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HUNTING NA-RICH STARS AMONG N-RICH STARS IN THE GALACTIC HALO

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Abstract. Globular clusters (GCs) provide stars to the halo as a result of two-body interactions and tidal forces exerted by the Galactic gravitational field. Therefore, to understand how the Galactic halo formed, it is crucial to estimate what fraction of the halo field stars are GC escapees. Identifying characteristic chemical patterns in halo stars is a promising approach, because GCs have unique chemical fingerprints, with concurrent and correlated enrichment in N and Na. Large existing surveys such as, e.g. APOGEE and SEGUE-1/2, use N enrichment to identify GC escapees. However, N enrichment is a necessary but insufficient condition, due to mixing processes affecting the N enhancement. To test this method, we report here the estimation of Na abundances of a sample of ∼30 N-rich Galactic Halo giant stars with high-resolution VLT/UVES and HET/HRS spectroscopy. Indeed, if a N-rich star in the halo is a GC escapee, it should also show Na enhancement. We find that less than 30% of our N-rich sample is also Na-rich, as expected from GC stars peculiar chemistry. Our analysis shows that the majority of N-rich stars in the Galactic Halo are likely not of GC origin and that previous works have possibly overestimated the fraction of GC stars in the halo by a factor of ∼3. We conclude that (i) future surveys need to take into account several elements (N, Na, C) in order to reliably identify GC escapees in the MW, (ii) our results support recent works suggesting that the disruption of GCs plays a minor role in the build-up of the MW stellar halo.

Keywords: galactic halo formation, chemically peculiar stars, globular clusters, abundances, spectroscopy

1 Introduction

Understanding how the halo of the Milky Way (MW) formed is still a complex problem to solve. Crucial insights are obtained thanks to globular clusters (GCs), ancient and massive agglomerate of stars that represent the fossil record of galaxy formation (e.g., Brodie & Strader 2006, Kruijssen et al. 2019). The MW hosts at least 160 GCs (Baumgardt & Vasiliev 2021) which lose their stars into the halo, disk or bulge due to the interaction with the gravitational potential of the MW, as well as internal relaxation processes. GC stars can be easily chemically tagged because almost all GCs host multiple stellar populations (MPs) in the form of star-to-star light element abundance variations (e.g., Gratton et al. 2012). Indeed, GCs are composed of ∼30-40% stars with comparable elemental abundances of field stars at the same metallicity, while up to ∼70% show enhanced N, Na and He together with depleted abundances of C and O (e.g., Bastian & Lardo 2018). Hence, knowing what fraction of the halo is represented by GCs stars provides an important piece of the puzzle for understanding the formation history of our Galaxy. Former spectroscopic surveys such as SEGUE, APOGEE, and Gaia−ESO provide large datasets to identify field stars exhibiting MPs. Existing attempts for finding GC escapee stars mainly rely on identifying chemical anomalies in C and N (SEGUE and APOGEE, e.g. Martell et al. 2011;

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Schiavon et al. 2017; Koch et al. 2019), although some studies using Mg and Al were also reported (e.g. Lind et al. 2015; Fernández-Trincado et al. 2017). These works found a large population of N-rich stars both in the halo (∼2-3%, Martell et al. 2011) and in the bulge (∼7% for stars at [Fe/H]< -1, Schiavon et al. 2017) of the MW, suggesting that these stars might be originated from GCs. N is a good tracer to identify stars that were formed in a GC because the variations exhibited by this element extend to the main sequence (Harbeck et al. 2003) as do the O and Na variations (D'Orazi et al. 2010), indicating that the origin of N inhomogeneities cannot be explained entirely by evolution along the red giant (RG) phase. However, N is not an ideal element to search for GC escapees because RG stars can modify their surface abundances of C, N, and O via mixing processes (e.g., Karakas & Lattanzio 2014; Lagarde et al. 2019). Additionally, Bekki (2019) showed that other processes might lead to N enrichment (such as pollution from asymptotic giant branch stars) and concluded that the vast majority of N-rich stars are not of GC origin, both in the bulge and halo. Another way to identify chemically peculiar stars formed in GCs is to use either Na or Al abundances, as these elements are not altered by mixing. Among Na and Al, the best tracer of GC escapee stars is Na, because large Na variations of up to one dex are exhibited by GC stars at any metallicity, while the Al spread in GCs is sensitive to metallicity (Carretta et al. 2009). Unfortunately, neither the Gaia-ESO nor the APOGEE surveys can be used to systematically detect Na-enriched stars. For instance, the APOGEE spectral band contains two Na lines that become undetectable at [Fe/H]< -0.7 (Mészáros et al. 2015). On the other hand, only the UVES spectra of the Gaia-ESO survey (only 10% of the survey) have Na lines, and only a small fraction of them target halo giant stars.

In this paper, we then estimate the Na abundances of a sample of red giant stars in the Galactic Halo with high resolution spectra. The majority of the sample are selected to be rich in N, through the measurement of the strength of the CN, a molecular band located in the UV part of the spectra (at ∼3883Å), tracer of N abundance (Martell & Grebel 2010; Martell et al. 2011). The goal of this study is to determine whether the CN-rich stars also show a Na enhancement and in which fraction, in order to verify how well a N enrichment is able to trace and identify stars with GC origin. Section 2 will briefly describe the data and analysis, while in Section 3 we will present the results. We will conclude in Section 4 and refer the interested reader to a forthcoming paper (Martocchia et al., in prep) for more details and discussion on this study.

2 Data & Analysis

The data used in this analysis consist of optical spectra of 47 red giant stars of the Galactic Halo, selected from the Sloan Extension for Galactic Understanding and Exploration (SEGUE) sample of the SDSS (Yanny et al. 2009). Giants were selected in the Hertzprung-Russell diagram, which was built from the effective temperatures $T_{\rm eff}$ and gravities log(g) estimated by the SEGUE Stellar Parameters Pipeline (SSPP) of the SDSS (Rockosi et al. 2022). The SSPP also offers other stellar parameters such as the metallicity [Fe/H]. We refer the interested readers to Martell & Grebel (2010) and Martell et al. (2011) for more details about the selection. Our stars have $4800 \leq T_{\rm eff} \leq 5300$ K and $1.5 \leq$log(g)≤ 3.2 dex, and span a wide range in metallicity, i.e. $-1.8 \leq$[Fe/H]≤ -0.9 dex. In total, we collected spectra of 10 stars with VLT/UVES (R$\sim 70,000$, spectral coverage from $\sim$ 4700Å$-$6900Å) and spectra of 40 stars with the HET/HRS (R$\sim 15,000$, $\sim$ 6000Å$-$7900Å). These stars have Gaia DR3 G-band magnitudes from 14.6 to 17.2 mag (Gaia Collaboration et al. 2023).

Sodium abundances were computed by fitting the observed spectra with synthetic templates around the Na I lines at 6154.22Å and 6160.74Å. To calculate synthetic spectra, we adopted the atmospheric parameters from the SSPP ($T_{\rm eff}$, log(g) and [Fe/H]), while we assumed a microturbulent velocity $v_t = 2$ km/s for all the stars. Atomic and molecular line lists were taken from the most recent Kurucz compilation[*]. Model atmospheres were calculated with the ATLAS9 code (Castelli & Kurucz 2004) using an α-enhanced composition ([α/Fe]$= +0.3$ dex) for each star in the sample. Model spectra were generated using SYNTHE (Kurucz 2005) and then fitted to the observed spectra with a χ^2 minimisation algorithm to find the model that best fits our data. All the steps mentioned above were performed with the python routines `iSPy3`[†]. To estimate the errors associated with the abundance measurements, we consider a typical error of ±100 K in $T_{\rm eff}$, an error of ±0.2 dex in log(g), an error of ±1 km/s in the microturbulent velocity, and an error of ±0.2 dex in [Fe/H]. The errors were calculated as in in Martocchia et al. (2021).

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[*] `http://wwwuser.oats.inaf.it/castelli/linelists.html`

[†] `https://github.com/soerenslarsen/ISPy3`

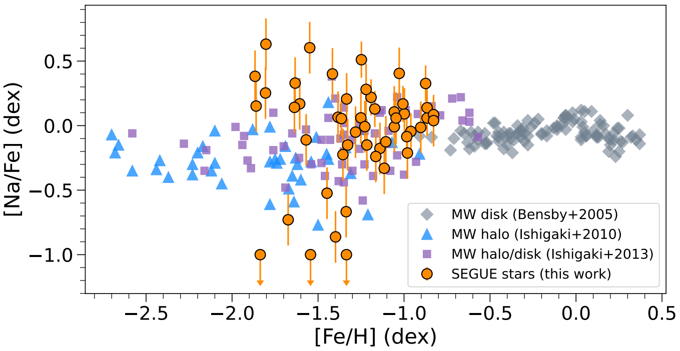

Fig. 1. [Fe/H] vs. [Na/Fe] of stars in the MW disk and halo from the literature. Blue triangles indicate stars in the MW halo from Ishigaki et al. (2010), while purple squares are stars in the halo and disk from Ishigaki et al. (2013). Grey diamonds represent MW disk stars from Bensby et al. (2005) while our sample is displayed with orange circles. Arrows indicate the upper limits on the estimated abundances.

3 Results

Figure 1 shows the estimated Na abundances as a function of the metallicity [Fe/H] for our sample stars, indicated as filled orange circles, compared to other field stars in the MW halo and disk from the literature. Blue triangles indicate halo stars from Ishigaki et al. (2010), while purple squares are halo and disk stars from the Ishigaki et al. (2013) sample. Grey diamonds represent thick and thin disk stars from Bensby et al. (2005). Arrows indicate the upper limits on the estimated abundances. Fig. 1 shows that the [Na/Fe] abundances of our SEGUE sample are mainly consistent with the bulk of stars in the MW halo, except for a few stars that are Na-richer. Na-rich stars within our sample are selected comparing their [Na/Fe] abundances with those of the GCs as a function of metallicity. Indeed, the left panel of Figure 2 shows [Fe/H] versus [Na/Fe] of our SEGUE sample (orange filled circles) compared with stars in 17 MW GCs, indicated as blue filled squares, from the sample of Carretta et al. (2009). Na-rich stars are selected at a threshold of $[\mathrm{Na/Fe}]=+0.3$ dex (for $[\mathrm{Fe/H}]<-0.85$), which roughly corresponds to the dip of the bimodal distributions of the Na abundances of GCs, in bins of 0.25 dex in [Fe/H]. More details will be reported in the forthcoming paper. In both panels of Fig. 2, the selection is represented by a green solid line within a grey shaded area. From this selection, we find that 8 stars are Na-rich. The right panel of Fig. 2 displays the CN indices (at 3883Å) of our sample stars as a function of [Na/Fe]. CN indices are calculated from the SDSS spectra with the formula reported in Martocchia et al. (2021). CN-rich stars are estimated according to the method reported in Martell et al. (2011), i.e. taking into account that we are mixing stars with different luminosities and metallicities and that this has an effect on the CN index. Additionally, as we are interested in stars that might have a GC origin, CN-rich stars are also selected to be poor in Carbon (see again, Martell et al. 2011). CN-rich (and C-poor) stars are indicated as red open squares in the right panel of Fig. 2. We found that only 8 stars out of 30 CN-rich stars are Na-rich, hence less than 30% of CN-rich stars in our sample seem to have a GC origin.

Finally, thanks to unprecedented data provided by Gaia DR3 (Gaia Collaboration et al. 2023), we were able to estimate the integrals of motion of our stars and compare them with those of the MW GCs. We assume that if a star is a GC escapee, it still retains the same orbital properties of the GC it belonged to in the past, as the gravitational potential of the MW did not significantly evolve in the last ~ 5 Gyr. Hence, we compared the energy, the angular momentum, the radial and vertical actions of our stars with those of the MW GCs, whose parameters were taken from Baumgardt & Vasiliev (2021). The orbital properties of both stars and GCs were calculated following the method and prescriptions reported in Savino & Posti (2019). As a preliminary result, we found no kinematical associations among our SEGUE stars and the MW GCs. A more detailed discussion on the method and its caveats will be provided in the forthcoming paper.

4 Conclusions

We estimated the Na abundances of a sample of field stars in the MW halo that are mainly CN-rich (i.e., rich in N). We found that less than 30% of our CN-rich stars are also enhanced in Na, by comparing their Na abundances with those of stars within GCs. Hence, we conclude that the majority of CN-rich stars in the Galactic Halo

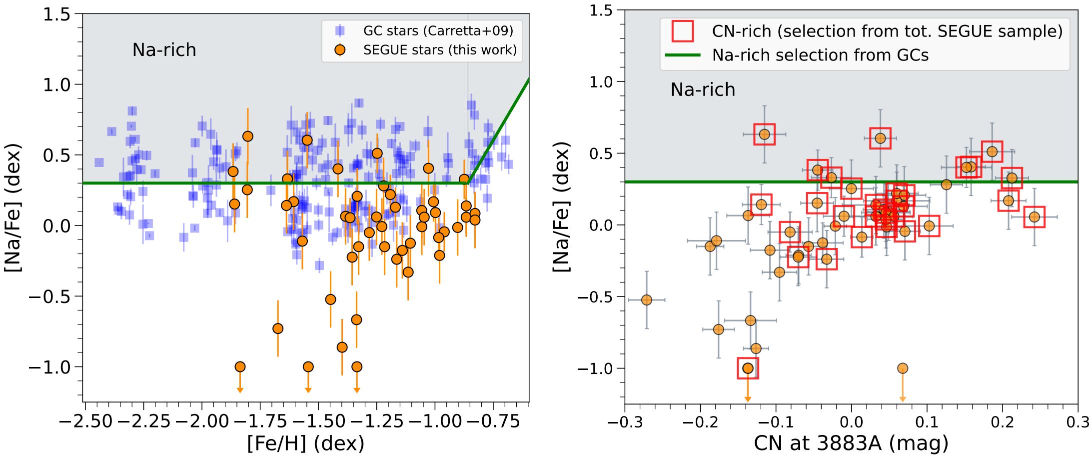

Fig. 2. *Left panel*: [Na/Fe] versus [Fe/H] for our SEGUE sample (orange filled circles) compared to stars in MW GCs from Carretta et al. (2009), indicated with blue filled squares. The green solid line indicates the selection of Na-rich stars, also represented by the grey shaded area. *Right panel*: CN at 3883Å as a function of [Na/Fe] for the stars in our sample. Red open squares represent CN-rich stars according to the selection from Martell et al. (2011).

are likely not of GC origin. Previous works (e.g., Martell et al. 2011) found that the halo is composed of 2-3% of GC stars based on CN-rich selected stars. We argue that this fraction was likely overestimated by a factor of ~ 3, although a more accurate number will need to be confirmed by future larger surveys, based on both N and Na abundances. Additionally, our results agree with recent simulation works finding that the disruption of GCs plays a minor role in the assembly of the MW halo (e.g., Reina-Campos et al. 2020).

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References

Bastian, N. & Lardo, C. 2018, ARA&A, 56, 83
Baumgardt, H. & Vasiliev, E. 2021, MNRAS, 505, 5957
Bekki, K. 2019, MNRAS, 490, 4007
Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, A&A, 433, 185
Brodie, J. P. & Strader, J. 2006, ARA&A, 44, 193
Carretta, E., Bragaglia, A., Gratton, R., & Lucatello, S. 2009, A&A, 505, 139
Castelli, F. & Kurucz, R. L. 2004, ArXiv Astrophysics e-prints
D'Orazi, V., Lucatello, S., Gratton, R., et al. 2010, ApJ, 713, L1
Fernández-Trincado, J. G., Zamora, O., García-Hernández, D. A., et al. 2017, ApJ, 846, L2
Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, A&A, 674, A1
Gratton, R. G., Carretta, E., & Bragaglia, A. 2012, A&A Rev., 20, 50
Harbeck, D., Smith, G. H., & Grebel, E. K. 2003, AJ, 125, 197
Ishigaki, M., Chiba, M., & Aoki, W. 2010, PASJ, 62, 143
Ishigaki, M. N., Aoki, W., & Chiba, M. 2013, ApJ, 771, 67
Karakas, A. I. & Lattanzio, J. C. 2014, PASA, 31, e030
Koch, A., Grebel, E. K., & Martell, S. L. 2019, A&A, 625, A75
Kruijssen, J. M. D., Pfeffer, J. L., Reina-Campos, M., Crain, R. A., & Bastian, N. 2019, MNRAS, 486, 3180
Kurucz, R. L. 2005, Memorie della Societa Astronomica Italiana Supplementi, 8, 14
Lagarde, N., Reylé, C., Robin, A. C., et al. 2019, A&A, 621, A24
Lind, K., Koposov, S. E., Battistini, C., et al. 2015, A&A, 575, L12
Martell, S. L. & Grebel, E. K. 2010, A&A, 519, A14
Martell, S. L., Smolinski, J. P., Beers, T. C., & Grebel, E. K. 2011, A&A, 534, A136

Martocchia, S., Lardo, C., Rejkuba, M., et al. 2021, MNRAS, 505, 5389
Mészáros, S., Martell, S. L., Shetrone, M., et al. 2015, AJ, 149, 153
Reina-Campos, M., Hughes, M. E., Kruijssen, J. M. D., et al. 2020, MNRAS, 493, 3422
Rockosi, C. M., Lee, Y. S., Morrison, H. L., et al. 2022, ApJS, 259, 60
Savino, A. & Posti, L. 2019, A&A, 624, L9
Schiavon, R. P., Zamora, O., Carrera, R., et al. 2017, MNRAS, 465, 501
Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377