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DISCOVERY OF A METAL-POOR FIELD GIANT WITH A GLOBULAR CLUSTER SECOND-GENERATION ABUNDANCE PATTERN

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ABSTRACT

We report on the detection, from observations obtained with the Apache Point Observatory Galactic Evolution Experiment spectroscopic survey, of a metal-poor ([Fe/H] = −1.3 dex) field giant star with an extreme Mg–Al abundance ratio ([Mg/Fe] = −0.31 dex; [Al/Fe] = 1.49 dex). Such low Mg/Al ratios are seen only among the second-generation population of globular clusters (GCs) and are not present among Galactic disk field stars. The light-element abundances of this star, 2M16011638-1201525, suggest that it could have been born in a GC. We explore several origin scenarios, studying the orbit of the star in particular to check the probability of its being kinematically related to known GCs. We performed simple orbital integrations assuming the estimated distance of 2M16011638-1201525 and the available six-dimensional phase-space coordinates of 63 GCs, looking for close encounters in the past with a minimum distance approach within the tidal radius of each cluster. We found a very low probability that 2M16011638-1201525 was ejected from most GCs; however, we note that the best progenitor candidate to host this star is GC ω Centauri (NGC 5139). Our dynamical investigation demonstrates that 2M16011638-1201525 reaches a distance $|Z_{max}| < 3$ kpc from the Galactic plane and minimum and maximum approaches to the Galactic center of $R_{min} < 0.62$ kpc and $R_{max} < 7.26$ kpc in an eccentric ($e \sim 0.53$) and retrograde orbit. Since the extreme chemical anomaly of 2M16011638-1201525 has also been observed in halo field stars, this object could also be considered a halo contaminant, likely to have been ejected into the Milky Way disk from the halo. We conclude that 2M16011638-20152 is also kinematically consistent with the disk but chemically consistent with halo field stars.

Key words: globular clusters: general – stars: abundances – stars: Population II

1. INTRODUCTION

It is a commonly accepted observational fact that second-generation stars make up a significant fraction of the population of most Galactic globular clusters (GCs; Carretta et al. 2009a, 2009b; Bastian & Lardo 2015), and they display unique inhomogeneities in their abundance of light elements involved in proton-capture processes. The elements C, N, O, F, Na, Al, Mg, and perhaps Si (e.g., Gratton et al. 2012; Mészáros et al. 2015 and references therein) provide useful information about the environment in which they were formed. A fraction of GC populations show a pronounced [Al/Fe] and [Mg/Fe] anti-correlation (e.g., Sneden et al. 2004; Johnson et al. 2005; Marino et al. 2008; Carretta et al. 2009a, 2012; Mészáros et al. 2015), a remarkable characteristic (i.e., a *chemical* *fingerprint*) of some second-generation stars, which are not typically observed in the field, except in some peculiar cases, as described below.

Interestingly, it has been suggested that ∼3% of field stars in the Galaxy show atypical light-element patterns similar to those seen only among the secondary population of Galactic GCs (e.g., Carretta et al. 2010; Martell & Grebel 2010; Martell et al. 2011; Ramírez et al. 2012). They could be explained by the escape of individual stars from those systems (Carretta et al. 2010; Carollo et al. 2013; Carretta 2013; Fernández-Trincado et al. 2013, 2015b, 2015c, 2016; Anguiano et al. 2016).

Only a few studies confirm the existence of such stars in the Galactic field. For example, (i) some Aquarius stream stars appear to originate from a GC (e.g., Wylie-de Boer et al. 2012); (ii) the Carretta (2013) study on NGC 6752 identifies a few field star candidates with clear chemical patterns of GCs; (iii) Ramírez et al. (2012) found an elevated Na/O ratio abundance in two field halo dwarf stars; (iv) Lind et al. (2015) recently discovered a metal-poor field halo star with a high Al–Mg ratio; (v) Martell et al. (2016) recently identified five stars in the Galactic halo with GC-like abundance patterns, and these stars are thought to be migrants from GCs; (vi) Schiavon et al. (2016) analyzed the chemical composition of 5,175 stars in fields centered on the Galactic bulge, and found 59 giant stars with elevated nitrogen abundances, anti-correlated with [C/Fe] and correlated with [Al/Fe] abundance; and several scenarios have been put forward to explain such anomalies in the Galactic bulge, i.e., the authors proposed that these stars may likely come from disrupting GCs, though an alternative scenario being considered is that N-rich stars could be formed in environments similar to GCs (for more details, see Schiavon et al. 2016). Detection of such light-element abundance inhomogeneities in non-GC stars is particularly important for understanding how many Galactic field stars could have been deposited by GCs.

In this work, we report the first discovery in Apache Point Observatory Galactic Evolution Experiment (APOGEE) data of a peculiar giant star in the Milky Way field that stands out due to its very low magnesium and high aluminum abundance as well as other very significant light-element abundance anomalies, such as a greatly enhanced nitrogen-to-iron ratio ([N/Fe] > 1.0). This star could be the most convincing evidence yet for a Galactic field star stripped from a GC.

2. A PECULIAR GIANT STAR OBSERVED BY APOGEE

The star of interest, 2M16011638-1201525, was found in APOGEE (Zasowski et al. 2013; Majewski et al. 2016), a near-infrared spectroscopic survey (part of the Sloan Digital Sky Survey III, SDSS-III; Eisenstein et al. 2011) targeting primarily Milky Way red giants, at a resolution of $R \approx 22{,}500$, acquired with the APOGEE multi-object spectrograph mounted at the SDSS 2.5 m telescope (Gunn et al. 2006). We refer the reader to Holtzman et al. (2015) and Nidever et al. (2015) for detailed information on the data and for the data reduction pipeline.

We turn our attention to the giant star 2M16011638-1201525, which has high [Al/Fe] $= 1.49$ and a strongly depleted [Mg/Fe] $= -0.31$ (manually confirmed using MOOG[26]). 2M16011638-1201525 has been identified as part of a sample of ∼265 giant stars originally surveyed spectroscopically by APOGEE in a field centered on $(l, b) = (0, +30)$, showing unusual chemical abundances and a high-quality stellar radial velocity. Figure 1 shows a comparison of our results with those derived from 393 giants in 10 GC stars (see Mészáros et al. 2015) and 59 bona fide field nitrogen-rich stars giants in the bulge from Schiavon et al. (2016). In particular we show that 2M16011638-1201525 has one of the most extreme combinations of abundances. 2M16011638-1201525 shows a radial velocity (with typical uncertainties of less than 1 km s^{-1}) dispersion (*vscatter*) less than 1 km s^{-1} over 4 visits, which makes it unlikely to be a variable star or a binary star. We also examine variations between 2MASS and DENIS magnitudes and USNO-B catalogs and find no evidence for photometric variations between those catalogs, i.e., $(K_{2MASS} - K_{DENIS}) = -0.016$ mag and $(R1 - R2) = 0.07$ mag.

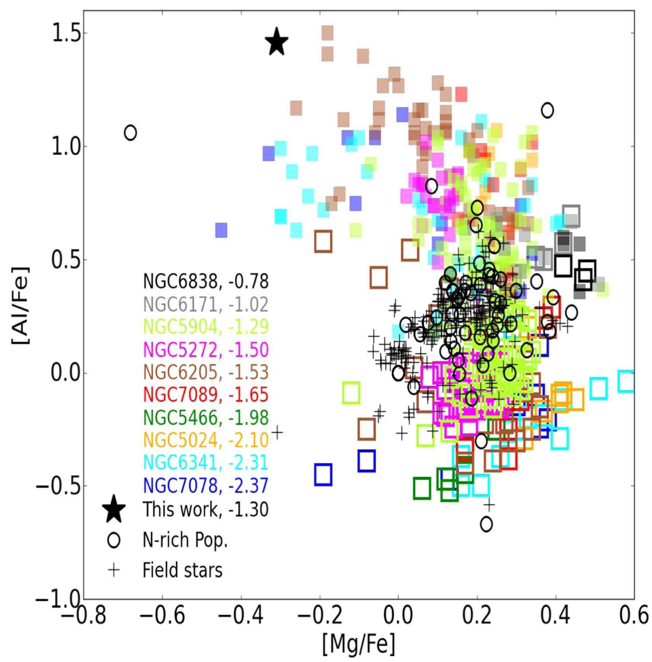

Figure 1. Al and Mg abundances of 393 red giant stars in 10 GCs from Mészáros et al. (2015). The first generation is marked as open square symbols, and the second generation as filled square symbols. The average metallicity ([Fe/H]) is listed after the cluster name. The black star symbol represents the star analyzed in this work, the black open circles the Schiavon et al. (2016) sample, and the plus symbols 211 stars with available ASPCAP abundances in the same field of 2M16011638-1201525.

Figure 1 shows the light-element anomalies of 2M16011638-1201525, in this case for Al and Mg abundances. Such extreme values of Al enhancements and Mg depletions are only observed in second-generation GC population, as seen in Figure 1.

The main atmospheric parameters (T_{eff}, log g, and [Fe/H]) of 2M16011638-1201525 were checked using an extended and updated version of iSpec[27] (Blanco-Cuaresma et al. 2014) to work in the spectral regime of APOGEE (∼1.51–1.7 μm). For a set of atmospheric parameters and atomic data, iSpec generates synthetic spectra, computed from the ATLAS atmosphere model (Kurucz 2005), and minimizes the difference with the observed spectrum using a least-squares algorithm.

We adopt the iSpec-recommended stellar parameters: $T_{eff} = 4572 \pm 100$ K, $\log g = 1.66 \pm 0.1$, and [Fe/H]

[26] http://www.as.utexas.edu/~chris/moog.html

[27] http://www.blancocuaresma.com/s/iSpec/

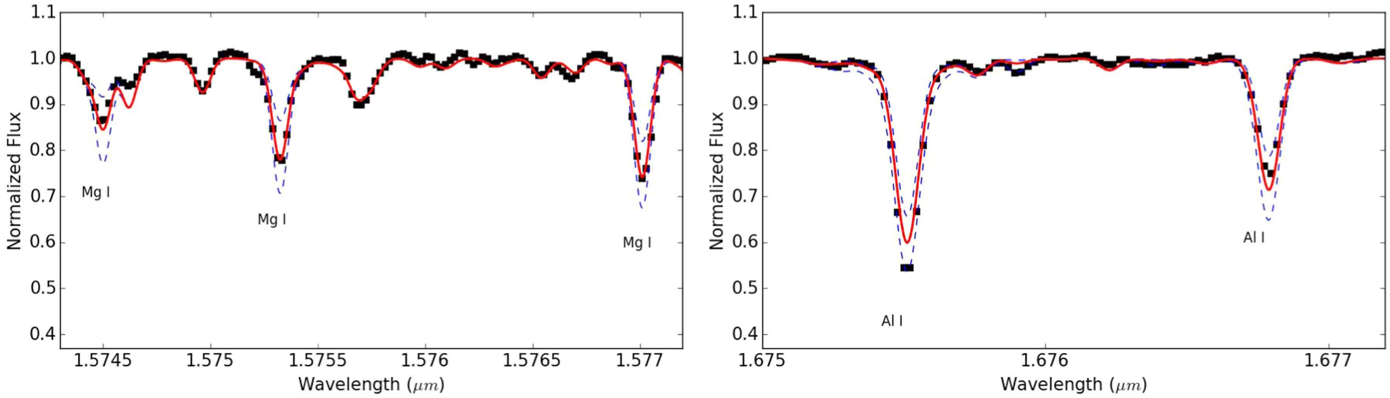

Figure 2. Best-fit for the Mg I and Al I lines (red curve) in the observed infrared spectrum (black filled squares) of 2M16011638-1201525 with S/N > 700. The two blue dashed curves correspond to synthetic spectrum abundance choices that are offset from the best fit by ±0.5 dex.

= −1.30 ± 0.1), which are entirely consistent with those obtained by the ASPCAP pipeline (García Pérez et al. 2016), and $T_{\rm eff} = 4575 \pm 92$ K, log $g = 1.61 \pm 0.11$, and [Fe/H] = −1.31 ± 0.05. Both sets of model parameters computed with the ATLAS model grid are consistent with those we found using MARCS stellar atmosphere models (Gustafsson et al. 2008; Zamora et al. 2015).

In this work,[28] we focus on the abundances of Al, Mg, C, N, and O, which are typical chemical signatures of GCs (Gratton et al. 2012). We did not include sodium, a typical species to separate GC populations, in our analysis as its lines in our APOGEE spectra (1.6373 and 1.6388 μm) are weak in the typical $T_{\rm eff}$ and metallicity for the star studied in this work, which would lead to unreliable abundance results.

APOGEE spectra have three main windows to determine aluminum abundances: 1.6718, 1.6750, and 1.6763 μm. We did not analyze the line at 1.6718 μm because it is poorly fitted in the core and this may be an indicator of NLTE or saturation effects (Hawkins et al. 2016). The selected lines at 1.6750 and 1.6763 μm show an offset of ±0.5 dex (see Figure 2) between the two best-fit abundances, i.e., the derived line-to-line abundance is A(1.6750 μm) = 6.81 and A(1.6763 μm) = 6.31. It is important to note that this discrepancy does not affect the discussion and conclusions of this work, i.e., the line-to-line and relative abundance indicates that the star is Al-rich. For 2M16011638-1201525 we have done a manual inspection of the best MOOG (v. Jan2016, Sneden 1973) fitted synthesis of Al, Mg, C, N, and O lines using atomic and molecular species, the most recent OH line list by Brooke et al. (2016), and Solar abundance values from Asplund et al. (2005). The best MOOG fitted synthesis of Al and Mg lines for 2M16011638-1201525 is shown in Figure 2. For our manual analysis, we adopted the best fit of the atmospheric stellar parameters recommended by iSpec, in good agreement with other independent analyses and methods. This step was necessary to provide a consistent comparison of the results from a manual abundance analysis with the values determined from the ASPCAP pipeline. Table 1 gives these abundances and those derived by the ASPCAP pipeline using a different line list of atomic and molecular species. For comparison the abundances derived from the photometric effective temperatures are given in the same table.

Table 1
Chemical Abundances of 2M16011638-1201525

	APOGEE DR12 $T_{\rm eff}$ 4575 K	This work $T_{\rm eff}$ 4572 K	Photometric $T_{\rm eff}$ 4340 K
[Fe/H]	−1.31	−1.30	−1.30
[C/Fe]	0.09	−0.15	−0.06
[N/Fe]	1.08	1.46	1.05
[O/Fe]	0.21	−0.06	0.03
[Mg/Fe]	−0.04	−0.31	−0.43
[Al/Fe]	1.06	1.49	1.28

Note. The solar reference abundances are from Asplund et al. (2005).

We additionally computed abundances assuming the effective temperature from photometry to check for any significant deviation in our results, i.e., a photometric effective temperature was calculated from the $J-K$ color relation using the methodology presented in González Hernández & Bonifacio (2009). Photometry is extinction-corrected using the Rayleigh–Jeans color excess method (see Majewski et al. 2011), which leads to an extinction value $\langle A_{\rm K}^{\rm WISE} \rangle \sim 0.157$ mag. For comparison, Table 1 shows the values obtained in each procedure. The observed small discrepancies do not affect the main result of our work about the extreme abundances of Mg, Al, and N.

Furthermore, our abundances were compared with those in the literature, i.e., chemical abundances from the DR12 data (García Pérez et al. 2016) and GC stars (Mészáros et al. 2015)—see Figure 1. Those values are quite different from ours, as also seen in the online[29] version from the best ASPCAP fit. This is due to the fact that we used the same wavelength windows as Mészáros et al. (2015; see their Table 3), which are significantly different from the ASPCAP DR12 windows. Also we did not use any of the weak Mg lines, which in these metal-poor stars mostly disappear from the spectra. These differences in [Mg/Fe], [Al/Fe], [N/Fe], [C/Fe], [N/Fe], and [O/Fe] abundances are also likely to be due to the updated line list which includes both atomic and molecular species used by MOOG in our procedure. The chemical abundances relevant to this work are not affected by the analysis methods used.

[28] To facilitate the reproducibility and reuse of our results, we have made all the simulations available in a public repository at https://github.com/Fernandez-Trincado/SDSS-IV-Project0184/blob/master/README.md.

[29] DR12 Science Archive Server: http://dr12.sdss3.org/irSpectrumDetail?commiss=0&locid=4520&show_aspcap=True&apogeeid=2M16011638-1201525.

Table 2
Phase-space Data

Coordinates	(J2000)
(α, δ)	(240°31825, −12°03127)
(l, b)	(358°87794, 29°5692)
Heliocentric Distance	[kpc]
	(2.67 ± 0.68)[a]
	(2.94 ± 0.62)[b]
V_{los}	[km s^{-1}]
	(82.23 ± 0.84)[a]
	(84.68 ± 0.79)[c]
Proper Motions	$(\mu_\alpha \cos\delta,\ \mu_\delta)$
	(mas yr^{-1})
	$(-11.5 \pm 1.7,\ -16.9 \pm 1.7)$[d]
	$(-12.3 \pm 2.1,\ -16.0 \pm 2.1)$[e]
	$(-15.7 \pm 2.7,\ -17.2 \pm 2.4)$[f]

Notes.
[a] Kordopatis et al. (2013).
[b] Hayden et al. (2014).
[c] SDSS-III/APOGEE.
[d] UCAC4.
[e] PPMXL.
[f] Tycho-2 (unfortunately, improvements in distance and proper motions are not available from the TGAS (Gaia Collaboration et al. 2016) catalog for this star).

3. GALACTIC MODEL AND SIMULATIONS

We performed a series of orbital[30] integrations using a semi-analytical, multicomponent model of the Milky Way potential to predict the orbital parameters of 2M16011638-1201525 in the Galaxy, based on the reliable (Table 2) six-dimensional phase-space coordinates (3D position and 3D velocity).

We consider axisymmetric and non-axisymmetric Galactic models, including a prolate bar and spiral-arms structures. The relevant parameters employed in the bar and the spiral arms are the same as those explained in Moreno et al. (2014) and Robin et al. (2012).

We employed the kinematical parameters of 2M16011638-1201525 and those associated with the Galactic model and consider their corresponding uncertainties as 1σ variations in a Gaussian Monte Carlo sampling. The adopted Solar motion with its uncertainties is $(U, V, W)_\odot = (-11.1 \pm 1.2, 12.24 \pm 2.1, 7.25 \pm 0.6)$ km s^{-1} (e.g., Schönrich et al. 2010; Brunthaler et al. 2011). In each computed orbit, we obtain the following orbital parameters: the maximum distance from the Galactic plane, Z_{max}; the maximum and minimum Galactocentric radii, r_{max} and r_{min}; and the orbital eccentricity, defined as $e = (r_{max} - r_{min})/(r_{max} + r_{min})$.

To estimate the effect of axisymmetric and non-axisymmetric components of the Galactic potential in the computed orbital parameters, we considered the following four configurations of the Galactic potential:

(i) Model 1: the axisymmetric model, which is the direct scaling of the Allen & Santillan (1991) model
(ii) Model 2: the non-axisymmetric model mentioned above, using the prolate bar with the spiral arms (see Pichardo et al. 2003, 2004)
(iii) Model 3: the non-axisymmetric model using the boxy bar with the spiral arms (see Pichardo et al. 2003, 2004)
(iv) Model 4: We also performed orbit integration of 2M16011638-1201525 using the *GravPot16*[31] code. We have assumed a Milky Way gravitational potential model using the mass distribution of the last version of the Besançon Galaxy model (see Fernández-Trincado et al. 2014; Robin et al. 2014) based on the superposition of many composite stellar populations belonging to the thin disk, dark matter halo component, and interstellar matter (ISM; e.g., Robin et al. 2003); the thick disk (shape B; see Robin et al. 2014) and stellar halo (Robin et al. 2014; Fernández-Trincado et al. 2015a); and a standard triaxial boxy-shape bar (Robin et al. 2012). The results are shown in Figure 4. We refer the reader to these papers for further details of the density profiles.

In these models the orbits of the star are integrated over 2 Gyr, with 10^4 orbits in Model 1 and 10^3 orbits in both Model 2 and Model 3. We have found that in Models 2, 3, and 4 the computed orbital parameters of 2M16011638-1201525 are very similar and thus do not depend sensitively on the assumed model of the Galactic bar.

For the orbital computation of 2M16011638-1201525, we also tested the set of distances and proper motions given in Table 2; small variations in these observables do not lead to substantial difference in the orbital parameters and do not affect the overall conclusions of this work.

We chose to use the accurate (<1 km s^{-1}) radial velocity from APOGEE. We adopted the spectro-photometric estimated distance from Hayden et al. (2014) based on Bayesian methods developed for APOGEE data, which is in good agreement with the distance measurements from the RAVE survey (see Table 2). We have adopted absolute proper motions from the UCAC4 catalog (Fourth U.S. Naval Observatory CCD Astrograph Catalogue; Zacharias et al. 2013), because the error in proper motion (with uncertainties <2 mas yr^{-1}) is smaller than those in other catalogs (see Table 2) and is less affected by potential systematic uncertainties (Vickers et al. 2016). We note that the small uncertainties on the proper motions are good enough to estimate the space-velocity vector accurately,[32] i.e., $(U_{LSR}, V_{LSR}, W_{LSR}) = (93.9 \pm 10.9, -246.1 \pm 68.9, 21.7 \pm 19.9)$ km s^{-1}.

4. POSSIBLE ORIGINS

A possible scenario producing very extreme Mg–Al–N nucleosynthesis could be an association with an intermediate-mass (∼3–6 $M_\odot$) AGB star (see Ventura et al. 2011; Schiavon et al. 2016) in a binary companion. A future work will be dedicated to investigating in more detail other mechanisms, including binary stellar mergers or pollution of the ISM by a previous generation of massive stars.

In the following subsections we will analyze other scenarios that could have led this peculiar star to its current phase-space location in the Galaxy.

[30] We have adopted a righthanded coordinate system for (U, V, W), so that they are positive in the directions of the galactic center, galactic rotation, and north galactic pole, respectively.

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

[32] The velocities $(U_{LSR}, V_{LSR}, W_{LSR})$ are estimated relative to the local standard of rest (LSR).

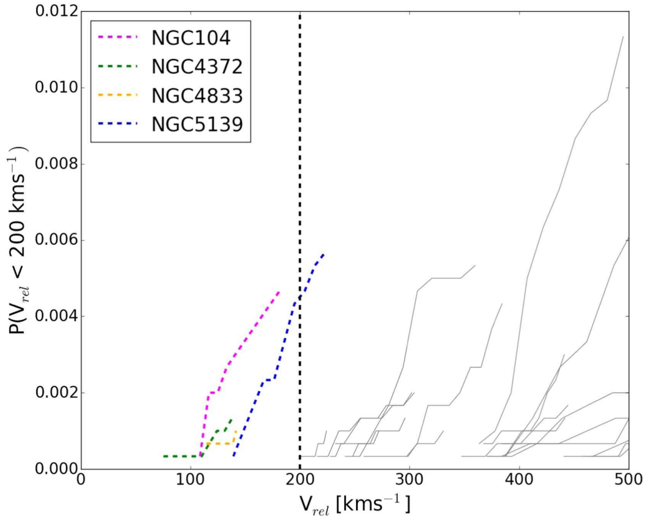

Figure 3. Cumulative probability distribution of the relative velocities ($V_{\rm rel}$) during close encounters between 2M16011638-1201525 and Galactic GCs from Moreno et al. (2014). The vertical dashed line shows the velocity threshold (200 km s^{-1}) adopted in this work.

4.1. A Dwarf Spheroidal (dSph) Galaxy Interloper?

Lind et al. (2015) argue that stars with low [Mg/Fe] ratios are commonly found in dSph galaxies. However, [Al/Fe] enhancement is not expected in these systems (see Koch & McWilliam 2008). Therefore, given the high Al enhancement and strongly depleted Mg observed in 2M16011638-1201525, we conclude that it seems unlikely that a merged and disrupted dSph galaxy could have hosted 2M16011638-1201525.

4.2. A Globular Cluster Escapee?

In order to study the ejection scenario of 2M16011638-1201525 from a not entirely disrupted GC into the Milky Way disk, we performed a kinematical analysis using Model 2 over a 2 Gyr period. It is based on a 3×10^3 Monte Carlo cluster and 2M16011638-1201525 orbits for a sample of 63 Galactic GCs with good proper motion measurements (see Moreno et al. 2014).

We assumed that 2M16011638-1201525 could have been ejected from a given GC, with a relative velocity below a certain threshold ($V_{\rm rel} < 200$ km s^{-1}), which may be possible in the interaction of black holes and/or binary systems (see Fernández-Trincado et al. 2015b). Then, we computed the cumulative probability distribution (see Figure 3) for the relative velocity ($V_{\rm rel}$), which is defined as the relative velocity during each close encounter, occurring at times $t < 2$ Gyr and within a distance less than or equal to the tidal radius of the GC ($\delta\ r < r_t$; Moreno et al. 2014). If a close past encounter is probable, then the GC could be identified as a possible progenitor of 2M16011638-1201525.

Our results suggest that our hypothesis of 2M16011638-1201525 being ejected from a given GC is negligible for 59 of the GCs and very small (<0.5%) for four GCs in our sample (see Figure 2): NGC 5139 (ω Cen), NGC 104 (47 Tucanae), NGC 4372, and NGC 4833.

Other parameters also disfavor the proposed hypothesis: 2M16011638-1201525 is metal-poor, [Fe/H] = −1.30 dex, with orbital parameters that reach a distance $|Z_{\rm max}| \sim 3$ kpc from the Galactic plane (see Figure 4), which are not consistent with the metallicity (Harris 1996) and orbital properties (Moreno et al. 2014) of three of the four clusters mentioned above: NGC 104 ([Fe/H] = −0.72 dex, $|Z_{\rm max}| \sim 3.13$ kpc), NGC 4372 ([Fe/H] = −2.17 dex, $|Z_{\rm max}| \sim 1.57$ kpc), and NGC 4833 ([Fe/H] = −1.85 dex, $|Z_{\rm max}| \sim 1.54$ kpc). Both NGC 4372 and NGC 4833 are more metal-poor than 2M16011638-1201525, while NGC 104 is more metal-rich—having a more Mg-rich population in particular (see Carretta et al. 2013)—than 2M16011638-1201525. Therefore, these 3 clusters are an unlikely origin for the star.

Our chemodynamical results show that among the more probable GC candidates associated with 2M16011638-1201525, NGC 5139 could be a possible progenitor system. This cluster is metal-poor, [Fe/H] = −1.53 dex (Harris 1996), and has an orbit that reaches a distance $|Z_{\rm max}| \sim 1.69$ kpc from the Galactic plane (Moreno et al. 2014). Additionally, NGC 5139 shows enrichment levels spanning ∼−1.8 dex to ∼−0.5 dex (e.g., Villanova et al. 2014 and references therein) and atypical light-element abundances with a pronounced Mg–Al anti-correlation (e.g., Norris & Da Costa 1995), like that seen in 2M16011638-1201525. From Figure 3, we conclude that this star could have been radially ejected in any direction from NGC 5139 (blue dashed line in Figure 3). 2M16011638-1201525 has a velocity greater than the cluster's escape velocity, i.e., $V_{\rm rel} > 60.4$ km s^{-1} (see Fernández-Trincado et al. 2015b and references therein), reaching a total energy (E) and angular momentum (Lz) from the ejection process slightly similar to those of NGC 5139. We note that 2M16011638-1201525 is moving on a retrograde orbit and has a specific angular momentum, $Lz = -307$ km s^{-1} kpc, similar to that of NGC 5139, i.e., $Lz = -342.5$ km s^{-1} kpc (see Moreno et al. 2014); this result could strengthen the association of this star with NGC 5139.

We emphasize that there is evidence which suggests NGC 5139 as a dominant contributor of retrograde stars and of stars with chemical anomalies generally found only within GCs (Altmann et al. 2005; Majewski et al. 2012; Fernández-Trincado et al. 2015c). These stellar debris and the newly discovered star strongly suggest that NGC 5139 was not formed on its present orbit and has been affected by frequent passages through the disk (e.g., Meza et al. 2005). Hence, much of the stellar debris claimed to be part of NGC 5139 follows orbital properties ($R_{\rm min}$, $R_{\rm max}$, $Z_{\rm max}$) slightly different from those of the host system.

We also highlight that 2M16011638-1201525 has halo-like radial velocity based on the kinematics predicted by the revised version of the Besançon Galaxy model (Robin et al. 2014), implying that this star could also be interpreted as a "halo interloper," especially given a retrograde motion and a peculiar chemical fingerprint that is consistent with the GC halo population.

4.3. A Galactic Bulge Interloper?

Schiavon et al. (2016) have recently discovered a new stellar population in the Galactic bulge (called the N-rich population), which clearly shows atypical light-element patterns, particularly elevated nitrogen abundance [N/Fe] > 1.0 dex. Such abundances are very different from what is seen in the normal stellar population of the Galactic bulge in the same spatial region (i.e., $|b| < 16°$, $-20° < l < 20°$, and 5 kpc $< d_\odot <$ 11 kpc).

We consider a possible scenario where 2M16011638-1201525 could be associated with this new stellar population,

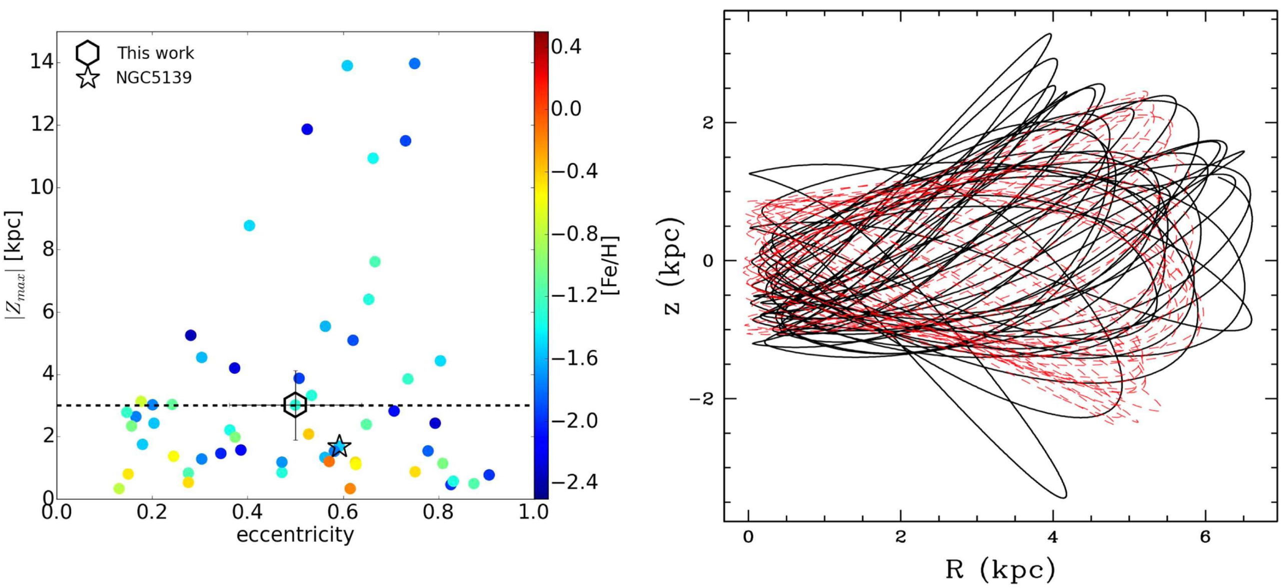

Figure 4. Left: maximum distance $|Z_{\rm max}|$ from the Galactic plane as a function of the orbital eccentricity for 2M16011638-1201525 and 63 GC from Moreno et al. (2014). The open star symbol refers to NGC 5139. The horizontal black dashed line represents 3 kpc, the higher limit for the thick disc proposed by Carollo et al. (2010). Right: meridional orbit of 2M16011638-1201525 computed with Model 3 (black line) and Model 4 (red dashed line).

since this star shows nitrogen enhancement similar to that of Schiavon's sample, i.e., 2M16011638-1201525, like the N-rich population, has elevated nitrogen abundance, [N/Fe] = 1.46 dex (see Table 1). Interestingly, our orbital solutions show that 2M16011638-1201525 passes through the Galactic bulge at its closest approach to the Galactic center $R_{\rm min} \sim 0.62$ kpc and reaches a maximum distance from the Galactic center at $R_{\rm max} < 7.26$ kpc (see the orbit projection in Figure 4) in an eccentric orbit $e = 0.53$. Given its peculiar chemical fingerprint and orbital elements within the Galactic disk, this star could be interpreted as a N-rich bulge interloper. It is interesting to note that there are a handful of N-rich stars from Schiavon's sample with intermediate Al abundance and Mg enhancement (see Figure 1), making it difficult to chemically link this population with 2M16011638-1201525, which falls outside the main group of field stars and within the locus of the second-generation GC population. However, there is also one star from Schiavon's sample that has Al enhancement and a strongly depleted Mg abundance and is likely within the Al–Mg tail of the N-rich population. On the other hand, one might expect N-rich contaminants with extreme Al–Mg abundance ratios. However, given the kinematic and chemical properties of 2M16011638-1201525, a GC-like second-generation identification seems more probable.

5. CONCLUSIONS

We made use of high-resolution, near-IR spectra from the SDSS-III/APOGEE survey, and we discovered the existence of a star within the Milky Way disk with light-element anomalies associated with one of the most extreme combinations of Mg and Al anti-correlation, seen only in second-generation GC populations. Our orbital computations based on reliable six-dimensional phase-space coordinates of this peculiar giant star, 2M16011638-1201525, show that it travels through the Milky Way in a coplanar, eccentric orbit relatively close to the Galactic plane, which suggests that this star has been dynamically ejected into the Milky Way disk from the halo.

A more exotic explanation of such peculiar chemistry in a disk-like orbit star is that it could be chemically linked with the ω Cen progenitor system, from which it might have been ejected. However, ω Cen is a very complex and unusual stellar system in the Milky Way, and its origin is still not well understood (GC or dSph galaxy?). Other GC progenitor candidates might be examined with more detail in the near future, given the upcoming and more accurate six-dimensional phase-space data set that will be produced by the *Gaia* space mission.

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This research made use of *GravPot16* (Fortran version), a community-developed core under the git version-control system on GitHub. Monte Carlo simulations were executed on computers from Instituto de Astronomía-UNAM, México.

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