Gaia DR2 orbital properties of selected APOGEE giants with anomalously high levels of $[N/Fe]$ in the bulge and halo of the Milky Way

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ABSTRACT
We have used a state-of-the-art orbital integration model in a more realistic gravitational potential, to explore the orbital properties of a sample of 76 selected N-rich stars across the Milky Way, using 6-dimensional information provided by Gaia and the APOGEE-2 survey. Orbits are integrated in the galaxy modelling algorithm GravPot16, which mimics the non-axisymmetric structure of the inner Milky Way. We present the more probable orbital elements using the newly measured proper motions from Gaia DR2 with existing line-of-sight velocities from APOGEE-2 survey and spectrophotometric distance estimations from the StarHorse code. We find that most of the N-rich stars, show typically maximum height to the Galactic plane below 1.5 kpc, and develop rather eccentric orbits, suggesting that these stars are confined in the inner regions of the Galaxy and are likely to be dynamically associated with a ‘classical bulge’. We show that ∼10% of the N-rich stars in the inner Galaxy share the orbital properties of the bar/bulge, having perigalactic and apogalatic distances, and maximum vertical excursion from the Galactic plane inside the bar region.

Key words: Galaxy: kinematics and dynamics (Galaxy): globular clusters: individual: NGC 6362

The advent of large spectroscopic surveys like APOGEE (Majewski et al. 2017) which is capable to see through the dusty part of the Milky Way, together with other complementary surveys such as Gaia-ESO survey (Gilmore et al. 2012; Randich et al. 2013, among other), clearly revealed that our own Galaxy hosts a significant population of peculiar abundance red giants residing preferentially in the inner regions of the Galaxy (e.g., Recio-Blanco et al. 2017; Schiavon et al. 2017; Fernández-Trincado et al. 2017c), with a few confirmed cases toward the disc and halo (Martell et al. 2016; Pereira et al. 2017; Fernández-Trincado et al. 2016a, 2017c; Reis et al. 2018; Koch et al. 2019).

The APOGEE high-resolution spectra ($R \approx 22,500$) on the near-IR $H$-band ($\lambda \sim 1.5$–1.7 $\mu$m) have shown that many of these stars are often typified by large nitrogen-overabundances ($[N/Fe] \gtrsim +0.5$, hereafter N-rich), accompanied by decreased abundances of carbon ($[C/Fe] \lesssim +0.15$), identified most obviously by their $^{12}\text{C}^{16}\text{O}$-band, enhanced $^{12}\text{C}^{14}\text{N}$-band features (see, e.g., Altmann et al. 2005; Martell & Grebel 2010; Martell et al. 2011; Lind et al. 2015; Martell et al. 2016; Fernández-Trincado et al. 2016a; Schiavon et al. 2017; Fernández-Trincado et al. 2017c, 2019), and other abundances of elements involved in proton-capture reactions, i.e., Mg and Al, often structured in coherent patterns. Furthermore, the vast majority of the N-rich stars investigated so far possess clear chemical abundance patterns on their light elements similar to the observed in second-generation globular cluster stars (group of stars as enhanced N and Al and depleted Mg, C and O abundances with respect to field at the same metallicity [Fe/H]).

The implicit assumption, that a few APOGEE N-rich stars in the field are former members of large or smaller accreted satellites occurring perhaps up to a few Gyr ago has not actually been demonstrated, and the origin of such an abundance signature remains still debated and can be ascribed to different exotic events, including external mech-

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anisms, like a binary mass-transfer channel and/or "in-situ" formation.

The current best interpretation is that these chemically anomalous field giants are former globular cluster stars (Khoperskov et al. 2018; Savino & Posti 2019), and as such, play an important role in deciphering the early history of the Milky Way itself (Martell & Grebel 2010; Carollo et al. 2013; Kundu et al. 2014; Lind et al. 2015; Fernández-Trincado et al. 2015a,b, 2016a,b; Recio-Blanco et al. 2017; Koppelman et al. 2018; Helmi et al. 2018; Tang et al. 2019; Ibata et al. 2019), currently there is no real working explanation for the origin of the gamut of extreme light and heavy elements simultaneously intervening in the chemical composition of the newly identified anomalous field stars. One of the most dramatic results from the APOGEE survey was discovered by Fernández-Trincado et al. (2017c), they identified a more exotic clump (7 out of 11 stars) of giant stars in the metal-poor tail ([Fe/H] $\lesssim -0.7$) of the thick disc metallicity distribution which exhibit significant Mg-underabundances with extreme enrichment in N and Al suggesting a possible link to extragalactic globular clusters (Pancino et al. 2017), which none of the well studied Galactic globular clusters in our own Galaxy can reproduce it. However, the dynamical history of such stars remains unexplored to date.

Beyond of the intrinsic value of identifying chemically anomalous field stars throughout the Milky Way and understand the related abundance phenomena, a satisfactory explanation for the unexplained chemical anomalies and its relation to the orbital parameters may also offer insight into the origin of such stars. The newly discovered N-rich stars in the Milky Way (e.g., Martell et al. 2016; Fernández-Trincado et al. 2016b, 2017c; Schiavon et al. 2017) have a number of essential parameters that remain unexplored. In an effort to remedy this deficiency, we conducted for the first time a dynamics characterisation of such stars to predict the orbital path across the Milky Way as well as reveal their birthplace in order to improve our understanding of their origins.

In this work we take advantage of the accurate proper motions of The European Space Agency’s Gaia mission Second Data Release (DR2) archive (Lindegren et al. 2018; Arenou et al. 2018), complemented along with radial velocity from APOGEE-2 (Nidever et al. 2015) and spectro-photometric distance from StarHorse (Queiroz et al. 2018), which permit an unprecedented combination of precision to fully resolve the space velocity and position vectors in order to study for the first time the dynamical behavior of these stars across of the Milky Way in a more realistic (as far as possible) Galactic model, like GravPot16.$^\dagger$

This paper is outlined as follows. In §1, we start by describing the APOGEE and Gaia data set and a series of selection criteria. In §2, we present the details of the Galactic model, followed by a discussion of the constraints on the free parameters of the model and the choices for the fiducial parameter values. We then move on to discuss the kinematic and dynamic behavior of our N-rich stars in §3, including an exploration of how the results depend on the free parameters. We summarize our key findings and conclude in §4.

1 DATA

The sample analysed in this work consist of N-rich stars located towards the bulge, disc and halo taken from Martell et al. (2016), Fernández-Trincado et al. (2016b), Schiavon et al. (2017) and Fernández-Trincado et al. (2017c). The apparent exclusivity of such stars is attributed to their unusual chemical compositions and relation to Galactic and extragalactic globular cluster stars. This phenomenon have been widely exploited in the APOGEE survey (Majewski et al. 2017) by the above authors and have been confirmed from optical follow-up observations (e.g., Pereira et al. 2017). $H$-band ($\sim \lambda 1.5–1.7\mu m$) high-resolution (R$\sim 22,500$) APOGEE spectra were obtained with the 300-fiber spectrograph installed on the 2.5m Telescope (Gunn et al. 2006) at the Apache Point Observatory as part of the Sloan Digital Sky Survey IV (Blanton et al. 2017). The reduction of the APOGEE spectra, as well as the determination of radial velocities, atmospheric parameters and stellar abundances were carried out by the ASPCAP pipeline (see, Nidever et al. 2015; Zamora et al. 2015; Holtzman et al. 2015; García Pérez et al. 2016) using reduction scripts designed for the 14th data release of SDSS (DR14, Abolfathi et al. 2018; Jönsson et al. 2018; Holtzman et al. 2018). We refer the reader to Zasowski et al. (2013) and Zasowski et al. (2017) for full details regarding the targeting strategies for APOGEE and APOGEE-2.

Here, we use the unprecedented 6-dimensional information of these stars provided by Gaia and the APOGEE survey, to investigate for the first time the orbital characteristics for a subset of this population.

1.1 6-D datasets

By cross-matching APOGEE-2 data to the Gaia (Gaia Collaboration et al. 2018), we have found Gaia counterparts to most of the N-rich stars studied in Martell et al. (2016), Fernández-Trincado et al. (2016b), Schiavon et al. (2017) and Fernández-Trincado et al. (2017c), with 5-D phase-space information, and only 7 of these stars has Gaia radial velocity information, with uncertainties on the order of 0.3–11 km/s. Our study is primarily based on proper motions from the Gaia catalog (Lindegren et al. 2018; Arenou et al. 2018), and APOGEE line-of-sight velocity because the error is generally smaller compared to other catalogues. The typical APOGEE uncertainties in radial velocity for our sample are of order of $\lesssim 2$ km s$^{-1}$.

In the following discussion (see §1.2), we used the revised spectrophotometric distances from the Bayesian StarHorse code (Queiroz et al. 2018) for those sources.

1.2 Distances

To obtain robust data, we employed precise spectrophotometric distances (with median distance uncertainties of $\lesssim 2$ kpc) estimated with the Bayesian StarHorse code (see, Queiroz et al. 2018, for more details) which combines atmospheric parameters ($T_{\text{eff}}$, log g and [M/H]) from the processed ASPCAP pipeline (García Pérez et al. 2016), multiband photometric information (APASS, 2MASS, and AllWISE) and the Gaia astrometric information when available with a Bayesian approach along with their associated uncertainties,
accounting for the global Gaia parallax zero-point shift of −0.029 mas (Lindegren et al. 2018; Arenou et al. 2018). As the parallax measurements can be uncertain (large > 22% and extending all the way up to 1400% uncertainty in the most extreme case), especially for distant stars, i.e., those located towards the Galactic bulge and halo, we believe that the choice to use spectrophotometric distances is well motivated to a large and homogeneously sampled number of N-rich stars, therefore from hereafter we decide to adopt the StarHorse distance calculations for orbital integration we define later.

A total of 75 out of 77 objects have reliable spectrophotometric distances determined using the StarHorse code as listed in Table 1: (i) One N-rich star, TYC 5619-109-1, from Fernández-Trincado et al. (2016b); (ii) Four "halo" N-rich stars from Martell et al. (2016); (iii) eleven N-rich stars from Fernández-Trincado et al. (2017c), and (iv) 59 "bulge" N-rich stars from Schiavon et al. (2017).

We also find that 2 out of 77 N-rich stars have reliable parallaxes and proper motions in the Gaia catalog: 2M02491285+5534213 with ϖ/σϖ > 20 and σϖ/ϖ < 4%, star from (Fernández-Trincado et al. 2017c), and 2M17431507−2815570 with ϖ/σϖ > 7 and σϖ/ϖ < 14%, star from (Schiavon et al. 2017). These stars are also listed in Table 1, namely the StarHorse code produce an estimated distance for 2M02491285+5534213 in good agreement with the distance derived as inverse of the parallax, for this star. For the second star, 2M17431507−2815570, the StarHorse code does not provide distance estimation, which can be attributed to uncertainties in the extinction in that direction, since it lies in a region where the extinction is higher. However, the small uncertainty in parallax for this star make it ideal to estimate the total velocity vector accurately, which we have included in our analysis.

The final sample so selected amounts to a total of 76 objects, from which 75 have spectrophotometric distance estimated from the StarHorse code, while one star, 2M17431507−2815570, have reliable Gaia parallax.

Complementary spectro-photometric distance estimates. Leung & Bovy (2019) derived precise distances for the whole APOGEE DR14 spectra sample from a neural-network ('deep learning') by training on the APOGEE-DR14/Gaia overlap, and makes use of no Galaxy priors and are thus not biased by such a prior. The left panel of Figure 1 shows the comparison between StarHorse and the distances from Leung & Bovy (2019) as well as the distance uncertainty as a function of our two sets of inferred distances (panel b in the same figure). Here it is clear, that StarHorse distances have smaller uncertainties at larger ranges than the ones obtained by Leung & Bovy (2019). As a result of the more precise estimates and the extinction treatment, we decided to use the StarHorse distances derived by Queiroz et al. (2018) as the main distance set along this work.

2 THE MILKY WAY MODEL

In order to construct a comprehensive orbital study of selected N-rich stars across the Milky Way, we use a state-of-the art orbital integration model in an more realistic (as far as possible) gravitational potential, that fits the structural and dynamical parameters to the best we know of the recent knowledge of our Galaxy.

For the computations in this work, we have employed the rotating "boxy/peanut" bar of the novel Galactic potential model called GravPot16 along other composite stellar components. The considered structural parameters of our bar model, e.g., mass, present-day orientation and pattern speeds, is within observational estimations that lie in the range of 1.1×10^{10} M_{⊙}, 20° and 30–50 km s^{-1} kpc, respectively. The density-profile of the adopted "boxy/peanut" bar is exactly the same as in Robin et al. (2012), while the mathematical formalism to derive the gravitational potential of this component, will be explained in a forthcoming paper (Fernandez-Trincado et al., in preparation).

GravPot16 considers on a global scale a 3D steady-state gravitational potential for the Galaxy, modelled as the superposition of axisymmetric and non-axisymmetric components. The axisymmetric potential is made-up of the superposition of many composite stellar populations belonging to seven thin discs, for each i-th component of the thin disc, we implemented an Einasto density-profile law (e.g., Einasto 1979; Robin et al. 2003), superposed along with two thick disc components, each one following a simple hyperbolic s-cant squared decreasing vertically from the Galactic plane plus an exponential profile decreasing with Galactocentric radius as described in Robin et al. (2014), we also implemented the density-profile of the interstellar matter (ISM) component with a density mass as presented in Robin et al. (2003).

The model, also correctly accounts for the underlying stellar halo, modelled by a Hernquist profile as already described in Robin et al. (2014), and surrounded by a single spherical Dark Matter halo component Robin et al. (2003), no time dependence of the density profiles is assumed. Our dynamical model has been adopted in a score of papers (e.g., Fernández-Trincado et al. 2016b, 2017b,a; Recio-Blanco et al. 2017; Albareti et al. 2017; Helmi et al. 2018; Libralato et al. 2018; Schiavacasse-Ulloa et al. 2018; Tang et al. 2018, 2019; Minniti et al. 2018). For a more detailed discussion, we refer the readers to a forthcoming paper (Fernandez-Trincado et al., 2019, in preparation).

For reference, the Galactic convention adopted by this work is: X−axis is oriented toward l = 0° and b = 0°, and the Y−axis is oriented toward l = 90° and b = 0°, and the disc rotates toward l = 90°; the velocity are also oriented in these directions. In this convention, the Sun’s orbital velocity vector are [U⊙,V⊙,W⊙] = [11.1, 12.24, 7.25] km s^{-1} (Brunthaler et al. 2011). The model has been rescaled to the Sun’s galactocentric distance, 8.3 kpc, and the local rotation velocity of 239 km s^{-1}.

For the computation of Galactic orbits of our N-rich stars, we have employed a simple Monte Carlo approach and the Runge-Kutta algorithm of seventh-eighth order elaborated by Fehlberg (1968). The uncertainties in the input data (e.g., α, δ, distance, proper motions and line-of-sight velocity errors), were randomly propagated as 1σ variation in a Gaussian Monte Carlo re-sampling. For each N-rich star we computed thousand orbits, computed backward in time during 3 Gyr. The average value of the orbital elements was found for our 1000 realizations, with uncertainty ranges given by the 16th and 84th percentile values, as listed in Table 2. As an additional test, we also run our backwards
orbits in an axisymmetric model to see how it affects our results, the results are illustrated in Figure 2, 4, and 9.

**Limitations of our model:** We further note the more important limitations of our calculation and model: (i) we ignore secular changes in the Milky Way over time, which are expected although the Milky Way galaxy has a quiet recent accretion history; and (ii) we do not consider the perturbations due to spiral arms, an in-depth analysis is important to note that our sample is dominated by ∆N-rich stars with reliable parallax information from Gaia, from the which the distances were determined as inverse of the parallax (1/π) with relative errors of <22% at most, and compared to other distance estimation methods.

| Galactic X | APOGEE-ID | RV ± ∆Δ | μR cos δ ± Δ | μΔ ± Δ | d⊙ ± Δ | Source | Comments |
|------------|-----------|----------|---------------|----------|----------|--------|----------|
| 0.28 ± 0.29 | 2M161168-132051 | 4.324927398277706 | 84.07 ± 0.88 | -11.707 ± 0.098 | -18.001 ± 0.058 | 2.8 ± 0.29 | StarHorse | FT-16 |
| 0.29 ± 0.21 | 2M160920-121342 | 4.54543796244889756 | 2.22 ± 0.10 | 0.019 ± 0.002 | 0.007 ± 0.001 | 1.32 ± 0.06 | Gaià | FT-16 |
| 0.35 ± 0.27 | 42142747.514809077312 | 5.3297521484341946 | 9.98 ± 0.27 | -1.479 ± 0.081 | -2.219 ± 0.049 | 3.7 ± 0.06 | StarHorse | FT-16 |
| 0.40 ± 0.37 | 30275751.3530949514111 | 6.0935896824686068 | 100.55 ± 0.57 | -1.057 ± 0.118 | -1.412 ± 0.099 | 13.59 ± 0.12 | StarHorse | FT-16 |
| 0.45 ± 0.40 | 30275751.3530949514111 | 6.6923868398859680 | -10.865 ± 0.51 | -0.411 ± 0.303 | -0.896 ± 0.237 | 4.42 ± 0.25 | StarHorse | FT-16 |
| 0.48 ± 0.42 | 2M1541184-3250160 | 7.088815625751707224 | -110.63 ± 0.13 | -3.125 ± 0.073 | -5.46 ± 0.047 | 3.37 ± 0.04 | StarHorse | FT-16 |
| 0.50 ± 0.43 | 2M1541184-3250160 | 7.088815625751707224 | -110.63 ± 0.13 | -3.125 ± 0.073 | -5.46 ± 0.047 | 3.37 ± 0.04 | StarHorse | FT-16 |

In this Section we present the main properties of the Galactocentric orbits determined for each of the 76 N-rich stars in our sample, both for the cases of an axisymmetric and a barred Galaxy model using four different values of the bar pattern speed Ωb = 35, 40, 45 and 50 km s⁻¹ kpc⁻¹. It is important to note that our sample is dominated by ∼76% of 100.55 ± 0.57 | -1.057 ± 0.118 | -1.412 ± 0.099 | 13.59 ± 0.12 | StarHorse | FT-16 |
| 0.45 ± 0.40 | 30275751.3530949514111 | 6.6923868398859680 | -10.865 ± 0.51 | -0.411 ± 0.303 | -0.896 ± 0.237 | 4.42 ± 0.25 | StarHorse | FT-16 |
| 0.48 ± 0.42 | 2M1541184-3250160 | 7.088815625751707224 | -110.63 ± 0.13 | -3.125 ± 0.073 | -5.46 ± 0.047 | 3.37 ± 0.04 | StarHorse | FT-16 |
| 0.50 ± 0.43 | 2M1541184-3250160 | 7.088815625751707224 | -110.63 ± 0.13 | -3.125 ± 0.073 | -5.46 ± 0.047 | 3.37 ± 0.04 | StarHorse | FT-16 |

**Table 1.** N-rich stars with reliable parallax information from Gaia, from the which the distances were determined as inverse of the parallax (1/π) with relative errors of <22% at most, and compared to other distance estimation methods.
N-rich stars identified in the inner Galaxy (e.g., Schiavon et al. 2017) which were supposed to belong to the Galactic bulge, therefore one would expect that most of our stars follow the typical orbital configurations of the bulge region, with a few exceptions as will be discussed below.

Figure 2 shows the shape of the orbit displayed by the mean orbital eccentricity\(^{1}\) \(e\) against the amplitude of the vertical oscillation \(|Z_{\text{max}}|\) for each N-rich star. The dashed horizontal line in the same figure represents the edge \(|Z_{\text{max}}|\) of the thick disk, \(Z = 3\) kpc (Carollo et al. 2010). Our N-rich star sample has median \(e\) of 0.89 and median \(|Z_{\text{max}}|\) of 1.3 kpc, which is dynamically consistent with both bulge and inner–halo population. There are a few stars with \(|Z_{\text{max}}| \gtrsim 3\) kpc and larger eccentricities \((\gtrsim 0.5)\), this suggest that most of these stars belong to the inner-halo, especially we confirm that all of N-rich stars analyzed in (Martell et al. 2016) are mostly consist with the Galactic (inner) halo and are characterized by eccentric orbits \((e \gtrsim 0.8)\) that can extend, on average, \(\lesssim 18.6 \pm 3.2\) kpc out the Galactic plane.

On the other hand, we find two N-rich stars from Schiavon et al. (2017) in orbits with \(|Z_{\text{max}}| \lesssim 3\) kpc and lower eccentricities \((\lesssim 0.5)\): the star 2M17464449−2531533 has an \(e \sim 0.5\) with \(|Z_{\text{max}}| \sim 1.5\) kpc, given these orbital properties, we expect it is a thick-disk contaminant, but more important, the orbit of this star have energies allowing this star to cross the bar’s corotation radius (CR \(\sim 6.5\) kpc), in this region two class of orbits appears around the Lagrange points \(L_4\) and \(L_5\) on the minor axis of the bar that can be stable, depending the bar pattern speed: a pure banana-like orbit (for a slow rotating bar of \(35\) km s\(^{-1}\) kpc\(^{-1}\)), with orbits that circulate \(L_4\) and \(L_5\), and orbits trapped around CR for a while (for a faster rotating bar of \(50\) km s\(^{-1}\) kpc\(^{-1}\)), the results are illustrated in Figure 7; the second star, 2M17431507−2815570, has an \(e < 0.5\) with \(|Z_{\text{max}}| < 0.5\) kpc, with an in-plane orbit confined inside the inner bar region \((r_{\text{gal}} \lesssim 0.5\) kpc\), the orbit is trapped by a higher-order resonance, depending on the bar patterns speed, such orbits have been also identified in bulge globular clusters (see, e.g., Pérez-Villegas et al. 2018).

For comparison, we plot our N-rich stars in the space of a characteristic orbital energy, \(E_{\text{char}} = (E_{\text{max}} + E_{\text{min}})/2\) as defined in Moreno et al. (2015), versus the orbital Jacobi constant \((E_J)\) in the reference frame of the bar, along with the expected Galactic trend of globular clusters (see Figure 3) adopting the inputs parameters of the late compilation of clusters properties given by Vasiliev (2018). This figure clearly shows the trends between the less bound (inner) halo N-rich stars (less negative orbital energies) against the more bound N-rich stars (more negative orbital energies), which have very similar orbital properties as observed in Galactic globular clusters. More general, these results provides observational support for the idea that the inner/outer stellar halo may have been assembled by kicking out captured possibly globular cluster stars with its own chemical enrichment history (e.g., Nissen & Schuster 2010; Carollo et al. 2013; Kunder et al. 2014; Fernández-Trincado et al. 2015a,b, 2016b,a; Koppelman et al. 2018; Khoperskov et al. 2018). In other words, these stars have presumably migrated from stellar clusters into the inner-halo.

For each generated set of orbits, we calculate the perigalactic distance \(r_{\text{per}}\), and the apogalactic distance \(r_{\text{apo}}\).

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\(^{1}\) the eccentricity \(e\) is defined as \((r_{\text{apo}} - r_{\text{per}})/(r_{\text{apo}} + r_{\text{per}})\)
the distribution of the average of these quantities are displayed in Figure 4 in both an axisymmetric model and a model including the Galactic bar potential. We found that most of the N-rich stars are characterized by close peripheral passages, on average, $z \lesssim 1$ kpc out of the Galactic center with energies allowing them to have orbits inward and around the bar's CR radius, while the apogalactic distance are larger than $CR \gtrsim 6.5$ kpc for a few cases, especially for those N-rich stars in halo-like orbits (subsample from Martell et al. 2016b; Fernández-Trincado et al. 2016b, 2017c), implying that these stars should on average be older. We also found two stars (2M17464449–281533 and 2M17431507–2815570) in (Schiaov et al. 2017) sample with larger apogalactic distance $>9$ kpc and lower vertical excursion from the Galactic plane ($z \lesssim 2$ kpc), the most likely is that these two stars are halo (inner) interlopers that happens to be at same distance and location as where bulge N-rich stars reside, suggesting that contamination from disk stars is relevant when attempting to trace this anomalous population, this is also supported by the dynamical behavior of N-rich stars from Fernández-Trincado et al. (2017c) in disk-like orbits also with lower vertical excursions from the Galactic plane as seen in Figure 2. However, there is not any obvious dependence among the metallicity and orbital properties, they were likely formed during the very early stages of the evolution of the Milky Way.

Following a similar interpretation as in Pérez-Villegas et al. (2018), we calculate the $z$-component of the angular momentum ($L_z$) in the inertial frame, as this quantity is not conserved in a model with nonaxisymmetric structures, we are interested only in the sign, in order to know whether the orbital motion of the N-rich stars has a prograde or a retrograde sense with respect to the Galactic rotation. For this reason in Figure 5 we plot the maximum and minimum of the $z$-component of the angular momentum. In general, most (about 46%) of the N-rich stars lie in prograde orbits,
Figure 2. Distribution of N-rich stars in orbital-parameter space (shown is the average of the eccentricity, $e$, versus the maximum vertical excursion from the Galactic plane, $|Z_{\text{max}}|$), for four different bar patterns speed as indicated in the title of each panel against the orbital solutions in the axisymmetric model (grey dot symbols). The orange unfilled circles, blue unfilled circles, black unfilled triangle and black unfilled circles highlight the N-rich stars from Schiavon et al. (2017), Martell et al. (2016), Fernández-Trincado et al. (2016b) and Fernández-Trincado et al. (2017c), respectively. The red and green filled hexagons mark the two N-rich stars highlighted in the text, 2M17431507−2815570 and 2M17464449−2531533, respectively. The dashed horizontal line represents the edge $|Z_{\text{max}}| \sim 3$ kpc of the thick disk (e.g., Carollo et al. 2010). The error bar are computed with uncertainty ranges given by the 16$^{th}$ (subscript) and 84$^{th}$ (superscript) percentile values.

While a significant fraction (about 50% depending on the bar angular velocity) of the N-rich stars identified in Schiavon et al. (2017) toward the bulge region have prograde and retrograde orbits at the same time (green symbols in Figure 5), it is not surprising as such dynamical behavior have been observed in bulge globular clusters (see, e.g., Pérez-Villegas et al. 2018), such orbital properties could be related to an early chaotic phase of the evolution of the central regions of the Milky Way (see, e.g., Pichardo et al. 2004; Pérez-Villegas et al. 2018), this provides observational support for the idea that most of such unusual stars in the inner Galaxy may have been assembled by kicking out globular cluster stars (Minniti et al. 2018; Kunder et al. 2018). Actually, most of these stars are bound objects to the Galaxy only for heliocentric distances smaller than $\lesssim 25$ kpc. In the case of the axisymmetric model we found about 54% of the N-rich stars have orbits in a retrograde sense respect to the direction of the Galactic rotation, this orbital property could

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be indicative of an early chaotic phase of the evolution of the Milky Way bulge, meaning that such stars were likely formed in a very early stage of the Galaxy, probably before bar formation, and a few of them were trapped by the bar structure later on.

It is also worth mentioning that in addition to the bulge N-rich stars there is another object in prograde-retrograde orbit, depending on the bar patterns speed. The prograde-retrograde star is TYC 5619-109-1 an extremely N-rich star studied in Fernández-Trincado et al. (2016b), which exhibit a significant retrograde signature, with respect to the Galactic rotation, which is trapped by a higher-order resonance inward CR (see Figure 7 and 8) in a potential with a faster bar ($\gtrsim 40$ km s$^{-1}$ kpc$^{-1}$), this retrograde sense is also seen in case of the potential as shown in Figure 9 and 10. When the slow ($\sim 35$ km s$^{-1}$ kpc$^{-1}$) is introduced to the model, there is an interesting dynamical effect produced, the star exhibit a dual motion in prograde-retrograde sense and going inside and outside of CR with low vertical excursion from the plane ($|Z_{max}| \lesssim 2$ kpc), we found this particular giant star is classified as a 'high-probability' (inner) stellar halo star, with a characteristic chaotic behavior.

Additionally, a few N-rich stars classified as "halo" stars in Martell et al. (2016), we found that four

Figure 3. Similar to Figure 2, here for the Galactic potential model including only the boxy bar in its non-axisymmetric components. In this case, the diagram plots the average of a 'characteristic' orbital energy (see text), $E_{char}$, versus the orbital Jacobi constant ($E_J$), in units of $10^5$ km$^2$ s$^{-1}$, computed in the reference frame of the bar. The symbols are similar as Figure 2, except the grey ‘x’ symbols, which represents the orbital properties of Galactic globular clusters adopting the recompiled information from Vasiliev (2018).
Figure 4. Orbital parameters as function of average perigalactic distance \( \langle r_{\text{per}} \rangle \) and average apogalactic distance \( \langle r_{\text{apo}} \rangle \) for the the axisymmetric model (grey dot symbols) and model with bar (with colored symbols as Figure 2).

stars (2M15113526+355140, 2M15204588+0055032, 2M1251355–0044438 and 2M17252263+4903137) reaches large vertical excursions (\( |Z_{\text{max}}| > 25 \text{ kpc} \)) from the Galactic plane, and have an overall eccentricity \( e > 0.8 \) (see Figures 7, 9, 8 and 10) in both an axisymmetric model and the model including the Galactic bar potential. These stars clearly resemble the halo population. Regarding the shape of their orbits, three of these stars move in a prograde sense with respect to the Galactic rotation, while one of them has an orbit with retrograde motion, we expect most of these stars having different orbital configurations from the rest, because it belongs to the halo component. With respect to the different values of the bar patterns speed, we can see that most orbits are not sensitive to the change of this parameter, except for TYC 5619-109-1 as discussed above.

Regarding, the newly N-rich stars identified in (Fernández-Trincado et al. 2017c), we found most of them (10 out of 11 stars) in prograde sense with respect to the Galactic rotation, except one star (2M02491285+5534213) with clear signature of retrograde motion as illustrated in Figure 5. This star dynamically resembles a (inner) halo star given its high vertical excursion from the plane with \( |Z_{\text{max}}| < 7.6 \text{ kpc} \), and higher eccentricity \( e > 0.7 \), the orbit is clearly going inside and outside of the bulge region in a higher-order resonance (see Figure 7 and 8). Furthermore, we found four objects (2M17535944+4708092, 2M12155306+1431114,
centricities (Kundu et al. (2017) in the Galactic plane (stars) have prograde orbits with low vertical excursions from these orbital properties are typically found in halo stars and orbital excursions going inside and outside CR (see Figure 7), also notice that the Galactic bar model (non-axisymmetric behaviour as compared to Galactic globular clusters. We can assemble an inner halo-bulge sample, and have similar dynamical be-
ties similar to the axisymmetric case, which could be related to a chaotic behavior associated with an early phase of evolution of the inner regions of the Milky Way (Pérez-Villegas et al. 2017), meaning that the majority of the N-rich stars were formed in a very early stage of the Milky Way, before bar formation, thus supporting the globular cluster escapee scenario (Fernández-Trincado et al. 2016a; Savino & Posti 2019; Khoperskov et al. 2018).

4 CONCLUDING REMARKS

In this work we have employed accurate data from the The European Space Agency’s Gaia mission Second Data Release (DR2) and APOGEE-2 survey to present the first dynamical characterisation of giant stars with anomalously high levels of [N/Fe] toward the bulge and halo of the Milky Way. This analysis have been carried out with the Milky Way model called GravPot16, where the orbits are integrated in both an full axisymmetric configuration of the model and a configuration including the Galactic bar potential, where we vary the angular velocity of the bar. The inclusion of a more realistic (as far as possible) rotating Galactic "bar/bulge" proved to be essential on the description of the dynamical behavior of N-rich stars across of the Milky Way, particularly in the N-rich sample located in the inner Galaxy, which shows a low eccentricity with no bar, whereas the orbits become highly eccentric with the presence of the bar, which in turn depends on the angular velocity, i.e., higher if \( \Omega_{\text{bar}} < 40 \) km s\(^{-1}\) or lower if \( \Omega_{\text{bar}} > 40 \) km s\(^{-1}\). From Figure 6, we can see that the Galactic bar induces to have smaller average perigalactic and apogalactic distances, and higher eccentricities. By this, it is very likely that either these peculiar population was formed early on before bar formation, or else was formed together with the bar. The main results can be summarized as follows:

- Our models predict that a significant fraction (\( \sim 54\% \)) of the N-rich stars have orbits with retrograde sense with respect to the direction of the Galactic rotation in the axisymmetric model, while than >41% have a particular and different behaviour, whose orbits change their sense of motion from retrograde to prograde with respect to the rotation of the bar, depending on the bar angular velocity, \( \Omega_{\text{bar}} \). This dynamical behaviour confirm that most of the N-rich giant belonged to a distinct population of the Milky Way, likely associated with accreted material and formed in a very early stage of the Galaxy, before bar formation. This provides observational support for the idea that most of the N-rich stars, especially those towards the inner Galaxy, may have been assembled by kicking out globular cluster stars, causing it to be now observed as a part of the inner Galactic halo.

- We can also notice that a minority, \( \sim 10\% \) of the N-rich stars within the bulge area, were identified in orbits that follow the bar structure, and share the orbital properties of the "bar/bulge", whose orbits are trapped by different resonances, depending on the bar angular velocity, \( \Omega_{\text{bar}} \), similar to some bulge globular clusters such as M 62 (see Minniti et al. 2018). It is likely, that these N-rich stars were formed before bar formation, and were trapped during or together the bar formation, as envisioned by (Pérez-Villegas et al. 2018).

- We found that approximately 46% of our sample follows high eccentric (\( e \gtrsim 0.6 \)) prograde orbits with the presence of the bar, which depends on the bar pattern speeds, higher considering a slow-rotating bar (\( \Omega_{\text{bar}} \sim 35 \) km s\(^{-1}\) kpc\(^{-1}\)) or lower for a fast-rotating bar (\( \Omega_{\text{bar}} \sim 50 \) km s\(^{-1}\) kpc\(^{-1}\)). On the other hand, the non-axisymmetric model (with a bar/bulge model) makes the distribution in eccentricities to be narrower than with the full axisymmetric configuration of our model. On the other hands, for most of the N-rich stars inside the CR, the orbits have a particular and different behaviour, e.g., the orbits are trapped by a higher-order resonance or corotation, depending on the bar patterns speed, \( \Omega_{\text{bar}} \), this means that most orbits are sensitive to the change of this parameter, which is negligible for stars whose orbits reach distance beyond the Sun's Galactocentric GravPot16.
distance. This proves that the bar/bulge is essential for the description of the dynamical behavior of these N-rich stars in the inner Galaxy.

- We also identified two N-rich stars, 2M1746444925315533 and 2M174315072815570, with larger apogalactocentric distances \( \geq 9 \) kpc and lower vertical excursion from the Galactic plane (\( \leq 2 \)) kpc, and appear to behave as halo-like orbits, the most likely is that these two stars are inner halo interlopers that happen to be at the same distance and location as where bulge N-rich stars reside, and this means that halo contamination could be not insignificant when studying chemically anomalous stars found within the bulge region (e.g., see Recio-Blanco et al. 2017).

**Figure 5.** Average of the maximum and minimal z-component \( L_z \) in the inertial frame in the model with nonaxisymmetric structures.

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Figure 6. Histograms of the corresponding average orbital parameters, showing the estimated dynamical properties of our sample. Orbital elements computed in the axisymmetric configuration of GravPot16 are shown, where the red and cyan histograms correspond to the full sample and the fraction of stars in retrograde sense with respect to the direction of the Galactic rotation, respectively. Orbital solutions from the non-axisymmetric configuration are also shown, where the grey, black, blue and gold correspond to the full sample, the fraction of stars that have prograde and retrograde orbits at the same time, the fraction of stars in prograde sense with respect to the rotation of the bar and the fraction of stars in retrograde sense of motion, respectively.
Figure 7. Orbital solutions in the non-axisymmetric model: Orbits for the sample of N-rich stars in X–Y projection in the potential with a slowly bar (grey line), $\Omega_{\text{bar}} = 55 \text{ km s}^{-1} \text{kpc}^{-1}$ and a faster bar (black line), $\Omega_{\text{bar}} = 50 \text{ km s}^{-1} \text{kpc}^{-1}$. The cyan solid line shows the size of the Galactic bar, and the cyan big circle the co-rotation radius, CR$\sim 6.5 \text{kpc}$. The small square symbol marks the present position of the star, and the red open and filled square marks its final position in the potential with slow and faster bar, respectively. The title indicate the origin of the star, M+16: Martell et al. (2016), FT+16:Fernández-Trincado et al. (2016b), S+17:Schiavon et al. (2017) and FT+17:Fernández-Trincado et al. (2017c), while the subtitle indicate the APOGEE id of each star. The title highlighted in red mark the stars: 2M17431507−2815570 and 2M17464449−2531533 (see text).
Figure 8. Orbital solutions in the non-axisymmetric model: R–z projection for the same sample as arranged in Figure 7.
Figure 9. Orbital solutions in the axisymmetric model: X–Y projection for the same sample as arranged in Figure 7.
Figure 10. Orbital solutions in the axisymmetric model: R–z projection for the same sample as arranged in Figure 7.