Discovery of a nitrogen-enhanced mildly metal-poor binary system: Possible evidence for pollution from an extinct AGB Star

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ABSTRACT

We report the serendipitous discovery of a nitrogen-rich, mildly metal-poor ([Fe/H] ≈ −1.08) giant star in a single-lined spectroscopic binary system found in the SDSS-IV Apache Point Observatory Galactic Evolution Experiment (APOGEE-2) survey, Data Release 14 (DR14). Previous work has assumed that the two percent of halo giants with unusual elemental abundances have been evaporated from globular clusters, but other origins for their abundance signatures, including binary mass transfer, must also be explored. We present the results of an abundance re-analysis of the APOGEE-2 high-resolution near-infrared spectrum of 2M12451043+1217401 with the Brussels Automatic Stellar Parameter (BACCHUS) automated spectral analysis code, and re-derive manually the main element families, namely the light elements (C, N), elements (O, Mg, Si), iron-peak element (Fe), s-process element (Ce), and the light odd-Z element (Al). Our analysis confirm the N-rich nature of 2M12451043+1217401, which has a [N/Fe] ratio of +0.69, and shows that the abundances of C and Al are slightly discrepant from that of a typical mildly metal-poor RGB star, but exhibit Mg, Si, O and s-process abundances (Ce) of typical field stars. We also detect a particularly large variability in its radial velocity over the period of the APOGEE-2 observations, and the most likely orbit fit to the radial velocity data has a period of 730.89 ± 106.86 days, a velocity semi-amplitude of 9.92 ± 0.14 km s$^{-1}$, and an eccentricity of 0.1276 ± 0.1174, which support the hypothesis of a binary companion, and that has probably been polluted by a now-extinct AGB star.

Key words. stars: abundances – stars: AGB and post-AGB – stars: evolution – stars: chemically peculiar — binaries: general – techniques: spectroscopic

1. Introduction

Today it is clear that stellar populations with distinctive light-element abundance patterns (Bastian & Lardo 2018; Fernández-Trincado et al. 2019d) are extremely common in globular clusters (GCs), while metal-poor stars ([Fe/H] ≲ −0.7) characterised by enhanced N ([N/Fe] ≳ 0.5) and depleted C ([C/Fe] ≲ 0.15) are rarely found in the field (Johnson et al. 2007; Martell et al. 2011; Carollo et al. 2013). While currently still inconclusive, there is tantalising evidence that stars with “anomalous chemistry” may be present beyond GC environments (e.g., Lind et al. 2015; Fernández-Trincado et al. 2016b; Recio-Blanco et al. 2017; Fernández-Trincado et al. 2019c).

To date, there have been a handful of stars fully characterised in terms of their chemistry and the chemical fingerprint of enriched second population$^1$ stars (e.g., Martell et al. 2016; Fernández-Trincado et al. 2016a, 2017; Schiavon et al. 2017; Fernández-Trincado et al. 2019b,a), especially through observations of molecular $^{16}$OH, $^{12}$C$^{15}$N and $^{12}$C$^{16}$O bands in the H-band of APOGEE (Majewski et al. 2017), which display the same chemical anomalies as stars in globular clusters, and exhibit conspicuous anomalies of the CNO elements, most notably N.

$^1$ Here, we refer to the second population as the groups of stars showing enhanced Si, N and Al, and depleted C and O abundances, with respect to other field stars at the same metallicity [Fe/H].

These nitrogen-enhanced stars (hereafter N-rich stars) have received significant attention in recent years, primarily because they are believed to be likely relics of surviving Galactic and/or extragalactic (see Fernández-Trincado et al. 2017, for instance) globular clusters (Martell & Grebel 2010), or now fully dissolved globular clusters (Fernández-Trincado et al. 2015b,a; Reis et al. 2018), and as such, play an important role in deciphering the early history of the Milky Way itself.

A special feature of N-rich stars is their low carbon-abundance ratios, with all stars having [C/Fe] ≲ 0.15 at [Fe/H] ≲ −0.7, and characterised by significant star-to-star variations in the abundances of elements involved in proton-capture reactions, i.e., C, N, O, Mg, and Al.

Empirically, within the population of N-rich stars several subclasses exist, defined by their stellar metallicity and their Al and/or Mg abundances. Most of the N-rich stars in the bulge (e.g., Schiavon et al. 2017) exhibit intermediate aluminum ([Al/Fe] ≲ +0.25) abundance ratios, similar to the thick disk. However, at higher metallicities, [Fe/H] > −0.7, Schiavon et al. (2017) identified a second group of N-rich stars chemically distinct from Milky Way stars across a variety of elements. Other groups of N-rich stars have been identified in the inner disk and the halo (Fernández-Trincado et al. 2016a, 2017), with [Al/Fe] ≳ +0.5, significantly above the typical Galactic level, across a range of metallicity. These stars are unlikely to have originated in tidally disrupted dwarf galaxies, because of the rarity of Al-rich...
stars in current dwarf galaxies (Shetrone et al. 2003; Hasselquist et al. 2017). Fernández-Trincado et al. (2017) found that some N-rich field stars are also Mg-rich, similar to second-population stars in globular clusters, while some have a factor of two less Mg than field stars at the same metallicity. There is also a subclass of N-rich stars with lower Al abundances, \([\text{Al}/\text{Fe}] \leq 0.1\), which tend to follow halo-like orbits with very little net rotation (Martell et al. 2016).

The range of elemental abundances that can be derived from APOGEE H-band spectra makes it possible to identify and study these classes of stars in detail. With that information we can quantify their occurrence rates in the field, and study their overall kinematic properties, in order to better understand their origins.

The origins of most of these N-rich stars are currently under investigation, with theories ranging from the formation of a N-rich star via AGB companion mass transfer or a massive evolved analog, to early accretion of GCs or dwarf former AGB companion has since become a faint white dwarf rich star via AGB companion mass transfer or a massive evolved analog. We quantify their occurrence rates in the field, and study their overall HAPOGEE (Martell et al. 2016).

which tend to follow halo-like orbits with very little net rotation (see Pereira et al. 2017), to early accretion of GCs or dwarf former AGB companion has since become a faint white dwarf rich star via AGB companion mass transfer or a massive evolved analog. Measuring additional properties of the N-rich stars may help to further distinguish among them, provide clues to their origins, and/or identify more sub-populations, or more broadly help to understand GC formation and evolution.

In this study, we present the serendipitous discovery of a N-rich star confirmed to be in a binary system with a compact object. The new object associated to 2M12451043\+1217401 is a nitrogen-enhanced and carbon-depleted metal-poor star with abundances of Al and Mg mildly discrepant from that of normal RGB stars. We hypothesise that this star is likely to be an example of the result of mass transfer from a binary companion, which is now in the white dwarf stage of stellar evolution. The discovery of such stars helps guide models that attempt to explain the unusual elemental abundances over a wide range of metallicities.

This paper is outlined as follows. In Section 2, we present details and information regarding our serendipitous discovery in the APOGEE-2 dataset. In Section 3, we describe and discuss the behaviour of the measured light and heavy elements. In Section 4, we present our main conclusions.

### 2. Data

For our analysis we make use of the publicly available H-band spectra from the APOGEE-2 survey (Majewski et al. 2017). We draw on the latest data release, DR14 (Abolfathi et al. 2018), obtained with the multi-object high-resolution spectrograph APOGEE mounted at the Sloan 2.5m Telescope (Gunn et al. 2006) at Apache Point Observatory, which began observation in 2014 as part of the Sloan Digital Sky Survey IV (Blanton et al. 2017). A detailed description of these observations, targeting strategy, data reduction, and APOGEE stellar-parameter estimates can be found in Zasowski et al. (2013), Zasowski et al. (2017), Nidever et al. (2015), Holtzman et al. (2015), Zamora et al. (2015) and García Pérez et al. (2016), respectively.

We start by searching for high-[N/Fe] outliers in the [N/Fe]-[Fe/H] abundance space in the first Payne data release of APOGEE abundances (see Ting et al. 2018, hereafter Payne-APOGEE). The Payne routine simultaneously derives best-fit values for all atmospheric parameters and abundances using neural networks, with the parameter space of the training set restricted to \([\text{Fe}/\text{H}] \geq -1.5\). For each source, it only reports values for the measurement with the highest SNR.

The sample was then restricted to the metallicity regions \([-1.5 \leq [\text{Fe}/\text{H}] \leq -0.7\], and giant stars with log \(g \geq 3.6\), which encompasses the transition between the Galactic thick disk and halo, following the same line of investigation as in Fernández-Trincado et al. (2017). Thus, we adopt the atmospheric parameters and [C,N,O/Fe] and [Fe/H] abundance ratios reported in the Payne catalog as the first-guess input parameters into the Brussels Automatic Stellar Parameter (BACCHUS) code (Masseron et al. 2016) in order to derive the metallicity and chemical abundances reported in Table 1. In addition to those literature values, we also systematically synthesised every element and line of 2M12451043\+1217401 at high spectral resolution, to compare with the Payne and ASPCAP determinations. We have made careful line selection, as well as providing abundances based on a line-by-line differential approach in the atomic and molecular input data. The abundances that are derived for 2M12451043\+1217401 using BACCHUS, found in Table 1, are generally in good agreement with those in the literature. In Appendix A, we describe the BACCHUS pipeline in more detail.

### Table 1. Comparison of mean elemental abundances derived from our target 2M12451043\+1217401 using the “abund” module in BACCHUS code, and those obtained with the Payne and ASPCAP pipeline.

| Element | BACCHUS† | Payne | ASPCAP
|---------|----------|-------|-------|
| \[\text{Fe}\] | Masseron et al. (2016) | Ting et al. (2018) | García Pérez et al. (2016) |
| \(\sigma_{\text{total}}\) | \(4886.9 \pm 92.7\) K | \(4886.9 \pm 92.7\) K | \(4886.9 \pm 92.7\) K |
| log \(g\) | 2.24 \(\pm 0.03\) | 2.24 | 2.22 \(\pm 0.08\) |
| \(\xi\) | 1.86 \(\pm 0.05\) km s\(^{-1}\) | 1.39 \(\pm 0.10\) km s\(^{-1}\) | 1.44 \(\pm 0.09\) km s\(^{-1}\) |
| [Fe/\(\text{H}\)] | \(-1.08 \pm 0.14\) | \(-1.09\) | \(-1.12 \pm 0.01\) |
| [C/Fe] | 0.06 \(\pm 0.24\) | 0.06 | 0.03 \(\pm 0.07\) |
| [N/Fe] | 0.69 \(\pm 0.22\) | 0.66 | 0.74 \(\pm 0.09\) |
| [O/Fe] | 0.46 \(\pm 0.23\) | 0.22 | 0.22 \(\pm 0.07\) |
| [Al/Fe] | 0.04 \(\pm 0.16\) | 0.04 | 0.05 \(\pm 0.08\) |
| [Mg/Fe] | 0.10 \(\pm 0.14\) | 0.22 | 0.22 \(\pm 0.04\) |
| [Si/Fe] | 0.22 \(\pm 0.12\) | 0.22 | 0.21 \(\pm 0.04\) |
| [Ce/Fe] | 0.49 \(\pm 0.20\) | 0.20 | 0.21 \(\pm 0.04\) |

Notes. The reported uncertainty for each chemical species in column 2 is: \(\sigma_{\text{total}} = \sqrt{\sigma_{\text{fit}}^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{fit}}^2} \). The Solar reference abundances are from Asplund et al. (2005) for light elements and Grevesse et al. (2015) for heavy elements. † The BACCHUS pipeline was used to derive the broadening parameters, metallicity, and chemical abundances.

The high-[N/Fe] outlier sample itself was defined by fitting a 5\(^{rd}\) order polynomial to the run of [N/Fe] with [Fe/H] and taking stars deviating from the fit by 2\(\sigma\). 2M12451043\+1217401 is a high-[N/Fe] outlier in chemical space, as compared to the bulk of the disk, bulge, and halo stars in the Payne-APOGEE sample. The sample in Fig. 1 contains stars with [C/Fe] \(\geq 0.15\), because higher [C/Fe] abundance ratios are not typically found in globular clusters, and we want to avoid contamination by CH stars, for instance.

In this first work, we have only analysed one star (2M12451043\+1217401), with large variability in radial velocity, out of 35 high-[N/Fe] outliers recently identified in Fernández-Trincado et al., (2019, in prep.), who analysed the...
same data set. The reader solely interested in the discussion of variability may see Appendix B and skip the latter sections.

While a comprehensive analysis of our new high-[N/Fe] outliers is beyond the scope of this paper, we did search in the literature for other high-[N/Fe] outliers in the more metal-poor ([Fe/H] ≤ −0.7) population, identified in the APOGEE sample by Martell et al. (2016), Schiavon et al. (2017), and Fernández-Trincado et al. (2016a, 2017), with available chemical abundances in the Payne-APOGEE catalog, to verify that both Payne-APOGEE abundances and the polynomial fit used in this work is properly returning high-[N/Fe] outliers by recovering the most obvious known nitrogen-enhanced population. The results of this comparison are shown in the left-bottom panel of Fig. 1.

Figure 2 displays an example for a portion of the observed APOGEE spectrum of 2M12451043+1217401, where the $^{12}$C$^{14}$N absorption feature is quite strong. As a comparison, we also show the APOGEE spectrum of a field star with a "normal" nitrogen abundance ([N/Fe] ≤ +0.5), 2M15182930+0206378, with stellar parameters and metallicity identical to that of the N-rich star. The N-rich star has remarkably stronger $^{12}$C$^{14}$N lines, which can only mean that it has much higher nitrogen abundance. We conclude that the nitrogen abundance reported here, which is the basis for our identification of a new high-[N/Fe] outlier in the Milky Way, is highly reliable, and detectable in 2M12451043+1217401.

3. Stellar parameters and chemical-abundance measurements

The first estimates for stellar parameters for 2M12451043+1217401 we adopted in the present work are $(T_{\text{eff}}, \log g, \xi, [\text{M/H}]) = (4750.2 \text{ K}, 2.24, 1.86 \text{ km s}^{-1}, -1.09)$, taken from Payne-APOGEE catalogue. With this set of parameters, we performed an abundance analysis using the LTE abundance code BACCHUS (Masseron et al. 2016), using the plane-parallel, one dimensional grid of MARCS model atmospheres (Gustafsson et al. 2008). The results are listed in Table 1. The metallicity listed in column 2 of Table 1 is the average abundance of selected Fe I lines, and is in acceptable agreement with that determined from the ASPCAP and Payne-APOGEE pipelines.

Here, we explore whether or not our chemical-abundance measurements have the ability to chemically tag stars associated with globular clusters by performing a chemical-tagging analysis. Because we are interested in searching for high-[N/Fe] outliers with chemical signatures typical of globular cluster members, we focus on the abundances of C, N, O, Si, Mg, and Al. We have also attempted to measure one additional element, namely Ce II, because it has three promising and detected lines (15784.8,
To put our results in context, we combined the chemical-abundance patterns ([Fe/H], [C/Fe], [N/Fe], [Mg/Fe], [Si/Fe], and [Al/Fe]) of 2M12451043+1217401, along with the chemical-abundance pattern of globular cluster stars, other unusual giant stars (e.g., Martell et al. 2016; Fernández-Trincado et al. 2016a, 2017; Schiavon et al. 2017) from the APOGEE survey, and the entire Milky Way sample, see Figure 1.

It is immediately clear from Figure 1 that the chemical-abundance pattern of 2M12451043+1217401 appears to be distinguishable from Galactic populations. Similarly, its elevated [N/Fe] ratio, as well as the chemical distribution in the α-elements, appear most similar to those seen in the chemistry of normal stars in GCs (often called first-generation stars), and comparable to a few nitrogen-enhanced metal-poor field stars at similar metallicity. On the other hand, the moderately enhanced nitrogen level of this star, [N/Fe] ≳ +0.69, suggests that this value is above the boundary that separates N-rich stars ([N/Fe] ≥ +0.5) from objects with “normal” N abundances ([N/Fe] ≤ +0.5), according to our strategy to separate these two population (see above text). This is strongly manifested in the [Fe/H] vs. [N/Fe] plane in Figure 1.

Figure 1 demonstrates that 2M12451043+1217401 seems to resemble the locus dominated by globular cluster stars and the nitrogen-enhanced metal-poor field stars discussed in Martell et al. (2016); Fernández-Trincado et al. (2016a); Schiavon et al. (2017) and Fernández-Trincado et al. (2017) in the [N/Fe]–[Fe/H] and [Al/Fe]–[Fe/H] planes, which suggest that this star might have originated in globular clusters. However, another possible source for the abundance pattern in 2M12451043+1217401, given its radial velocity variability, is binary mass transfer from an possible AGB companion (see, e.g., Starkenburg et al. 2014). The mass range for the donor star is determined by the minimum mass for the third dredge-up, and by the onset of effective hot bottom burning, which burns C into N quite effectively. It is important to note that without clear diagnostics such as mass, i.e., from an orbital solution, or a wide gamut of s-/r-process abundance patterns, the nature of the companion that polluted the N-rich binary star is not at all obvious from observations of [X/Fe] or [X/H] ratios (see below).

As can be seen in Figure 1, this star occupies the same region of Mg-Al abundance space as globular cluster stars, without strong evidence of MgAl cycles. The Si abundance is also moderately enriched, which is typical for globular clusters. While the abundance pattern of 2M12451043+1217401 seems consistent with globular cluster stars in the [N/Fe]–[Fe/H], [Mg/Fe]–[Fe/H], [Al/Fe]–[Mg/Fe], and [Al/Fe]–[N/Fe], it is distinct from the overall APOGEE data set, which contains bulge, disk and halo stars. We also see some distinction in carbon between 2M12451043+1217401 and the main body of N-normal stars and globular cluster population, with the N-normal stars and GCs stars typically having lower [C/Fe] (for a given metallicity). In Figure 1 we also compared the chemical-composition of a giant star in the main body of N-normal stars with similar stellar parameters and similar metallicity that 2M12451043+1217401, this clearly shows that our object display approximately the same
of 2M12451043. Clearly detected and well fitted. In the same figure the spectrum with the synthetic fits to the spectrum. The Ce II lines are strengthened in the brief examination reassures us the existence of a noticeably enhancement of the surface gravity values. This represents a modest enrichment driven by stellar parameters (see Table A.3), most sensitive to the surface gravity values. This represents a modest enhancement of the s-process in the Ce II lines in the APOGEE window, at 15784.8, 15958.4 and 16376.5 Å, we derive a cerium abundance of [Ce/Fe] = +0.49 ± 0.20, with an uncertainty mainly driven by stellar parameters (see Table A.3), most sensitive to the surface gravity values. This represents a modest enhancement of the s-process in the N-rich binary star, and is similar to the typical enhancement of [Ce/Fe] found in field stars with similar metallicities.

Figure 4 show three of the Ce II lines in 2M12451043+1217401 in the APOGEE window along with the synthetic fits to the spectrum. The Ce II lines are clearly detected and well fit. In the same figure the spectrum of 2M12451043+1217401 is compared to a field (normal) star with similar stellar parameters and with similar metallicity: this brief examination reassures us the existence of a noticeably strengthened in the s-process in 2M12451043+1217401, in view of the similarity between to the two stars in all the other relevant parameters, can only mean that it have mildly enhanced values of [Ce/Fe], but still comparable to the s-process content of a typical field star (see Figure 5), and differ only notably on the basis of their nitrogen composition as illustrated in Figures 2 and 5.

Figure 3 also show that 2M12451043+1217401 exhibit [Ce/Fe] ratios identical to typical RGB stars as seen in globular cluster environments (e.g., Masseron et al. 2019; Nataf et al. 2019) at similar metallicity, with the peculiarity that 2M12451043+1217401 is clearly enhanced in nitrogen as compared to a N-normal field star (see Figure 2). We showed that 2M12451043+1217401 is a mildly metal-poor binary star characterized by an enhancement of nitrogen with modest enhancement of the s-process elements. Therefore, we hypothesize it possible that the high [N/Fe] abundance ratio simultaneous with the basic pattern in Ce, C, and Al, could be due to pollution from a previous AGB companion which is now a white dwarf.

From a theoretical point of view, the intermediate-mass AGB stars, with masses of 3–8 M⊙, may influence nucleosynthesis where N is strongly enhanced by Hot-Bottom Burning (HBB) at the expense of C (Masseron et al. 2010), and may be able to produce simultaneously a considerable amount of nitrogen (Cristallo et al. 2015), in this case, the abundances that we measure are not its original ones but they reflect the chemical composition of the companion, plus some degree of dilution with the convective envelope of the accreting star. To summarise, although the mechanism responsible for the N production could be attributed to pollution from an intermediate-mass AGB star, no current AGB models reproduce the trend observed in Figure 5 for 2M12451043+1217401. Thus we cannot use N or Ce to place additional constraint on the mass of the progenitor. Thus, a future inventory of the chemistry of the system, in particular, the elements formed by neutron-capture processes, would hint at the range of mass of the companion, and possibly help confirm or refute the association with an extinct AGB star.

We have shown that 2M12451043+1217401 does show radial velocity variation, which is consistent with being a binary. It is indeed possible that an intermediate-mass companion has undergone its AGB phase and dumped shell-nucleosynthesis processed material onto the observed star, in a similar fashion to what happens for CH and CEMP stars (e.g., Cristallo et al. 2016), increasing the content of N, C, and Al, as compared to a typical field RGB star (see Figure 5).

4. Concluding remarks

In this work, we communicate the serendipitous discovery of an unusual red-giant star that show significantly enhanced [N/Fe] among metal-poor field stars. Based on high-resolution NIR spectroscopic data from the APOGEE-2 survey, we determined the atmospheric parameters, spectrotscopic distance, radial velocity variability, abundances of light elements (C, N, O, Mg, Al and Si), and the elements created by the s-process (Ce II) for 2M12451043+1217401. Combining the large radial velocity variation, and nitrogen over-abundance, we hypothesise that an possible AGB-binary system may produce a [N/Fe] over-abundance in some N-rich stars within the Milky Way, since mass transfer happened in the past, and the star is a normal RGB star where we see the effects due to the pollution of a companion that has undergone its AGB phase and dumped shell-nucleosynthesis processed material onto the observed star, i.e., the AGB companion deposits its N-rich outer layers onto its RGB companion through accreting winds, the binary system produces N (destroying C in the process), that is then mixed throughout the RGB envelope. The companion star in the system is now a possible white dwarf. A future inventory of the chemistry of this binary system, in particular the elements involved in the neutron-capture reactions (i.e.,
Fig. 4. Example spectra and the fitted synthesis of Ce II lines for 2M12451043+1217401 in the observed infrared spectrum (grey unfilled squares). The printed best fitted abundance (black thick line) values might not be the same as in Table 1 because the table contains averaged values, not individual fits. The blue and green lines correspond to synthetic spectrum abundance choices that are offset from the best fit by ±0.2 dex. The spectrum of the N-rich star is compared to the spectrum of a normal star with $[\text{Ce/Fe}]=+0.34$ dex (red line correspond to APOGEE_ID: 2M12251747+1450078, labeled here as Normal RGB), with similar stellar parameters.

A dynamical study of 2M12451043+1217401 shows that this system has a retrograde motion with a highly eccentric orbit, consistent with the Galactic inner halo population. The results are described in Appendix C and illustrated in Figure C.1. By this we mean that this system was formed early on before the inner halo formation, or else, the system formed together with the inner-halo. The present paucity of halo binary N-enriched stars could therefore also have implications for the binary fraction in the field, which to date has been difficult to determine. This study further supports the idea that AGB stars could be the key players in the pollution of $^{12}$C-$^{14}$N via a slow stellar wind which has pol-
Fig. 5. The chemical abundance pattern of 2M12451043+121740 (N-rich Binary star), for elements X, where X is displayed at the label of the figure. Each determined abundance is shown as an open red circle. These abundances are compared to a N-normal RGB star (black diamond symbols) with similar atmospheric parameters and similar metallicity that the N-rich Binary star.

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Appendix A: Line-by-line abundances

Table A.1 and A.2 list the atomic and molecular lines used to derived abundances from a line-by-line differential analysis using the the current version of the Brussels Automatic Stellar Parameter (BACCHUS) code (see Masseron et al. 2016), which relies on the radiative transfer code Turbospectrum (Alvarez & Plez 1998; Plez 2012) and the MARCS model atmosphere grid (Gustafsson et al. 2008). For each element and each line, the abundance determination proceeds as in Hawkins et al. (2016), and summarized here for guidance: (i) A spectrum synthesis, using the full set of (atomic and molecular) lines, is used to find the local continuum level via a linear fit; (ii) cosmic and telluric rejections are performed; (iii) the local S/N is estimated; (iv) a series of flux points contributing to a given absorption line is automatically selected; and (v) abundances are then derived by comparing the observed spectrum with a set of convolved synthetic spectra characterised by different abundances. Four different abundance determinations are used: (i) Line-profile fitting; (ii) a core line-intensity comparison; (iii) a global goodness-of-fit estimate; and (iv) equivalent width comparison. Each diagnostic yields validation flags. Based on these flags, a decision tree then rejects the line or accepts it, keeping the best-fit abundance. We adopted the χ² diagnostic for the abundance decision, it is the most robust. However, we store the information from the other diagnostics, including the standard deviation between all four methods. The linelist used in this work is the latest internal DR14 atomic/molecular linelist (linelist.20170418), and the Ce II lines from Cunha et al. (2017). For a more detailed description of these lines, we refer the reader to a forthcoming paper (Holtzman et al., in preparation). In particular, a mix of heavily CN-cycle and α-poor MARCS models were used, as well as the same molecular lines adopted by Smith et al. (2013), were employed to determine the C, N, and O abundances. In addition, we have adopted the C, N, and O abundances that satisfy the fitting of all molecular lines consistently; i.e., we first derive 16O abundances from 16OH lines, then derive 12C from 12C16O lines and 14N from 14C14N lines, and the CNO abundances are derived several times to optimize the CO, CN, and CN abundances (see, e.g., Smith et al. 2013; Fernández-Trincado et al. 2019d).

We additionally evaluated the possibility to apply the approach of fixing Teff, log g to values determined independently of spectroscopy, in order to check for any significant deviation in the chemical abundances. For this, the photometric effective temperature, Teff phot = 4806.6 K, was calculated from the J2MASS − K2MASS color relation using the methodology presented in González Hernández & Bonifacio (2009); for 2M12451043+1217401 we adopt J2MASS − K2MASS = 0.637 mag and [Fe/H] = −1.09. Photometry is extinction-corrected using the Rayleigh Jeans Color Excess (RJCE) method (see Majewski et al. 2011), which leads to (AWISE) ≈ 0.023 mag. The resulting temperature, Teff eff = 4806.6 K, is in very good agreement with the spectrometric temperatures from ASPCAP and Payne-APOGEE. In conclusion, this small Teff discrepancy does not affect our results. In the following, our analysis is restricted to the atmospheric parameters as listed in Table 1. The same table also lists the abundance measurements in this star obtained with the BACCHUS code and compared to ASPCAP and Payne-APOGEE pipelines. Here, we also list the total error bar on our measurements, which is based on the contributions from the statistical and systematic uncertainties.

Appendix B: Variability

Here we use multi-epoch radial velocity measurements available in the APOGEE-2 DR14 database, 2M12451043+1217401 was observed multiple times in a series of 25 "visits" in order to meet the signal-to-noise ratio requirements of the APOGEE-2 survey. The radial velocities for each visit are determined using an iterative scheme, i.e., the individual visit spectra are combined using initial guesses for the relative radial velocities into a co-added spectrum, which is then used to re-derive the relative visit velocities (see, e.g., Nidever et al. 2015; Price-Whelan et al. 2018).

Generally, observations from the APOGEE-2 survey have a relatively short (∼ 6 months) baseline, which is a potential limitation to enable the detection of N-rich stars formed through the binary channel. Here, however, we find that the large scatter (> 9.92 km s⁻¹) shown by the measured radial velocities in...
Table A.1. Atomic lines and derived log abundances for the light elements Fe, Al, Mg, and Si, and the heavy element Ce.

| Element | $\lambda_{\text{air}}$ (Å) | log ($\epsilon$) |
|---------|-----------------|-----------------|
| Fe I    | 15207.5         | 6.194           |
|         | 15245.0         | 6.317           |
|         | 15294.6         | 6.225           |
|         | 15394.7         | 6.377           |
|         | 15500.8         | 6.210           |
|         | 15501.3         | 6.216           |
|         | 15531.8         | 6.443           |
|         | 15534.2         | 6.415           |
|         | 15588.3         | 6.518           |
|         | 15591.5         | 6.308           |
|         | 15604.2         | 6.180           |
|         | 15621.7         | 6.324           |
|         | 15632.0         | 6.296           |
|         | 15723.6         | 6.356           |
|         | 15769.1         | 6.583           |
|         | 15769.4         | 6.583           |
|         | 15774.1         | 6.400           |
|         | 15895.2         | 6.456           |
|         | 15904.3         | 6.419           |
|         | 15920.6         | 6.324           |
|         | 15964.9         | 6.460           |
|         | 15967.7         | 6.414           |
|         | 15980.7         | 6.331           |
|         | 16006.8         | 6.356           |
|         | 16007.1         | 6.357           |
|         | 16040.7         | 6.437           |
|         | 16042.7         | 6.172           |
|         | 16071.4         | 6.453           |
|         | 16125.9         | 6.505           |
|         | 16153.2         | 6.419           |
|         | 16179.6         | 6.379           |
|         | 16195.1         | 5.969           |
|         | 16284.8         | 6.489           |
|         | 16517.2         | 6.402           |
|         | 16524.5         | 6.427           |
|         | 16561.8         | 6.483           |
|         | 16465.9         | 6.300           |
|         | 16665.5         | 6.468           |

$\langle A(\text{Fe}) \rangle \pm \sigma_{\text{mean}} = 6.37 \pm 0.12$

| Element | $\lambda_{\text{air}}$ (Å) | log ($\epsilon$) |
|---------|-----------------|-----------------|
| Al I    | 16719.0         | 5.253           |
|         | 16750.6         | 5.237           |
|         | 16763.4         | 5.503           |

$\langle A(\text{Al}) \rangle \pm \sigma_{\text{mean}} = 5.33 \pm 0.12$

| Element | $\lambda_{\text{air}}$ (Å) | log ($\epsilon$) |
|---------|-----------------|-----------------|
| Mg I    | 15740.7         | 6.586           |
|         | 15748.9         | 6.556           |
|         | 15765.8         | 6.537           |

$\langle A(\text{Mg}) \rangle \pm \sigma_{\text{mean}} = 6.56 \pm 0.02$

| Element | $\lambda_{\text{air}}$ (Å) | log ($\epsilon$) |
|---------|-----------------|-----------------|
| Si I    | 15376.8         | 6.450           |
|         | 15557.8         | 6.629           |
|         | 15884.5         | 6.475           |
|         | 15960.1         | 6.623           |
|         | 16060.0         | 6.738           |
|         | 16094.8         | 6.728           |
|         | 16215.7         | 6.762           |
|         | 16241.8         | 6.775           |
|         | 16680.8         | 6.570           |
|         | 16682.8         | 6.766           |

$\langle A(\text{Si}) \rangle \pm \sigma_{\text{mean}} = 6.65 \pm 0.12$

| Element | $\lambda_{\text{air}}$ (Å) | log ($\epsilon$) |
|---------|-----------------|-----------------|
| Ce II   | 15784.8         | 1.029           |
|         | 15958.4         | 1.055           |
|         | 16376.5         | 0.911           |

$\langle A(\text{Ce}) \rangle \pm \sigma_{\text{mean}} = 0.998 \pm 0.06$

We conducted a search for the orbital period using the genetic algorithm PIAKIA (Charbonneau 1995) to determine the orbital parameters that best fit the available data. Following the analysis described by Mennessent et al. (2012, 2018a,b) we

2M12451043+1217401 implies the clear existence of at least one companion. So far, no evidence of strong radial velocity variations has been found in stars with nitrogen over-abundances in the APOGEE survey (see, e.g., Martell et al. 2016; Fernández-Trincado et al. 2016a, 2017; Schiavon et al. 2017). Therefore, establishing the presence of radial velocity variation among these stars would be required in order to understand if many, or all such objects, formed through the binary channel.

Although APOGEE-2 observed our star during multiple "visits", we omitted one observation with a signal to noise ratio (SNR) below 4 per pixel from our radial velocity analysis. The observations are summarized in Table B.1, which lists the APOGEE radial velocities, their uncertainties, and the signal-to-noise ratio (SNR) per pixel for each epoch.

We conducted a search for the orbital period using the genetic algorithm PIAKIA (Charbonneau 1995) to determine the orbital parameters that best fit the available data. Following the analysis described by Mennessent et al. (2012, 2018a,b) we
Fig. B.1. Radial velocity measurements for 2M12451043+1217401 from 24 visits of the APOGEE-2 survey (top panel) with the best-fit, with the residual velocities (bottom panel).

In order to estimate the errors for the results obtained from PIKAIA, we proceeded to calculate the confidence intervals for the region corresponding to 68.26% of the sample ($1\sigma$). The results are listed in Table B.2. The fit produces a good match to the available data (residuals $\approx 1$ km s$^{-1}$, see bottom panel in Fig. B.1).

It is important to note that 2M12451043+1217401 was identified as a "bimodal binary" in the bimodal period samplings of The Joker code in Price-Whelan et al. (2018), corresponding to periods between $P \approx 650$–950 days and eccentricity between $\approx 0.07$–0.3: $(P_1, e_1) = (939.80, 0.31)$ days and $(P_2, e_2) = (689.85$ days, 0.07). The best-fit orbital parameters from PIKAIA are an orbital period of 730.89 ± 106.86 days, a velocity semi-amplitude of 9.918 ± 0.138 km s$^{-1}$, and an eccentricity of 0.128 ± 0.117. These are in acceptable agreement with the shorter period reported by Price-Whelan et al. (2018).

Visual inspection of the spectrum of 2M12451043+1217401 does not reveal any obvious signs of binary interaction, such as emission lines from an accretion disk. If this is a post-mass-transfer binary system, the primary would have evolved into a white dwarf by this point, making it quite difficult to detect in the $H$-band. Alternately, if there was very strong mass loss from the primary, the binary system could have disrupted or significantly widened. For the case of SB1 binaries, where only one component is detected in the spectrum, the mass information is
Table B.1. APOGEE Observations

| Julian date | RV (km s\(^{-1}\)) | \(\sigma\) (km s\(^{-1}\)) | SNR (pixel\(^{-1}\)) |
|-------------|---------------------|-----------------------------|---------------------|
| 2457059.94391 | -88.85              | 0.16                        | 20                  |
| 2457060.91321 | -89.43              | 0.15                        | 20                  |
| 2457062.99631 | -89.45              | 0.15                        | 20                  |
| 2457064.89865 | -90.54              | 0.17                        | 18                  |
| 2457114.79574 | -92.80              | 0.22                        | 17                  |
| 2457118.85652 | -92.28              | 0.43                        | 8                   |
| 2457121.82661 | -92.55              | 0.19                        | 16                  |
| 2457122.80708 | -93.23              | 0.14                        | 23                  |
| 2457141.73865 | -93.40              | 0.21                        | 15                  |
| 2457142.73487 | -93.09              | 0.17                        | 18                  |
| 2457148.68704 | -94.02              | 0.19                        | 16                  |
| 2457167.65509 | -92.67              | 0.79                        | 5                   |
| 2457449.88122 | -74.01              | 0.12                        | 26                  |
| 2457465.78237 | -74.55              | 0.12                        | 22                  |
| 2457468.79933 | -73.70              | 0.14                        | 22                  |
| 2457472.79234 | -74.23              | 0.14                        | 23                  |
| 2457473.86693 | -73.25              | 0.16                        | 20                  |
| 2457475.83189 | -73.32              | 0.13                        | 22                  |
| 2457492.72504 | -73.91              | 0.12                        | 23                  |
| 2457496.80519 | -73.52              | 0.21                        | 14                  |
| 2457499.79405 | -73.47              | 0.16                        | 19                  |
| 2457504.78284 | -69.84              | 0.89                        | 4                   |
| 2457530.70246 | -73.99              | 0.19                        | 16                  |
| 2457533.71368 | -73.81              | 0.11                        | 25                  |
| 2457534.73149 | -74.29              | 0.19                        | 14                  |

Notes. ¹ Reduced Heliocentric J2012. ² Values omitted for spectra with SNR < 5.

Table B.2. Orbital elements for the donor of 2MASS J12451043+1217401 obtained by minimization of the \(\chi^2\) parameter given by Eq. B.1. The values \(\tau^\prime = \tau - 2450000\) and the limits of the confidence intervals within one standard deviation (1\(\sigma\)) are given.

| Parameter | Best value | Lower limit | Upper limit |
|-----------|------------|-------------|-------------|
| \(P_o\) (d) | 730.89 ± 108.86 | 679.61 | 895.33 |
| \(\tau^\prime\) | 57179.0117 ± 59.5272 | 57129.9301 | 57248.9845 |
| \(\omega\) | 3.45 ± 0.53 [rad] | 2.961 | 4.022 |
| \(\epsilon\) | 0.1276 ± 0.1174 | 0.0569 | 0.2916 |
| \(K_2\) (km s\(^{-1}\)) | 9.92 ± 0.14 | 9.856 | 10.131 |
| \(\gamma\) (km s\(^{-1}\)) | -82.37 ± 0.89 | -83.22 | -81.44 |

Fig. B.2. Estimated mass of the unseen companion as a function of \(\sin i\). for three different angles showing possible range of masses for the companion (see Figure B.2).

Appendix C: Dynamical behaviour

Here we present a first attempt to predict the probable orbit of the newly discovered N-rich binary across the Milky Way. To do this, we have used a state-of-the-art orbital integration model in an (as far as possible) realistic gravitational potential, that fits the structural and dynamical parameters of the Galaxy based on the recent knowledge of our Milky Way. For the computations in this work, we have employed the rotating "boxy/peanut" bar model of the novel galactic potential model, called GravPot16\(^{2}\), along with other composite stellar components. The considered structural parameters of our bar model, e.g., mass, present-day orientation, and pattern speeds, is within observational estimates that lie in the range of \(1.1\times10^{10}\) M\(_{\odot}\), 20\(^{°}\), and 35–50 km s\(^{-1}\) kpc, respectively.

For reference, the Galactic convention adopted by this work is: \(X\)-axis is oriented toward \(l = 0^\circ\) and \(b = 0^\circ\), and the \(Y\)-axis is oriented toward \(l = 90^\circ\) and \(b = 0^\circ\), and the disk rotates toward \(l = 90^\circ\); the velocity components are also oriented along these directions. In this convention, the Sun’s orbital velocity vector is \([U_0,V_0,W_0] = [11.1, 12.24, 7.25]\) km s\(^{-1}\) (Brunthaler et al. 2011). The model has been rescaled to the Sun’s Galactocentric distance, 8.3 kpc, and a local rotation velocity of 239 km s\(^{-1}\). For computation of the Galactic orbits, we have a simple Monte Carlo procedure and the Runge-Kutta algorithm of seventh-eighth order elaborated by Fehlberg (1968). The uncertainties in the input data (e.g., distances, proper motions, and line-of-sight velocity errors listed in Table C.1) are assumed to follow a Gaussian distribution and were propagated as 1\(\sigma\) variations in a Gaussian Monte Carlo re-sampling. We have sampled a half million orbits, computed backward in time for 3 Gyr. Fig. C.1 shows the probability densities of the resulting orbits projected on the equatorial (left column) and meridional (right column) Galactic planes, in the non-inertial reference frame where the bar is at rest. The orbital path (adopting central values) is shown by the black line

\(^{2}\) https://fernandez-trincado.github.io/GravPot16/
Table C.1. Phase-space data

| Coordinates (J2000) | (12000) |
|--------------------|---------|
| (α, δ)             | (191°.293486, 12°.29486) |
| (l, b)             | (296°.973729363, 75°.0936328462) |
| Heliocentric Distance [kpc] | (4.54 ± 0.93)\textsuperscript{a} |
| (RV) ± σ\textsubscript{RV} [km s\textsuperscript{-1}] | (13.02 ± 1.49)\textsuperscript{b} |
| Proper Motions (µ\textalpha{} cos δ, µδ) [mas yr\textsuperscript{-1}] | (-82.8 ± 9.9)\textsuperscript{c} |
|                  | (-1.32 ± 0.12, -4.19 ± 0.06)\textsuperscript{d} |

Notes. \textsuperscript{a} Estimated distance computed by Bailer-Jones et al. (2018); \textsuperscript{b} Estimated distance computed using the StarHorse code (Queiroz et al. 2018); \textsuperscript{c} The average radial velocity of the binary system computed from the 24 visits of the APOGEE/DR14 spectra (see text); \textsuperscript{d} Absolute proper motions from Gaia Collaboration et al. (2018).

in the same figure. The green and yellow colours correspond to more probable regions of the space, which are crossed more frequently by the simulated orbits.

We derive the distance to 2M12451043+1217401 using StarHorse\textsuperscript{3}, a Bayesian distance estimator initially developed for APOGEE stars (Queiroz et al. 2018). For completeness, we provide dynamical solutions and orbit calculations for both the StarHorse distance of 13 kpc and the Bailer-Jones et al. (2018) distance of 4.5 kpc. The two columns on the left of Fig. C.1 shows possible orbits given the StarHorse distance and different bar speeds (35, 40, 45 and 50 km s\textsuperscript{-1} kpc), and the two columns on the right show the same figures for the Bailer-Jones et al. (2018) distance.

\textsuperscript{3} https://data.sdss.org/sas/dr14/apogee/vac/apogee-tgas/apogee_tgas-DR14.fits
Fig. C.1. Kernel Density Estimate (KDE) smoothed distribution of simulated orbits employing a Monte Carlo approach, showing the probability densities of the resulting orbits projected on the equatorial and meridional Galactic planes in the non-inertial reference frame where the bar is at rest. The green and yellow colors correspond to more probable regions of the space, which are crossed more frequently by the simulated orbits. The black line is the orbit of 2M12451043+1217401 adopting the central inputs. The small white star marks the present position of the cluster, whereas the white square marks its initial position. In all orbit panels, the white dotted circle show the location of the co-rotation radius (CR), the horizontal white solid line shows the extension of the bar. Columns 1 and 2 show the results adopting the estimated distance from the StarHorse code, while columns 3 and 4 for estimated distance from Bailer-Jones et al. (2018).