Mg I, and Al I. The grey vertical bands indicate some of the wavelenght regimes of the spectral features used in our analysis. **The spectra have been shifted to a common wavelength scale.**

grants from dwarf galaxies? We find this possibility unlikely because our stars display [Al/Fe] much higher than observed in dwarf galaxy stellar populations today (e.g., Shetrone et al. 2003; Hasselquist et al. 2017). However, these stars could be former members of a dwarf galaxy (with intrinsically lower Mg) polluted by a massive AGB star in a binary system, which could produce the chemical pattern observed. Such an exotic binary system seems to be unlikely. Indeed, no star in our sample exhibits significant photometric and/or radial velocity variability (see Table 2). Follow-up observations (e.g., more radial velocity data) would confirm/disprove the binary hypothesis.

Recently, Ventura et al. (2016) has reported a remarkable agreement between the APOGEE Mg-Al anticorrelations (two elements sensitive to the metallicity of the GC polluters) observed in Galactic GCs ($-2.2 \lesssim$[Fe/H]$\lesssim -1.0$) and the theoretical yields from massive AGB stars (m-AGBs). This further supports the idea that SG-GC stars formed from the winds of m-AGBs, possibly diluted with pristine gas with the same chemical composition of the FG stars (see also Renzini et al. 2015). At higher metallicities $-1 <$ [Fe/H] < -0.7, however, the maximum Al spread (with respect to the FG) expected from the ejecta of m-AGBs is in the range $+0.2 < \Delta(\mathrm{Al}) < +0.5$ (Ventura et al. 2016, Dell'Agli et al. 2017 in prep.) but only a modest Mg depletion is expected. The high Al observed ([Al/Fe]$\gtrsim$+0.6) in the atypical stars at these metallicities could be explained under the m-AGBs pollution framework if they are earlier SG members of dissolved GCs (see Schiavon et al. 2017b) where the FG stars formed with higher levels of Al. The FG stars in metal-rich ([Fe/H]$\gtrsim -1.0$) Galactic GCs such as M 107, M 71, 47 Tuc, and NGC 5927 (Mészáros et al. 2015; Pancino et al. 2017) are known to be formed with a higher Al (compared to a purely solar-scaled mixture); but both FG and SG stars exhibit similarly high Mg abundances - with no significant spread between the two stellar generations, as predicted by the m-AGBs self-enrichment scenario (Ventura et al. 2016, Dell'Agli et al. 2017 in prep).

Therefore, the chemical composition of our atypical metal-rich stars, particularly the observed Al overabundances coupled with low Mg, cannot be explained by invoking pollution from m-AGBs alone (formed with a solar-scaled or an α-enhanced mixture).A possible explanation for these chemical anomalies is that these stars escaped from GCs whose FG stars formed with a chemical composition enriched in Al but with a lower Mg content in comparison with the standard solar-scaled or α-enhanced mixture. This could be obtained if we hypothesize that the gas cloud from which the GC formed was mainly polluted by SN explosions of stars of about $\sim$20$-$30 M$_\odot$, characterized by medium or large rotation rates during their life, according to the most recent yields by Limongi & Chieffi (2017, in prep.). Under these conditions the gas ejected is expected to be slightly enriched in Al but Mg-poor. If the FG stars formed with this chemistry, then subsequent pollution from m-AGBs would form SG stars with the same chemical composition of the atypical Mg-poor SG-like stars reported here.

[Mg/Fe] (or [Mg/α]) from high-resolution integrated-light spectroscopic observations in extragalactic GCs – even with average metallicities similar to our atypical Mg-poor stars – is generally lower than in Galactic GCs with similar metallicity (e.g., Pancino et al. 2017). A low [Mg/Fe] ratio coupled with high Al (when available) is also observed in some extragalactic GCs (e.g., in M 31 and LMC GCs; see e.g., Colucci et al. 2009, 2012). At present, possible explanations for the low Mg content in some extragalactic GCs include both internal and external effects, which could also work simultaneously (e.g., Pancino et al. 2017). The internal effect is linked to the particular formation and chemical evolution of a given GC (e.g., NGC 2419), while the external effect is related to the specific chemical evolution of their host galaxies.

In short, the unique Mg-deficiency of the discovered atypical metal-rich stars with SG-like chemical patterns (as well as their orbital properties) suggest that these stars may have an extragalactic origin; e.g., they could be former members of dissolved extragalactic GCs, the remnants of stellar systems accreted long time ago by our Galaxy. This finding should encourage future dedicated searches (e.g., with on-going massive spectroscopic surveys like APOGEE-2, Gaia-ESO, etc.) of chemically atypical Galactic stars, something that would represent a major advance to understand the formation and evolution of our own Galaxy.

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Table 1. Abundance anomalies identified in this study

APOGEE ID	$T_{\rm eff}$ (K)	log g (dex)	[Fe/H] (dex)	[C/Fe] (dex)	[N/Fe] (dex)	[O/Fe] (dex)	[Al/Fe] (dex)	[Mg/Fe] (dex)	[Si/Fe] (dex)	[Ni/Fe] (dex)	[Na/Fe] (dex)
2M17535944+4708092	4154.6	1.36	-0.86±0.03	-0.05 ± 0.02	...	0.19 ± 0.02	0.48 ± 0.03	0.06 ± 0.03	0.46 ± 0.02	-0.09 ± 0.01	-0.40 ± 0.20
		0.96		-0.13±0.03	0.97±0.05	0.34±0.05	0.56±0.08	0.07±0.15	0.59±0.02	-0.11±0.03	0.26±0.08
2M17585001-2338546	4169.4	1.63	-0.75±0.03	-0.27 ± 0.05	...	-0.02 ± 0.04	1.00 ± 0.11	-0.05 ± 0.03	0.16 ± 0.04	0.02 ± 0.02	-0.07 ± 0.16
		1.06		-0.30±0.03	0.96±0.05	0.17±0.06	0.95±0.21	-0.25±0.09	0.32±0.05	0.07±0.05	0.31±0.05
2M17350460-2856477	4218.9	1.66	-0.74±0.03	-0.33 ± 0.06	...	0.02 ± 0.04	0.76 ± 0.13	0.02 ± 0.04	0.18 ± 0.04	0.05 ± 0.02	0.04 ± 0.18
		1.13		-0.20±0.04	0.92±0.05	0.26±0.04	0.71±0.22	-0.07±0.07	0.31±0.05	0.08±0.06	0.36±0.02
2M12155306+1431114	4279.5	1.59	-0.87±0.04	-0.04 ± 0.07	...	0.11 ± 0.05	0.67 ± 0.13	-0.05 ± 0.04	0.21 ± 0.04	0.04 ± 0.03	-0.11 ± 0.19
		1.08		-0.22±0.04	0.93±0.03	0.07±0.04	0.65±0.14	-0.28±0.04	0.29±0.10	-0.004±0.06	0.229±0.07
2M16062302-1126161	4325.8	1.50	-1.06±0.03	-0.41 ± 0.01	...	0.09 ± 0.01	0.89 ± 0.01	0.04 ± 0.02	0.26 ± 0.01	-0.01 ± 0.00	...
		1.07		-0.30±0.07	0.93±0.04	0.17±0.04	0.99±0.02	-0.10±0.09	0.38±0.01	0.002±0.01	...
2M17454705-2639109	4419.2	1.85	-0.81±0.04	-0.23 ± 0.06	...	0.08 ± 0.05	0.97 ± 0.09	0.03 ± 0.04	0.23 ± 0.02	0.04 ± 0.02	-0.58 ± 0.26
		1.36		-0.11±0.01	0.88±0.03	0.24±0.08	1.22±0.27	0.02±0.15	0.34±0.04	0.03±0.04	0.33± ...
2M17492967-2328298	4428.5	1.77	-1.46±0.04	0.03 ± 0.09	...	0.01 ± 0.07	0.90 ± 0.14	0.15 ± 0.06	0.33 ± 0.05	0.11 ± 0.03	...
		0.91		-0.31±0.03	1.20±0.06	0.09±0.04	1.08±0.21	0.20±0.10	0.41±0.04	0.17±0.04	...
2M17534571-2949362	4484.7	2.18	-0.72±0.03	0.07 ± 0.06	...	0.13 ± 0.05	1.11 ± 0.11	0.05 ± 0.04	0.26 ± 0.04	0.03 ± 0.02	0.11 ± 0.17
		1.53		-0.12±0.07	1.11±0.10	0.14±0.03	1.18±0.16	-0.23±0.12	0.39±0.07	0.04±0.04	0.43±0.04
2M11462612-1419069	4564.8	1.79	-1.22±0.04	-0.39 ± 0.11	...	-0.16 ± 0.10	0.96 ± 0.18	-0.25 ± 0.06	0.30 ± 0.06	0.01 ± 0.05	...
		1.32		-0.30±0.06	0.81±0.07	-0.03±0.04	1.11±0.29	-0.43±0.12	0.41±0.07	-0.06±0.05	...
2M17180311-2750124	4725.3	2.19	-0.87±0.04	-0.13 ± 0.07	...	0.15 ± 0.08	1.15 ± 0.10	-0.04 ± 0.04	0.32 ± 0.05	0.09 ± 0.03	0.29 ± 0.18
		1.73		-0.09±0.02	0.95±0.06	0.01±0.03	1.26±0.16	-0.13±0.12	0.35±0.04	0.03±0.05	0.65± ...
2M02491285+5534213	4762.3	2.06	-1.72±0.04	0.09 ± 0.01	0.67 ± 0.02	0.22 ± 0.03	0.19 ± 0.01	0.17 ± 0.03	0.19 ± 0.01	0.14 ± 0.02	...
		1.44		-0.18±0.01	1.03±0.07	0.12±0.07	0.30±0.03	0.08±0.07	0.31±0.04	0.17±0.03	...

NOTE—The first and second rows show the DR13 and our manual results, respectively. The Na abundances for the [Fe/H] < -1.0 stars (not listed) are not not reliable.

Table 2. Variations between 2MASS and DENIS magnitudes and radial velocities (σRV) over the period of the APOGEE observations. Columns 5, 6, 7, and 8 show the median perigalactic distance, the median apogalactic distance, the median maxium distance from the Galactic plane, and the median eccentricity, respectively.

APOGEE ID	$K_{2MASS} - K_{DENIS}$ (mag)	N_{visits}	σRV km s^{-1}	median r_{peri} kpc	median r_{apo} kpc	median Z_{max} kpc	median e
2M17535944+4708092	...	3	0.21	$3.84^{+4.3}_{-2.4}$	$21.54^{+48}_{-5.5}$	$18.79^{+43.4}_{-7.6}$	$0.76^{+0.16}_{-0.19}$
2M17585001-2338546	-0.064	1	...	...	...	...	...
2M17350460-2856477	0.134	2	0.23	...	...	...	...
2M12155306+1431114	...	13	0.13	$4.078^{+3.8}_{-2.9}$	$17.6^{+29}_{-1.9}$	$16.04^{+17.41}_{-1.9}$	$0.69^{+0.2}_{-0.15}$
2M16062302-1126161	-0.071	4	0.24	$1.15^{+0.49}_{-0.76}$	$5.7^{+0.33}_{-0.43}$	$3.32^{+0.43}_{-0.43}$	$0.66^{+0.19}_{-0.09}$
2M17454705-2639109	-0.056	1	...	...	...	...	...
2M17492967-2328298	0.117	2	0.10	...	...	...	...
2M17534571-2949362	...	2	0.07	$0.92^{+0.89}_{-0.66}$	$6.18^{+2.08}_{-0.97}$	$0.74^{+1.74}_{-0.43}$	$0.73^{+0.18}_{-0.12}$
2M11462612-1419069	0.048	4	0.08	...	...	...	...
2M17180311-2750124	0.039	2	0.08	$0.167^{+0.56}_{-0.12}$	$5.40^{+1.0}_{-1.59}$	$2.27^{+0.79}_{-0.68}$	$0.94^{+0.04}_{-0.19}$
2M02491285+5534213	...	3	0.20	...	...	...	...

Note—The orbital eccentricity is defined as $e = (r_{apo} - r_{peri})/(r_{apo} + r_{peri})$, with r_{apo} and r_{peri} the perigalactic and apogalactic radii of the orbit, respectively. The orbital elements given here are estimates from Monte Carlo simulations of 10^5 orbits.

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