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# APOGEE discovery of a chemically atypical star disrupted from NGC 6723 and captured by the Milky Way bulge

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## ABSTRACT

The central ('bulge') region of the Milky Way is teeming with a significant fraction of mildly metal-deficient stars with atmospheres that are strongly enriched in cyanogen ( $^{12}\text{C}^{14}\text{N}$ ). Some of these objects, which are also known as nitrogen-enhanced stars, are hypothesised to be relics of the ancient assembly history of the Milky Way. Although the chemical similarity of nitrogen-enhanced stars to the unique chemical patterns observed in globular clusters has been observed, a direct connection between field stars and globular clusters has not yet been proven. In this work, we report on high-resolution, near-infrared spectroscopic observations of the bulge globular cluster NGC 6723, and the serendipitous discovery of a star, 2M18594405–3651518, located outside the cluster (near the tidal radius) but moving on a similar orbit, providing the first clear piece of evidence of a star that was very likely once a cluster member and has recently been ejected. Its nitrogen abundance ratio ( $[\text{N}/\text{Fe}] \gtrsim +0.94$ ) is well above the typical Galactic field-star levels, and it exhibits noticeable enrichment in the heavy *s*-process elements (Ce, Nd, and Yb), along with moderate carbon enrichment; all characteristics are known examples in globular clusters. This result suggests that some of the nitrogen-enhanced stars in the bulge likely originated from the tidal disruption of globular clusters.

**Key words.** stars: abundances – stars: chemically peculiar – globular clusters: individual: NGC 6723 – techniques: spectroscopic

## 1. Introduction

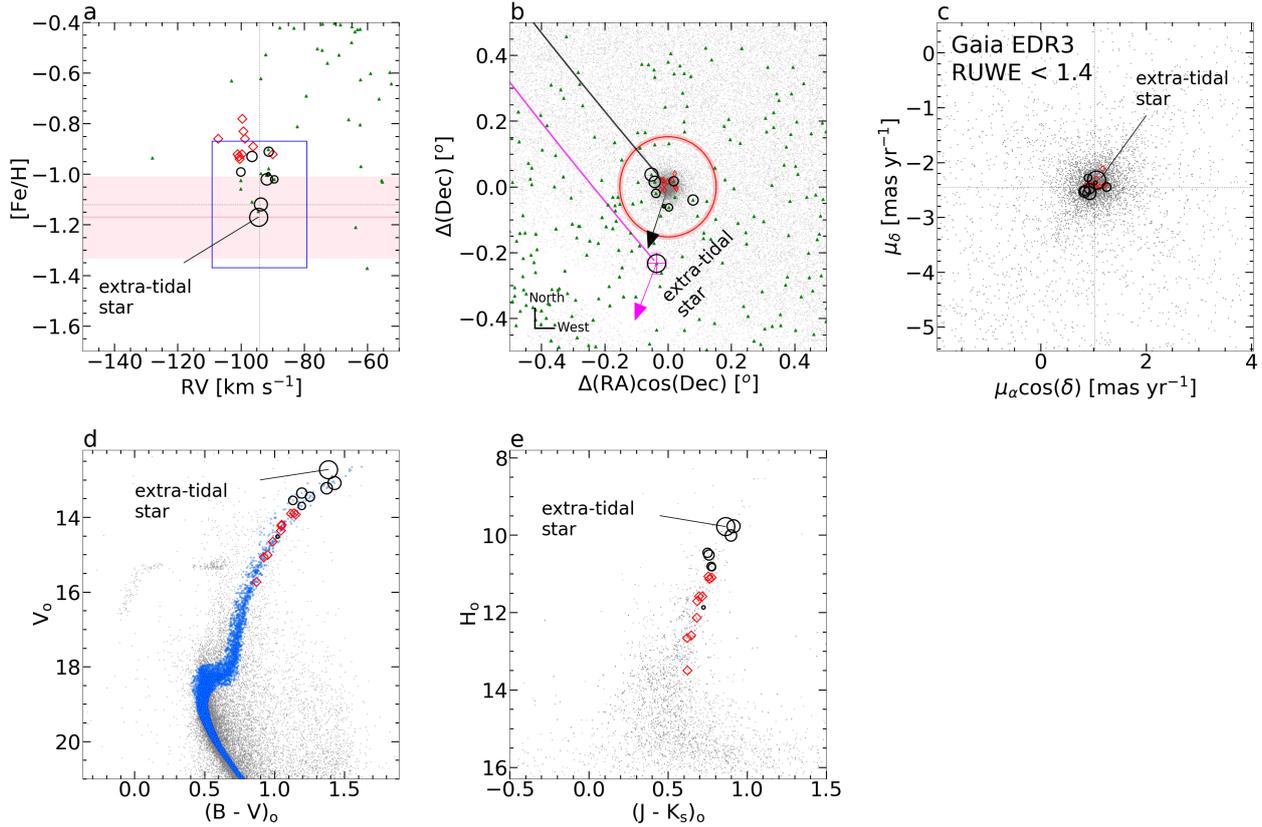
The great majority of stars in the halo of the Milky Way (MW) have elemental-abundance ratios, spanning a wide range of metallicities ( $-7.5 < [\text{Fe}/\text{H}] < 0.0$ ) that are similar to one another and overall track the general level of metallicity. However, there are a number of important exceptions, including carbon-enhanced ( $[\text{C}/\text{Fe}] \gtrsim +0.7$ ) metal-poor (CEMP) stars, in particular at very low metallicities ( $[\text{Fe}/\text{H}] < -2.0$ ) (Frebel et al. 2006; Lee et al. 2013; Placco et al. 2014, 2018; Yoon et al. 2019) and the class of CH stars (with  $-2.0 < [\text{Fe}/\text{H}] < -0.2$ ) (Karinkuzhi & Goswami 2014), as well as the carbon-deficient stars (with  $[\text{C}/\text{Fe}] \lesssim +0.5$ ,  $-2 < [\text{Fe}/\text{H}] < +0.1$ ) with light-element abundances (e.g. N, Al, and Si) whose chemical compositions mimic the abundance patterns observed in some of the stars in Galactic (and extragalactic) globular cluster (GC) populations (e.g. Fernández-Trincado et al. 2017, 2020a; Schiavon et al. 2017b; Bekki 2019; Hanke et al. 2020; Mészáros et al. 2020).

Multiple potentially pieces of evidence support the origin of CEMP stars in low-mass galaxies that have been accreted by the MW (Yoon et al. 2019), either due to mass-transfer binaries (CEMP-*s* stars, Beers & Christlieb 2005) or from natal gas polluted by high-mass stars in the early Galaxy (CEMP-no stars, Beers & Christlieb 2005). However, the mildly metal-poor giants with stellar atmospheres that are strongly enriched in  $^{12}\text{C}^{14}\text{N}$  (in cases with available data, with distinctive Al and Si abundances as well), are referred to as nitrogen-enhanced (N-rich) stars (Fernández-Trincado et al. 2016a, 2017, 2019a; Schiavon

et al. 2017b) or NRS (Bekki 2019), and defined in Johnson et al. (2007) as nitrogen-enriched metal-poor (NEMP) stars, which are CEMP stars with  $[\text{C}/\text{N}] < -0.5$  and  $[\text{N}/\text{Fe}] > +0.5$ . They have resisted a unifying explanation of the nucleosynthetic processes responsible for their abundance anomalies. These stars share chemical-abundance patterns that are hypothesised to be associated with the so-called second-generation stars in GCs (see e.g. Schiavon et al. 2017a; Fernández-Trincado et al. 2019b, 2020b; Mészáros et al. 2020), with only a handful of exceptions, such as the binary hypothesis (see e.g. Fernández-Trincado et al. 2019c). There are also a handful of known early asymptotic giant branch (early-AGB) stars in GCs (see, e.g. Mészáros et al. 2020), which exhibit a nitrogen enrichment similar to that of the N-rich stars, but with a modest enrichment in carbon ( $[\text{C}/\text{Fe}] > +0.15$ ).

Recent studies (Bekki 2019; Fernández-Trincado et al. 2020c,d,e) have found that a significant fraction (~66%) of the known metal-poor N-rich stars in the Galactic field currently reside in the inner MW. However, the site and process for the formation of these stars remain as long-standing questions (Bekki 2019). The metal-poor N-rich stars stand out among the variety of metal-poor stars in our own MW, as they are uniquely suited to the application of chemical tagging, with direct bearing on the origin of the in situ structure of the inner halo and bulge. As such, these stars play a crucial role in reconstructing the formation and evolutionary history of the MW.

NGC 6723 is an old ( $\gtrsim 12.50$  Gyr; Dotter et al. 2010; Oliveira et al. 2020), massive ( $1.72 \times 10^5 M_{\odot}$ ; Baumgardt et al. 2019) GC situated in the bulge region ( $d_{\odot} \sim 8.3$  kpc), with an orbit constraining it to lie  $\lesssim 2.85$  kpc from the Galactic Centre



**Fig. 1.** Properties of the extra-tidal star compared with likely members of NGC 6723. *Panel a:* metallicity – radial velocity plane for stars in the APOGEE-2 catalogue in the region of NGC 6723 (green triangles). The black open circles are potential members of NGC 6723; sizes reflect their  $V_0$  magnitudes, with decreasing size for fainter magnitudes. The pink line and shaded region indicate the  $([Fe/H]) \pm \sigma_{[Fe/H]}$  of the extra-tidal star. The black dotted lines indicate the nominal  $[Fe/H]$  and radial velocity of NGC 6723 from Harris (1996, 2010). The red unfilled diamonds refer to probable members analysed in the literature (Crestani et al. 2019). The blue rectangle indicates the region adopted to choose potential cluster members, based on radial velocity and metallicity (see Sect. 2). *Panel b:* positions for stars in the APOGEE-2 and *Gaia* EDR3 (grey dots) catalogues in the region of NGC 6723. The magenta cross symbol indicates the *Gaia* astrometric uncertainty. The big red and shadow circumference show the cluster tidal radius ( $r_t = 9.14 \pm 0.49'$ ) of NGC 6723 determined in this work from HST + *Gaia* EDR3 data set (see Sect. 8). The orbital paths of the cluster (black line) and the extra-tidal star (magenta line) are shown, along with the proper motion vectors (black arrow) of the cluster from Baumgardt et al. (2019), and the extra-tidal star (magenta arrow); their lengths (scaled up for visibility) and directions are essentially identical. *Panel c:* proper-motion plane for the selected candidates. *Panels d and e:*  $V_0$  versus  $(B - V)_0$  and 2MASS  $H_0$  versus  $(J - K_s)_0$  Colour-Magnitude Diagram (CMD) centred on NGC 6723, showing all the stars within the cluster tidal radius, and the probable cluster members (cyan symbols) within a  $2\sigma$  deviation from the best isochrone fitting (Souza et al. 2020; Oliveira et al. 2020). The largest open circle in all panels indicate the extra-tidal star.

(Baumgardt et al. 2019). It is currently located at a position where the foreground interstellar reddening is low,  $E(B - V) \sim 0.063$  (Lee et al. 2014), making it an excellent target to identify and study the family of N-rich stars in the bulge region of the MW, in order to probe for a linkage between GC environments and field stars with nitrogen over-abundances.

The Apache Point Observatory Galactic Evolution Experiment (APOGEE-2, Majewski et al. 2017) is a cornerstone mission of the Sloan Digital Sky Survey IV (SDSS-IV, Blanton et al. 2017), which has been designed primarily to investigate the chemical history of the MW. APOGEE and APOGEE-2 have delivered an exquisite data set by combining high-resolution near-IR spectroscopic observations from the Sloan 2.5 m telescope at Apache Point Observatory (APO) and the Irénée du Pont 2.5 m telescope at Las Campanas Observatory (LCO): the largest and most precise census of more than 24 chemical species for hundreds of thousands of stars throughout the MW. These surveys have revealed numerous giant stars with light-element abundances that deviate from the general patterns, and are at odds with current chemical-evolution models. Their origins have

remained obscure, due to limitations on the numbers of such stars and the precision of the previously available data.

In this work, we take advantage of the APOGEE-2 data set to alleviate the lack of data towards the Galactic Bulge. We report on the discovery of an extra-tidal star candidate in the vicinity of a GC (NGC 6723) toward the bulge region, with nitrogen over-abundances well above that of normal Galactic field stars, and with a modest carbon enrichment. The other properties of this star, including metallicity and kinematics, strongly suggest it was once a cluster member. This is the first demonstration of a direct link between a mildly metal-poor N-rich field star with a modest carbon enrichment and a parent GC in the bulge region of the MW.

## 2. Data and sample selection

We present a spectroscopic study of the bulge GC NGC 6723, and its surrounding regions, based on high-resolution ( $R \sim 22\,000$ ) near-infrared  $H$ -band ( $\lambda \sim 15\,145 \text{ \AA}$  to  $16\,960 \text{ \AA}$ ,

vacuum wavelengths) spectra taken as part of the APOGEE-2 survey (Majewski et al. 2017; Zasowski et al. 2017), included within the sixteenth SDSS-IV (Blanton et al. 2017) data release (DR16, Ahumada et al. 2020). The observations were taken at the twin APOGEE-2 spectrographs mounted on the 2.5 m Sloan Foundation telescope (Gunn et al. 2006) at the Apache Point Observatory in New Mexico, and on the 2.5 m Irénée du Pont telescope (Bowen & Vaughan 1973) at Las Campanas Observatory in Chile. We refer the reader to the APOGEE-2 technical papers for further details regarding the data reduction pipeline for APOGEE-2 (see, e.g. Nidever et al. 2015; García Pérez et al. 2016; Holtzman et al. 2018).

We have analysed the available APOGEE-2 spectra towards the bulge GC NGC 6723, included in the APOGEE-2 fields 000-17-C and 359-17-C, which contain reliable spectral information for 526 stars. Probable cluster members were selected based on the nominal radial velocity (RV) of the cluster (with a velocity difference no larger than  $15 \text{ km s}^{-1}$ ), and metallicity within 0.25 dex from the value reported in (1996, 2010 edition). The initial search was made within the blue box highlighted in panel a of Fig. 1, and limited to spectra with a  $\text{SNR} > 60 \text{ pixel}^{-1}$ .

We decided to adopt the uncalibrated ASPCAP [M/H] scale, which tracks all metals relative to the Sun (listed in Table 1), as a first guess to the stellar metallicity. This gives the overall metallicity of the stars, as it is derived by fitting the entire wavelength region covered by the APOGEE-2 spectrographs. Finally, we use Fe I lines to measure the [Fe/H].

The final sample contains eight potential members of NGC 6723. We find that seven of these stars are located inside the tidal radius, as shown in panel b of Fig. 1. There is one star, 2M18594405-3651518 (referred to here as the extra-tidal star), which has a RV and proper motions (see panels a and c of Fig. 1), and an orbital path similar to that of the NGC 6723 members. These very probable members lie in the upper part of the prominent red giant branch (RGB) in the extinction-corrected 2MASS and  $V_o$  versus  $(B - V)_o$  Colour-Magnitude Diagrams (CMDs), as displayed in panels d and e of Fig. 1, and have *Gaia* proper motions similar to the nominal value for the cluster.

Following the same methodology and techniques described in several APOGEE papers (Fernández-Trincado et al. 2016a, 2017, 2019a,b,c,d, 2020b; Hawkins et al. 2016), we employed the BACCHUS software (Masseron et al. 2016) to manually analyze each star of our sample, in order to re-examine the reliability of each atomic and molecular line present in each spectrum, and provide chemical abundances for 14 chemical species, listed in Table 1. These abundances have been computed adopting a line-by-line approach under the assumption of local thermodynamic equilibrium (LTE). With this independent methodology, we obtain complementary abundance ratios not provided by the ASPCAP pipeline (García Pérez et al. 2016), in particular for the heavy neutron-capture (*s*-process) elements (Ce II, Nd II, and Yb II). Figure 2 illustrates the best spectral-synthesis calculation on clean selected features for the extra-tidal star.

Importantly, none of the newly identified stars in this work have strong RV variability over the temporal span of the APOGEE-2 observations (visit-to-visit variations,  $\sigma_{\text{RV}} < 1 \text{ km s}^{-1}$ ), which were obtained during 2018-05-24 (visit 1) and 2018-05-25 (visit 2). Therefore, with the current data there is no evidence that any of these objects are members of binary systems.

Furthermore, we found that our sample has a *Gaia* re-normalised unit weight error (RUWE) value  $< 1.4$ , as listed in Table 1, indicating that they are astrometrically well-behaved

sources in the *Gaia* Early Data Release 3 (*Gaia* EDR3) catalogue (Gaia Collaboration 2021).

Panels a to c of Fig. 1 show the metallicity versus kinematic, sky positions, and astrometric properties of our sample, as well as the serendipitous discovery of an chemically atypical extra-tidal star in the vicinity of NGC 6723; a result not previously seen. We find that 5 of the 7 cluster members are strongly enhanced in nitrogen,  $[\text{N}/\text{Fe}] > +0.86$ , well above the Galactic levels (which is typically  $\lesssim +0.5$ ), and a clear indicator of the presence of nitrogen-enhanced stars in NGC 6723. The CMDs displayed in Figs. 1d and e show that most of the stars in our sample lie in the upper part of the prominent red giant-branch (RGB) of NGC 6723, and do not exhibit a wide metallicity variation. This is also supported by the spectroscopic values.

### 3. Atmospheric parameters and elemental abundances

We used the BACCHUS code (Masseron et al. 2016) to derive the metallicity (from Fe I lines), broadening parameters, and chemical abundances for the stars in our sample, based on careful line selection, and carried out a detailed inspection of each APOGEE-2 spectrum in order to examine the reliability of the abundance ratios, in the same manner as described in Fernández-Trincado et al. (2019a). The adopted atmospheric parameters and the typical uncertainties are listed in Table 1.

The BACCHUS code 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 previous APOGEE-2 works (Hawkins et al. 2016). In summary, the steps are: (i) a spectrum synthesis, using the full set of (atomic and molecular) lines to find the local continuum level via a linear fit; (ii) cosmic and telluric line rejections are performed; (iii) the local signal-to-noise ratio (S/N) per element is estimated; (iv) a series of flux points contributing to a given absorption line are automatically selected; and (v) abundances are then derived by comparing the observed spectrum with a set of convolved synthetic spectra characterised by different abundances.

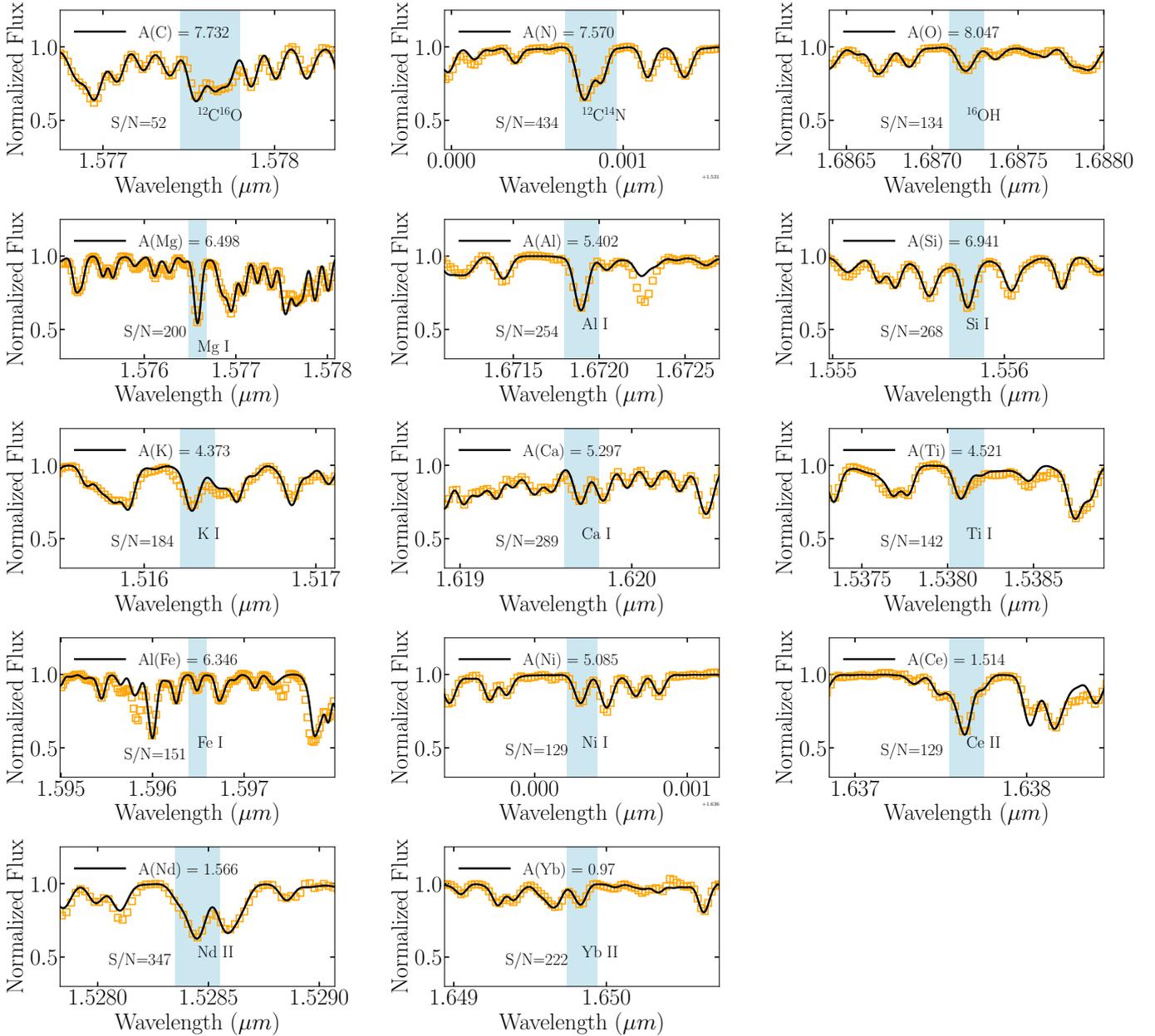
Four different abundance determinations are used: (i) line-profile fitting; (ii) core line-intensity comparison; (iii) global goodness-of-fit estimate; and (iv) equivalent-width comparison. Each diagnostic yields validation flags. Based on these flags, a decision tree then rejects or accepts the line, keeping the best-fit abundance. We adopted the  $\chi^2$  diagnostic as the abundance determinant, because it is considered to be the most robust. However, we stored the information from the other diagnostics, including the standard deviation between all four methods. The line list used in this work is the latest internal DR14 atomic/molecular linelist (linelist.20170418), including the *s*-process elements (Ce II, Nd II, and Yb II)–(Hasselquist et al. 2016; Cunha et al. 2017). For a more detailed description of these lines, we refer the reader to a forthcoming paper (Holtzman et al., in prep.).

In particular, a mix of heavily CN-cycled and  $\alpha$ -poor MARCS models were used, as well as the same molecular lines adopted by APOGEE-2 (Smith et al. 2013), in order 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; that is to say, we first derive  $^{16}\text{O}$  abundances from  $^{16}\text{OH}$  lines, then derive  $^{12}\text{C}$  from  $^{12}\text{C}^{16}\text{O}$  lines, and  $^{14}\text{N}$  from  $^{12}\text{C}^{14}\text{N}$  lines; the C–N–O abundances were derived iteratively to minimize the  $^{16}\text{OH}$ ,  $^{12}\text{C}^{16}\text{O}$ , and  $^{12}\text{C}^{14}\text{N}$  dependences (Smith et al. 2013).

**Table 1.** Top table: Final abundances for the stars analyzed in this work, adopting stellar atmospheric parameters from photometry ( $T_{\text{eff}}$ ) and  $\log g$  from 12.5 Gyr PARSEC isochrones, as determined using local thermodynamic equilibrium (LTE) model atmospheres. Middle table: The final abundances as determined by the ASPCAP pipeline. Bottom table: List of the main physical parameters of our stars.

APOGEE_ID	$T_{\text{eff}}$ (K)	$\log g$	[M/H]	$\xi_r$ ( $\text{km s}^{-1}$ )	[C/Fe]	[N/Fe]	[O/Fe]	[Mg/Fe]	[Al/Fe]	[Si/Fe]	[K/Fe]	[Ca/Fe]	[Ti/Fe]	[Fe/H]	[Ni/Fe]	[Ce/Fe]	[Nd/Fe]	[Yb/Fe]	
This work																			
2M18590940–3640192	4397	1.28	-1.11	1.766	-0.45	+1.02	+0.46	+0.37	+0.16	+0.42	-0.01	+0.09	+0.29	-0.93	-0.06	+0.04	...	...	
2M18592786–3636509	4425	1.41	-0.96	1.931	-0.58	+1.53	+0.55	+0.32	+0.40	+0.29	+0.19	+0.30	+0.47	-0.91	-0.07	+0.29	...	...	
2M18593255–3641374	4349	1.27	-1.02	1.817	-0.17	+0.56	+0.60	+0.30	+0.24	+0.35	+0.21	+0.36	+0.19	-1.02	+0.01	+0.15	+0.22	...	
2M18593691–3641280	4498	1.62	-0.87	1.549	-0.20	+0.86	+0.14	+0.33	+0.52	+0.37	+0.14	+0.21	+0.08	-1.00	+0.05	+0.11	...	...	
2M18594472–3639043	4364	1.30	-1.05	1.761	-0.53	+1.06	+0.16	+0.31	+0.19	+0.41	+0.02	+0.14	+0.19	-0.99	-0.09	+0.05	...	...	
2M18594565–3637016	4056	0.74	-1.01	2.046	-0.21	+0.45	+0.47	+0.31	+0.24	+0.35	+0.21	+0.32	+0.19	-1.02	+0.03	+0.13	+0.07	+0.59	
2M18594898–3635401	4054	0.74	-0.97	2.812	-0.29	+1.18	+0.39	+0.10	+0.21	+0.31	+0.31	+0.35	+0.45	-1.12	+0.03	+0.22	...	+0.76	
2M18594405–3651518	4130	0.80	-1.09	2.733	+0.55	+0.94	+0.54	+0.18	+0.17	+0.38	+0.33	+0.24	+0.37	-1.17	+0.11	+1.19	+1.54	+1.29	
APOGEE_ID																			
ASPCAP																			
2M18590940–3640192	4377	1.32	-1.11	2.503	-0.22	+0.71	+0.28	+0.28	-0.03	+0.26	+0.10	+0.16	+0.06	-1.11	-0.03	-0.07	...	...	
2M18592786–3636509	4391	1.65	-0.96	2.126	-0.24	+0.99	+0.22	+0.24	+0.19	+0.23	+0.24	+0.23	+0.31	-0.98	+0.01	+0.24	...	...	
2M18593255–3641374	4327	1.53	-1.03	1.849	-0.06	+0.09	+0.28	+0.24	+0.02	+0.31	+0.25	+0.22	...	-1.02	+0.04	+0.00	...	...	
2M18593691–3641280	4847	2.29	-0.88	2.017	-0.20	+1.01	+0.14	+0.18	+0.48	+0.22	+0.27	+0.26	+0.42	-0.90	+0.04	+0.49	...	...	
2M18594472–3639043	4597	1.58	-1.05	2.545	-0.26	+0.88	+0.22	+0.22	+0.05	+0.22	+0.14	+0.13	+0.23	-1.06	+0.01	+0.30	...	...	
2M18594565–3637016	4121	1.14	-1.01	2.025	-0.13	+0.17	+0.28	+0.33	+0.05	+0.28	+0.24	+0.24	...	-1.00	+0.02	...	...	...	
2M18594898–3635401	4204	1.31	-0.98	2.123	-0.24	+0.94	+0.22	+0.25	+0.21	+0.21	+0.29	+0.28	...	-0.99	+0.01	+0.13	...	...	
2M18594405–3651518	4058	-0.19	-1.09	1.995	+0.04	+0.82	+0.04	+0.33	+0.11	+0.19	+0.30	+0.18	...	-1.15	-0.13	...	...	...	
APOGEE_ID																			
$S/N$	$RV$	$\sigma_{RV}$	$E(B-V)$	$V_o$	$(B-V)_o$	$H_o$	$(J-K_s)_o$	$\mu_\alpha \cos(\delta)$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$	$\mu_\delta$
	( $\text{km s}^{-1}$ )	( $\text{km s}^{-1}$ )																	
			CTIO	CTIO	CTIO	2MASS	2MASS	2MASS											
2M18590940–3640192	128	-96.5	0.01	0.063	13.34	1.19	10.51	0.76	$0.92 \pm 0.02$	$-2.47 \pm 0.01$	1.18	2							
2M18592786–3636509	187	-91.3	0.00	0.063	13.45	1.25	10.45	0.75	$0.84 \pm 0.02$	$-2.51 \pm 0.02$	1.16	2							
2M18593255–3641374	123	-89.5	0.04	0.063	13.69	1.19	10.83	0.78	$0.89 \pm 0.02$	$-2.28 \pm 0.02$	1.18	2							
2M18593691–3641280	98	-91.4	0.11	0.063	14.52	1.02	11.86	0.72	$1.04 \pm 0.03$	$-2.37 \pm 0.02$	1.10	2							
2M18594472–3639043	165	-100.1	0.01	0.063	13.54	1.13	10.81	0.77	$1.25 \pm 0.02$	$-2.45 \pm 0.02$	1.20	2							
2M18594565–3637016	258	-91.9	0.29	0.063	13.22	1.37	10.01	0.89	$0.84 \pm 0.02$	$-2.53 \pm 0.02$	1.13	2							
2M18594898–3635401	281	-93.7	...	0.063	13.08	1.43	9.77	0.91	$0.93 \pm 0.02$	$-2.55 \pm 0.02$	1.21	2							
2M18594405–3651518	270	-94.5	0.06	0.520	12.72	1.38	9.78	0.86	$1.06 \pm 0.02$	$-2.32 \pm 0.02$	1.19	2							

**Note.** The synthetic spectra were based on 1D Local Thermodynamic Equilibrium (LTE) model atmospheres calculated using MARCS models (Gustafsson et al. 2008) and the Solar abundances from Asplund et al. (2005), except for Ce II, Nd II, and Yb II, for which we have adopted the Solar abundances from Grevesse et al. (2015).



**Fig. 2.** High-resolution near-IR  $H$ -band spectrum of the extra-tidal star. The spectral regions are shown with orange squares. Superimposed is the best-fit of a MARCS/BACCHUS spectral synthesis (black line). The light blue shaded regions show the strength of the molecules ( $^{12}\text{C}^{16}\text{O}$ ,  $^{12}\text{C}^{14}\text{N}$ ,  $^{16}\text{OH}$ ), and the atomic lines, namely the  $\alpha$ -elements (Mg I, Si I, Ca I, Ti I), the odd- $Z$  elements (Al I, K I), the iron-peak elements (Fe I, Ni I), and the  $s$ -process elements (Ce II, Nd II, Yb II), expressed in air wavelengths. The legends in each panel show the absolute abundance,  $A(X)$ , of the species under consideration, and the signal-to-noise (S/N) in the regions of the features, respectively.

It is important to perform consistent chemical-abundance analyses using atmospheric parameters determined independently, in order to check for any significant deviation in the derived abundances. To achieve this, the photometric effective temperatures were calculated using the  $J - K_s$  (2MASS) colour-relation methodology (González Hernández & Bonifacio 2009). For the extra-tidal star, we adopted the extinction correction obtained from the Rayleigh Jeans Colour Excess (RJCE) method (Majewski et al. 2011). Thus, the photometry is extinction corrected, adopting  $E(B - V) = 0.063$  (see, e.g., Lee et al. 2014) for stars inside the cluster tidal radius, and assuming an  $E(B - V) = 0.520$  (Majewski et al. 2011) for the extra-tidal star, which lies in a region outside the cluster that is severely affected by extinction, given their position toward the Galactic bulge where the reddening

variation may be substantial (see, e.g. Alonso-García et al. 2017), even if the projected distance between the extra-tidal star and cluster is small.

We assumed a surface gravity from the PARSEC isochrones (Bressan et al. 2012), using  $\approx 12.5$  Gyr as the estimated age of NGC 6723 (Dotter et al. 2010; Oliveira et al. 2020), and the uncalibrated metallicity ( $[M/H]$ ), as derived by ASPCAP/APOGEE-2 runs. The adopted stellar parameters are listed in Table 1.

The adoption of a purely photometric temperature scale enables us to be somewhat independent of the ASPCAP/APOGEE-2 pipeline, which provides important comparison data for future pipeline validation. The final results presented in this paper are based on computations done with the BACCHUS code

**Table 2.** Abundance-ratio uncertainties for the model parameters with  $\Delta T_{\text{eff}} = 100$  K,  $\Delta \log g = 0.3$  dex,  $\Delta \xi_t = 0.05$  km s<sup>-1</sup>, the uncertainties on the mean due to line-to-line scatter ( $\sigma_{[X/H],\text{mean}}$ ), and corresponding total error.

2M18594405 -3651518	$\sigma_{[X/H],\log g}$	$\sigma_{[X/H],T_{\text{eff}}}$	$\sigma_{[X/H],\xi_t}$	$\sigma_{[X/H],\text{mean}}$	$\sigma_{[X/H],\text{total}}$
	[dex]	[dex]	[dex]	[dex]	[dex]
<sup>12</sup> C <sup>16</sup> O → <sup>12</sup> C	0.065	0.018	0.004	0.110	0.129
<sup>12</sup> C <sup>14</sup> N → <sup>14</sup> N	0.075	0.094	0.023	0.071	0.142
<sup>16</sup> OH → <sup>16</sup> O	0.018	0.097	0.014	0.068	0.121
Mg I	0.005	0.089	0.022	0.052	0.106
Al I	0.011	0.080	0.006	0.117	0.142
Si I	0.045	0.023	0.006	0.094	0.107
K I	0.025	0.044	0.009	0.137	0.146
Ca I	0.023	0.023	0.007	0.085	0.091
Ti I	0.007	0.070	0.033	0.246	0.258
Fe I	0.016	0.042	0.005	0.154	0.161
Ni I	0.027	0.047	0.010	0.155	0.165
Ce II	0.123	0.067	0.025	0.125	0.189
Nd II	0.075	0.071	0.023	0.130	0.168
Yb II	0.092	0.024	0.004	0.020	0.097
2M18594898 -3635401	$\sigma_{[X/H],\log g}$	$\sigma_{[X/H],T_{\text{eff}}}$	$\sigma_{[X/H],\xi_t}$	$\sigma_{[X/H],\text{mean}}$	$\sigma_{[X/H],\text{total}}$
	[dex]	[dex]	[dex]	[dex]	[dex]
<sup>12</sup> C <sup>16</sup> O → <sup>12</sup> C	0.035	0.064	0.009	0.052	0.090
<sup>12</sup> C <sup>14</sup> N → <sup>14</sup> N	0.042	0.108	0.004	0.069	0.135
<sup>16</sup> OH → <sup>16</sup> O	0.049	0.139	0.003	0.035	0.152
Mg I	0.025	0.073	0.016	0.017	0.081
Al I	0.014	0.111	0.009	0.116	0.161
Si I	0.033	0.007	0.003	0.079	0.086
K I	0.038	0.009	0.004	0.014	0.042
Ca I	0.037	0.033	0.003	0.026	0.056
Ti I	0.067	0.070	0.043	0.199	0.225
Fe I	0.036	0.072	0.008	0.116	0.141
Ni I	0.011	0.021	0.003	0.070	0.074
Ce II	0.059	0.013	0.004	0.069	0.092
Nd II	0.049	0.043	0.005	0.043	0.078
Yb II	0.150	0.027	0.002	0.047	0.159

**Notes.** The total error is defined as:  $\sigma_{[X_i/\text{Fe}],\text{total}} = \sqrt{\sigma_{[X_i/\text{Fe}],\log g}^2 + \sigma_{[X_i/\text{Fe}],T_{\text{eff}}}^2 + \sigma_{[X_i/\text{Fe}],\xi_t}^2 + \sigma_{[X_i/\text{Fe}],\text{mean}}^2}$ .

using the mentioned photometry and atmospheric parameters, as listed in Table 1.

The abundance values are sensitive to all of the atmospheric parameters, depending on the chemical species. To estimate their uncertainties, we have varied the atmospheric parameters one at a time by the typical values of  $\Delta T_{\text{eff}} = \pm 100$  K,  $\Delta \log g = \pm 0.3$  dex, and  $\Delta \xi_t = \pm 0.05$  km s<sup>-1</sup>, and then computed the abundances for all species for each of these possibilities for two stars – one cluster member (2M18594898–3635401) and the extratidal star (2M18594405–3651518). Thus, each line for each star has a corresponding  $\sigma_{T_{\text{eff}}}$ , which refers to its response to  $\Delta T_{\text{eff}}$ ;  $\sigma_{\log g}$  the response to  $\Delta \log g$ ;  $\sigma_{\xi_t}$  the response to  $\Delta \xi_t$ , and the uncertainties on the mean due to line-to-line scatter. The uncertainties are propagated in quadrature to compute the uncertainty of each chemical species in the two stars. The computed uncertainties are listed in Table 2.

Even though the BACCHUS code has its own procedure to include or reject lines on a star-by-star basis, it is still important to select the lines beforehand, due to the uncertainty related to the synthesis approach, such as line saturation. All the selected atomic and molecular lines were visually inspected to ensure that the spectral fit was adequate.

The individual oxygen abundances are also listed in Table 1. We caution about the accuracy of [O/Fe], as they display larger scatter, which may be due to telluric features and uncertain determinations in the  $T_{\text{eff}}$  regime of our objects. As highlighted by previous works, the uncertainty arises because BACCHUS determines these abundances from the strengths of <sup>12</sup>C<sup>14</sup>N and <sup>12</sup>C<sup>16</sup>O lines, which become too weak for stars at relatively low metallicities ([Fe/H] ≲ -1.0). Figures 2 and 3 clearly shows that K I, Ce II, Nd II, and Yb II enhancement of the extratidal star compared to other NGC 6723 stars can be convincingly claimed. Consequently, we conclude that the Ce, Nd, and Yb enhancement was likely inherited from the initial gas composition of NGC 6723.

## 4. Results

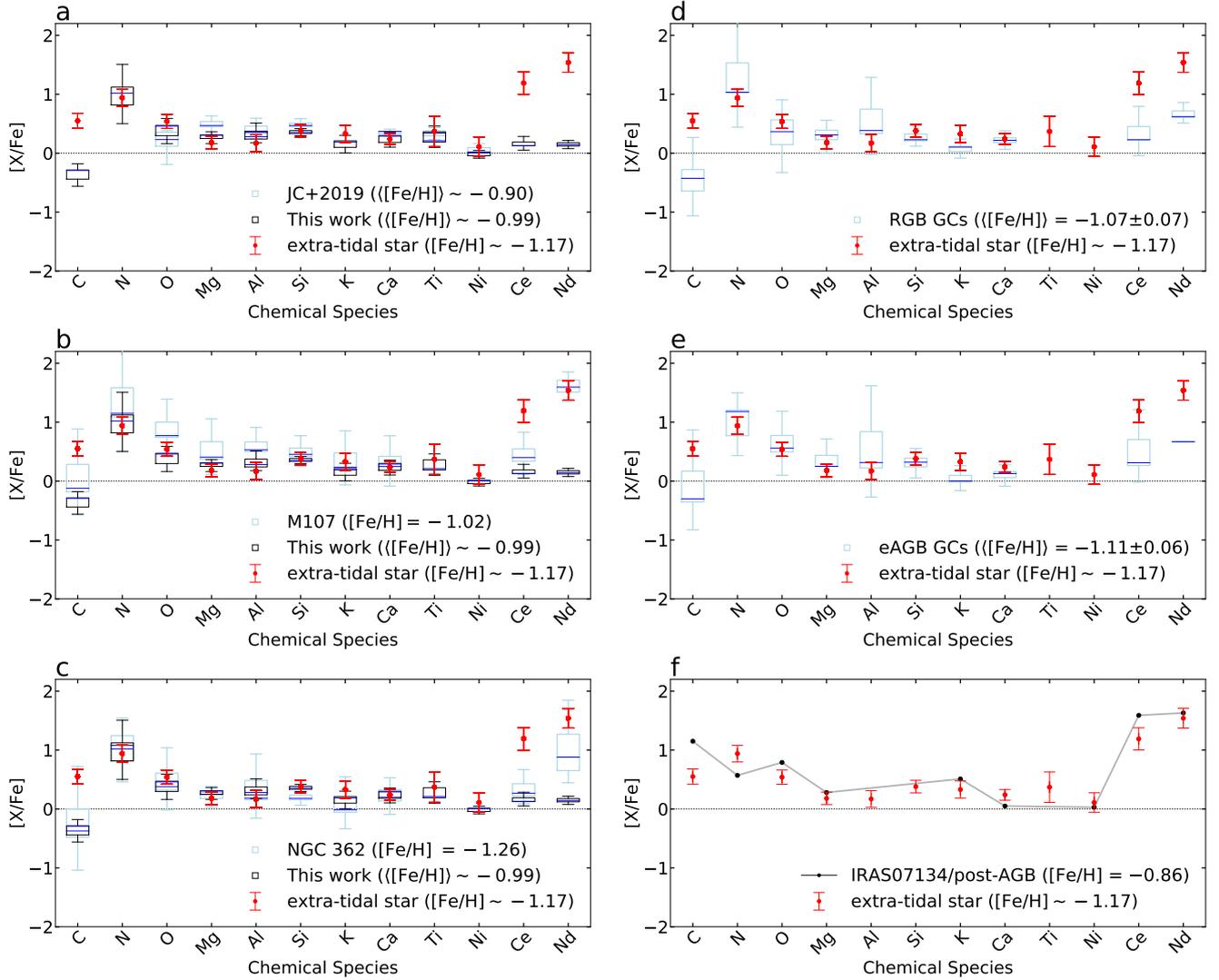
### 4.1. NGC 6723 stars

For the selected stars, we derive abundance ratios covering the main element families, namely the light elements (C, N), the  $\alpha$ -elements (O, Mg, Si, Ca, Ti), the odd-Z elements (Al, K), the iron-peak elements (Fe, Ni), and products of the slow neutron-capture (*s*-) process (Ce, Nd, Yb), and have abundance determinations from spectra in the *H*-band of APOGEE-2 (Mészáros et al. 2020). For the cluster members, we find metallicity consistent with previous estimates for this cluster,  $\langle [\text{Fe}/\text{H}] \rangle = -1.00$ , with a small, 0.06 dex, star-to-star scatter, commensurate with recent results based on high-resolution spectroscopy (Rojas-Arriagada et al. 2016; Crestani et al. 2019), which indicate a mono-[Fe/H] behaviour.

We obtained a mean nitrogen abundance ratio of [N/Fe] = +0.95, with an observed star-to-star scatter (0.34 dex) that well exceeds the observational uncertainties. The abundance ratios for the other elements up to the iron peak (O, Mg, Al, Si, K, Ca, Ti, and Ni) appear to be homogeneous within the permitted error variation, and replicate the chemical patterns observed for Galactic GCs of comparable metallicity, as shown in panels b and c of Fig. 3. The heavy *s*-process elements, such as Ce and Nd, are lower ([Ce/Fe], [Nd/Fe] ≲ +0.29) compared to M107, a GC with similar metallicity as NGC 6723, excepting Yb, which we find to be higher in some NGC 6723 stars. It has been noted previously that *s*-process-element enhancements ≳ +0.4 are usually rare, and are reported for only a few clusters (Mészáros et al. 2020), particularly at the metallicity of NGC 6723, suggesting they arise from pollution by AGB stars (Ventura et al. 2016; Mészáros et al. 2020).

The large star-to-star abundance variation inside the cluster – especially in the case of N – is indicative of the presence of multiple populations (MPs) in NGC 6723, as found in other massive (≳ 10<sup>5</sup> M<sub>⊙</sub>) GCs at all metallicities. There is thus strong evidence for an intrinsic spread in [N/Fe], including a clear C–N anti-correlation. However, we find no clear Al–N correlation or Al–O anti-correlation (see Fig. 4). In other words, NGC 6723 exhibits MPs based on the N abundances, despite appearing to have single populations in the Al abundances. This is similar to other Galactic GCs at this metallicity (Mészáros et al. 2020), for which it has been suggested that lower spreads in Al could be ascribed to operation of a modest Mg–Al cycle. If the intra-cluster polluters were in fact low-mass (≲ 3 M<sub>⊙</sub>) stars, we would expect low Al production (Mészáros et al. 2020) in NGC 6723. The low mean abundance and small Al spread ( $\langle [\text{Al}/\text{Fe}] \rangle = +0.28 \pm 0.12$ ) measured for the NGC 6723 sample supports this conclusion.

The stars we have studied in NGC 6723 have [C/Fe] < -0.17, and display a similar C–N anti-correlation as M107, with



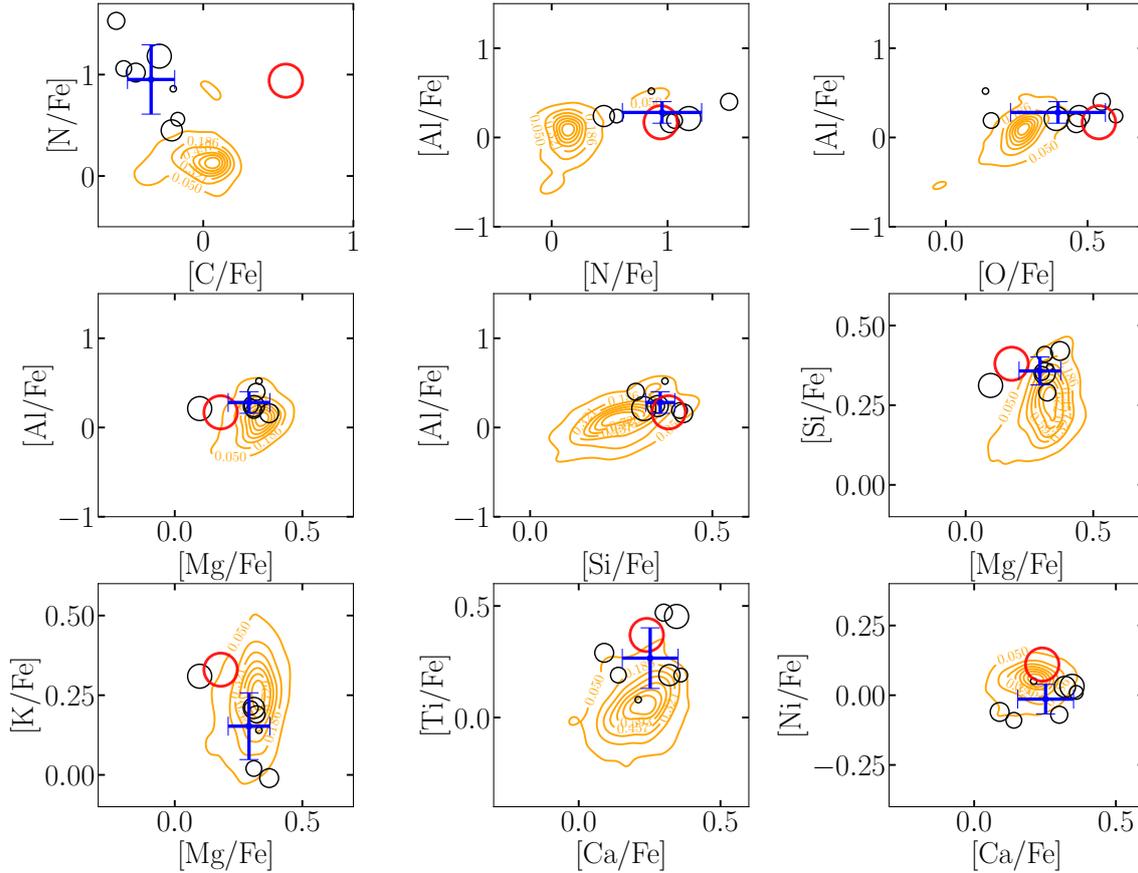
**Fig. 3.** Comparison of elemental-abundance ratios of likely member stars for NGC 6723 with other GCs of similar metallicity, and the extra-tidal star with RGB and early-AGB (eAGB) cluster stars, and IRAS07134 star. *Panel a:* elemental-abundance patterns for our sample (black boxes and red dot) compared to the spectroscopic study of NGC 6723 [Crestani et al. \(2019\)](#); (light blue boxplots). *Panel b:* comparison with M 107 ([Mészáros et al. 2020](#)). *Panel c:* comparison with NGC 362 ([Mészáros et al. 2020](#)). *Panel d:* elemental-abundance patterns for the extra-tidal star compared to those of RGB GC stars. *Panel e:* compared with early-AGB GC stars ([Mészáros et al. 2020](#)). *Panel f:* comparison with a field post-AGB star, IRAS 07134 ([De Smedt et al. 2016](#)), with comparable atmospheric parameters. Boxes represent the inter-quartile ranges (IQR), whiskers the  $1.5 \times \text{IQR}$  limits, and blue lines the medians.

$\langle [\text{C}/\text{Fe}] \rangle = -0.35 \pm 0.16$ . Additionally, NGC 6723 exhibits a star-to-star  $[\text{Mg}/\text{Fe}]$  scatter with no significant  $[\text{Al}/\text{Fe}]$  spread. No Mg-Al anti-correlation is apparent, and the scatter is small. In addition, inspection of the  $[\text{Si}/\text{Fe}]$  ratio, as a function of  $[\text{Al}/\text{Fe}]$  or  $[\text{Mg}/\text{Fe}]$ , for the few stars with reliable Si measurements, did not reveal any clear trend. This suggests no net production of these elements, but rather is the likely result of the conversion of Mg into Al during the Mg-Al cycle ([Mészáros et al. 2020](#)).

Figure 4 compares the C, N, O, Mg, Al, Si, Ca, Ti, Ni, and Ce abundances of our sample with Galactic Bulge stars. The behaviour of those chemical species matches the mean  $\langle [X_i/\text{Fe}] \rangle$  (with  $X_i$  meaning the chemical species) of MW stars at similar metallicity, while the  $[\text{N}/\text{Fe}]$  abundance ratios are clearly super-Solar. Our results for  $[\text{Si}/\text{Fe}]$  are in reasonable agreement with optical observations ([Rojas-Arriagada et al. 2016](#); [Crestani et al. 2019](#)).

NGC 6723 has a uniform and constant  $[\text{Ca}/\text{Fe}]$  abundance ratio ( $\langle [\text{Ca}/\text{Fe}] \rangle = +0.25 \pm 0.10$ ), in agreement with optical observations ([Crestani et al. 2019](#)), which indicates that it is not affected by the H-burning process ([Mészáros et al. 2020](#)), as Ca is mostly produced by supernovae. For the odd-Z element K, we find that NGC 6723 exhibits a weak K-Mg anti-correlation, with  $\langle [\text{K}/\text{Fe}] \rangle = +0.15 \pm 0.10$ , suggesting that this population might have formed from super-AGB ejecta ([Ventura et al. 2012](#)).

For the remaining chemical species, we find that the average  $\langle [\text{O}/\text{Fe}] \rangle (+0.40 \pm 0.17)$ ,  $\langle [\text{Ti}/\text{Fe}] \rangle (+0.27 \pm 0.14)$ ,  $\langle [\text{Ni}/\text{Fe}] \rangle (-0.01 \pm 0.05)$ ,  $\langle [\text{Ce}/\text{Fe}] \rangle (+0.14 \pm 0.08)$ ,  $\langle [\text{Nd}/\text{Fe}] \rangle (+0.15 \pm 0.07)$ , and  $\langle [\text{Yb}/\text{Fe}] \rangle (+0.68 \pm 0.09)$  ratios are comparable to values for M107 and NGC 362, and in agreement with previous results ([Rojas-Arriagada et al. 2016](#); [Crestani et al. 2019](#)). However, some differences are noteworthy for Nd, compared to GCs at similar metallicity, but it does agree with the production of other *s*-process species such as Ba ([Rojas-Arriagada et al. 2016](#)), with small star-to-star scatter.



**Fig. 4.** Distributions of various elemental-abundance ratios from the APOGEE-2 survey for bulge field stars in close proximity to the Galactic Centre ( $-20^\circ < l < 20^\circ$  and  $|b| < 20^\circ$ ), and comparison with stars in NGC 6723. The field-star abundances are represented by orange iso-abundance contours. The member stars of NGC 6723 and the extra-tidal star analyzed in this work are shown with black and red open circles, respectively. The circle sizes reflect their  $V_o$  magnitudes, with decreasing size for fainter magnitudes. The blue cross symbol denotes the average ( $\langle [X_i/Fe] \rangle$ ) and its associated star-to-star scatter ( $\sigma_{([X_i/Fe])}$ ) of the abundance derived from the seven member NGC 6723 stars analyzed in this work.

#### 4.2. Extra-tidal star candidate

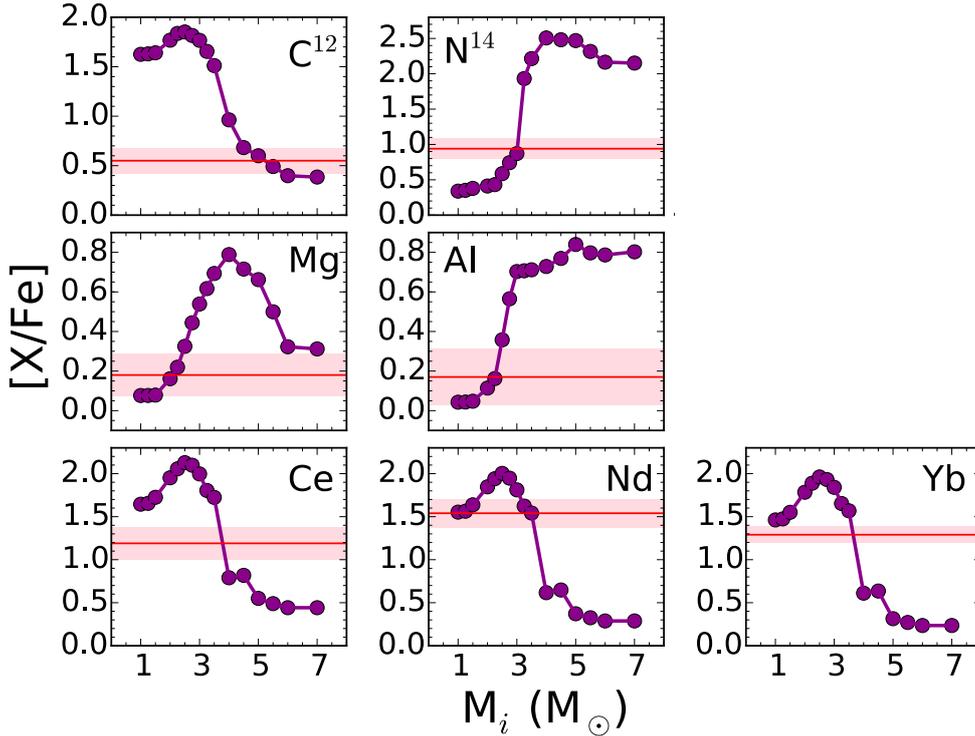
Panels (d) and (e) of Fig. 1 show the existence of an extra-tidal star in the smoothly curved morphology of the upper RGB in the  $V_o$  versus  $(B - V)_o$  (Lee et al. 2014), and  $H_o$  versus  $(J - K_s)_o$  diagrams, extending from the cluster centre out to  $\sim 1.3$  tidal radii. The brightness and bluish offset in all three diagrams from the equally bright RGB stars indicate that this extra-tidal star is in reasonable agreement with the expected behaviour for AGB stars in GCs. Figure 1a also shows that this extra-tidal star has similar metallicity and radial velocity, and Figs. 1b and c demonstrate the similarity of the orbital paths and proper motions to NGC 6723 member stars as well. Thus, these properties are vetted not only by chemical abundances, but by photometry and kinematics as well.

The  $\alpha$ -element (Mg, Si, Ca, and Ti), the odd-Z element (Al and K), and the iron-peak element Ni abundance ratios fall between  $-0.09$  and  $+0.52$  for our extra-tidal star. This is similar to the members of NGC 6723 and other GC stars with comparable metallicity, within the uncertainties (see Table 2 and Fig. 3). Figure 3 also shows that the extra-tidal star is strongly enhanced in the  $s$ -process elements (Ce II, Nd II, and Yb II), which is in agreement with other GC stars at similar metallicity (Mészáros et al. 2020).

Figure 2 reveal that the newly identified extra-tidal star has a stellar atmosphere strongly enriched in  $^{12}\text{C}^{14}\text{N}$  features, which

indicates a high enrichment in nitrogen ( $[\text{N}/\text{Fe}] = +0.94$ ), well above usual Galactic levels. However, this particular star has a carbon abundance higher than the abundance ratios measured for NGC 6723 member stars as shown in panel a of Fig. 3, but in reasonable agreement with the most C-rich stars in GCs of comparable metallicity (see panels b and c of Fig. 3). This atypical chemical pattern suggests that the extra-tidal star is not a genuine second-generation star as other typical N-rich field/GC stars, but indeed is part of a second-type of N-rich star with modest carbon enrichment, likely a GC star with AGB-like chemical patterns. Figures 2 and 3 also clearly show that K I, and Ce II enhancement of the extra-tidal star can be convincingly claimed. Thus, we conclude that the Ce, Nd, and Yb enhancement was inherited from the initial gas composition of NGC 6723.

We also find that the oxygen abundance is in reasonable agreement with levels seen for NGC 6723 stars (Rojas-Arriagada et al. 2016; Crestani et al. 2019). From the strength of the  $^{12}\text{C}^{16}\text{O}$  and  $^{16}\text{OH}$  molecular features (see Fig. 2), one would expect that more oxygen in the atmosphere means that more carbon is locked into  $^{12}\text{C}^{16}\text{O}$ , and is not available to form  $^{12}\text{C}^{14}\text{N}$ , as the strength of the  $^{12}\text{C}^{14}\text{N}$  features is anti-correlated with  $[\text{O}/\text{Fe}]$ . From Table 1, even a small change in the surface temperature and  $\log g$  requires some adjustment to the carbon and oxygen abundance, but  $[\text{N}/\text{Fe}]$  is relatively insensitive to small  $T_{\text{eff}}$  and surface gravity changes, and we can be confident that this star is indeed nitrogen enriched.



**Fig. 5.** Predicted abundance ratios, as a function of the initial stellar mass, for low-and-intermediate-mass stars.  $[X_i/Fe]$  values were obtained from stellar yields by Karakas et al. (2014, 2018). For comparison, the red line and shaded red bands represent the observed abundance ratios and sensitivities for our extra-tidal star.

## 5. Possible origins for the observed chemical composition of the extra-tidal star

There are several competing scenarios that might explain the unusual chemical abundances of our extra-tidal star, in the context of an escaped member of NGC 6723 that was tidally disrupted and captured by the MW’s bulge.

It appears likely that some stars (C-poor or C-enriched) belonging to the family of mildly metal-poor N-rich stars (peaking at  $[Fe/H] \sim -1.0$ ) could be relics of initially massive clusters such as NGC 6723. It is reasonable to assume that some of those objects were formed in Galactic GCs and later dynamically ejected into the Galactic field when their parent GCs were ultimately disrupted and destroyed, possibly during disc–bulge crossing events (see, e.g., Leon et al. 2000; Lane et al. 2010; Fernández-Trincado et al. 2015a,b, 2016b; Kundu et al. 2019b,a, 2021; Hanke et al. 2020; Sollima 2020). However, this has not heretofore been directly demonstrated.

With the newly analyzed extra-tidal star, we want to investigate the possible origin of neutron-capture (*s*-process) enrichment, simultaneous with the observed enrichment in nitrogen and its apparent carbon enrichment.

Figure 5 shows the observed photospheric abundances of our target star, along with theoretical (C, N, Mg, Al, Ce, Nd, and Yb) abundance ratios from nucleosynthetic AGB models closest to  $[M/H] \sim -1.09$ . We obtained these models by interpolating the stellar yields from Karakas et al. (2014, 2018). From inspection, an over-abundance of the elements created by the *s*-process (Ce II, Nd II, and Yb II) support the idea that AGB stars with initial masses of  $\sim 3.7 M_{\odot}$  could reasonably explain the observed *s*-process enrichment. As also seen in this figure, the C and N enrichments could be explained, at  $\sim 2\sigma$ , with initial masses of  $\sim 3.7$  and  $\sim 2.5 M_{\odot}$ , respectively, while Mg and Al suggest an initial mass of  $\sim 2.5 M_{\odot}$ . Thus, most of these species are in agreement with production by an AGB star having an initial mass  $\sim 2.5$  or  $3.7 M_{\odot}$ , which underwent a mass-transfer event,

resulting in pollution of an intermediate-mass companion that today has evolved to the tip of the RGB. We caution about the accuracy of the estimated  $[O/Fe]$  values, as they display a larger scatter, possibly due to telluric features and uncertain determinations in the  $T_{\text{eff}}$  regime of our objects. As highlighted in previous works, the uncertainty arises because BACCHUS determines these abundances from the strengths of  $^{12}\text{C}^{14}\text{N}$  and  $^{12}\text{C}^{16}\text{O}$  lines, which become too weak for stars at relatively low metallicities ( $[Fe/H] -1.0$ ). For this reason, we do not draw conclusive constraints in the mass of the progenitor based on the individual oxygen abundance listed in Table 1.

It is also possible that this star is itself an AGB star (perhaps with no relationship to NGC 6723), which could also explain the puzzle of its high nitrogen and *s*-process enrichment. However, such a range in mass would correspond to a very young star ( $\sim 0.5\text{--}0.7$  Gyr), which is likely too low to support this hypothesis. The AGB stage of stellar evolution is also very short-lived, so there is a low probability of finding an AGB star.

Taking into account the above results, we speculate on several possible scenarios that could be viable to explain the unusual nature of our object, in the context of an escaped member of NGC 6723 that was tidally disrupted and captured by the bulge of the MW.

- Extrinsic mechanism (binary-mass transfer system). The over-abundance of *s*-process elements could come from the accretion of *s*-process-rich matter from a former thermally pulsing (TP)-AGB companion during its heavy mass-loss phase on the AGB (Brown et al. 1990), which has since evolved into a faint white dwarf (see, Fernández-Trincado et al. 2019c, for instance). Figure 5 indicates that our measured abundance ratios, from the light elements (C, N), the  $\alpha$ -element (Mg), and the odd-Z element (Al), to the *s*-process elements (Ce, Nd, and Yb), could have originated from material previously enriched in a TP-AGB companion with an initial mass of  $\sim 2.5$  and  $\sim 3.7 M_{\odot}$ , respectively.

Consequently, if the case of an extrinsic mechanism is favoured, and the extra-tidal star is/was part of a binary system before/after leaving the cluster, it would be possible that the star accreted N-rich material from the companion when the latter reached the AGB phase with the inferred mass. In this case, the abundances that we measure are not its original ones, but they reflect the chemical composition of the interior of the companion, plus some degree of dilution in the convective envelope of the accreting star. In addition to the nitrogen and *s*-process enrichment, carbon should also be over-abundant, as a result of a third dredge-up episode in the donor. Such a star could have polluted the extra-tidal star with C, N, and *s*-process-rich material, but lost so much mass that the binary may be disrupted, or become so wide that RV variations would be very small, which could explain the lack of a detectable white dwarf companion. However, the current PMs and radial velocity of the extra-tidal star appear to support that this object was detached from the cluster by tidal disruption, consistent with the low relative velocity between this cluster and the star during close encounters. In such a case, the possibility that our object was part of a binary system before departure from the cluster would not be supported (see e.g. Fernández-Trincado et al. 2016a).

The absence of RV variation over the temporal span of the APOGEE-2 observations (<1 day) and *Gaia* EDR3 ( $-93.22 \pm 1.23 \text{ km s}^{-1}$ ) provide no evidence that our object (the extra-tidal star) is currently a binary with a white dwarf companion. Long-term RV monitoring of this unusual object would naturally be the best course to rule out an origin by the binary channel.

If there is any possibility to support the binary hypothesis in the future, perhaps from careful long-term RV monitoring, then it is worth mentioning that, if the donor material was lost in a wind from a  $\sim 2.5\text{--}3.7 M_{\odot}$  AGB star, it must have been shed very recently. However, this scenario is not compatible with its apparent brightness in Figs. 1d and e, as the object is intrinsically bluer and more luminous than other observed stars in NGC 6723.

- Intrinsic mechanism. A second scenario is that our unusual object could itself be an AGB star. In this case, it was enhanced in *s*-process elements via the third dredge-up of nucleosynthetic products created in the stellar interior and shell helium-burning (via thermal pulses), followed by subsequent mixing that can result in an over-abundance of C and N at the surface (Karakas et al. 2014). Moreover, if the extra-tidal star is an actual evolved object, possibly an early-AGB or an AGB star, it would have a mass in the range  $\sim 2.5$  to  $\sim 3.7 M_{\odot}$  to explain the observed photospheric chemical composition. As pointed out above, this would imply that a GC origin of this star is ruled out.
- A third possibility could be that our star is an *s*-process-enriched red giant that is the result of star formation in an *already s*-process-enriched medium, where AGB stars have played a more dominant role in chemical evolution (Ventura et al. 2016). Hence, a valid possibility is that the extra-tidal star inherited its present chemical composition while it was still a cluster member, likely from gas lost by a previous generation of  $\sim 2.5\text{--}3.7 M_{\odot}$  AGB stars. This mass range is also fairly well-supported by the observed [Mg/Fe], and [Al/Fe] abundance ratios, as shown in Fig. 5.
- A fourth plausible interpretation is that N-rich stars towards the bulge region are among the oldest in the Galaxy, and their abundances are in fact the imprints of the very early chemical enrichment by spinstars, metal-poor, fast-rotating

massive stars (Chiappini et al. 2011; Barbuy et al. 2014), which polluted the interstellar medium from which bulge GCs formed. An enhancement in N and modest enhancement in C, as well as some contribution to the neutron-capture elements (*s*-process nucleosynthesis) might be expected. This scenario would predict that all of the stars in NGC 6723 (and indeed in all bulge GCs formed in situ) would be N-rich stars, whereas if the third possibility is correct, then there should exist first-generation stars in the cluster that do not exhibit enhanced nitrogen.

We conclude that it is very likely that we have identified a former cluster member (the extra-tidal star), with observed abundances consistent with production by AGB stars that played an important role in the chemical enrichment of NGC 6723, which is in-line with previous results for GCs at similar metallicity (Ventura et al. 2016; Mészáros et al. 2020).

It is important to note that, at  $[\text{Fe}/\text{H}] \sim -1.17$ , it seems likely that the *s*-process would dominate the production of such elements, invoking the AGB progenitor (Kobayashi et al. 2020) rather than other possible sources such as binary neutron star (NS-NS) mergers (Wanajo et al. 2014). In addition, if we were to assume that the *n*-capture came from an NS-NS merger, then we would need a second progenitor to account for the N and other light elements.

We also note some differences between the extra-tidal star and MW field stars. Figure 4 shows a comparison between this star (red symbol) and bulge field stars at similar metallicity from the APOGEE-2 survey. While this result reinforces that N-rich stars of different generations (Martell et al. 2016) populate different regions of the canonical abundance planes, some similarities are noteworthy with Galactic field stars. The unique nature of our star is clear in the [C/Fe]–[N/Fe], [N/Fe]–[Al/Fe], [O/Fe]–[Al/Fe], [Mg/Fe]–[Al/Fe], [Mg/Fe]–[Si/Fe], [Mg/Fe]–[K/Fe], and [Ca/Fe]–[Ti/Fe] planes, which slightly exceed the Galactic levels, while some similarities remain for the  $\alpha$ -elements Mg, Si, Ca, and Ti, the odd-*Z* elements Al and K, and the iron-peak element Ti. In contrast to bulge field stars, the extra-tidal star clearly has higher [C, N, O/Fe] abundance ratios ( $> +0.5$ ). These differences (and similarities) suggest that the extra-tidal star exhibits the typical chemical patterns similar to those of evolved stars in GC at  $[\text{Fe}/\text{H}] \sim -1.0$  (Mészáros et al. 2020), as shown in panel e of Fig. 3. However, it is important to note that our extra-tidal star shows a lower metallicity compared to the cluster mean, but all its chemical patterns show good agreement with the other members of NGC 6723. This low-metallicity effect could be explained if some variability signature is detected in this star, as there is some evidence in the literature (Muñoz et al. 2018) that variability affects the measurement of the iron abundance in some way, causing a large offset with respect to the cluster mean. Another detailed photometric/spectroscopic analysis of this star is needed to investigate possible variability effects on the metallicity derivation. We note that, according to its radial velocity, proper motions, position in the CMD, and atmospheric parameters, this star is/was very likely a cluster member.

## 6. Expected Radial Profile of halo field stars with a globular cluster-like abundance patterns toward NGC 6723

We compute the predicted number ( $N_{\text{gc}}$ ) of halo field stars with globular cluster-like abundance patterns observed in APOGEE-2 (see, e.g., Fernández-Trincado et al. 2016a, 2017, 2019a; Schiavon et al. 2017b) towards the field of NGC 6723 using the

smooth halo density relations presented in [Horta et al. \(2021\)](#), and by adopting the same Monte Carlo implementation of the Von Neumann Rejection Technique ([Press et al. 2002](#)) as in Eq. (1) in [Mateu et al. \(2009\)](#) and Eq. (7) in ([Fernández-Trincado et al. 2015b](#)).

We find the expected number of observed APOGEE-2 halo field stars with a possible GC origin in the range  $5.5 \text{ kpc} < d_{\odot} < 9.5 \text{ kpc}$ , over a circular sky area of one-degree radius with centred in NGC 6723, and astrometric and kinematic properties as the cluster to be  $N_{\text{gc}} < 0.05$  (from 1000 Monte Carlo realisations). This indicates that the region around NGC 6723 is underdense, not overdense, in Galactic halo field stars with globular cluster-like abundance patterns, leaving enough room to favour the scenario of a genuine extra-tidal star associated with NGC 6723.

## 7. Galactic orbit

We used the GravPot16<sup>1</sup> algorithm for the calculation of the orbital path of both NGC 6723 and the extra-tidal star around the MW. The GravPot16 model is composed of multiple potentials for the Galactic disc and a box/peanut bulge. For the Sun's position in the MW we assumed a distance to the Galactic Centre of  $R_{\odot} = 8 \text{ kpc}$ . In order to correct for the solar motion, we used the Sun's velocity respect to the local standard of rest ( $U_{\odot}, V_{\odot}, W_{\odot}$ ) = (11.10, 12.24, 7.25)  $\text{km s}^{-1}$  ([Brunthaler et al. 2011](#)) and the velocity of the local standard of rest (LSR)  $v_{\text{LSR}} = 244.5 \text{ km s}^{-1}$ , based on  $R_{\odot}$  and assuming the composite rotation curve of [Sofue \(2015\)](#).

For NGC 6723 and the extra-tidal star, we integrated over a 2 Gyr timespan, and calculated their orbital paths and orbital parameters using three different values of the angular velocity of the bar  $\Omega_{\text{bar}} = 33, 43, \text{ and } 53 \text{ km s}^{-1} \text{ kpc}^{-1}$ . For NGC 6723, we adopted the observational parameters from [Baumgardt et al. \(2019\)](#); for the extra-tidal star, we adopted the observational parameters given in Table 1, except for the distance, for which we assumed two different values, e.g.,  $8.3 \pm 0.83 \text{ kpc}$ , the same heliocentric distance as NGC 6723 ([Baumgardt et al. 2019](#)), and  $6.24 \pm 1.69 \text{ kpc}$ , the estimated distance from the StarHorse code ([Anders et al. 2019](#)) (the algorithm combines the *Gaia* astrometric information with multiband photometric information and a number of Galactic priors), which have smaller uncertainties at large ranges, as previously expected, and which have been proven to be an useful tool in confirming the dichotomy with APOGEE-2/DR16 and dissecting the bulge stellar populations ([Queiroz et al. 2018, 2020](#)).

A simple Monte Carlo analysis was performed for the complete calculation, taking into account the errors in distance, RV, and proper motions, which were randomly propagated as  $1\sigma$  variations, assumed to follow Gaussian distributions. For both objects we computed 1000 orbits. Figure 6 shows the probability densities of the resulting orbits on the  $X$ - $Y$ ,  $X$ - $Z$ , and  $Y$ - $Z$  planes in the non-inertial reference frame where the bar is at rest, where the dark area correspond to the most probable regions of the space, which are crossed more frequently by the simulated orbits. We found that both cluster and extra-tidal star are situated in the inner region of the bulge. For the full ensemble of orbits, we also calculated the deviations in the orbital parameters due to the different values of the angular velocity of the bar, ( $\Delta r_{\text{peri}}, \Delta r_{\text{apo}}, \Delta Z_{\text{max}}, \Delta e$ ): NGC 6723 (0.02 kpc, 0.65 kpc, 0.37 kpc, 0.01), extra-tidal star at  $d_{\odot} = 8.3 \text{ kpc}$  (0.01 kpc, 0.52 kpc, 0.29 kpc, 0.01), and extra-tidal star at  $d_{\odot} = 6.24 \text{ kpc}$

(0.06 kpc, 0.07 kpc, 0.05 kpc, 0.03). With the different values of  $\Omega_{\text{bar}}$ , we can see that the predicted orbits are not significantly affected by the change of this parameter, and consequently, it does alter our conclusions.

The median orbital parameters, assuming  $\Omega_{\text{bar}} = 43 \text{ km s}^{-1} \text{ kpc}$  for NGC 6723 and the extra-tidal star, are as follows: ( $r_{\text{peri}}, r_{\text{apo}}, Z_{\text{max}}, e$ ): NGC 6723 ( $0.05 \pm 0.08 \text{ kpc}$ ,  $3.28 \pm 0.12 \text{ kpc}$ ,  $3.87 \pm 0.12 \text{ kpc}$ ,  $0.97 \pm 0.04$ ), extra-tidal star at  $d_{\odot} = 8.3 \text{ kpc}$  ( $0.06 \pm 0.14 \text{ kpc}$ ,  $3.36 \pm 0.10 \text{ kpc}$ ,  $3.98 \pm 0.12 \text{ kpc}$ ,  $0.97 \pm 0.07$ ), and extra-tidal star at  $d_{\odot} = 6.24 \text{ kpc}$  ( $1.56 \pm 1.07 \text{ kpc}$ ,  $4.28 \pm 0.66 \text{ kpc}$ ,  $2.46 \pm 0.82 \text{ kpc}$ ,  $0.46 \pm 0.24$ ). We confirm that both NGC 6723 and the newly found extra-tidal star possess trajectories indicating that they are confined to the bulge region ( $\lesssim 4 \text{ kpc}$ ) and have similar orbital properties, suggesting that the extra-tidal star shares an identical dynamical history as NGC 6723, as expected of stripped cluster stars. Figures 1b and 7 show that the extra-tidal star is in-line with the cluster's orbit. Figure 7 also suggests that the orbital path of NGC 6723 is tracing out the trailing arm, and our extra-tidal star candidate is located along the leading arm.

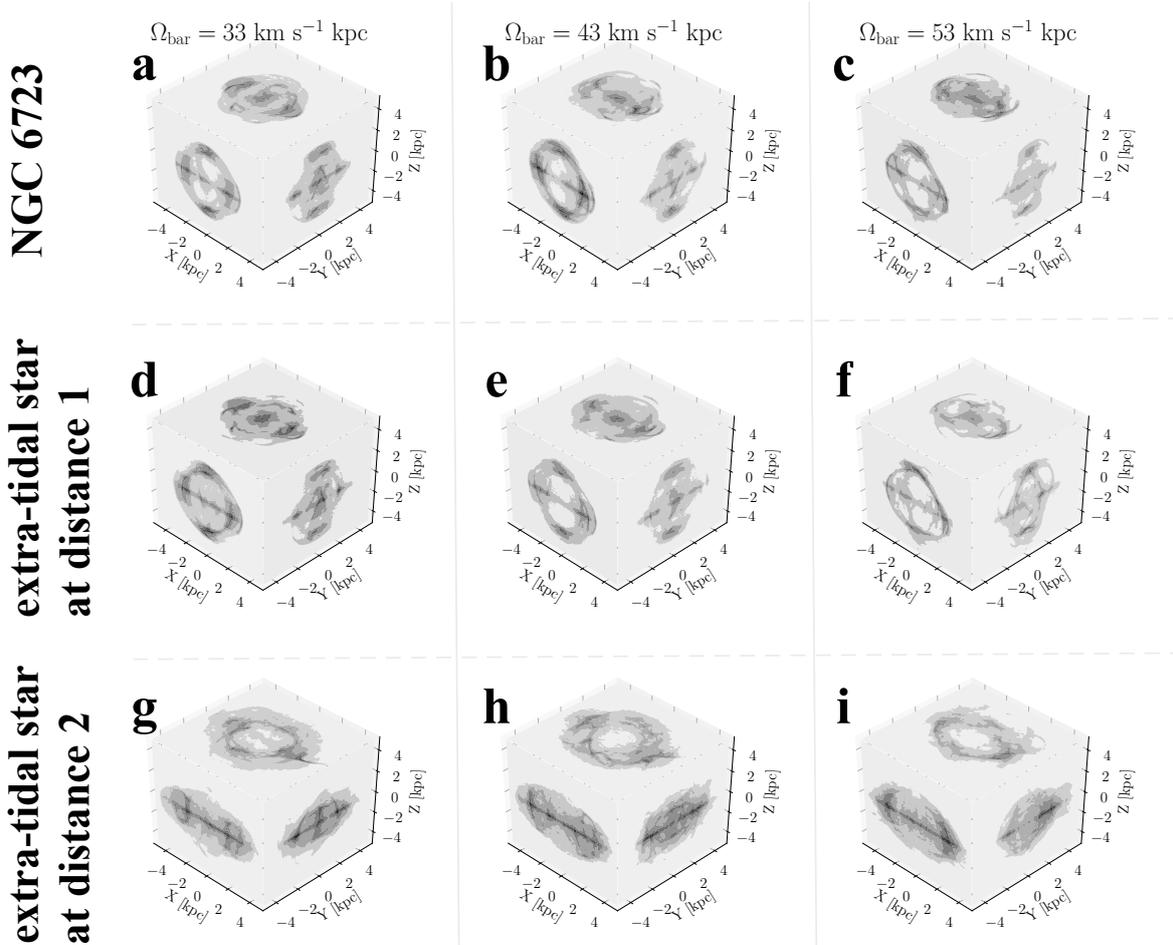
## 8. Comments on the tidal radius

The tidal radius for NGC 6397 has been measured by several studies, resulting in different values. For instance, a recent work by [de Boer et al. \(2019\)](#) using *Gaia* DR2 data determined a tidal radius that peaks at  $r_t = 67.66 \pm 9.50 \text{ pc}$  ( $\sim 26.7'$ ) from a generalised lowered isothermal LIMEPY model. This is considerably larger than previously thought. The [Baumgardt et al. \(2019\)](#) value, using the same data set and a different analysis method, adopted  $r_t = 36.95 \text{ pc}$  ( $\sim 14.6'$ ), which is substantially larger than the value of  $r_t = 10.51'$  listed by [Harris \(1996; 2010, 2010 edition\)](#).

Moreover, simulations from [Moreno et al. \(2014\)](#) calculated tidal radii between 29 and 31.4 pc using a 6-D dataset in an axisymmetric and non-axisymmetric Galactic potential, including a rotating Galactic bar and a 3-D model for the spiral arms. Their results indicate good agreement with the tabulated value from [Harris's](#) compilation and the cluster Jacobi radii determined in [Piatti et al. \(2019\)](#). Furthermore, the observed cluster stellar-density maps from near-infrared observations (see, e.g., [Chun et al. 2015](#)) suggest the existence of over-density features of some number of stars from  $\sim 6.3' \lesssim r \lesssim 15.77'$ , exhibiting azimuthally irregular patterns. Our newly identified extra-tidal star lies in this region as shown in Fig. 7, and placed well outside the Jacobi radius ( $\gtrsim 11'$ ; [Piatti et al. 2019](#)). This called our attention to the recent derived slightly larger  $r_t$  values from [de Boer et al. \(2019\)](#), based on *Gaia* DR2. This value, should be viewed with caution, as it has its own limitations toward the bulge regions, and could lead to fitting non-physically motivated core [King \(1962\)](#) and tidal radii.

With the new improved data from *Gaia* EDR3 ([Gaia Collaboration 2021](#)), and the available *Hubble* Space Telescope (HST) imaging data within  $1.1'$  from the cluster center ([Sarajedini et al. 2007](#)), we can determine updated structural parameters with better precision. To construct number density profiles, we make use of star counts by adopting the same technique as in [Cohen et al. \(2021\)](#) to combine both surveys. Briefly, the stellar density is found in annuli of varying radii around the centre of the cluster, and these density values are fitted by a King profile ([King 1966](#)). The HST+*Gaia* EDR3 data is fairly well-fit by the ([King 1966](#)) profile. The stellar-density profile is shown in Fig. 8. For NGC 6723 we have determined a radius  $r_t = 9.14 \pm 0.49'$ , which is in good agreement with the values

<sup>1</sup> <https://gravpot.utinam.cnrs.fr>



**Fig. 6.** Thousand-orbit realisations of NGC 6723 and the extra-tidal star time-integrated for 2 Gyr. The dark colours correspond to the most probable regions of the space, which are crossed more frequently by the simulated orbits, assuming three different values of the angular velocity of the bar ( $\Omega_{\text{bar}} = 33, 43, \text{ and } 53 \text{ km s}^{-1} \text{ kpc}$ ). *Panels a–c:* orbits of NGC 6723, using as initial conditions the observed values from [Baumgardt et al. \(2019\)](#); the *middle and bottom rows* show the orbits of the extra-tidal star, adopting the observed values from the [Table 1](#), and an assumed heliocentric distance at 8.3 kpc (*panels d–f*), and 6.24 kpc (*panels g–i*).

reported in [Harris \(1996, 2010 edition\)](#), and by dynamical studies of NGC 6723 (see, e.g., [Moreno et al. 2014](#); [Piatti et al. 2019](#)).

Our finding is in line with recent studies in the vicinity of NGC 6723, for example, near-infrared *J*-, *H*-, and *K*-band observations from the WFCAM camera on the 3.8 m UKIRT [Chun et al. \(2015\)](#), suggesting the existence of extra-tidal features  $\gtrsim 11'$  (Fig. 7), and is in good agreement with a rather high destruction ratio of  $\nu_{\text{tot}}/\nu_{\text{evap}} \sim 0.81\text{--}2.0$  [Gnedin & Ostriker \(1997\)](#), [Moreno et al. \(2014\)](#) (where  $\nu_{\text{tot}}$  is the total destruction rate of this cluster, and  $\nu_{\text{evap}}$  is the evaporation rate per Hubble time). The newly identified extra-tidal star lie near the weak extended substructure beyond the tidal radius in the southern region of NGC 6723 (see, e.g., [Chun et al. 2015](#)) as highlighted in Fig. 7, suggesting that this star has left the GC's potential. Thus, our findings provide strong support for the idea of linking N-rich field stars to GCs in the bulge region of the MW ([Bekki 2019](#)).

## 9. Concluding remarks

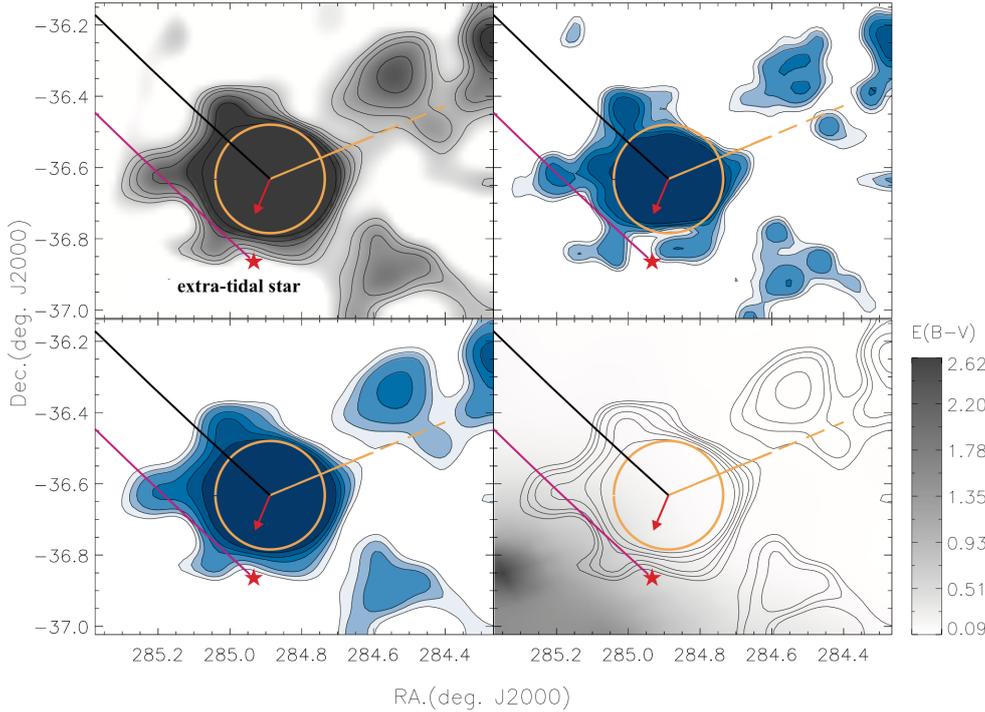
Our finding is in-line with recent studies in the vicinity of NGC 6723, e.g., near-infrared *J*-, *H*-, and *K*-band observations from the WFCAM camera on the 3.8 m UKIRT ([Chun et al. 2015](#)), suggesting the existence of extra-tidal features around

this cluster (see Fig. 7). Thus, our findings provide strong support for the idea of linking some of the observed N-rich field stars to GCs in the bulge region of the MW (e.g., [Schiavon et al. 2017b](#); [Fernández-Trincado et al. 2019a](#)).

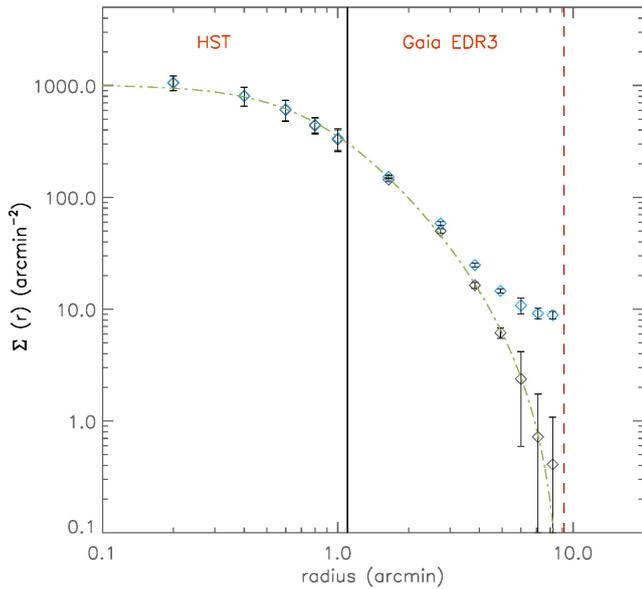
We also conclude that it is very likely that we have identified a former cluster member, with observed abundances consistent with production by AGB stars that played an important role in the chemical enrichment of NGC 6723, which is in-line with previous results for GCs at similar metallicity ([Mészáros et al. 2020](#)).

There are also several competing scenarios that might explain the unusual chemical abundances of the newly identified extra-tidal star, in the context of an escaped member of NGC 6723 that was tidally disrupted and captured by the MW's bulge. In summary:

- Extrinsic mechanism: The over-abundance of the *s*-process elements in this star could come from the accretion of *s*-process-rich matter from a former thermally pulsing AGB companion during its heavy mass-loss phase on the AGB, which has since evolved into a faint white dwarf star.
- Intrinsic mechanism: This star could be an intrinsic AGB star, enhanced in *s*-process elements during the third dredge-up of nucleosynthetic products created in the stellar interior and shell helium-burning (via thermal pulses), followed by



**Fig. 7.** Modified Fig. 10 from [Chun et al. \(2015\)](#). The red ‘star’ symbol shows the position of the newly identified extra-tidal star. The orange circle indicates the cluster tidal radius ( $r_t = 9.14 \pm 0.49'$ , see Sect. 8), and the red arrow defines the proper motion of NGC 6723 from [Baumgardt et al. \(2019\)](#). The orange solid and dashed line shows the direction of the Galactic Centre and Galactic plane, respectively. *Top-left panel:* star-count map around the cluster; the top-right panel is the surface-density map, smoothed by a Gaussian kernel  $0.07^\circ$ ; the *lower-left panel* is the same data, but smoothed with a  $0.11^\circ$  kernel; the *bottom-right panel* shows the distribution map of  $E(B-V)$ . The iso-density contour levels shown are  $2.0\sigma$ ,  $2.5\sigma$ ,  $3.0\sigma$ ,  $4.0\sigma$ ,  $5.0\sigma$ , and  $7.0\sigma$ . The orbital path of the cluster (black line) and the extra-tidal star (purple line) is over-plotted.



**Fig. 8.** Stellar-density profile of NGC 6723 determined from the HST+*Gaia* EDR3 data set. Small orange symbols show densities before background subtraction. The best fit [King \(1966\)](#) profile is shown in lime and cyan, respectively. The red dashed line shows the determined tidal radius ( $r_t = 9.14 \pm 0.49'$ ) in this work, while the black line in 1.1' separate the HST from *Gaia* EDR3 data set.

subsequent mixing that can result in an over-abundance of carbon and nitrogen at the surface.

- This star could be an *s*-process-enriched red giant resulting from star formation in an already *s*-process-enriched medium, where low-mass AGB stars have played a dominant role in chemical evolution.

Finally, the newly identified extra-tidal star displays a  $[N/Fe]$  ratio similar to other metal-poor N-rich field stars, but which are not carbon enriched (one of the typical signatures of second-

generation GC stars)–(see e.g., [Fernández-Trincado et al. 2016a, 2017, 2019a](#); [Schiavon et al. 2017b](#)), suggesting that the extra-tidal star is not a genuine second-generation star, but it is part of a sub-family of the N-rich stars with modest carbon enrichment as that observed in some Galactic GC stars at similar metallicity, likely associated with the intermediate-mass ( $\lesssim 3 M_\odot$ ) population of early-AGB stars.

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