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# High-speed stars II: An unbound star, young stars, bulge metal-poor stars, and Aurora candidates. <sup>★</sup>

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## ABSTRACT

*Context.* The data from the Gaia satellite led us to revise our conception of the Galaxy structure and history. Hitherto unknown components have been discovered and a deep re-thinking of what the Galactic halo is in progress.

*Aims.* We selected from the Gaia catalogue stars with extreme transverse velocities with respect to the Sun ( $|V_T| > 500 \text{ km s}^{-1}$ ) and observed them with FORS2 at the ESO VLT, to classify them using both their chemical and dynamical properties. Two apparently young stars, identified in paper I, were observed with UVES.

*Methods.* We derived abundances for Na, Mg, Ca, Ti, Mn, and Fe, analysing the spectra with MyGisFOS, while for Ba we used line profile fitting. We computed actions from parallaxes and kinematical data.

*Results.* The stars span the metallicity range  $-3.5 \leq [\text{Fe}/\text{H}] \leq -0.5$  with  $\langle [\text{Fe}/\text{H}] \rangle = -1.6$ . Star GHS143 has a total speed of about  $1440 \text{ km s}^{-1}$ , which is almost three times faster than the local escape velocity of  $522 \text{ km s}^{-1}$ , strongly implying this star is unbound to the Galaxy. Remarkably, this star is not escaping from the Galaxy, but it is falling into it. Ten stars are apparently young with masses in excess of  $1.3 M_{\odot}$ . Their interpretation as evolved blue stragglers is doubtful. The existence of a young metal-poor population is possible. The two stars observed with UVES show no lithium, suggesting they are blue stragglers. We detected a metal-poor population, confined to the bulge, that we call SpiteF, and argue that it is the result of a recent accretion event. We detect 102 candidates of the Aurora population that should have formed prior to the formation of the disc.

*Conclusions.* Our sample is non-homogeneous and mainly retrograde. The stars are metal poor, and 23% have  $[\text{Fe}/\text{H}] \leq -2.0$ . Our selection is efficient at finding very metal-poor stars, but it selects peculiar populations.

**Key words.** Stars: abundances - Galaxy: abundances - Galaxy: evolution - Galaxy: formation - Galaxy: kinematics and dynamics - Galaxy: halo

## 1. Introduction

The stars belonging to the Galactic disc, such as the Sun, move around the Galactic centre with a velocity dependent on their distance from the Galactic centre. At the Galactic radius of about 8 kpc, where the Sun dwells, the velocity of the stars around the Galactic centre is  $220 \text{ km s}^{-1}$  (the recommended IAU value; Kerr & Lynden-Bell 1986). The Galactic disc moves as a rigid body up to about the Sun, while further out the speed of the stars is more or less constant. For this reason, disc stars do not show a high speed when observed from the Earth. Halo stars instead can have any orbit around the centre of the Galaxy. If the Milky Way has formed in a hierarchical scenario, we expect the halo to contain stars that were formed in accreted dwarf galaxies as well as, possibly, stars that formed during the collapse of the halo. According to Haywood et al. (2018), what are usually called ‘halo

stars’ are a mixture of the following: (1) stars that were formed in the massive satellite galaxy that was accreted 8 to 10 Ga ago, which was initially discovered by Belokurov et al. (2018) using Gaia data release 1 (Gaia Collaboration et al. 2016a) and later confirmed by Haywood et al. (2018) and also by Helmi et al. (2018) using Gaia data release 2 (Gaia Collaboration et al. 2018); and (2) disc stars that were scattered in halo-like orbits as a result of the collision. The Galactic structure resulting from this accretion was called Gaia-Sausage by Belokurov et al. (2018) and Gaia-Enceladus by Helmi et al. (2018), following a now well-established convention in the literature we shall refer to as Gaia-Sausage-Enceladus (GSE). Other accretion events have since been discovered and some of them are discussed in detail in Sec. 4. Recently, Belokurov & Kravtsov (2022) claimed the discovery of a population of stars that formed in the last turbulent phases of the Galactic collapse, prior to the formation of the disc. This population should represent the dawn of star formation, for

<sup>★</sup> Based on observations made at VLT with FORS2 under programmes 0105.D-0213,0106.D-0435, and UVES programme 0108.D-0372.

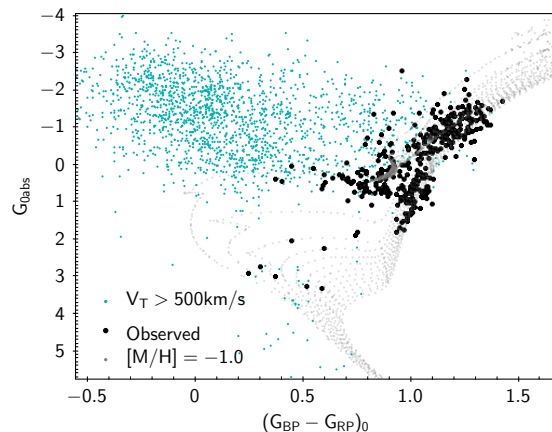
this reason they call it Aurora<sup>1</sup>. Di Matteo et al. (2019), based on Gaia data release 2 (Gaia Collaboration et al. 2018) kinematic data and Apache Point Observatory Galactic Evolution Experiment (APOGEE Majewski et al. 2017) chemical abundances, found no evidence for the existence of stars that formed during the collapse of the Galactic halo. The halo, as explored by the data they took into consideration, seems to be formed exclusively by thick disc stars, heated by the collision that gave rise to GSE and stars that were formed in the colliding galaxy itself. The issue is clearly still open to debate.

By looking at the Toomre diagrams in Fig.6 of Haywood et al. (2018), it is clear that there are groups of stars that have a high retrograde rotation and high speed. These stars may indeed be the result of other minor accretion events. Since dwarf galaxies have a shallow gravitational potential, they cannot retain large amounts of chemically enriched material and the stars that formed in dwarf galaxies are generally more metal poor than stars in the Galactic disc (exceptions are e.g. Fornax and Sgr, the most massive dwarf spheroidal galaxies).

Among the halo stars, we are especially interested in metal-poor and extremely metal-poor (MP  $[\text{Fe}/\text{H}] \leq -1.0$  and EMP  $[\text{Fe}/\text{H}] \leq -3.0$ ) stars. These stars formed from a gas cloud that was hardly enriched in metals by supernovae explosions, the last stage of the evolution of the massive stars. This low metal content of the gas was the typical chemical composition of a pristine phase of the Universe. The massive stars have a short life; if formed in the pristine Universe, they are long gone at present and are no longer observable. The pristine low-mass stars are still observable today because their lifetime is longer than the age of the Universe, but their chemical composition is a witness of a long gone chemical composition that characterised the pristine Universe. The knowledge on the detailed chemical composition of these old stars is providing us information on the early Universe. In fact, the chemical content of the primordial stars puts constraints on the masses of the first generations of massive stars that exploded as supernovae and enriched the primordial interstellar medium and also on the physics of the supernovae explosions.

In the classical picture, the halo is populated only by old metal-poor stars since no high-density molecular clouds, suitable to sustain a recent star formation, are present in the halo. Most apparently, young stars found in the halo are near the turnoff and can be interpreted as blue straggler stars. Yet, since the availability of Gaia parallaxes, stars that are compatible with young metal-poor stars among giants become apparent in colour-magnitude diagrams. An excellent example is figure 2 of Hattori et al. (2018), although these stars are not further discussed in that paper. Even though a recent star formation could not have taken place in the halo, it could have taken place in Local Group dwarf galaxies, which then lost these stars due to a tidal interaction with the Milky Way. For instance, Fornax is known to have had a star formation ongoing up to until 100 Ma ago (de Boer et al. 2012). If many of the dwarf galaxies contain these metal-poor young stars, then it would not be surprising to find some of them in the Galactic halo.

The mass of the Galactic halo is much smaller than the mass of the Galactic disc. This means that halo stars are a minor component of the Galactic stars (about 1%) and the majority of MP and EMP stars belong to the halo. It must be however noted that a minority of MP and EMP stars can also be found on disc orbits (Sestito et al. 2020; Di Matteo et al. 2020). In general, MP stars are not common objects. In order to find them, large amounts



**Fig. 1.** Colour magnitude diagram of the high transverse speed stars (cyan) selected from the Gaia DR3 catalogue using the query in appendix B and those observed (black). PARSEC isochrones (Bressan et al. 2012) of metallicity  $-1.0$  (grey) are over plotted.

of data have to be gathered and analysed. In the past years, several projects focussed on the search and chemical investigations of MP and EMP stars, based on photometry or on the analysis of low-resolution spectra obtained by large surveys. However, there are other ways to select halo stars. A way to select halo stars is to rummage in the kinematic database and select stars whose speed is faster than the speed of disc stars. In this way we do not really select halo stars, but we cut out disc stars.

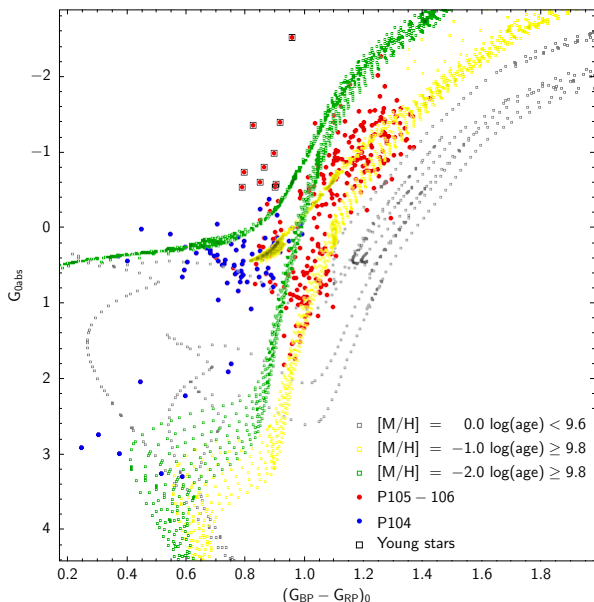
We began this research in Caffau et al. (2020b, hereafter Paper I), by selecting stars with a high transverse speed from the Gaia (Gaia Collaboration et al. 2016b) second data release (Gaia Collaboration et al. 2018) and observing them at a low spectral resolution with the FOcal Reducer/low dispersion Spectrograph 2 (FOR2) at the ESO 8.2 m Very Large Telescope in ESO period 104. Given the very promising results of the first 72 stars presented in Paper I, the programme was continued in ESO periods 105 and 106. In this paper we describe these observations, their analysis, and our conclusions from this chemo-dynamical study.

## 2. Target selection

In Paper I we selected from Gaia DR2 (Gaia Collaboration et al. 2018) stars with transverse velocity<sup>2</sup> in excess of  $500 \text{ km s}^{-1}$  and we privileged ‘blue’ stars because we were aiming at selecting the most metal-poor population of these high-speed stars. For the following observations, during ESO period 105 and 106, we used Gaia EDR3, we kept the condition of transverse velocity in excess of  $500 \text{ km s}^{-1}$  but observed also redder stars with the aim of obtaining a representative metallicity distribution function for high-speed stars. We excluded in any case stars with  $(G_{BP} - G_{RP}) > 1.5$  because of the complexity of modelling the spectra of stars cooler than this limit. The Gaia DR3 identifiers of all our programme stars (including those in Paper I) can be found in appendix A. The input catalogues used for the three ESO periods are different, also because they had folded in the range of right ascension suitable for the given period, colour and magnitude cuts are also different, and the Gaia catalogues used were

<sup>2</sup>  $V_t = 4.740470446 \sqrt{(\mu_\alpha/\varpi)^2 + (\mu_\delta/\varpi)^2}$ , where  $\varpi$  is the parallax and  $\mu_\alpha, \mu_\delta$  are the proper motions in right ascension and declination. All these quantities have been taken from the Gaia catalogue, where they are provided in units of mas.

<sup>1</sup> Latin for dawn.



**Fig. 2.** Colour magnitude diagram of the observed high-speed stars. The stars discussed in Paper I are in blue, which were observed in ESO period 104, and those observed in period 105 and 106 are in red. We provide PARSEC isochrones (Bressan et al. 2012) of metallicity 0.0 (grey),  $-1.0$  (yellow), and  $-2.0$  (green) of different age ranges. The age difference between consecutive isochrones of any given metallicity is 1 Ga. The apparently young stars observed in periods 105 and 106 are identifiable with an open square around the symbol.

different. We stress that in this investigation we have no claim of completeness, therefore the lack of homogeneity among the observations in the different ESO periods does not affect any of our results. To provide an idea of what the general population of high transverse speed stars is, we show in Fig. 1 our observed stars together with a selection obtained on the Gaia DR3 catalogue with the adql query in appendix B. We focussed on giant stars for two reasons: *i*) the cooler temperatures imply stronger lines at any given metallicity, making the chemical analysis easier with the low resolution spectra we used; *ii*) the age-metallicity degeneracy is weaker for giant stars. The magnitudes were limited to  $G \leq 14.3$  in order to observe a large sample in a relatively short amount of time.

In Fig. 2 we show the colour-magnitude diagram in Gaia DR3 (Gaia Collaboration et al. 2022) broad band observed colours<sup>3</sup>. We note that this is the case also for the stars in Paper I shown as blue dots, while in figure 1 of Paper I the Gaia DR2 colours were used. To guide the eye we show also three sets of PARSEC isochrones (Bressan et al. 2012) of metallicity  $-2.0$ ,  $-1.0$  and  $0.0$ . For the two most metal-poor sets only old isochrones are shown with ages between 6 and 14 Ga, at steps of 1 Ga. For the solar metallicity ones only young isochrones are shown, with ages between 1 and 3 Ga. It is clear from the figure how the stars observed in periods 105 and 106 are redder than those observed in period 104. It is also clear, from the comparison with the isochrones, that the colours imply that the majority of the stars should have metallicities in the range  $-2.0$  to  $-1.0$ , with only few more metal-poor or metal-rich. In a colour-magnitude diagram the metallicity, to a first approximation, decreases along a vector orthogonal to the Red Giant Branch (RGB), the most

metal-poor stars being the bluest. This colour dependence saturates around metallicity  $-2.5$ , when line blanketing has no further effect on the broad band colours. This behaviour is clear in Fig. 2 where isochrones of several metallicities are shown. From Fig. 1 it appears that we have sampled the blue-edge (most metal-poor stars) of the RGB and have observed several stars on the red-edge (most metal-rich). Similar to what done in Paper I we assign to each star a working name GHSXXX where GHS stands for Gaia High Speed and XXX is a three digit integer. In Table A.1 we provide Gaia DR3 source IDs for each star.

One feature that stands out from Fig. 2 is that there are ten stars that are far too blue and luminous to lie on old isochrones of whatever metallicity. We refer to these stars as ‘young’ and we derived their ages and masses using isochrones as described in Sect.5.1.

### 3. Observations and radial velocities

#### 3.1. FORS

In periods 105 and 106, we observed 287 FORS spectra of 278 stars. The instrumental setup was the same as used for Paper I. We discuss in this paper together the stars observed in periods 105, 106 and 104 (Paper I) for a total of 350 stars. Two of the stars observed are not discussed in the main text: star GHS36 of Paper I that was not analysed chemically, due to the low S/N ratio in the spectrum and star GHS076, observed in period 105, a reddened B-type star discussed in appendix C. Variable stars are also discussed in appendix C.

We used GRISM 600B+22 and a  $0''.28$  slit. The CCD was read with a binning  $1 \times 1$ . This configuration provides a resolving power of about 2800 in the spectral range 330–621 nm. In Fig. 3 we show an example for the very metal-poor star GHS337. The spectra were reduced using the ESO FORS pipeline.

For each spectrum a first estimate of the radial velocity was determined, like in Paper I by template matching. This was used to shift the spectrum to rest wavelength and fed to MyGisFOS (Sbordone et al. 2014) for the chemical analysis. Among the MyGisFOS output there is also the radial velocity shift derived for each feature. For each star the shifts derived for the features retained for the abundance analysis were averaged and a correction was applied to the radial velocity derived from template matching. In Fig. 4 we show the comparison of our radial velocities with those of Gaia RVS. The errors on the Gaia radial velocities range from  $0.8 \text{ km s}^{-1}$  to  $10.5 \text{ km s}^{-1}$  with a median value of  $2.6 \text{ km s}^{-1}$  and a standard deviation of  $1.6 \text{ km s}^{-1}$ . On average there is a small offset of about  $9 \text{ km s}^{-1}$ , in the sense Gaia–FORS, with a standard deviation of about  $34 \text{ km s}^{-1}$ . Since the FORS radial velocities are affected by systematic errors caused by instrument flexures and centring of the star on the slit (Caffau et al. 2018, 2020a), we prefer to use the Gaia radial velocities, whenever available, yet we consider the good correlation between the two sets of radial velocities, satisfying.

#### 3.2. UVES observations

A possible diagnostic to distinguish blue straggler stars from truly young stars, is the Li abundance, since blue stragglers generally do not have measurable lithium (Hobbs & Mathieu 1991; Pritchett & Glaspey 1991; Glaspey et al. 1994; Ryan et al. 2001). With the FORS spectra it is not possible to use the Li diagnostic because the only available Li abundance indicator, the  $\text{Li I}$  resonance doublet at 670.7 nm, is not within the observed wavelength range and in any case the resolution is too low. For this reason,

<sup>3</sup> The absolute magnitudes were computed as  $G_{abs} = G + 5 + 5 \log(\varpi/1000)$ , where  $\varpi$  is the parallax in mas as provided by the Gaia catalogue.

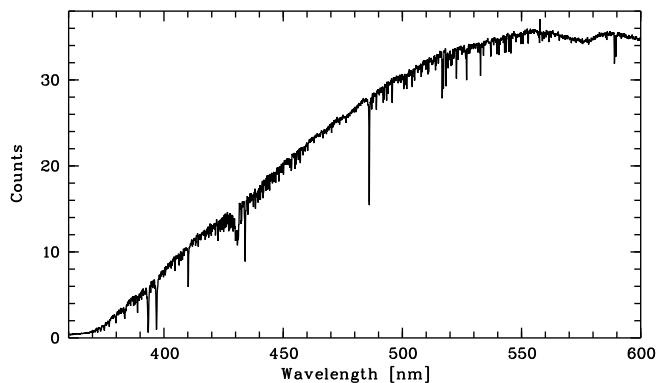


Fig. 3. Observed FORS spectrum of GHS337.

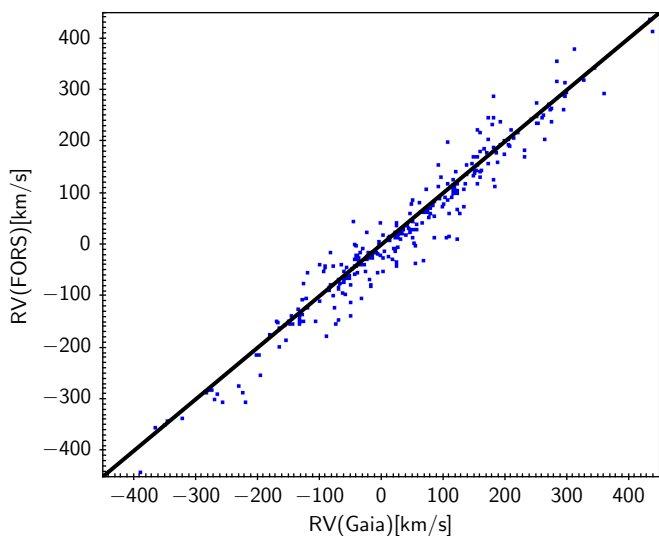


Fig. 4. Comparison of the radial velocities measured with FORS with those of Gaia RVs. The black line is the bisector, to guide the eye.

we requested a high resolution follow-up of two of the sub-giant candidate blue stragglers from Paper I with UVES in the ESO period 108, in order to measure the  $\text{Li I}$  resonance doublet. We were allocated nine hours of observation, but only three were executed on two targets. The stars GHS69 and GHS70 were observed between December 2021 and March 2022 in service mode using the standard setting DIC1 390+580 (326–454 nm in the blue arm and 476–684 nm in the red arm). With a slit of  $1''.0$  and a  $1 \times 1$  binning this setting provides a resolving power of  $\sim 40\,000$ . With one hour observing blocks (corresponding to 3000 s integration) we expected to obtain  $60 \leq \text{S/N} \leq 80$  at 671 nm and  $30 \leq \text{S/N} \leq 40$  at 400 nm. The constraint on the seeing was better than  $1''.2$ , all observations were taken at airmass  $\sim 2$ . The star GHS70 was observed twice, since the mean seeing of the first observation was above the requested one. With these constraints, we achieved a mean S/N lower than expected around the  $\text{Li I}$  doublet, with  $\text{S/N} \sim 42$  for GHS69, and  $\text{S/N} \sim 55$  for GHS70 (by summing the two exposures).

#### 4. Kinematics

In order to characterise the stellar kinematics, we used the `galpy` code together with its default Galactic potential (MW-Potential2014, Bovy 2015). We further adopted the Schönrich

et al. (2010) solar peculiar motions, 8 kpc as solar distance and  $220 \text{ km s}^{-1}$  as circular velocity at the solar distance (Kerr & Lynden-Bell 1986), that is consistent with the recent determination by Bovy et al. (2012,  $218 \pm 6 \text{ km s}^{-1}$ ).

For all the stars, we fed `galpy` with Gaia DR3 coordinates, proper motions and radial velocities. Distances were obtained from Gaia DR3 parallaxes, corrected for the zero-point according to the prescriptions of Lindegren et al. (2021). Similarly to Bonifacio et al. (2021), uncertainties on the derived quantities were evaluated by extracting random realisations of the input parameters (positions, proper motions, distances and radial velocities) considering the error in the input parameters and the astrometric covariance matrix using the `Pyia` code (Price-Whelan 2018). For each stars, 1000 realisations were fed to `galpy` and we adopted as uncertainties the standard deviations of the calculated quantities.

There is always some concern in deriving distances by inverting parallaxes (see e.g. Luri et al. 2018) and some prefer to use bayesian estimates (see e.g. Bailer-Jones et al. 2021). One should be aware, however that most of the troubles arise when the parallax error is large, the example in Luri et al. (2018) has been obtained assuming 0.3 mas errors on the parallaxes. Our sample has a mean parallax error of 0.016 mas and the relative errors range from 2% to 21% with a median of 8%. In fact, when we compare the distances obtained from inverting the parallax with the bayesian photogeometric estimates of Bailer-Jones et al. (2021), we obtain an excellent correlation. A linear fit of the two distance estimates yields a slope of 0.87 and a root-mean-square deviation of 0.3 kpc. None of our main results would change, had we adopted the bayesian distance estimates. Finally we should also note that the use of bayesian distance estimates introduces a bias, that is due to the assumed prior. We chose not to use bayesian estimates to avoid this bias. A similar approach was used also by Marchetti et al. (2022).

Gaia DR3 radial velocities (RV) are not available for three stars, namely GHS91, GHS248 and GHS277. For these stars we adopted the RVs measured from the FORS spectra and a formal error of  $30 \text{ km s}^{-1}$ , consistent with the standard deviation discussed in Sect. 3.

We decided to perform the same analysis also on the stars from Paper I. In this case 5 stars do not have RVs from Gaia DR3 (GHS29, GHS65, GHS66, GHS69, GHS70). For these stars we used the RVs and errors derived from the FORS spectra in Paper I. Stars GHS22, GHS33, GHS37, GHS58, GHS64 were indicated as unbound in Paper I, while they are found to be bound in the present analysis. This difference is due to the zero-point corrected parallaxes adopted here and entirely consistent with the discussion on the parallax zero point presented in section 4.2 of Paper I. On the other hand, with a total galactocentric space velocity of  $1439.8 \text{ km s}^{-1}$ , GHS143 results unbound to the Milky Way according to the current analysis (see Sect. 4.1).

Out of the 348 stars in our combined sample, 346 belong to the halo and two to the thick disc according to the criteria introduced by Bensby et al. (2014). Ninety of the halo stars belong to the GSE and 17 to the Sequoia (Seq, Barbá et al. 2019; Myeong et al. 2019; Villanova et al. 2019, but see also Myeong et al. 2018; Koppelman et al. 2018) structures, following the criteria introduced by Feuillet et al. (2021).

We noticed among our targets, a group of stars located in the inner part of the Galaxy. In order to assess the presence among our targets of stars confined to the bulge, we repeated the analysis described above but this time adding to the MWPotential2014 Galactic potential a rotating bar (Dehnen 2000) generalised to three dimensions as in Monari et al. (2016). We identify 16 stars

having an apocentric radius  $r_{ap}$  lower than 3.5 kpc and for which more than 50% of the random realisation of the input parameters fed to `galpy` returned a  $r_{ap} < 3.5$  kpc. We classify them as bulge stars. It is worth notice that 14 out of 16 stars are in retrograde motion ( $L_Z < 0$ ). Star GHS247 belongs both to the bulge and Sequoia, according to our adopted definitions.

With 222 over 348 analysed stars (64%, we exclude GHS076) having  $L_Z < 0$ , our sample is dominated by stars in retrograde motion. Excluding GSE (90 stars, 51 with  $L_Z > 0$ ), Seq (17 stars, all with  $L_Z < 0$ ), the two thick disc stars ( $L_Z > 0$ ) and the stars confined to the bulge (16 of which 14 with  $L_Z < 0$ ), the remaining 223 halo stars are divided into 141 retrograde (63%) and 82 prograde (37%) motions.

Of the group of ten young stars, as identified from the CMD in Sect 2, GHS108 and GHS110 are bulge stars, GHS212 belongs to GSE and GHS120 to Seq. Star GHS143, the only star classified as unbound within our sample, is also a young star. Star GHS110 is photometrically variable according to Gaia, however its classification is uncertain (see section C.2).

We present in figure 5 the target stars in several, commonly used, kinematic planes (Lane et al. 2022), using combinations of orbital Energy (E) and angular momentum  $L_Z$  (top-right panel), eccentricity (bottom-left panel), actions ( $J_\phi=L_Z$ ,  $J_R$ ,  $J_Z$ , bottom middle and right panels), and velocity components in galactocentric cylindrical coordinates ( $V_T$ ,  $V_R$ ,  $V_Z$ , top left and middle panels). In the action diamond in the bottom-right panel, quantities are normalised to the total action  $J_{tot}=|J_\phi|+J_R+J_Z$ .

Halo and thick disc stars are shown as blue and yellow stars in the figure, respectively. Stars belonging to GSE, Seq or to the bulge are shown as big filled, red, green and magenta circles, respectively. Cyan filled squares are stars classified as young. Grey points are stars from the "good parallax sub-sample" of Bonifacio et al. (2021) and are plotted only for reference. The shaded red and green boxes in the figure, correspond to the Feuillet et al. (2021) criteria employed to select likely GSE and Seq candidates, respectively. The selection of GSE can be found in the lower row, middle panel, that of Seq on the bottom row right panel.

Figure 6 shows the target stars in the Y vs X plane (top-right panel, Galactocentric Cartesian coordinates), the height over the galactic plane Z vs the cylindrical radius R ( $R = \sqrt{X^2 + Y^2}$ ) top-left panel), maximum height over the galactic plane  $Z_{max}$  vs  $r_{apo}$  plane (bottom-left panel) and apocentric vs pericentric distances ( $r_{peri}$  vs  $r_{apo}$ , bottom-right panel). The position of the Sun is  $(X, Y, Z) = (8.0, 0, 0.0208)$  and  $R = 8.0$ , everything expressed in kpc.

Several investigations have introduced chemical and dynamical criteria to select stars likely sharing common origins (e.g. Helmi et al. 2018; Naidu et al. 2020; Feuillet et al. 2021; Limberg et al. 2022; Buder et al. 2022). Such criteria are based on extensive databases, like Gaia, APOGEE, GALAH, and H3 to name a few. If one adopts some of these criteria for our sample of stars, one is lead to tag a few stars as belonging to some of these structures. However, this does not take into account the existence of any significant signal in our sample, that points towards the presence of a prominent feature. Such an outcome can be clearly seen from our analysis of the stars selected from the Gaia Universe Model (GUM, Robin et al. 2003<sup>4</sup> see Sec. 6.4). We thus decided to perform a clustering analysis among the stars

of our small sample, based on the derived integrals of motion only, in order to have some objective insight into the groups of stars that can be found. The details of this analysis can be found in appendix D.

The main conclusion is that two main structures are present among the stars of our sample. One is connected to GSE and, indeed, the clustering analysis recovers a selection similar to that introduced in Feuillet et al. (2021). In the [Mg/Fe] vs [Fe/H] plane, when we consider stars selected according to our clustering analysis and to the Feuillet et al. (2021) selection criteria, we detect qualitatively similar trends. However, since these latter are now widely used in the literature, and are based on a much more extensive database, we decided to use them in the end. Similarly, we decided to still tag stars as Seq according to Feuillet et al. (2021), although our clustering analysis does not reveal the presence of a structure compatible with the Feuillet et al. (2021) criteria. Indeed, our GUM analysis and the lack of a clear pattern in Fig. 17 cast doubts on the reality of the association of these stars between them and with the Seq accretion event.

The second structure revealed by our clustering analysis, is composed of stars at low energy and belonging to the inner part of the Galaxy. The kinematics of these stars is, however, clearly affected by the presence of the bar. Therefore, we decided to repeat our analysis but this time adding a rotating bar to the standard `galpy` potential. We ended up with 16 stars only that respect the criterion  $r_{ap} < 3.5$  kpc, these are the stars we tagged as SpiteF (see Sec. 6.4). Comparing in the [Mg/Fe] vs [Fe/H] plane the stars selected in this second structure by our clustering analysis (34 stars, see Appenidx D) with the 16 SpiteF stars, we believe that a much clearer signal is apparent considering this latter selection.

In summary, the clustering analysis we performed convinced us that GSE and SpiteF stars represent prominent groups among the stars of our sample and not just overdensities corresponding to random fluctuations of parameters. It is interesting to note that an analysis similar to the one described in the appendix, performed on the GUM sample does not reveal any significant cluster. This is expected, since GUM does not contain any sub-structure, but is a sanity check, for the clustering analysis. We describe this analysis in appendix D.

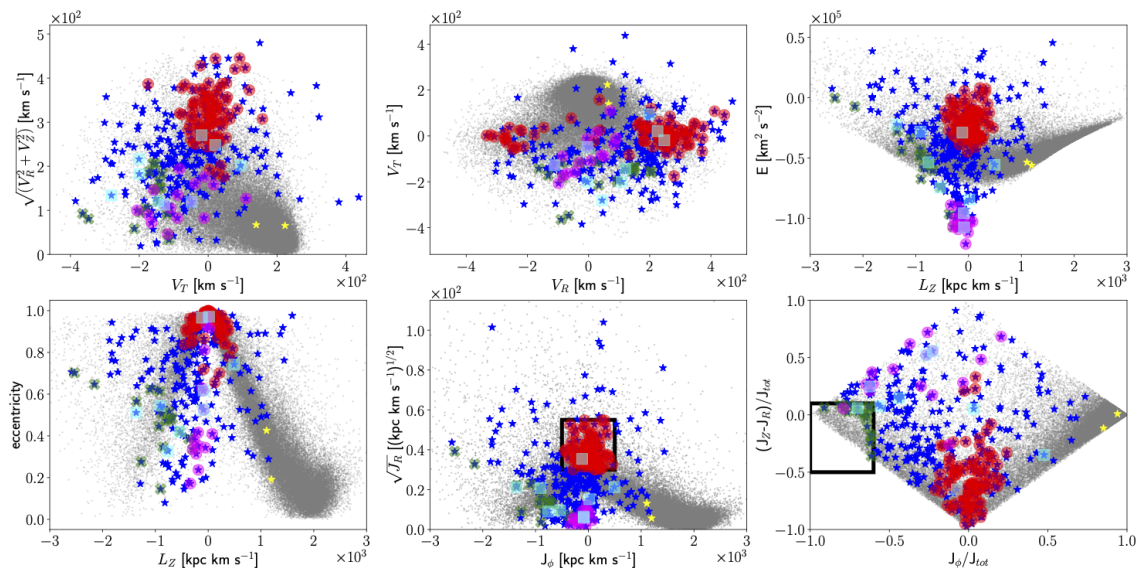
#### 4.1. GHS143 an unbound star

Star GHS143 has a total galactocentric space velocity of  $\sim 1440 \text{ km s}^{-1}$  which, compared to a local escape velocity of  $521.7 \text{ km s}^{-1}$ , suggests that the orbit of this stars is unbound to the Galaxy<sup>5</sup> and make this an hyper-velocity star. To our knowledge, four stars only have larger space velocities (see Table A.1 in Li et al. 2022b, and references therein), GHS143 being the only late-type star among them. Boubert et al. (2018) identified one late-type star only (LAMOST J115209.12+120258.0) unbound to the galaxy. Li et al. (2022b) identified 52 marginally hyper-velocity stars candidates which, similarly to GHS143, are metal-poor late type halo stars. Their galactocentric space velocities are, however, significantly lower ( $< 750 \text{ km s}^{-1}$ ).

The large galactocentric space velocity of GHS143 is dominated by the Y component (in cartesian coordinates), which is also affected by the largest uncertainty:  $v_{X,YZ} = (535 \pm 149, -1318 \pm 408, 222 \pm 59 \text{ km s}^{-1})$ . The total uncertainty on the space velocity is  $438 \text{ km s}^{-1}$ , while the difference between the space

<sup>4</sup> Available at <https://gea.esac.esa.int/archive/>, see also the Gaia DR3 documentation [https://gea.esac.esa.int/archive/documentation/GDR3/Data\\_processing/chap\\_cu2sim/sec\\_cu2UM/](https://gea.esac.esa.int/archive/documentation/GDR3/Data_processing/chap_cu2sim/sec_cu2UM/).

<sup>5</sup> The total orbital energy E of this star is positive. However for the MWPotential2014 this does not always indicate that one star is unbound to the Galaxy, as clearly specified in the `galpy` documentation.



**Fig. 5.** Target stars (coloured filled symbols) are presented in several planes. Top panels:  $E$  vs  $L_z$  (right, orbital energy versus the vertical component of the angular momentum),  $V_R$  vs  $V_T$  (middle, radial versus transversal velocity component in galactocentric cylindrical coordinates) and  $V_T$  vs  $\sqrt{(V_R^2 + V_z^2)}$  (left, Toomre diagram: transversal velocity component, versus a combination of the radial and vertical velocity components in galactocentric cylindrical coordinates). Bottom panels:  $(J_z - J_R)/J_{tot}$  vs  $J_\phi/J_{tot}$  (right, action diamond, where:  $J_{tot} = |J_\phi| + J_R + J_z$ , the box is the region used to select Seq candidates),  $J_\phi = L_R$  vs  $\sqrt{J_R}$  (middle, square root of the radial action versus the vertical component of the angular momentum, the box indicates the region used to select GSE candidates), orbital eccentricity vs  $L_z$  (left). Grey dots are stars of the "good parallax sub-sample" of Bonifacio et al. (2021) and are plotted for reference. Filled blue and yellow stars indicate targets classified as halo and thick disc, respectively. Filled circles are GSE (red), bulge (magenta) stars. Green crosses are Seq star.

Filled cyan squares are young stars.

**Table 1.** Masses, ages, and metallicities for the young stars.

Star	Mass $M_\odot$	Age Ma	[Fe/H] dex
GHS108	1.9	941	-1.39
GHS110	2.2 – 2.8	398 – 628	-1.32
GHS114	1.4 – 2.1	646 – 2024	-1.56
GHS117	2.2 – 2.8	315 – 698	-1.59
GHS120	1.4 – 2.1	571 – 1845	-2.17
GHS143	3.1 – 3.8	156 – 279	-1.74
GHS145	1.3 – 2.1	631 – 2545	-1.79
GHS189	1.7 – 2.3	485 – 1388	-1.69
GHS209	1.4 – 2.3	498 – 1999	-1.67
GHS212	1.7 – 2.2	574 – 1270	-1.71

velocity of GHS143 and the local escape velocity is  $918 \text{ km s}^{-1}$ . The minimum value of this difference obtained over 1000 random realisation of the input parameters is  $227 \text{ km s}^{-1}$ , while the standard deviation is  $465 \text{ km s}^{-1}$ . Notice that GHS143 (Gaia DR3 6632370485122299776) has  $\text{RUWE}=1.33$ , lower than the recommended threshold of 1.4, and  $\text{parallax\_over\_error}=2.7$ .

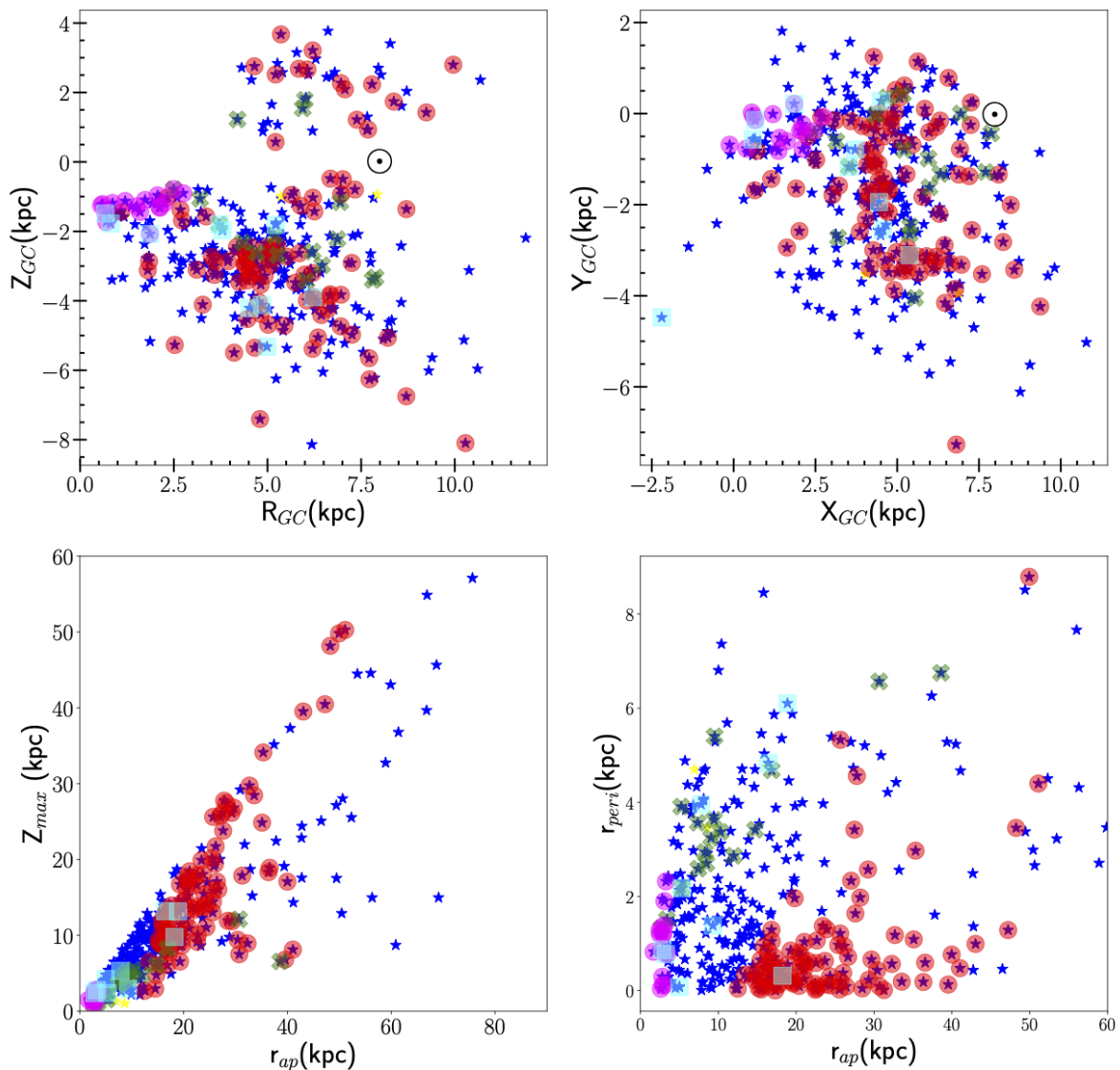
## 5. Chemical analysis

### 5.1. Stellar parameters

We adopted the reddening from the maps of Schlafly & Finkbeiner (2011). The procedure to determine  $T_{\text{eff}}$  and  $\log g$  is iterative and is described in detail in Lombardo et al. (2021). In a nutshell: the dereddened  $G_{BP} - G_{RP}$  Gaia DR3 colour is

compared to the synthetic photometry to derive  $T_{\text{eff}}$  and bolometric correction, the  $\log g$  is then determined from the Stefan-Boltzman equation, the extinction coefficients are updated and the whole procedure is iterated to convergence. The synthetic colours were computed from the ATLAS 9 fluxes of the grid of Mucciarelli et al. (in preparation). For most stars we used a subset of the whole grid suitable for giant stars, it covers effective temperatures from 3500 K to 5625 K in steps of 125 K, surface gravities from 0.0 to 3.0 (c.g.s. units) in steps of 0.5 dex, and metallicities from -5.0 to 0.5, the metallicity steps are of 0.5 dex between -5.0 and -2.5 and 0.25 dex for metallicities above -2.5. Two stars, GHS292 and GHS312, are warm horizontal branch stars and for these two we used a smaller grid, covering the same metallicity range, but effective temperatures from 4875 K to 6000 K in steps of 125 K and surface gravities from 2.0 to 4.0 (c.g.s. units) in steps of 0.5 dex. As convergence criteria we adopted  $\Delta T < 50$  and  $\Delta \log g < 0.05$ , where  $\Delta$  denotes the difference between the current parameters and those of the previous iteration. The required iterations were typically two in  $T_{\text{eff}}$  and one in  $\log g$ . The stellar parameters were then used to derive the metallicity from the spectrum by using MyGIsFOS (Sbordone et al. 2014). The metallicity so derived was then used to update the stellar parameters and the process was iterated again. A single iteration at this stage was sufficient to achieve convergence in the above-defined sense. The microturbulent velocities ( $\xi$ ) are derived by using the calibration of Mashonkina et al. (2017). Our estimate of the uncertainties (statistical plus systematic) is of 100 K in effective temperature and 0.2 dex in surface gravity.

In a first run we assumed for all stars a mass of  $0.8 M_\odot$ , appropriate for an old stellar population, then for the 10 young

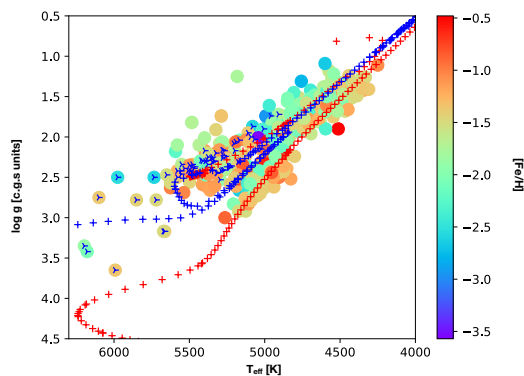


**Fig. 6.** The top panels show  $Y$  vs  $X$  (right, galactocentric Cartesian coordinates),  $Z$  vs  $R$  (left, galactocentric height over the galactic plane versus galactocentric cylindrical distance). The bottom panels show  $r_{peri}$  vs  $r_{ap}$  (right, pericentric versus apocentric distances),  $Z_{max}$  (maximum height over the galactic plane) vs  $r_{ap}$  (left). Symbols are the same as in fig. 5. The position of the Sun is shown in the top two panels with the solar symbol.

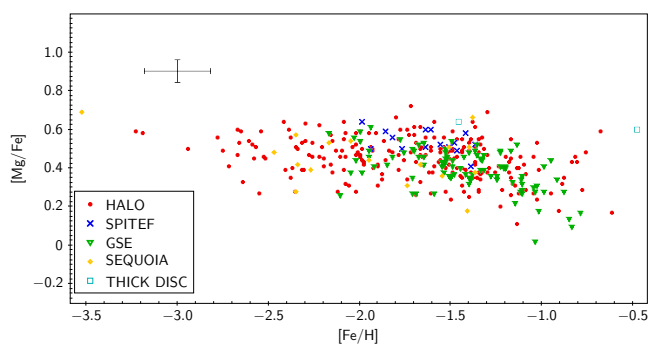
stars we used the derived metallicity to interpolate in the PARSEC isochrones (Bressan et al. 2012; Marigo et al. 2017) to derive their masses and ages. We then re-derived their atmospheric parameters with the new masses. As expected the largest change was to  $\log g$  while the temperature hardly changed, neither did the metallicity (see Sect. 5.2). The region of the colour-magnitude diagram where the young stars are found is characterised by the presence of loops and different evolutionary stages from sub-giant to core helium burning. This implies an ambiguity in the derived masses and ages, depending on the assumed evolutionary stage. We therefore provide for each star a range

of masses and ages when different solutions are possible. The results on masses and ages for the young stars are summarised in Table 1. We considered the effect of errors on the photometry. The largest effects come from the uncertainty on the reddening and on the parallax, however the combined error of both is negligible compared to the uncertainty on the evolutionary stage of the star. We stress that we only use the photometry to derive stellar masses and ages, thus our adopted effective temperatures and surface gravities do not enter into this derivation. In Fig. 7 the adopted stellar parameters, compared to PARSEC isochrones, are shown.

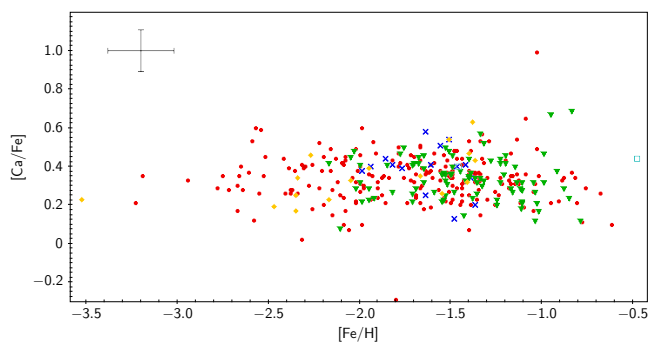




**Fig. 7.** Observed stars in the ( $T_{\text{eff}}$ ,  $\log g$ ) diagram, compared to PARSEC isochrones of metallicity  $-1.0$  and age of  $0.2$  (blue crosses) and  $10$  Ga (red crosses), to guide the eyes. Filled circles with a cross are from Caffau et al. (2020b).



**Fig. 8.**  $[\text{Mg}/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  for the observed sample. The different Galactic components identified kinematically are shown by different symbols and colours, as detailed in the legend.



**Fig. 9.**  $[\text{Ca}/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  for the observed sample. Symbols are the same as in Fig. 8.

## 5.2. FORS spectra

The derived atmospheric parameters were used as input to MyG-IsFOS (Sbordone et al. 2014) to derive the chemical abundances from the spectra, as done in Paper I. In spite of the low resolution of the FORS spectra, the high S/N ratios (always above 100 at 500nm) and the large spectral coverage allowed us to determine the abundances of Na, Mg, Ca, Ti, Mn, Fe and Ba. The results are summarised in Figs. 8 to 13. The full table with all abundances for each star is available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>. For star GHS110, that is a variable star, we only provide  $T_{\text{eff}}$ ,  $\log g$ , and

**Table 2.** Carbon enhanced stars.

Star	$[\text{C}/\text{H}]$	$[\text{Fe}/\text{H}]$	$[\text{Ba}/\text{Fe}]_{NLTE}$
GHS151	$-3.08$	$-3.53$	$+1.2$
GHS162	$-0.79$	$-1.80$	$+1.5$
GHS230	$-1.29$	$-1.74$	$+1.3$
GHS268	$-1.23$	$-1.48$	$+1.0$
GHS284	$-1.19$	$-1.34$	$+1.3$
GHS341	$-1.47$	$-2.09$	$+0.5$

$[\text{Fe}/\text{H}]$  but refrain from doing a multi-element abundance analysis given the additional uncertainty on its effective temperature and surface gravity, as discussed in Sect. C.2. For nine stars we have two spectra, mostly observed both in periods 105 and 106, in some cases one spectrum was observed, but assigned C quality and then re-observed with A quality. In these cases we ran MyG-IsFOS independently on the two spectra, in order to be able to estimate the errors on the abundances derived from different spectra. The comparison is generally quite good, with abundances derived from the different spectra showing a standard deviation of the order of 0.1 dex or less, with the exception of the cases of spectra of different quality, like C and A, in this case the standard deviation can be as large as 0.3 dex. For these nine stars we averaged the different abundances and use the spectrum-to-spectrum scatter as error estimate on the abundances.

### 5.2.1. Carbon abundances

Although we let MyGIsFOS fit the G-band to provide the abundance of C we do not provide these values since we estimate it to be very uncertain. The uncertainty on these values arises from two facts: i) the width of the band makes the continuum placement highly uncertain; ii) MyGIsFOS interpolates between synthetic spectra of different metallicity, that have different ionisation structure (see appendix F), and this affects the band formation. Nevertheless we believe these abundances output by MyGIsFOS are useful to alert us in case of large carbon over-abundances. In this way we flagged six stars for which we performed a traditional fitting of the G-band to determine their carbon abundances that are reported in Table 2. This allowed us to identify six stars that are enhanced in carbon, although only one has a large enough enhancement to be classified as Carbon Enhanced Metal Poor star: GHS162. Remarkably all six stars are also clearly enhanced in Ba, which suggests pollution from an AGB companion. For all these stars the error on the Gaia radial velocity is  $\geq 1.4 \text{ km s}^{-1}$ , being as large as  $4.6 \text{ km s}^{-1}$  for GHS341. This makes it possible that at least some of them are radial velocity variables. Further scrutiny of these stars is encouraged.

### 5.2.2. $\alpha$ elements abundances

The abundance ratios of the  $\alpha$  elements Mg, Ca and Ti to iron are shown in figures 8, 9 and 10. While all three elements show a plateau below  $[\text{Fe}/\text{H}] = -1.5$ , it is obvious that at any metallicity there is a large scatter, and that many stars have low  $\alpha$ -to-iron ratios. Part of the scatter is due to the observational uncertainties, yet, given the size of uncertainties, it is likely partly intrinsic. As discussed in Sect. 6.5, it is tempting to identify stars with low  $\alpha$ -to-iron ratios with stars accreted from dwarf galaxies, that have experienced a slow or bursting star formation. There is no obvious distinction between the different Galactic components that are identified in the plots. The case of the Sequoia star GHS151 is intriguing, it is the most metal-poor star in our

sample,  $[\text{Fe}/\text{H}]=-3.5$ , and it has  $[\text{Mg}/\text{Fe}]=+0.7$ ,  $[\text{Ca}/\text{Fe}]=+0.2$ ,  $[\text{Ti I}/\text{Fe}]=-1.0$  and  $[\text{Ti II}/\text{Fe}]=-0.8$ . It is theoretically expected that not all  $\alpha$  elements vary in lockstep, especially at the lowest metallicities, because the nucleosynthesis sites are not the same. The resolution of our spectra is too low to make a strong claim about this, however this star certainly deserves a closer scrutiny and analysis with higher resolution spectra. There is a clear offset of about 0.15 dex in the  $[\text{Ti}/\text{Fe}]$  ratios derived from Ti I and Ti II lines, and we attribute most of this to NLTE effects on Ti I lines (Sitnova et al. 2016). For the readers interested in Galactic chemical evolution we recommend to use the abundances derived from the Ti II lines.

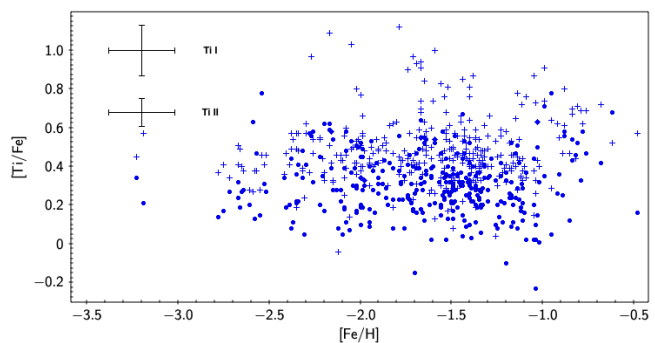
### 5.2.3. Sodium and manganese abundances

On average the stars appear enhanced in Na, with no clear distinction among the different Galactic components as shown in Fig. 11. This is not expected for metal-poor stars (see e.g. figure 8 of Andrievsky et al. 2007). This is very likely due to the fact that in our analysis we have neglected the deviations from Local Thermodynamic Equilibrium that are important for Na I D lines (see e.g. Andrievsky et al. 2007, figure 1). Another possible cause of concern is contamination with interstellar (IS) Na I D lines, that at the resolution of our spectra, can contaminate the stellar lines, even if the star has a high radial velocity. We provide no Na measure of any of the Bulge stars, since they are all clearly contaminated by IS lines, in some cases a wide structure of these lines is even visible. In order to obtain reliable Na abundances in these stars higher resolution spectra are necessary. These will allow to disentangle IS from stellar lines in many cases and in many cases other non-saturated Na I lines will be usable. Corrections for NLTE effects should also be considered. Two stars, among the most metal-poor, stand out for having a very high  $[\text{Na}/\text{Fe}]$  ratio: GHS080 and GHS144. While GHS080 has essentially a solar  $[\text{Ba}/\text{Fe}]$  ratio, GHS144 is strongly enhanced in barium,  $[\text{Ba}/\text{Fe}]=+1.14$ . For the latter star one may suspect a pollution from an AGB companion. The error on the Gaia radial velocity is  $2.1 \text{ km s}^{-1}$  a little bit large for a 13th magnitude star, leaving margin for possible radial velocity variations. Higher resolution observations and radial velocity monitoring for this star are encouraged.

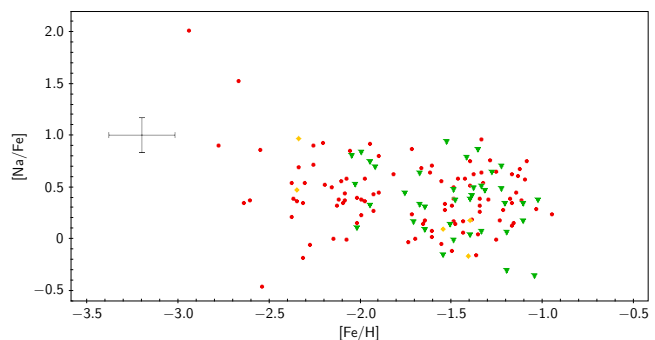
The  $[\text{Mn}/\text{Fe}]$  ratios in our sample of stars are on average solar as shown in Fig. 12, however there is a clear tendency to subsolar values at metallicities below  $-2.0$ . This is certainly due to NLTE effects (Bergemann & Gehren 2008), that for stars of these parameters should be in the range  $+0.2$  to  $+0.4$  dex and would bring  $[\text{Mn}/\text{Fe}]$  to a very flat behaviour. This can be theoretically expected since both Mn and Fe are formed in nuclear statistical equilibrium.

### 5.2.4. Ba abundances

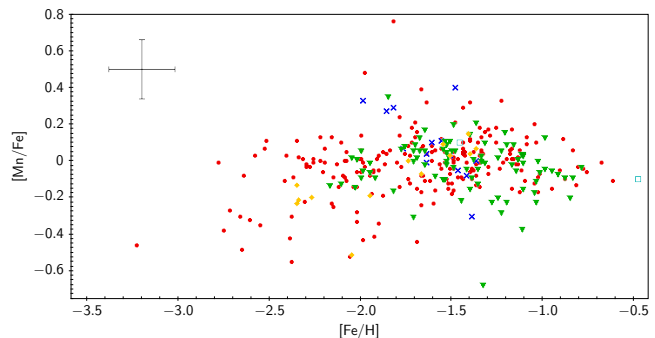
Given the limitations of MyGIsFOS for ionised species, characterised by large over or under abundances, with respect to iron, as explained in appendix F, we determined the Ba abundances with line profile fitting. We used the Ba II 455.4 nm resonance line, taking into account the full hyperfine and isotopic structure, for an assumed solar isotopic ratio. For each star we computed an ATLAS 9 model atmosphere using the new set of opacity distribution functions of Mucciarelli & Bonifacio (in preparation). The adopted microturbulence in the ODFs was  $1 \text{ km s}^{-1}$  and in the model computation we assumed a mixing length parameter 1.25. To compute the line profiles we used the turbospectrum



**Fig. 10.**  $[\text{Ti}/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  for the observed sample. Filled circles A(Ti) from Ti I and crosses from Ti II lines, but A(Fe) is always from Fe I lines.



**Fig. 11.**  $[\text{Na}/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  for the observed sample.

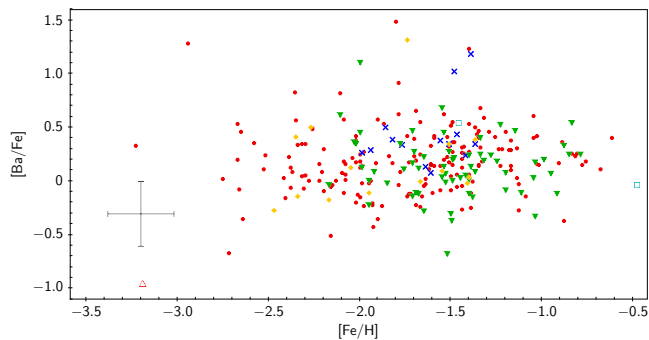


**Fig. 12.**  $[\text{Mn}/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  for the observed sample.

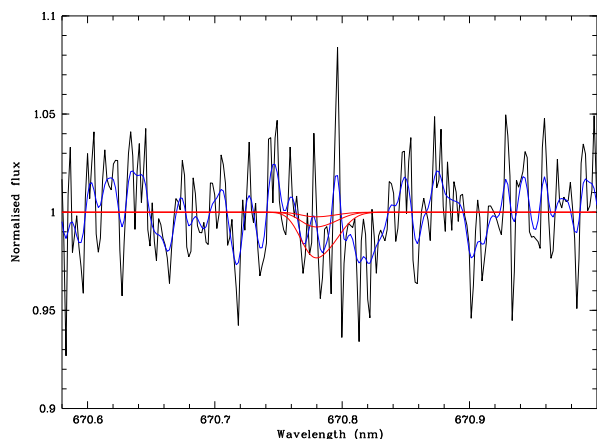
(Alvarez & Plez 1998; Plez 2012) spectrum synthesis code. We interpolated the NLTE corrections of Korotin et al. (2015) and applied them to the derived LTE Ba abundances. The  $[\text{Ba}/\text{Fe}]$  ratios are displayed in Fig. 13

### 5.3. UVES spectra

With the stellar parameters in Paper I and the new spectra obtained with UVES, we derived again the metallicities for the two blue straggler candidates GHS69 and GHS70 using MyGIsFOS (Sbordone et al. 2014), and we obtained  $[\text{Fe}/\text{H}]=-2.23\pm 0.26$  for GHS69 and  $[\text{Fe}/\text{H}]=-1.89\pm 0.15$  for GHS70. The new metallicities are slightly lower than the one found in Paper I ( $[\text{Fe}/\text{H}]=-1.94$  for GHS69, and  $[\text{Fe}/\text{H}]=-1.59$  for GHS70), but compatible within errors. The abundances for Fe I, Fe II, Mg I, Ca I, Mn I, Co I and Ni I are available as an on-line table at CDS. They are unremarkable except perhaps, that the  $\alpha$  elements are slightly low, for this metallicity.  $[\text{Mg}/\text{Fe}]$  and  $[\text{Ca}/\text{Fe}]$  are around  $+0.3$  dex for both stars. The S/N ratios obtained allowed us to derive only up-



**Fig. 13.** [Ba/Fe] versus [Fe/H] for the observed sample. NLTE corrections have been applied to the Ba abundances. Symbols in Fig. 8, the red open triangle is an upper limit for star GHS118, belonging to the halo.



**Fig. 14.** Spectra of GHS69 in the region of the Li I 670.7 nm doublet. Red lines represent synthetic spectra with Li abundances of  $A(\text{Li})=1.0, 1.5, 2.0$  dex. Blue line represents GHS69 spectrum with a broadening of  $3 \text{ km s}^{-1}$ .

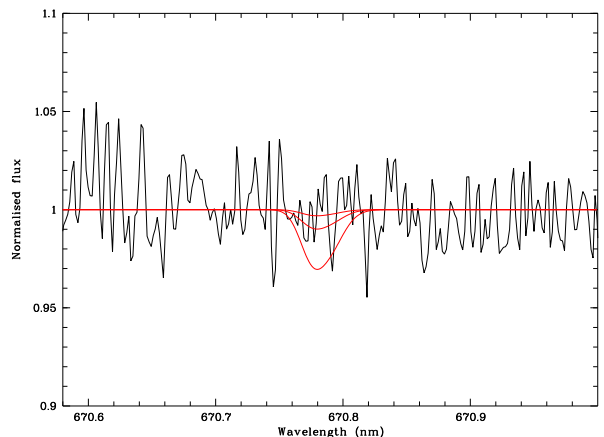
per limits for the Li abundance for the two stars. To obtain upper limits on Li abundance, we estimated the minimum measurable equivalent width (EW) at  $1\sigma$  detection for the Li I doublet using the Cayrel formula<sup>6</sup> (Cayrel 1988). We then computed the curve of growth for the Li doublet by measuring the EW of the Li doublet in synthetic spectra for different values of  $A(\text{Li})$ . The synthetic spectra were computed with the spectral-synthesis code SYNTHÉ (see Kurucz 2005; Sbordone et al. 2004), starting from ATLAS 9 1D plane-parallel model atmosphere computed using an ODF by Castelli & Kurucz (2003), and atomic data including the hyperfine structure of the Li doublet from Kurucz’s database<sup>7</sup>.

### 5.3.1. GHS69

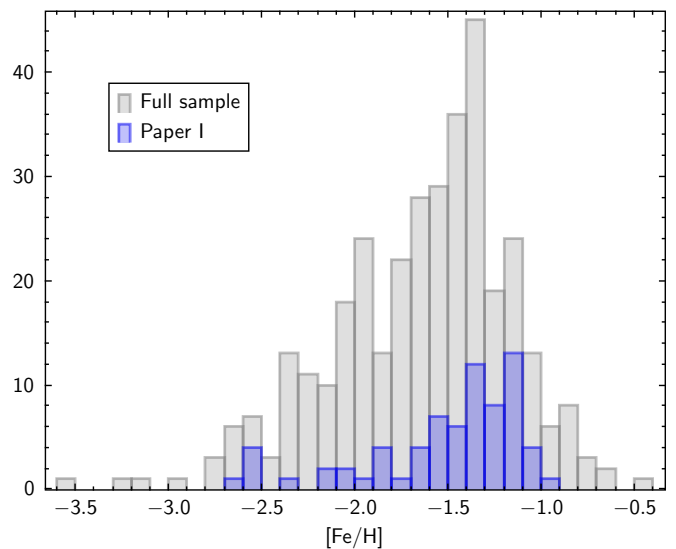
For star GHS69, a model atmosphere with  $T_{\text{eff}}=6700 \text{ K}$ ,  $\log g=3.8$ ,  $\xi=1 \text{ km s}^{-1}$ , and  $[\text{Fe}/\text{H}]=-2.5$ , a  $S/N \sim 42$  would imply a minimum measurable EW for the Li doublet of  $0.8 \text{ pm}$ , which corresponds to a Li abundance of  $2.0 \text{ dex}$ , thus the  $1\sigma$  upper limit is  $A(\text{Li}) < 2.0$ . The spectrum of GHS69 (black) is

<sup>6</sup> Cayrel’s formula estimates the error on the EW of an isolated line ( $\delta W$ ), and it is written in the form  $\delta W \simeq 1.5 \times (\text{FWHM} * \delta x)^{1/2} / (S/N)$ , where FWHM is the full-width half maximum of the line,  $\delta x$  is the pixel size of the spectrum and  $S/N$  is the signal-to-noise in the continuum neighbouring the line.

<sup>7</sup> <http://kurucz.harvard.edu/atoms/0300/>



**Fig. 15.** Spectra of GHS70 in the region of the Li I 670.7 nm doublet. Red lines represent synthetic spectra with Li abundances of  $A(\text{Li})=1.0, 1.5, 2.0$  dex.



**Fig. 16.** Metallicity distribution of the observed sample, including the sample of Paper I.

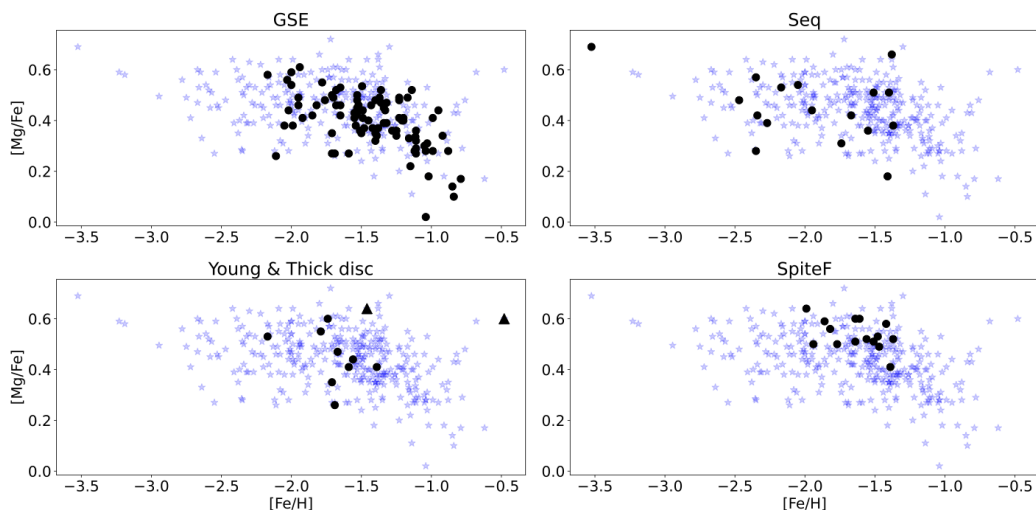
compared to three synthetic spectra with  $A(\text{Li})=1.0, 1.5, 2.0$  dex in Fig. 14. In blue, the GHS69 spectrum degraded with a broadening of  $3 \text{ km s}^{-1}$  is plotted for a better comparison.

### 5.3.2. GHS70

For the star GHS70, a model atmosphere with  $T_{\text{eff}}=6500 \text{ K}$ ,  $\log g=3.7$ ,  $\xi=1 \text{ km s}^{-1}$ , and  $[\text{Fe}/\text{H}]=-2.0$ , a  $S/N \sim 55$  would imply a minimum measurable EW for the Li doublet of  $0.6 \text{ pm}$ , which corresponds to a Li abundance of  $1.8 \text{ dex}$ , thus the  $1\sigma$  upper limit is  $A(\text{Li}) < 1.8$ . The spectrum of GHS70 (black) is compared to three synthetic spectra with  $A(\text{Li})=1.0, 1.5, 2.0$  dex in Fig. 15.

## 6. Discussion

The basic result of Paper I was that the stars that are extreme in kinematics are not necessarily extreme in chemistry. The whole sample (including the 72 stars of Paper I) shows a marked peak



**Fig. 17.**  $[Mg/Fe]$  vs  $[Fe/H]$  for the programme stars. In the various planes specific groups (filled black circles and black triangles) are plotted on top of all stars (cyan stars). Top panels: GSE (left) and Seq (right) candidates. Bottom panels: young (filled circles) and thick disc stars (filled triangles, left panel) and bulge (right).

around  $-1.4$  and a decrease towards lower metallicities, as shown in Fig. 16. Because the present sample is larger than that in Paper I, we have now 81 stars with  $[Fe/H] \leq -2.0$ , 22 stars with  $[Fe/H] < -2.5$  and four stars with  $[Fe/H] < -3.0$ .

Our dataset allows chemical and kinematical data to be combined to gain further insight into the origins of the different sets of stars. In Fig. 17 we show our targets in the  $[Mg/Fe]$  vs  $[Fe/H]$  plane, highlighting GSE, Seq, young, thick disc and bulge stars, on top of the ensemble of the targets. The apparent bifurcation in the plane visible at about  $[Fe/H] \approx -1.5$  dex is mostly due to stars belonging to GSE (top-left) and the bulge (bottom-right). Stars GHS036 (see Caffau et al. 2020b) and GHS110 (variable star, young and bulge) for which a full chemical abundance analysis was not performed, are not shown in the figure.

Our sample has allowed us to highlight four sets of stars that we consider particularly interesting: (i) one unbound star; (ii) the young stars; (iii) a set of metal-poor bulge stars; and (iv) candidate stars of the Aurora population, supposed to be formed before the creation of the Galactic disc. We shall discuss each of these in turn.

### 6.1. On the origin GHS143

Koposov et al. (2020) discovered a main-sequence A-type star (S5-HVS) with a total speed of about  $1700 \text{ km s}^{-1}$  that they interpret as ejected from the Galactic Centre. The mass of S5-HVS is estimated to be  $2.35 M_{\odot}$ , that of GHS143 is considerably larger ( $3.1$  to  $3.8 M_{\odot}$ ), consistent with the fact that it is evolved. In order to gain insights into the origin of GHS143, we backwards integrated its orbit. At odds with S5-HVS1, GHS143 is currently approaching the Galactic plane and, thus, was not expelled by the Galactic Centre, as a consequence of an encounter with the central super massive black hole (the Hills mechanism, Hills 1988). We then searched for possible past association with Milky Way (MW) satellites and Galactic Globular clusters (GCs). We therefore back-integrated their orbits as well, considering the phase space positions from Pace et al. (2022); Baumgardt et al. (2019); Vasiliev & Baumgardt (2021); Baumgardt & Vasiliev (2021) as already available in galpy.

The closest encounter occurred with the GC NGC 6584,  $\sim 1$  Ma ago at a distance of  $2.5 \text{ kpc}$ . The colour-magnitude diagram of NGC 6584 (Vasiliev & Baumgardt 2021, and <https://people.smp.uq.edu.au/HolgerBaumgardt/globular/>) shows an extended sequence of blue stragglers, some of which could be more massive than twice the mass of the Turn-Off stars. The metallicity of the star is  $-1.74$  while that of NGC 6584 is  $-1.50$  (Dalessandro et al. 2012) thus the two are compatible within errors. The closest encounter with a dwarf galaxy occurred with the Sagittarius dwarf spheroidal (Sgr dSph)  $\sim 8$ - $10$  Ma ago, at a distance of  $9.8 \text{ kpc}$ . If we consider 1000 random realisations of the initial parameters, the closest encounters are obtained with the same objects at median distances of  $3.0 \text{ kpc}$  (standard deviation, std,  $1.8 \text{ kpc}$ ) and  $9.8 \text{ kpc}$  (std= $1.9 \text{ kpc}$ ) for NGC 6584 and Sgr, respectively. The encounters are compatible with NGC 6584 within 2 std and with Sgr within slightly over 2 std and 2 half light radii ( $r_h = 2.59 \text{ kpc}$ , McConnachie 2012).

Finally, we used the GALSTREAM library (Mateu 2023, and references therein), to search for association with any of the many known stellar streams identified in the last period in the galaxy. Again, we could not find any clear association, with the closest stream being that associated to the GC NGC 6362 at a distance of  $5.3 \text{ kpc}$ . We notice that candidate hyper/high-velocity stars likely originating from the Large Magellanic Cloud and the Sgr dSph were reported (Erkal et al. 2019; Huang et al. 2021; Li et al. 2022a,b). Even though the high mass and corresponding young age of this star may suggest its origin in the ejection of a runaway disc star, its low metallicity ( $[Fe/H] = -1.74$  dex) opens also the possibility that GHS143 may be a debris of a low-mass, dwarf galaxy (see Boubert et al. 2018, and references therein). Recently, Li et al. (2022b) identified a number of late-type, metal-poor candidates hyper-velocity stars and proposed ejection from dwarf galaxies or globular clusters as their likely origin.

One can invoke a binary system in which the massive companion explodes as supernova resulting in the disruption of the system and the secondary star leaving with a high kinetic energy (Perets & Šubr 2012) or a type Ia supernova in which the donor star becomes unbound after the thermonuclear detonation of the white dwarf (Geier et al. 2015). It is also interesting to

consider the possibility of an asymmetric supernova explosion as an accelerating mechanism for a companion star of a Supernova (hereafter SN Tauris 2015). However at the present time we see no way of discriminating among these possible mechanisms.

## 6.2. Young stars

The set of ten young stars, whose estimated ages range from 300 Ma to 2.5 Ga and metallicities from  $-1.3$  to  $-2.2$ , as summarised in Table 1, is unexpected. Although in Paper I we had in fact suggested the presence of some young stars, here there are many more. It is interesting to note that also in the sample of nearby high-velocity stars selected from Gaia DR2 by [Hattori et al. \(2018\)](#) there are several stars compatible with a young age (see their Figure 2). One could wonder whether the apparently young age could be a problem of overestimated reddening. From Fig. 2 it is easy to estimate that the  $E(G_{BP} - G_{RP})$  should be smaller by about 0.2 mag, in order for the young stars to fall on an old red-giant branch. This is impossible, since the highest colour excess for these stars is  $E(G_{BP} - G_{RP}) = 0.122$  for GHS145, six out of the ten young stars have a colour excess smaller than 0.08. Rare objects, like post-AGB stars can have colours in the range covered by our young stars, however, such stars are typically 0.5 to 2 magnitudes brighter than our brightest young star (GHS143), according to the catalogue of [Vickers et al. \(2015\)](#), that includes most of the known post-AGB stars. The presence of debris discs or dust-shells around the stars would make them redder, not bluer, so also these objects can be discarded. We believe that the only two classes of stars that can occupy this region of the colour-magnitude diagram are young stars of mass in excess of 1.5 solar masses or evolved blue stragglers.

### 6.2.1. Young or rejuvenated

The issue is to decide if these are truly young stars or they are ‘rejuvenated’ old stars, that is, evolved blue stragglers. A look at the masses in Table I suggests that only a few could be evolved blue stragglers, in fact most of them are likely more massive than  $2 M_{\odot}$ . The most credited channels to rejuvenate stars and create blue stragglers involve binary stars. Either mass transfer in a binary system ([McCrea 1964](#)) or merging of two stars in a binary (e.g. [Zinn & Searle 1976](#)). It is possible to create a blue straggler also by direct collision of two stars, previously unbound (see e.g. [Hills & Day 1976](#)). Among the many papers on the topic we refer the reader to [Livio \(1993\)](#), [Preston & Sneden \(2000\)](#) and [Carney et al. \(2005\)](#), that we found very illuminating. Whichever of the above mechanisms is invoked it is not possible to create a star whose mass is larger than the sum of the masses of the two stars involved.

If we consider the star formation history of [Haywood et al. \(2016\)](#), it is clear that outside the Galactic disc, we do not expect stars younger than about 8 Ga. Now in an isochrone of 8 Ga and metallicity  $-1.5$  the most massive stars are about  $0.9 M_{\odot}$ . This implies that stars of mass larger than  $1.8 M_{\odot}$  cannot be formed by merging or colliding, or through mass transfer, of two stars of 8 Ga or older. The upper limit is even lower if you consider that some of the mass must be lost in the process of blue straggler formation. Blue stragglers that have masses larger than twice the mass of Turn-off stars are known both in open clusters (e.g. M 67 [Milone et al. 1992](#)) and globular clusters (e.g. NGC 6397 [Saffer et al. 2002](#)). In these cases the evolution of a triple system through a common envelope phase of the inner cou-

ple is invoked (see [Meyer & Meyer-Hofmeister 1980](#)). However, these massive blue stragglers are rare. [Fiorentino et al. \(2014\)](#) determined pulsational masses for blue stragglers in the Globular Cluster NGC 6541 (metallicity  $-1.76$ , age 13.25 Ga thus compatible with our halo population) and found masses in the range  $1.0 - 1.1 M_{\odot}$ . [Raso et al. \(2019\)](#) found in 47 Tuc five stars with mass estimate, derived from the spectral energy distribution, larger than twice the TO mass. However the errors on these estimates are large enough that they are all consistent, within  $1 \sigma$ , with a mass smaller than twice the TO mass.

### 6.2.2. Mergers of three stars as a possible explanation of the observations

In order to claim that all the young stars are evolved blue stragglers it is necessary to postulate that most of them descend from the common envelope evolution of a triple system and in the case of GHS143 it is not sufficient but we would need a quadruple system. The fraction of binary and multiple systems is discussed in [Arenou \(2011\)](#). For solar type stars the generally assumed fraction of triple systems is 8.4%, based on the investigation of [Duquennoy & Mayor \(1991\)](#). This is an upper limit to the number of triple systems that may form a massive blue straggler, since the architecture of the system must be such that the inner couple undergoes the common envelope phase and the semi-major axis of the orbit of the third star is small enough that it will experience friction and ultimately spiral into this common envelope. Recently [Moe et al. \(2019\)](#) have argued that the fraction of close binary stars, defined as those having a semi-major axis  $a \lesssim 10$  au, increases with decreasing metallicity. This result relies on the completeness correction that the authors apply to various samples, the trend in the uncorrected data is not detectable (see their figure 3). These authors find that for solar type stars with  $[\text{Fe}/\text{H}] \leq -1.0$ , the fraction of close binaries is about 50% and the fraction of triples plus quadruples is of the order of 35%. This number is much larger than the 8.4% cited above. For the sake of discussion let us consider 35% the fraction of multiple systems potentially suitable to be the progenitors of a massive blue stragglers. In our view the crucial question to ask is what is the fraction of these systems that will result in the fusion of at least three stars. Some insight may come from the study of [Toonen et al. \(2022\)](#) who perform extensive simulations on the fate of destabilised triple systems. One striking result is that although collisions in destabilised triple systems are fairly common, for only at most 2.4% of them the collision includes the third star. Most collisions occur only in the inner couple of the hierarchical system. If we add the estimate of the fraction of destabilised triple systems that is at most 4%, we obtain a fraction of massive blue stragglers  $F_{MBS} = 0.35 \times 0.04 \times 0.024 = 0.000336 \approx 0.3\%$ . In our view even this large fraction of triples would still imply a tiny fraction of triple fusions. We therefore do not expect more than a few per cent of the stars to be blue stragglers descendants from triple systems.

### 6.2.3. Where do they come from?

We back integrated the orbits of all the young stars for 1 Ga and did the same for all the known Globular Clusters, dwarf galaxies and stellar streams, to look for close encounters. If a close encounter with a GC can be identified, this would support a BSS nature for the given star. GHS143 had a wide encounter with NGC 6584 1 Ma ago and is further discussed in Sect. 6.1. Of the remaining stars seven appear to have had an encounter, within

several kpc about 550 Ma ago with Tuc III. These distances may appear large, however our estimated errors on the minimum distance are of the order of 1.5 to 2 kpc, therefore most of these encounters are significant at less than  $3\sigma$ . Although suggestive we discard a possible origin in Tuc III for any of these stars for two reasons: *i*) the metallicity of Tuc III is  $-2.4$  with a small metallicity dispersion, less than 0.1 dex (Simon et al. 2017), while our stars are about 1 dex more metal-rich, on average; the only star that has a metallicity compatible with Tuc III is GHS120 ( $[\text{Fe}/\text{H}]=-2.17$ ); *ii*) the colour magnitude diagram of Tuc III (see Figure 1 of Simon et al. 2017), does not show any radial velocity members that can be interpreted as a young population, blue stragglers or evolved blue stragglers. Two more stars, GHS209 and GHS212, had the closest approach with a dwarf galaxy with Bootes III, the minimum distances are 5.3 kpc and 13.2 kpc. Although the metallicity of both stars is about  $-1.7$ , thus compatible with the metallicity of Bootes III ( $-2.1$  Carlin et al. 2009), within errors, the large minimum distance makes this origin not very probable, although it cannot be ruled out. There are very few confirmed members of Bootes III, thus it is unclear if the colour-magnitude diagram of this galaxy supports the existence of a young population, blue stragglers or evolved blue stragglers.

For what concerns close encounters with Globular Clusters and known stellar streams, the situation is complex. For each star we have a large number (up to 92) of close encounters (at less than 1 kpc) with GCs and over ten with streams. For each star there are several GCs that have compatible metallicity and possess a sizeable blue straggler population, thus making the association plausible. For streams, we often do not have the information on the metallicity, thus it is difficult to assess the likelihood of the association. This state of affairs does not allow to draw clear conclusions on the possible association of any of these stars with either GCs or known stellar streams. We stress that in any case the orbits of our young stars do not coincide with that of any dwarf galaxy, GC or stellar stream. Thus even if an association existed we would still have to think of a mechanism that ‘kicks’ the star out of its Galactic orbit placing it in the high speed state in which we observe it.

In a series of papers Hammer et al. (2021, 2023) argued that the orbital energy of most Milky Way dwarf galaxies is too high for them to be long lived satellites and suggest a recent first infall of  $\lesssim 2$  Ga for most of them. If the galaxies were gas rich at the time of the infall, the interaction with the hot gas of the Milky Way halo would strip them of the gas and, likely, trigger a starburst. Carina is known to possess a young population (Monelli et al. 2003; Weisz et al. 2014), as well as Fornax (de Boer et al. 2012). It seems that a recent starburst is possible among dwarf galaxies, even though their dominant population is old. We add that Caffau et al. (2024) in a sample of high radial velocity stars have found two stars apparently younger than 1 Ga and masses larger than 1.8 solar masses. These objects appear to be similar to the young stars found in this paper. In spite of the fact that when we backwards integrate the orbits of our young stars, we find no close encounter with any known dwarf galaxy or stellar stream we still think it plausible that they were born in a dwarf galaxy that had a starburst during its infall in the Milky Way. The fact that its remnant/stream has not yet been identified suggests that these galaxies were very small in mass. In fact the fewer stars in the galaxy, the fewer stars in the stream, thus the stream is more difficult to detect observationally. In fact, in our view, this is the only way to explain young metal-poor stars in the Galactic halo, since the halo does not contain metal-poor gas of high enough density to support a recent star formation event.

### 6.3. Distinguishing an evolved blue straggler from a young star

Is it possible to distinguish between an evolved blue straggler and a genuine young star of the same mass? We suggest that it may be possible by looking at the stellar rotation. The masses of Blue Stragglers cover the range from late F type to early B type (see e.g. Straizys & Kuriliene 1981, for a mapping of masses to spectral types). The best comparison to blue stragglers are the stars studied in Zorec & Royer (2012). In this exhaustive study one finds clearly that for masses up to  $\leq 2.5 M_{\odot}$  there is a lack of slow rotators (defined as  $v \sin i \leq 100 \text{ km s}^{-1}$ ), and the distribution has a wide and flat peak between 110 and  $220 \text{ km s}^{-1}$  of  $v \sin i$ . At larger masses the distribution is bimodal, and a peak with slow rotators appears, yet it comprises only 20% of the stars. When these stars evolve to the RGB or even to the red clump, their rotation slows down, but one can still find rotational velocities in excess of  $20 \text{ km s}^{-1}$  (Lombardo et al. 2021).

The rotation of blue stragglers in Globular Clusters is extensively discussed in Mucciarelli et al. (2014), that also contains an exhaustive set of references. To summarise the discussion: most Globular Cluster blue stragglers have projected rotational velocities in the range  $30\text{--}40 \text{ km s}^{-1}$ , the exceptions are M4 and  $\omega$  Cen, that have a small, but significant population of stars that have projected rotational velocities above  $40 \text{ km s}^{-1}$ . In fact, Ferraro et al. (2023) have shown that blue stragglers with projected rotational velocities above  $40 \text{ km s}^{-1}$  are only found in loose globular cluster, suggesting that these are blue stragglers formed through mass accretion in binary system. This because mass accretion transforms part of the orbital angular momentum into rotational angular momentum of the accreting object. On the other hand Ferraro et al. (2023) also argue that, in spite of the fact that breaking mechanisms are not fully understood, these objects slow down in less than one Ga, based on the observed correlation between rotational velocities and ages (Leiner et al. 2018) among blue stragglers in Open Clusters and in the field. They also argue that collisional blue stragglers probably slow down even faster, since no fast rotating blue stragglers are observed in dense environments where collisions are expected to dominate. It is reasonable to expect that a sample of evolved blue stragglers will have, on average, lower rotational velocities than ‘normal’ stars of the same mass. This because at the beginning of the spin-down, caused by the envelope expansion, as the star leaves the Main Sequence, the blue stragglers should arrive with lower projected rotational velocities, than young stars of the same mass. The paucity of fast rotators seems to hold also for field blue stragglers, in Preston & Sneden (2000) the bulk of the stars has  $v \sin i \leq 40 \text{ km s}^{-1}$  and the highest measured projected rotational velocity is  $160 \text{ km s}^{-1}$ . We are aware that we are here ignoring the difference in metallicity and age between the Pop I stars in the Zorec & Royer (2012) sample and the Pop II stars in GCs, however only among Pop I stars we can find a sample of stars of masses comparable to those of blue straggler stars. We are making the assumption that for the rotational history of a star the mass is the most important quantity.

From what above said, we expect that evolved blue stragglers should, on average, have lower rotational velocities than young stars that occupy the same place in the colour-magnitude diagram. This is also supported by the observation of an evolved blue straggler in 47 Tuc (Ferraro et al. 2016). It is important to understand that this is a statistical criterion, it cannot be applied to a single star, but only to a sample of stars. We thus encourage observations at high spectral resolution of these young stars in order to probe the distribution of their rotational velocities.

It is interesting in this context to look at the two stars observed with UVES. In Paper I we did not estimate ages and masses for these two stars. Since they are both subgiants there is no ambiguity as to their mass and age estimate. GHS69 has a mass of  $0.78 M_{\odot}$  and an age of 8.6 Ga; GHS70 has a mass of  $0.81 M_{\odot}$  and an age of 8.0 Ga. Thus they appear young, but not nearly as young as the more evolved stars discussed above. Moreover their masses are fully compatible with a blue straggler status, as hinted by the upper limits on lithium.

#### 6.4. SpiteF: Metal-poor bulge stars, relics of an accretion event

The bulge stars we detected reach down to the very metal-poor regime ( $[\text{Fe}/\text{H}] \approx -2$  dex). They thus belong to the metal-poor tail of the bulge metallicity distribution function (Ness et al. 2013a; Gonzalez et al. 2015), a rare bulge population. Surveys dedicated to the search for the most metal-poor stars in the bulge were able to detect stars down to the extremely metal-poor regime ( $[\text{Fe}/\text{H}] < -3$  dex, Howes et al. 2016; Lucey et al. 2022; Sestito et al. 2023). The  $[\text{Mg}/\text{Fe}]$  of our bulge stars is remarkably uniform and enhanced by about 0.5 dex and with a very small dispersion (0.06 dex). The sample of Howes et al. (2016) has 29% of the stars (four out of 14) that overlap with the metallicity range of the bulge stars in our sample, and their  $[\text{Mg}/\text{Fe}]$  has a significantly larger dispersion than ours (0.1 dex), which can hardly be attributed to their errors, since they use spectra of much higher resolution than ours. Lucey et al. (2022), also cover the metallicity range of our sample and show a larger dispersion in  $[\text{Mg}/\text{Fe}]$ . In fact Lucey et al. (2022) state: “the inner bulge and halo distributions are not significantly different in  $[\text{Ca}/\text{Fe}]$  or  $[\text{Mg}/\text{Fe}]$ , as they both have large scatter.”. To be noted that the ‘inner bulge’ of Lucey et al. (2022) is defined as stars with  $r_{\text{ap}} < 3.5$  kpc, thus consistent with our definition of stars confined to the bulge. An alternative definition of the SpiteF structure is discussed in appendix E.1. It is true that the metal-poor bulge sample of Lucey et al. (2019) shows a negligible scatter in in  $[\text{Mg}/\text{Fe}]$  and other  $\alpha$  elements. One should however keep in mind that the sample of Lucey et al. (2019) has been selected using a not clearly defined combination of medium resolution ( $R \approx 11\,000$ ) spectroscopy, centred on the infra-red Ca II triplet and SkyMapper photometry (Casagrande et al. 2019), that includes an intermediate-band filtered centred on the UV Ca II H&K lines. It is thus possible that their selection function implied a low scatter in  $\alpha$  elements. It is clear that all the above-discussed samples are heavily biased. Howes et al. (2016); Lucey et al. (2019) and Lucey et al. (2022) are biased on metallicities and, possibly, on  $\alpha$ -to-iron ratios, our sample is biased on transverse velocities. What is of essence here, however, is that our sample that is unbiased with respect to chemical composition turns out to be metal-poor and with a small scatter in  $[\text{Mg}/\text{Fe}]$ . The converse is not true, the chemically biased samples do not all show high transverse velocities. The presence of young stars in the bulge has been noted in the past (Bensby et al. 2013; Ness et al. 2014; Ferraro et al. 2021). However, at odds with the two young stars in our sample, the young stars detected so far in the bulge are metal-rich ( $[\text{Fe}/\text{H}] > -0.5$  dex).

The ratio of  $\alpha$  elements to iron is often used to distinguish between stars that have been formed in external dwarf galaxies and then accreted by the Milky Way and stars that were formed in the Milky Way. This is discussed in Sect. 6.5 with respect to the stars classified as halo. It should however be kept in mind that while many dwarf galaxies show a sequence of low  $[\text{Mg}/\text{Fe}]$  for their higher metallicity stars, with respect to Milky Way halo

stars, at lower metallicities the sequences merge to a plateau and the  $[\text{Mg}/\text{Fe}]$  criterion becomes not informative. This is due to the fact that at very low metallicities, in any galaxy, Mg and Fe are only produced by massive stars that end their lives as core-collapse supernovae. Only when Type Ia supernovae begin to explode, producing large amounts of Fe, but little or no Mg and other  $\alpha$  elements, the  $[\text{Mg}/\text{Fe}]$  starts to decrease. Since Type Ia supernovae are the result of the evolution of binary systems formed by less massive stars which have a longer lifetime, they begin to explode later when the metallicity of the galaxy has already increased, due to the enrichment from core-collapse supernovae alone. This is obvious for Ultra Faint dwarf galaxies (see figure 1 of François et al. 2016), but also for classical dwarf galaxies (see figure 11 of Tolstoy et al. 2009). As discussed in Sect. 6.5 the use of  $[\text{Mg}/\text{Fe}]$  criterion at low metallicities can lead to serious contamination.

It is noticeable in Fig. 6 that our bulge stars lie on a well defined sequence with a positive slope in the Z vs R plane (top-left panel), at  $R < 3$  kpc and  $-2 < Z < -0.5$  kpc. This group of stars was noticed already during the target selection phase. A random sample of bulge stars should occupy a range of Z values at any given R. This issue is further elaborated upon in Appendix E.2 where we compare our sample to that of Rix et al. (2022). Figures E.2 and E.3 show in fact that selecting from the Rix et al. (2022) sample either in metallicity or transverse speed, we end up with a wide range in Z for any given R. Of the 16 bulge stars in our sample 14 are on retrograde orbits. Kunder (2022) wrote an extensive review of bulge kinematics, based on RR Lyr stars. The latter are metal poor and in fact of the same metallicity range of our sample. The dominant structure of the bulge is a triaxial bar (e.g. Wegg & Gerhard 2013, and references therein), that is characterised by cylindrical rotation (Howard et al. 2009; Zoccali et al. 2017). A structure of this kind can form from a disc that undergoes instability (Martinez-Valpuesta & Gerhard 2011). The RR Lyr rotate slower than the bar, but there is no consensus on whether the RR Lyr trace the bar or if they have a more spherical distribution (Kunder 2022, and references therein). Ferraro et al. (2021), from the properties of two bulge Globular Clusters, Terzan 5 and Liller 1, that host a young stellar population, argued in favour of a hierarchical assembly of the bulge. The two clusters could be the relics of nuclear star clusters in the merging galaxy. This view is opposite to that of Rojas-Arriagada et al. (2019), who argued, based on the  $[\text{Mg}/\text{Fe}]$  distribution of bulge stars, that accretion cannot have played a major role in the formation of the bulge, considering the chemical composition of present-day dwarf galaxies in the Milky Way vicinity.

The Pristine Inner Galaxy Survey (Arentsen et al. 2020) was specifically targeted at metal-poor stars in the bulge and inner disc, and determined rotation curves for these populations, that are very similar for different metallicity bins. So far the extensive kinematic surveys of the bulge have relied only radial velocities (see e.g. Ness et al. 2013a; Arentsen et al. 2020). Under these conditions only the rotational velocity projected along the line of sight can be deduced. In all these studies a dispersion around the mean rotational velocity is observed, and this includes also a retrograde population. In the present study, however, we make use of full three dimensional space velocities. In particular if the bulge does contain a pressure-supported component, as hinted at by the kinematics of RR Lyr stars, in a radial velocity investigation, it would be seen as a dispersion around the mean projected rotational component deduced from radial velocities.

We tentatively associate the metal-poor bulge population to an accretion event that remained confined to the bulge. We call this population/accretion event SpiteF, in memory of François

Spite, who began this investigation with us and recently passed away. There are three reasons for which we believe this is an accretion event and not a selection effect.

1. We selected the stars only on  $r_{ap}$ , yet all our bulge stars are metal-poor and, as above-mentioned, such stars are rare.
2. The stars show constant [Mg/Fe] and [Ca/Fe] ratios with a small dispersion that can be fully attributed to observational errors. As above-mentioned other bulge samples in the same metallicity range show a larger dispersion in [Mg/Fe].
3. The stars occupy a range in Z for any given R and a narrow range in Y for any given X.

A random selection of bulge stars would not have these characteristics. The SpiteF contains two young stars (GHS108 whose estimated mass is  $1.9 M_{\odot}$  and GHS110 whose estimated mass is in the range  $2.0\text{--}2.8 M_{\odot}$ , see Table 1), if we assume the recent star formation to have occurred at the time of accretion, when the merging galaxy was still gas-rich, this implies that the accretion event is very recent, at most 1 Ga ago (see ages in Table 1). Whether it is dynamically possible that a recent accretion event penetrates to the bulge, rather than remaining in the halo is a difficult question to answer and is further discussed in Appendix E.3.

We used the GUM to get some insight in our selection biases. We are aware that GUM is based on an older version of the Besançon model (Robin et al. 2003) and that our knowledge on the bulge structure has considerably evolved since. Yet we believe this comparison can give useful indications.

We queried the GUM, with the same query that we used for the Gaia source catalogue. The sample is made of 6685 stars. In GUM stars are labelled as thin disc, thick disc, spheroid and bulge. The selected sample (6685 stars) is dominated by the bulge (70%) and the spheroid (halo in our definitions, 28%) with negligible contributions of thick disc (15 stars) and thin disc (90 stars). This can be expected, from our selection on transverse velocity. We analysed this sample using galpy, similarly as we did with the observed stars.

The GUM bulge stars are mostly confined to galactic latitudes and longitudes comprised between  $-15 < b < +15$ ,  $l > 340$  and  $l < 30$ , with a density which is decreasing moving away from  $b=0$ . All but 34 of our stars, are located outside of this area, covering a region dominated by halo stars, consistently with our classification. The halo sample (including stars in the l,b region dominated by bulge stars) is composed by 1898 stars, 1439 (76%) of which in retrograde motion ( $L_z < 0$ ). The largest density of stars in both prograde and retrograde motion is also observed around the Galactic bulge, at  $-30 < b < +30$ ,  $l > 320$  and  $l < 40$ , while almost only stars in retrograde motion are found outside of this area. Therefore, our sample is, actually, expected to be dominated by stars in retrograde motions.

Thirty-four of our stars are located in the region  $-14 < b < -8$  and  $350 < l < 1$ , which is dominated by the bulge in the GUM model, with 271 (80%) versus 67 (20%) halo stars. halo stars are in almost equal number in pro/retrograde motion (33/34), while bulge stars are predominantly on retrograde orbits (157/114, 58% versus 42%). However, bulge stars in the GUM models in pro/retrograde motions occupy different spatial regions. This is especially clear when looking at the stars in cartesian galactocentric coordinates X, Y, Z, our stars being concentrated in the region of the planes strongly dominated by retrograde stars. According to the GUM model, it is, therefore, again expected that also this particular group of stars is predominantly in retrograde orbits. Indeed, only 8 out the 34 stars of our sample in this region are prograde (23%), the others being in retrograde motion.

Fifteen, out of these 34 stars, belong to the sample that we labelled as ‘bulge’ stars, the sixteenth being GHS108, which is somewhat separated by the rest of the sample at  $b < -18$ . These stars were identified as those having apocentric distances ( $r_{ap}$ ) from the galactic centre lower than 3.5 kpc. This condition is verified after integration under a potential which combines a rotating bar to the standard MWPotential2014 potential in galpy. However, they were identified also considering the MWPotential2014<sup>8</sup>. The remaining of the 34 stars in this spatial region, do not respect this condition, and are classified as halo.

Stars confined to  $r_{ap} < 3.5$  kpc represent a 4.6% of our sample (16/348), and a 0.8% and a 0.1% of the entire GUM bulge and complete GUM samples (37/4682, 3/1898), respectively. If we limit the request to the l,b region previously indicated, none is left in the GUM sample. This supports the fact that the bulge population that we have discovered is real, and not a result of our selection function.

GUM does not have built in sub-structures like GSE or Sequoia, it is however interesting to point out that 7% of the GUM sample would be classified as Sequoia, to be compared with the 5% of our sample. This shows that one may conclude that a given dynamic group exists, even when none exist in the underlying universe, and casts some doubt on the reality of the stars we labelled as Sequoia as belonging to a real structure.

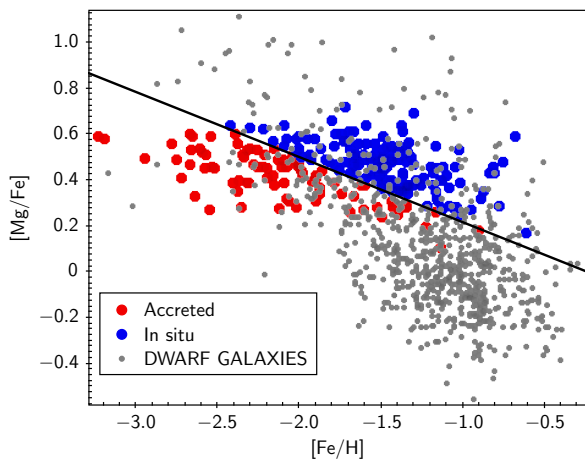
We also find 1081 stars that we would classify as GSE (16%) to be compared with 26% in the observed sample. This suggests that GSE is certainly real, but our selection criterion implies some contamination. The contamination of a pure dynamical selection for GSE has been discussed, for instance by Bonifacio et al. (2021).

### 6.5. Halo stars and Aurora candidates

We classify all the stars that are not in GSE, Sequoia, bulge or Thick Disc as halo stars and these are the majority of the stars, comprising 224 unique stars. The discovery of GSE (Belokurov et al. 2018; Haywood et al. 2018; Helmi et al. 2018) allowed to realise that much of the samples of halo stars used in the past were heavily contaminated by GSE stars. At the same time it was clear that the collision of the GSE progenitor with the Milky Way would also result in the scattering of stars formed in the disc into halo orbits (see e.g. Zolotov et al. 2009; Jean-Baptiste et al. 2017). For this reason in the recent literature people call *in situ* stars, both those formed during the gas collapse and those formed in the disc and scattered into halo orbits by the collision with the GSE progenitor or other major mergers. This usage brings about confusion with the older literature, in the following we shall, nevertheless, stick to it. We can eliminate from our halo sample the stars that we classified as GSE, keeping in mind that this dynamical selection still has a 20% contamination (see e.g. Bonifacio et al. 2021) and conversely we can expect the non-GSE sample to still contain GSE stars (see e.g. Amarante et al. 2022; Orkney et al. 2023). Yet it is even more tricky to separate the sample between *accreted* and *in situ*. At metallicities above  $-1.0$  the Mg abundance or generally the abundance of  $\alpha$  elements can be used to identify the accreted component (Fuhrmann 1998; Gratton et al. 2003) at lower metallicities this is not so simple. Hawkins et al. (2015) argued that the [Al/Fe] ratio is a much more powerful indicator to select accreted stars. Theoretically this can be understood as a combination of metallicity depen-

<sup>8</sup> Using the MWPotential2014, we identified 18 bulge stars, two of them not confirmed after integration in the potential including a rotating bar





**Fig. 18.** Our programme halo stars split between accreted (red dots) and in situ (blue dots), using the  $[Mg/Fe]$  criterion of Belokurov & Kravtsov (2022). The grey dots are from Local Group dwarf galaxies, taken from the SAGA database (Suda et al. 2008, 2017).

dent Al yields (Woosley & Weaver 1995; Nomoto et al. 2013) and the lowering of the ratio when the Fe production of Type Ia SNe kicks in. For Mg instead only the latter mechanism is useful to identify stars that were formed in an environment that was characterised by low or bursting star formation. We stress that these chemical criteria work only if the accreted component comes from dwarf galaxies, if the accreted stars come from a more massive galaxy, or anyway, by a galaxy characterised by continuous and vigorously star formation, these will not work.

Belokurov & Kravtsov (2022) used the  $[Al/Fe]$  ratio to create a high purity sample of halo *in situ* stars. The study of this sample in the Lz-E plane reveals that in the lowest metallicity bin ( $-1.7 \leq [Fe/H] < -1.3$ ) there is no presence of a fast rotating disc, that appears instead in the metallicity bin  $-1.3 \leq [Fe/H] < -0.9$ . They call this phenomenon the spin-up and identify it as the formation of the disc, that, supported by galaxy formation simulations, they estimate to have formed 10–11 Ga ago for a duration of 1–2 Ga. Moreover they identify the lowest metallicity population, characterised by high energy and a wide range in angular momentum, as that formed in the turbulent and chaotic phase of the collapse, literally the dawn of Galactic star formation.

In our sample we do not have the luxury to use  $[Al/Fe]$ , however we use the criterion on  $[Mg/Fe]$  shown in figure 2 of Belokurov & Kravtsov (2022). In Figure 18 we show our stars, that are not in GSE, Sequoia, bulge or Thick Disc, divided into accreted and in situ. For reference we show also the points from Local Group dwarfs galaxies, retrieved from the SAGA database (Suda et al. 2008, 2017). This shows that the criterion is fairly good, since most of the points of LG galaxies lie in the accreted region, however the in situ sample is likely to have some contamination. According to this criterion the Aurora candidate stars are 102. Belokurov & Kravtsov (2022), further introduced a cut on the energies and distances of the stars, namely:  $-0.75 \times 10^5 \text{ km}^2/\text{s}^2 < E < -0.4 \times 10^5 \text{ km}^2/\text{s}^2$ <sup>9</sup> and  $d \leq 15$  kpc. We do not trim down the number of our Aurora candidates to take also these criteria into account. We also note that in subsequent papers of their same (Belokurov & Kravtsov 2023b,a) authors the definition of Aurora is revised, as is the Milky Way potential adopted to compute the integrals of motion. Clearly the

<sup>9</sup> We note the typo in Belokurov & Kravtsov (2022), page 692,  $10^5$  should be  $10^{-5}$

field is still evolving and we are not in a position to comment on this evolution.

We stress that our are candidates and higher resolution spectroscopic observations, including Al abundances, are encouraged to establish the possible membership to Aurora. The full chemical and kinematical data is available in a Table at CDS, thus the researchers interested in performing follow-up observations can pick their targets according to the criteria they consider more appropriate. From the limited chemical inventory at our disposal we cannot see any significant difference between the Aurora candidates and the other stars.

In Fig. 19 we show the sample of our *Aurora* candidates in the Lz-E plane. These candidates are simply our halo in situ sample, with  $[Fe/H] < -1.3$ . The morphology is very similar to that of figure 1 of Belokurov & Kravtsov (2022), bottom row, last panel to the right.

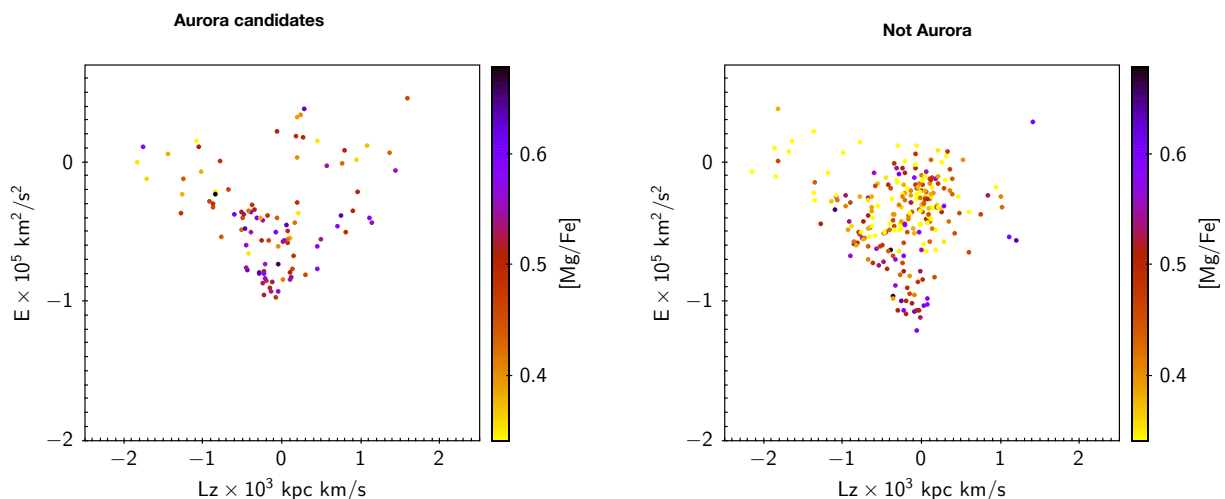
According to our criteria, out of the ten young stars, six are classified as halo, of these five belong to the Aurora population and only one to the accreted population. Young age is incompatible with an origin in the first 2 Ga of the Milky Way formation, as is expected for Aurora. This implies that the chemical criterion based on  $[Mg/Fe]$  introduces substantial contamination between the two populations, at least for data of this precision. To estimate the level of contamination one needs  $[Al/Fe]$  data. One of the issues that requires further theoretical and observational investigation on the Aurora stars, is their metallicity distribution. In our sample the bulk of the stars lie in the interval  $-1.8 \leq [Fe/H] \leq -1.4$  decreasing rapidly at lower metallicity, the most metal-poor stars being at  $-2.4$ . Is this result simply driven by small number statistics? Why do we not find extremely metal-poor stars in Aurora? Are all extremely metal-poor stars formed in dwarf galaxies and subsequently accreted? If so what were the sources that pre-enriched the gas out of which Aurora stars were formed? Where they halo stars, or was it the pollution from SNe in the dwarf galaxies that created a metallicity floor in the halo stars, before it began star formation? Assembling larger and more accurate samples of Aurora stars may answer some of these questions.

## 7. Conclusions

Our selection on a high transverse speed is certainly at the origin of the large number of stars on retrograde orbits. The main conclusion of our investigation is that the stars selected with a high transverse velocity are not a homogeneous group. When we began this investigation, we suspected that we might detect traces of past accretion events among them. This is true since we detected stars from the GSE structure and from the Sequoia structure, as well as from the SpiteF, tentatively identified in this paper. However, the majority of stars cannot be identified with accretion events and must be considered as halo stars. By using a chemical selection on  $[Mg/Fe]$ , we could highlight 102 candidates of the Aurora population as defined by Belokurov & Kravtsov (2022).

We encourage further investigation of the tentative SpiteF structure. We have provided circumstantial evidence that it is associated with a recent accretion event and argue that it is unlikely that it is just a result of our selection bias. We however underline that this possibility cannot be totally ruled out yet. The existence of late accreting galaxies with a recent burst of star formation is in line with the scenario described in Hammer et al. (2021, 2023).

Unbound stars, such as GHS143, are extremely rare. In Paper I we have signalled the possible presence of unbound stars,



**Fig. 19.** Candidate Aurora stars in our sample, in the Lz–E plane (left panel), and the other stars (right panel).

which turned out to be bound instead after the revision of parallaxes in Gaia DR3. What is even more surprising is that this star is falling into the Galactic potential and not escaping from it, as is the case for other unbound stars previously found. The most promising encounter with a stellar system is that with the globular cluster NGC 6582, albeit at two standard deviations. The corollary is that one should look for the presence of an intermediate mass black hole at the centre of NGC 6582, since this would provide the mechanism to supply GHS143 with its current kinetic energy. Other acceleration mechanisms, such as ejection from a binary system, in which the primary companion has undergone a SN explosion are possible. The formation of young stars in a globular cluster is something difficult to envisage, due to the lack of gas, but we shall keep the cases of Terzan 5 and Liller 1 in mind (Ferraro et al. 2021).

The finding of what is likely a metal-poor young population has been somewhat of a surprise. In Paper I we were more inclined to interpret these stars as blue stragglers, and certainly some of them are. However, in this investigation we have concentrated on the masses of these stars and found that they are exceedingly large; blue stragglers typically have masses around  $1 M_{\odot}$  and below  $1.3 M_{\odot}$ . We recall that when pulsational masses were determined for blue stragglers, they were found to be in good agreement with the evolutionary masses that were derived from isochrones, as we did, (Fiorentino et al. 2014). Thus there is no reason to believe that our mass estimates are not accurate. Clearly, at this stage we cannot exclude that all of these stars are evolved blue straggler descendants from triple systems, but we find this hypothesis contrived, and in contrast with the very few massive blue stragglers found so far in the literature. We have proposed a test to distinguish between truly young stars and evolved blue stragglers: the former should, on average, have higher rotational velocities than the latter. This requires higher resolution follow-up observations of these stars. The colour-magnitude diagram of the high-speed stars indicates that there are many other stars that are consistent with a young or evolved blue straggler status. These stars are a prime target to further investigate this issue.

The UVES observations of two of the apparently young stars investigated in Paper I imply that the  $670.7 \text{ nm Li I}$  doublet is not detected and the upper limits imply an abundance that is below the Spite plateau (Spite & Spite 1982b,a; Sbordone et al. 2010). Although this supports the blue straggler nature of these stars, the result is not conclusive. For both stars the upper limit should be pushed down below  $A(\text{Li}) \approx 1.0$  with higher quality spectra to be able to reach a stronger conclusion.

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## Appendix A: Target stars

Table A.1. Names and Gaia DR3 identifiers for our target stars

Name	Gaia DR3 id
GHS01	6408116258177723776
GHS02	6406908375935227136
GHS03	6568152615142338944
GHS04	6467021184886451712
GHS05	6402407078410758144
GHS06	6459038215072888576
GHS07	6578634740526049024
GHS08	6396836437107984000
GHS09	6792492500909072768
GHS10	6375153449333298048
GHS11	6480138079431700480
GHS12	6480968592964063616
GHS13	6469971896141617408
GHS14	6779859249744647168
GHS15	6450745698376857600
GHS16	6453807460302929280
GHS17	6697340214885797248
GHS18	6472285955798151168
GHS19	6443749093572296320
GHS20	6686309364478769152
GHS21	6455330593146017664
GHS22	6425686935027126016
GHS23	6678886836357605760
GHS24	6454181878372335104
GHS25	6424093364721856640
GHS26	6673777852499865472
GHS27	4659670836211433728
GHS28	2892473389378566656
GHS29	5188812082642658944
GHS30	5401875170994688896
GHS31	5388804142407125248
GHS32	3481141194650183936
GHS33	5371147153902398080
GHS34	6186384413992963072
GHS35	6186522402702308992
GHS36	6070459535828774400
GHS37	5792409434759815680
GHS38	5819863862157033728
GHS39	6494419743340318848
GHS40	6378867354796867584
GHS41	6500170326593156352
GHS42	6344288714832612224
GHS43	6390856571321213568
GHS44	6490034581730775296
GHS45	6490954013971262976
GHS46	4629181692264635520
GHS47	4817932482581995776
GHS48	4849168336616387712
GHS49	4945774589328875520
GHS50	4697867771333023744
GHS51	5008808800675101056
GHS52	5008468123868998400
GHS53	4719106247173470592
GHS54	5120933594860876544
GHS55	4709272180814135936
GHS56	4687368809680370176
GHS57	4684725274488105728
GHS58	4924385446036517760

Table A.1. continued.

Name	Gaia DR3 id
GHS59	4901276357319875072
GHS60	4901665206478819200
GHS61	4703413673624094208
GHS62	4977325865764082688
GHS63	2321153334969276160
GHS64	6567028295783009664
GHS65	6578468095795178112
GHS66	6376033402233095040
GHS67	6431108077108143488
GHS68	6363531542708636032
GHS69	5189373658205822848
GHS70	5791687571014695168
GHS71	4907295702445579776
GHS72	4983217530100818176
GHS073	5246774448712573312
GHS074	5464821314034339456
GHS075	5400199515274230912
GHS076	5335896261418144512
GHS077	3479111049508586240
GHS078	3467123383468755328
GHS079	6185397739746042240
GHS080	6158820275960197376
GHS081	6168833906311688704
GHS082	6188285877618232192
GHS083	6188952593982134400
GHS084	6164028215864795520
GHS085	6190776275751144320
GHS086	5769999326196730240
GHS087	6124121132097402368
GHS088	6172555134696611072
GHS089	6221350429945324032
GHS090	6106866049448870400
GHS091	5906261080680763648
GHS092	6216808072534120576
GHS093	5795956218759895296
GHS094	6199825801908510080
GHS095	6001009845939999104
GHS096	5820475465505773312
GHS097	5823880137628573952
GHS098	5807115608941452032
GHS099	5809181660013572992
GHS100	5914788652362791168
GHS101	5818235966468374272
GHS102	5802555247021285760
GHS103	5817399547356081792
GHS104	5811622919419811712
GHS105	5813048986006795392
GHS106	5919704946794195712
GHS107	5919241704497101824
GHS108	6743400234444296320
GHS109	6438773631658600832
GHS110	6734274043115986176
GHS111	6708752832046080896
GHS112	6709429688837208704
GHS113	6446167263239773696
GHS114	6660061925981458816
GHS115	6724884733535094016
GHS215	6548706893010307712
GHS116	6759345867468008320
GHS117	6723858816145372544
GHS118	6639733192933584640

Table A.1. continued.

Name	Gaia DR3 id
GHS119	6725398102402401536
GHS120	6654836978006631936
GHS121	6657610152491402240
GHS122	6703622308933487744
GHS123	6710061495703908608
GHS124	6644138936026516864
GHS125	6644182229296625408
GHS126	6719559180233706368
GHS127	6658033498828025600
GHS128	6732823997746014592
GHS129	6711011572528262272
GHS130	6727332315145507840
GHS131	6730967884676130048
GHS132	6661006990584788224
GHS133	6437230084835781248
GHS134	6435544984482961408
GHS135	6662545722747834624
GHS136	6633963230792340352
GHS137	6715529298307602176
GHS138	6433337199495213056
GHS139	6715711301840606208
GHS140	6661669583779428480
GHS141	6632232152810751488
GHS142	6730547355843299840
GHS143	6632370485122299776
GHS144	6715108524650751104
GHS145	6431315919166662400
GHS146	6438403096241999744
GHS147	6436884219708078976
GHS148	6432994632905279616
GHS149	4044446251671465600
GHS150	6726211496149367168
GHS151	6726207068062588160
GHS152	6680627019666959232
GHS153	6475332462000476800
GHS154	6424891713242837632
GHS155	6658676438250022656
GHS156	6373751572009351808
GHS157	6445943065946638848
GHS158	6659358788294532096
GHS159	6697640862596021504
GHS160	6665227019292614400
GHS161	6647138330729258240
GHS162	6741699461753415680
GHS163	6639271707287676160
GHS164	6759529344169496960
GHS165	6666726856229854976
GHS166	6796363262874820480
GHS167	6685546612647538560
GHS169	6689078862471972224
GHS170	6443729130564198144
GHS171	6685927421627177600
GHS172	6797044341609133184
GHS173	6643886804265865344
GHS174	6640961691018592128
GHS175	6669295968226934144
GHS176	6754545399700231936
GHS177	6474154300931920128
GHS178	6670239486643467392
GHS179	6447711355521757824
GHS180	6850286783435901568

Table A.1. continued.

Name	Gaia DR3 id
GHS181	6679621207045185280
GHS182	6671398921654234624
GHS184	6674250127104208768
GHS185	6805170454092098688
GHS186	6464518421544150016
GHS188	6476230419403065728
GHS189	6409485837349533440
GHS190	6476479355707573376
GHS191	6465543303819966720
GHS192	6477482453910217728
GHS193	6477737025212150528
GHS194	6410024838564847744
GHS195	6809524618920019840
GHS196	6579524863908225408
GHS197	6479895400896199168
GHS198	6570773301106866048
GHS199	6410742265605581056
GHS200	6577763721159122816
GHS201	6676759487516643584
GHS202	6589825157556394880
GHS203	6456587609813249536
GHS204	6678553203298351616
GHS205	6456746489243603968
GHS206	6412415142484095488
GHS207	6775157600584648832
GHS208	6584883127668353024
GHS209	6585219956184571648
GHS210	6519464075600798080
GHS212	6380245322040654976
GHS213	6485376840021854848
GHS214	6549893059898174336
GHS216	6488964550758904448
GHS217	6620131271429742464
GHS218	6408639556993271168
GHS219	6526793076516023808
GHS220	6494632155242530176
GHS221	6543884916047853312
GHS222	6395827669549221376
GHS223	6625197335678814208
GHS224	6610555792166870528
GHS225	6604051944665974656
GHS226	4900325966956503040
GHS227	4638383814314197248
GHS228	4719222967204604544
GHS229	4705166776194991488
GHS230	5002359512143209600
GHS231	4706695612753634048
GHS232	4925067486843323264
GHS233	5006315211381992448
GHS234	4960618924017083008
GHS235	4709117768150098176
GHS236	4962433942836758528
GHS237	2321267065703224320
GHS238	4930039787661776896
GHS239	4931202693006868736
GHS240	4744503625745191808
GHS241	4751801221857764096
GHS242	4948075248690809600
GHS243	4828700412269231872
GHS247	4037996035430475904
GHS248	6727695561968103680



Table A.1. continued.

Name	Gaia DR3 id
GHS249	6727647016003354112
GHS251	6727262839751268608
GHS252	6726960027365884928
GHS253	6727000498823237376
GHS254	6734285553628576512
GHS255	4044903682871414912
GHS256	4045089088020401536
GHS257	6734881454571852672
GHS258	4044716491016787200
GHS259	6726771529840056192
GHS260	6726100037506559104
GHS261	6725786947220199040
GHS262	4044669972293549184
GHS263	6727838502804991104
GHS264	6725823613397479936
GHS265	6724945412835328768
GHS266	6726512354342331520
GHS267	4038117501457765376
GHS268	4036049040854615040
GHS269	4045078165976720640
GHS270	6726511529708519040
GHS371	4044697391366831488
GHS372	6733322901158296192
GHS373	6726816919056054016
GHS271	2306798282955504896
GHS272	4972994958180431360
GHS273	4688513916687143040
GHS274	4685472564442295680
GHS275	4902917550222823424
GHS276	5011444467485885056
GHS277	4698962919274310528
GHS278	4956345603356257792
GHS279	4622163406464165376
GHS280	5496239828735395712
GHS281	5242575280666939648
GHS282	5659111104633796224
GHS283	5451988918123679616
GHS284	5373547525219529984
GHS285	5370387941123150336
GHS286	3477848844520166528
GHS287	5379743032720204160
GHS288	3470573788395088256
GHS289	3470203837092167552
GHS290	6184615986979107072
GHS291	6155020569933314816
GHS292	5844585178525184000
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GHS294	6094901301356994944
GHS295	6114612624260756096
GHS296	6273531636891321984
GHS297	6274166295618635008
GHS301	6106034131463681152
GHS302	5793152189225305600
GHS303	5785885963551502720
GHS311	6005027083467410688
GHS312	5902898327464861696
GHS315	5793965793469740544
GHS316	6009153825488821248
GHS319	6670601874506513152
GHS320	6846937636656976128
GHS321	6471981562876265344

Table A.1. continued.

Name	Gaia DR3 id
GHS322	6472175764117277952
GHS323	6692433987842986624
GHS324	6686342727784978816
GHS325	6694064524930075136
GHS326	6681027551137071744
GHS327	6696370200815375744
GHS328	6429536600114085120
GHS329	6471075427855732352
GHS330	6779593889485911424
GHS331	6482816425335411328
GHS332	6453858828111935488
GHS333	6778364841643442816
GHS334	6471283304276414720
GHS335	6425109657062446464
GHS336	6774572007563813888
GHS337	6481694098841003520
GHS338	6369854486186048896
GHS339	6484277985525429504
GHS340	6677197471101594112
GHS341	6677416102116682496
GHS342	6781914168256940544
GHS343	6775382759950459776
GHS344	6775379701933700736
GHS345	6451791402653847936
GHS346	6580668630879478272
GHS347	6579947213812310016
GHS348	6782909879114518016
GHS349	6575448287109093888
GHS350	6578906766575595776
GHS351	6786759406762161408
GHS352	6459085528432629504
GHS353	6397098464472800128
GHS354	6461290530282488320
GHS355	6402073479711443712
GHS356	6411301646442226816
GHS357	6625938990631507456
GHS358	6566282380222388096
GHS359	6624839036622440576
GHS360	6386080739486924544
GHS361	6504959661804736384
GHS362	6384892167417294336
GHS363	6512326905107154048
GHS364	6512769355458511232
GHS365	6393487530847705344
GHS366	2379631410648067968
GHS367	6492089843841047808
GHS368	6341831375063721088
GHS369	2310689007929797760

## Appendix B: ADQL query used

The ADQL query used to select high transverse speed stars in Fig. 1

```
SELECT
*
FROM gaiadr3.gaia_source
WHERE
4.740470446*pm/parallax >= 500
AND
phot_g_mean_mag between 7 and 13
```

## Appendix C: Remarks on individual stars

### C.1. GHS076 a highly reddened B type star

Since the colour selection was done on the observed Gaia  $G_{BP} - G_{RP}$  and no cut on Galactic latitude, it is not surprising that among the selected targets we found a highly reddened B star. Star GHS076 (=Gaia DR3 5335896261418144512) is at low Galactic latitude ( $b = 1.40284$ ,  $l = 293.75475$ ) and is predicted by the Planck reddening maps (Irfan et al. 2019) to have  $A_V = 3.3$ , in Fig. C.1 we show a portion of the spectrum of GHS076 that covers the two Diffuse Interstellar Bands at 579.7 nm and 578.0 nm (see e.g. Elyajouri et al. 2018), the interstellar Na I D doublet and the stellar He I 587.5 nm line. From the two DIBs shown in Fig. C.1 one can estimate  $A_V(578.0) = 3.2$  and  $A_V(579.7) = 3.5$  (R. Lallement, priv. comm.) in substantial agreement with the Planck-based estimate. To determine the atmospheric parameters of this star we assumed a solar metallicity (as appropriate for a disc young star) and computed ATLAS 9 models (Kurucz 2005), in its Linux version (Sbordone et al. 2004; Sbordone 2005), using the new opacity distribution functions of Mucciarelli & Bonifacio (in preparation).

We computed Balmer lines  $H_\gamma$  and  $H_\beta$  in LTE using SYNTHÉ and He I lines in NLTE using the Kiel code Steenbock & Holweger (1984) and the same 36 level model atom used in Caffau et al. (2014), collisions with hydrogen were computed with the Steenbock & Holweger (1984) generalisation of the Drawin (1969) formalism assuming  $S_H = 1/3$ . Using a well established practice in the analysis of B-type stars, for each Balmer line we computed profiles for several values of effective temperature and surface gravity. For each temperature we fitted the observed line profile to determine the surface gravity values. This set of  $T_{\text{eff}}$  and  $\log g$  values determines a curve in the  $T_{\text{eff}}$ ,  $\log g$  plane. Likewise for the He I lines we computed NLTE line profiles for several values of  $T_{\text{eff}}$  and  $\log g$ . For each He I line and each value of  $\log g$  we fitted  $T_{\text{eff}}$ . Again these points define a curve in the  $T_{\text{eff}}$ ,  $\log g$  plane. The ‘best’ parameters for the star are defined by the region that is enclosed by all these curves. In our case this results in  $T_{\text{eff}} = 21000$  K and  $\log g = 3.4$ . We can detect in our spectrum clearly several metallic lines like C II, N II, O II, Mg II, Al III, S II, however a quick check showed that an NLTE analysis is required to determine the chemical abundances of this star and we are not equipped to do so for all these ions. A higher resolution spectrum of this highly reddened, and relatively bright ( $G = 13.15$ ) would certainly be valuable for the study of DIBs and interstellar features.

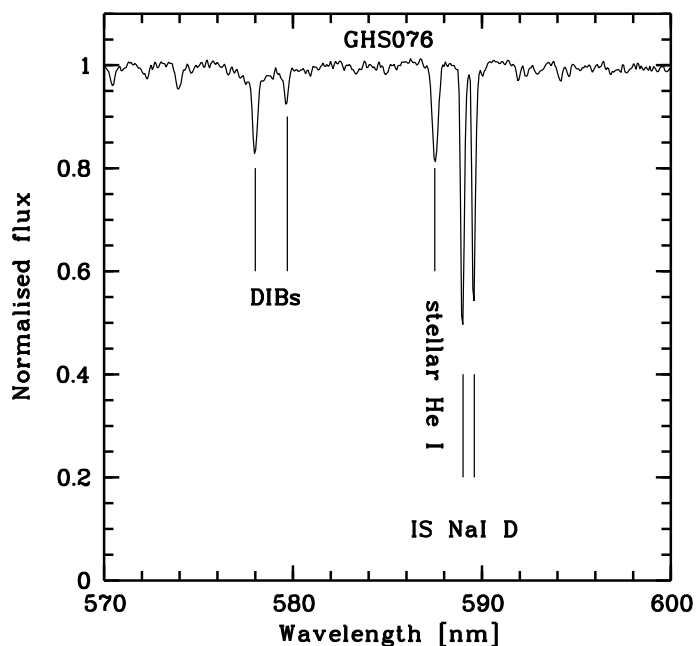


Fig. C.1. Portion of the spectrum of GHS076 displaying stellar and interstellar features.

### C.2. Variable stars

Five stars in our sample are variables: GHS029, GHS046, GHS065, GHS110, GHS236. The first two were already discussed as RR Lyr in Paper I.

GHS065 was reported as one of the two CEMP stars in the sample. Gaia DR3 classifies it as  $\delta$  Scuti/ $\gamma$  Dor, however with a low probability (0.12). We inspected the Gaia epoch photometry and the peak-to-peak magnitude variation is of the order of 0.02 mag in all three bands. We believe this implies that the photometric parameters derived in Paper I are correct.

GHS110 is classified as a Type II Cepheid, subclass W Vir, by Gaia DR3, albeit with a very low probability of 0.05. The Gaia DR3 period is 8.5927 days, which is coherent with the Lomb-Scargle (Lomb 1976; Scargle 1982) periodogram that we computed for the  $G$  band epoch photometry, note however that the false alarm probability for this peak is 0.01 casting some doubt on the reality of this period. We tried to phase the epoch photometry with this period and could not find a curve that can be reasonably fitted. We believe the star is probably multi-periodic and longer and better sampled time series are required to elucidate its nature. For the  $G_{BP} - G_{RP}$  the situation is even worse, however the peak-to-peak variation in colour is of only 0.07 mag, i.e a change in  $T_{\text{eff}}$  of the order of 150 K. In the impossibility of determining a reliable light curve to derive what the appropriate colour was at the time of observation, we stick with the parameters derived from the mean photometry and consider an error on  $T_{\text{eff}}$  of 150 K for deriving the stellar metallicity.

Star GHS236 is classified as RS CVn by Gaia DR3, with a low probability of 0.26. Inspection of the spectrum does not show any sign of chromospheric activity, distinctive of RS CVn, thus not supporting this classification. The Lomb-Scargle periodogram shows a highly significant peak corresponding to a period of 32.59 days. Such a period does not rule out an RS CVn, however the majority of these close binaries have periods less than 20 days (see e.g. Martínez et al. 2022). Phasing the  $G$  data with this period the light curve is quite reasonable, the colour curve is much more scattered. However, for our purpose

what is relevant is that the peak-to-peak variation in  $G_{BP} - G_{RP}$  colour is of the order of 0.04 mag i.e. roughly 100 K in effective temperature. This supports our atmospheric parameters deriving using the mean colour.

## Appendix D: Clustering analysis

The motivation for performing a clustering analysis has been given in Sect. 4. We did so on the stars of our sample using the HDBSCAN<sup>10</sup> library and a Gaussian Mixture model<sup>11</sup>. After a number of attempts using different input variables, we decided to use  $E$ ,  $L_Z$  and  $J_R$  only. The data was scaled using a ‘RobustScaler’ within the scikit learn package.

### D.1. Minimum size 15 and minimum samples 10

HDBSCAN was setup with `min_cluster_size=15` and `min_samples=10`. Under these conditions, HDBSCAN identifies 3 clusters, the most prominent of which can be identified with GSE (cluster "1", 90 members) and bulge (cluster "2", 34 members) stars, although the stars belonging to the groups are not exactly the same as those of Sect.,4. A third group of 17 stars was also identified. Figure D.1 is analogous to figure 5, but this time unclustered stars are presented in grey and stars from Bonifacio et al. (2021) in yellow, while coloured stars are stars belonging to the different clusters.

### D.2. Dimensionality reduction

If we perform a dimensionality reduction using the t-SNE<sup>12</sup> (T-distributed Stochastic Neighbour Embedding) library first and then apply HDBSCAN on the resulting projection, we end up with 7 clusters. Similarly, the two most prominent clusters, "6" and "4", with 72 and 62 members each, occupy in the planes of figure 5 regions similar to those of GSE and bulge stars but, again with larger scatter when we look at them in the  $[Mg/Fe]$  vs  $[Fe/H]$  plane for bulge stars. Here, however, clusters 5 (19 stars) and perhaps 2 (22 stars) and 0 (33 stars) seems also to present a coherent behaviour in this plane. Figures D.2 presents the t-SNE projection resulting from the dimensionality reduction process, showing the different clusters identified by HDBSCAN with different colours. Figure D.3 is analogous to figure D.1. Figure D.4 presents each cluster separately in the  $E$  vs  $L_Z$  plane to allow the association of a kinematic structure with the chemical behaviour presented in fig. D.5. It may be noticed here that the region defined by Feuillet et al. (2021) to select likely GSE candidates is roughly coincident with the stars selected in cluster 6 (bottom-middle panel in Figs. D.3 and D.4), apart for a few stars having higher values of  $J_R$  in our case.

### D.3. Gaussian mixture model

We also applied a Gaussian mixture model (GMM) to the stars in our sample by using the same quantities and scaling and applying a t-SNE dimensionality reduction first. Using the t-SNE projection to train the model, the BIC estimator suggest a number of components between 4 and 6 to represent our sample (figure D.6). Figure D.7 shows the t-SNE projection with stars as-

signed to different groups by applying a GMM with 4 components. Again, figures D.8 and D.9 are analogous of figures 5, 6, 17. Clusters 0 and 1 can be identified with GSE and bulge stars, respectively. The GSE selection box results once again very similar to stars assigned to component 0 of the GMM, with a few stars at higher  $J_R$ . Also, once more clusters 0 and 1 have defined patterns in the  $[Mg/Fe]$  vs  $[Fe/H]$  plane but bulge stars appear also more dispersed with respect to the pattern described by the stars selected in section 4.

### D.4. Conclusions on the clustering analysis

In summary, the criteria adopted in Feuillet et al. (2021) seems to be broadly consistent with the major group identified in our clustering analysis with HDBSCAN and the Gaussian Mixture model using  $E$ ,  $L_Z$  and  $J_R$  as input variable, especially when a dimensionality reduction is applied first using the t-SNR algorithm. It is remarkable that a detection this clear can be made with a clustering analysis on a sample of about 350 stars.

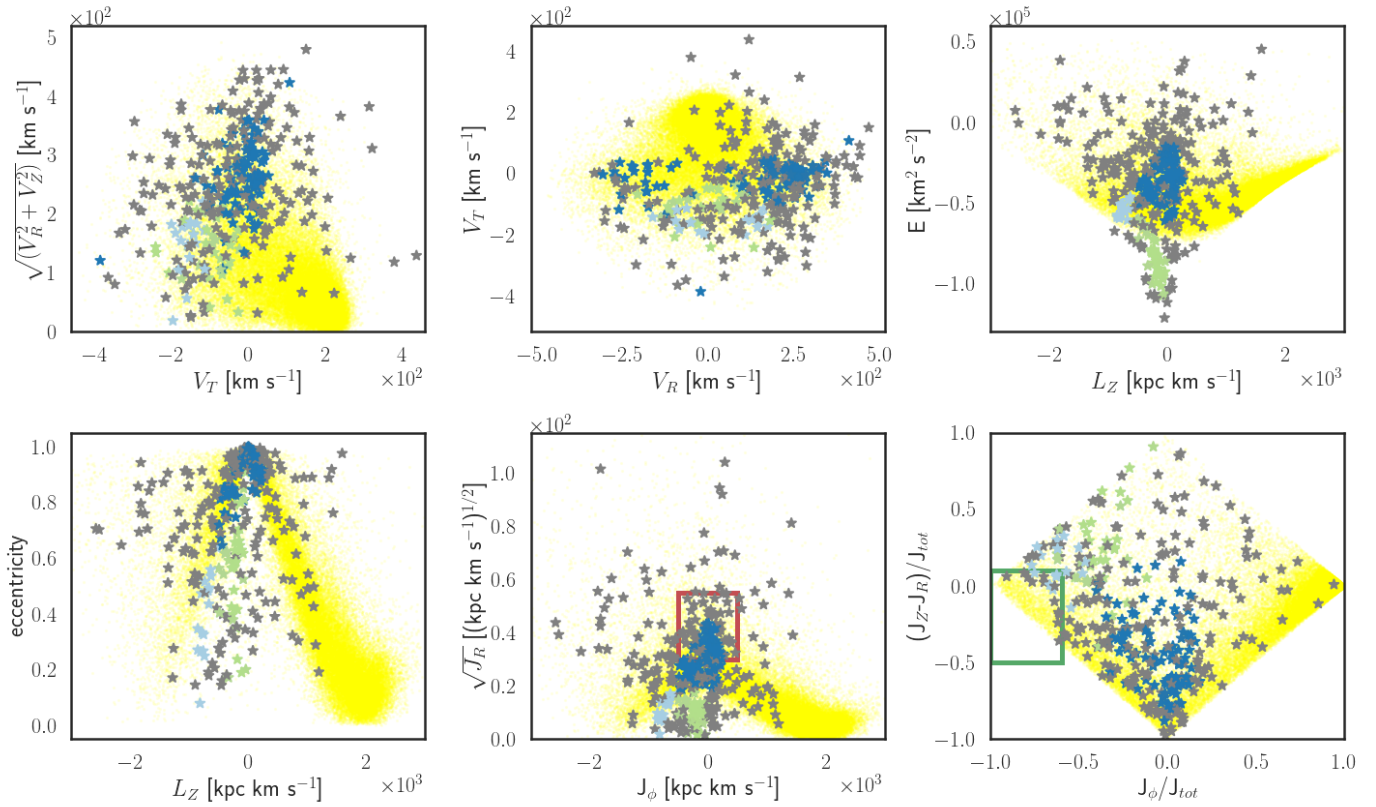
The second most prominent group is composed by stars which have low orbital energy and found in the inner part of the Galaxy. These two groups are identified as well in all the experiments we made. We associate this group to the stars confined to the bulge that we identified in section 4. However, while the reality of the group seems unquestionable, stars belonging to this group present a larger scatter in the  $[Fe/H]$  vs  $[Mg/Fe]$  plane when selected according to our clustering analysis with respect to the group identified in section 4. This is the main reason why we decided to define the SpiteF structure requiring  $r_{ap} < 3.5$  kpc. This choice is, to some extent arbitrary, however it is also consistent with the notion that the inner bulge is more spherical and different from the bar and pseudo-bulge (see e.g. Lucey et al. 2019; Reggiani et al. 2020, and references therein).

Finally, HDBSCAN when coupled with a dimensionality reduction technique, identify up to 7 clusters. Besides, GSE and bulge stars, at least one but up to 3 more clusters seem to present a chemical signature in the  $[Fe/H]$  vs  $[Mg/Fe]$  plane.

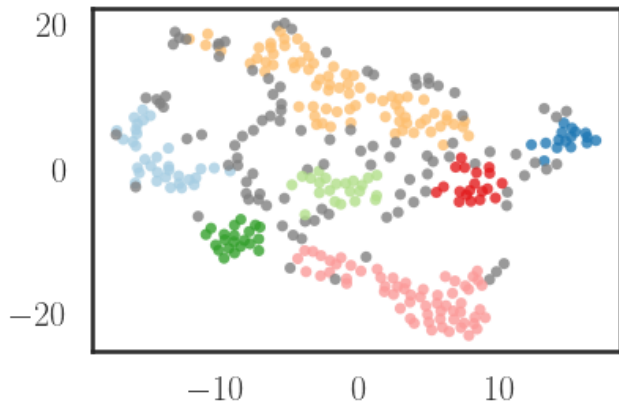
<sup>10</sup> <https://hdbscan.readthedocs.io/en/latest/index.html>

<sup>11</sup> <https://scikit-learn.org/stable/modules/mixture.html>

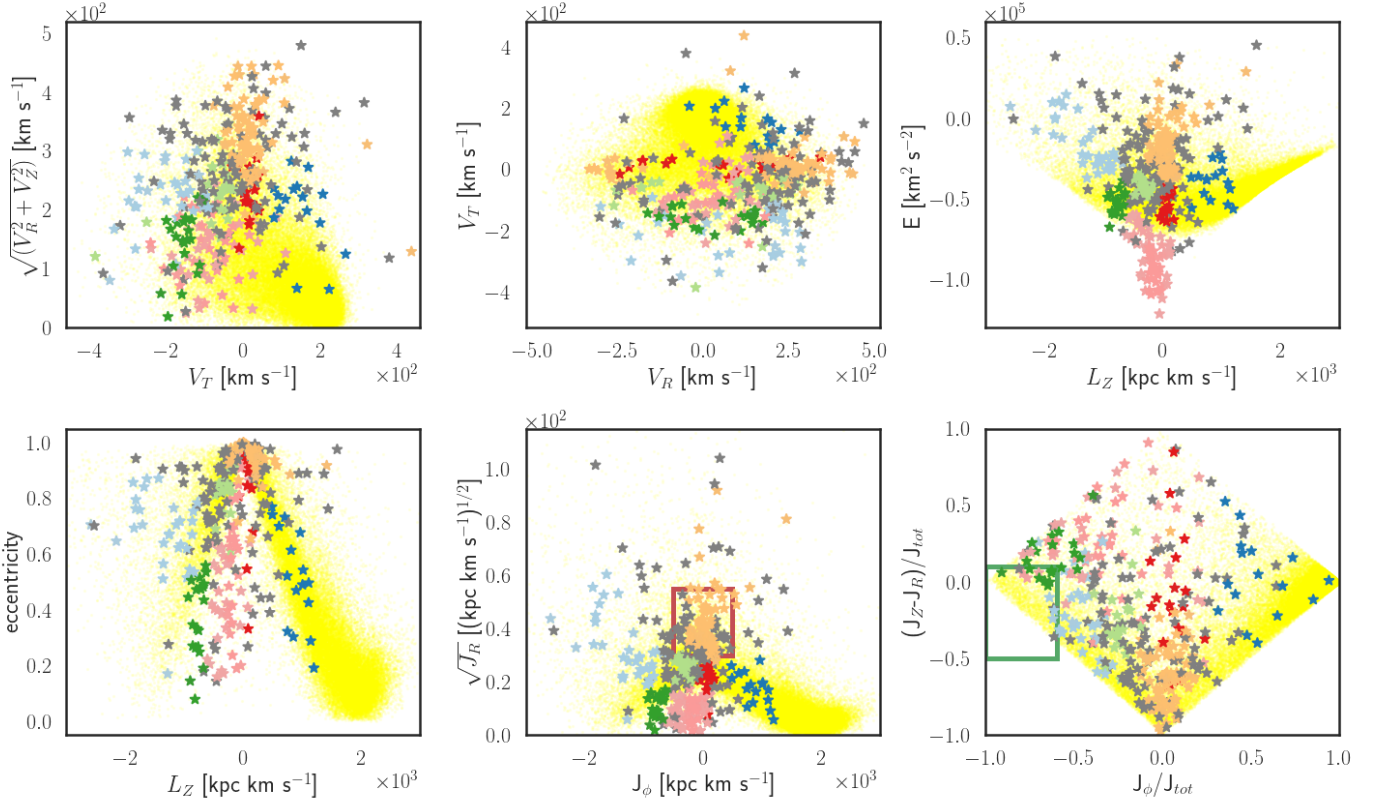
<sup>12</sup> <https://scikit-learn.org/stable/modules/generated/sklearn.manifold.TSNE.html>



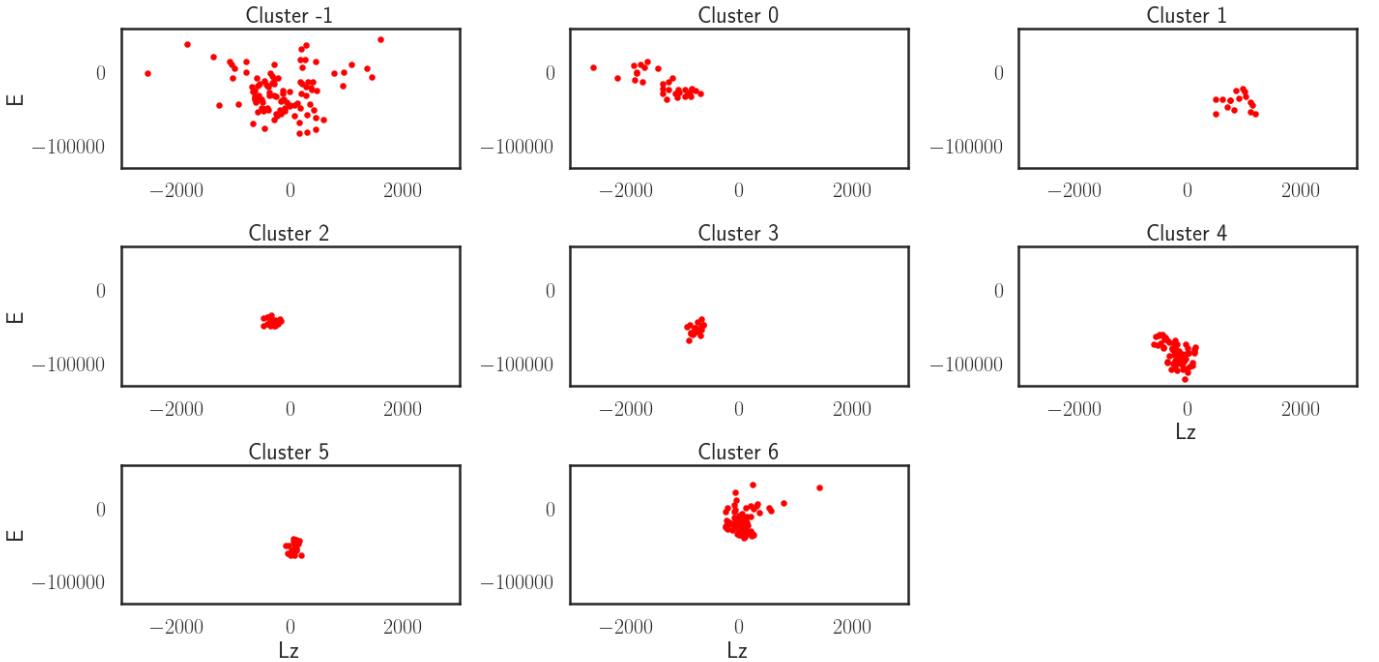
**Fig. D.1.** Same planes as in fig. 5. Programme targets are marked by filled stars: grey for unclustered, green blue and light blue for the three identified clusters. Blue and green clusters can be associated to stars classified as GSE and bulge in section 4. Yellow points are stars from Bonifacio et al. (2021). The areas used to select GSE and Seq stars in section 4 are still outlined here for reference but using red and green squares in the bottom middle and right panels, respectively.



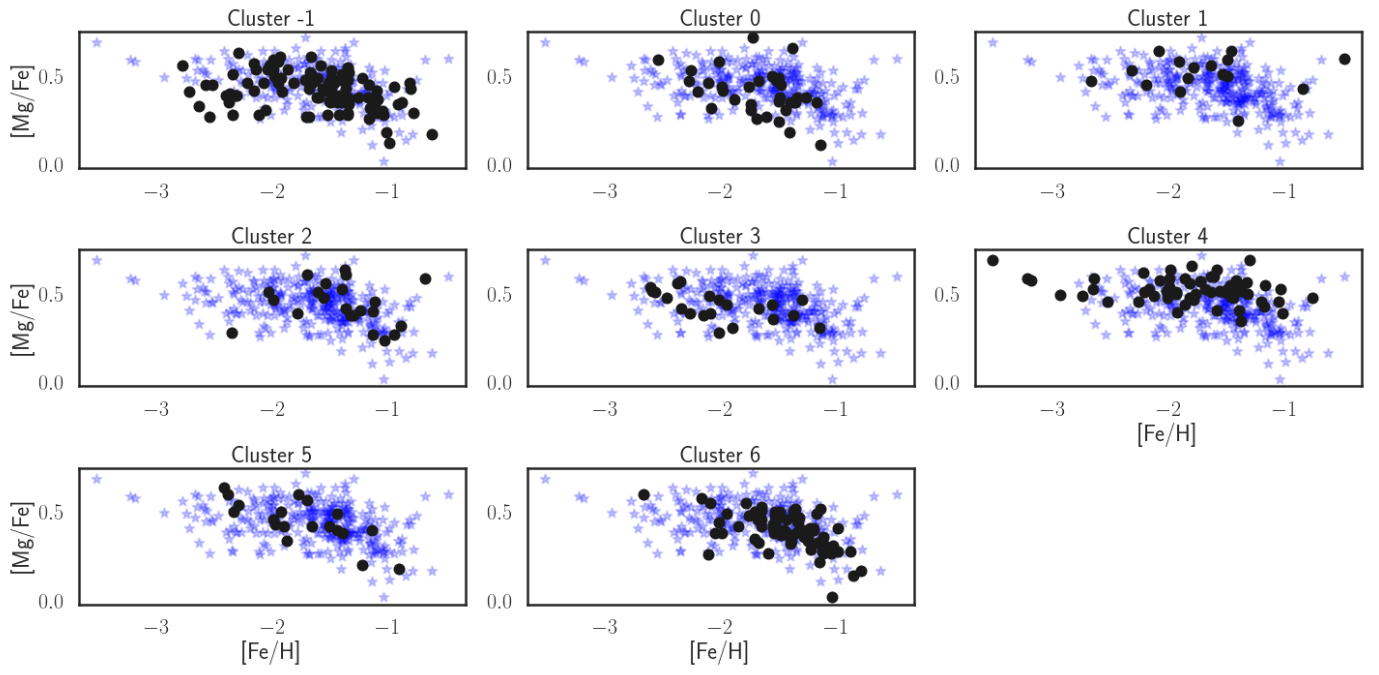
**Fig. D.2.** Two-dimensional t-SNE projection of the  $E$ ,  $L_Z$  and  $J_R$  distribution of the program stars. The 7 clusters identified by HDBSCAN are indicated with different colours. Grey filled circles are unclustered stars.



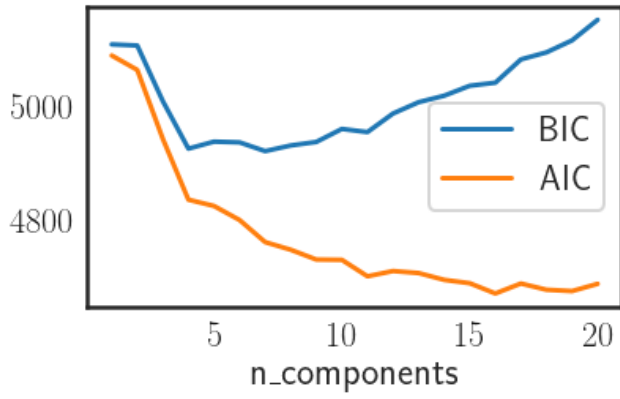
**Fig. D.3.** Similar to fig. D.1 but for the clusters identified using HDBSCAN using the t-SNE projection of the input parameters.



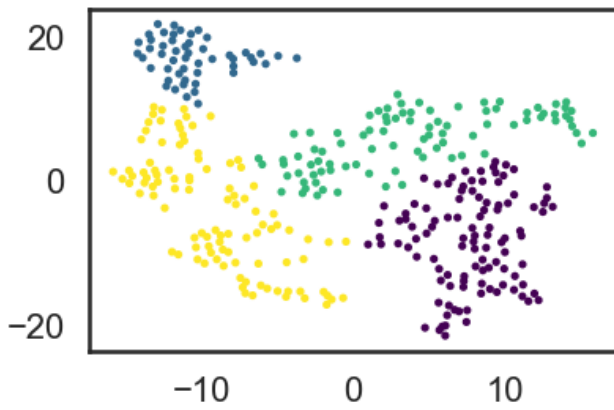
**Fig. D.4.**  $E$  vs  $L_Z$  plane. On each panel we plot stars belonging to one of the 7 clusters (the top label indicates the number of the cluster from 0 to 6) identified using HDBSCAN using the t-SNE projection of the input parameters. Unclustered stars (top-left panel) are labelled ‘Cluster -1’.



**Fig. D.5.** Similar to fig. 17 but for the clusters identified using HDBSCAN using the t-SNE projection of the input parameters. Clusters 6 and 4 can be associated with GSE and bulge stars as defined in section 4 (see figs. D.4 and 5).

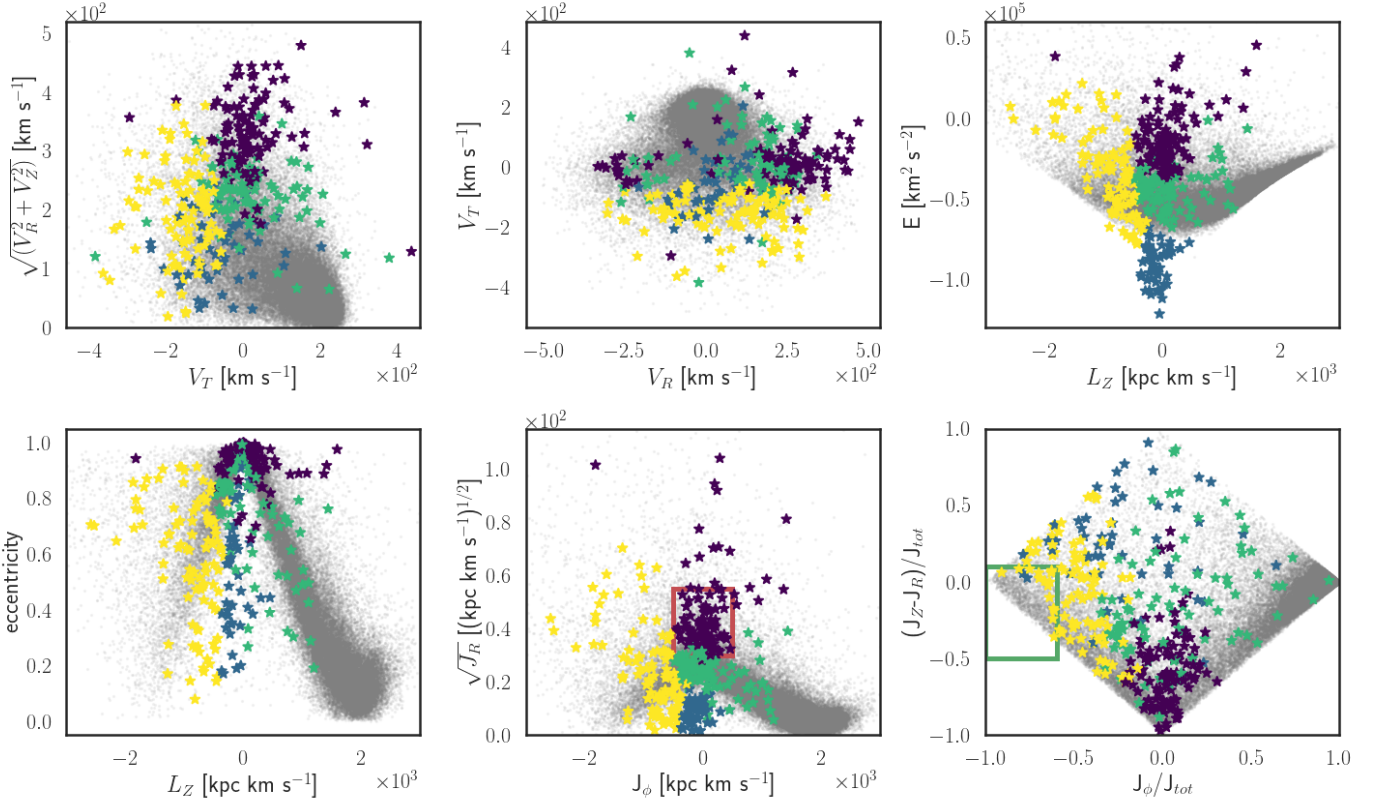


**Fig. D.6.** AIC and BIC estimators for the GMM applied on the two-dimensional projection of the input parameters.

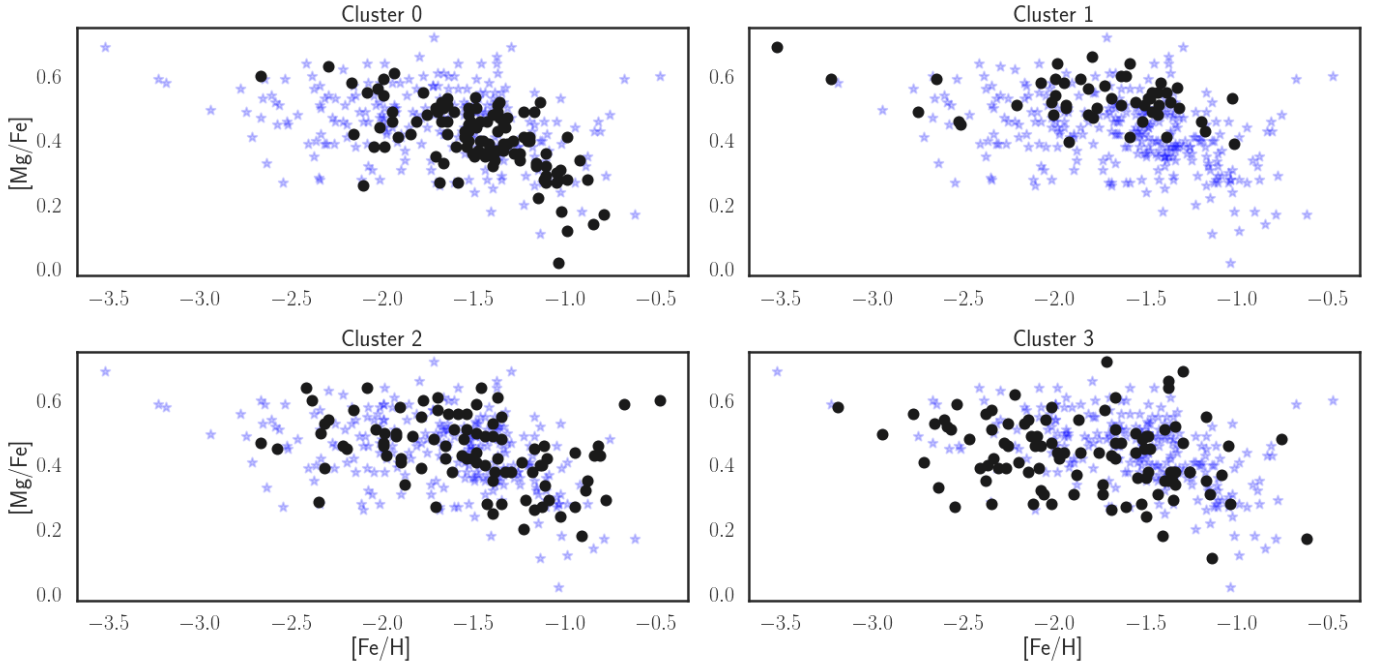


**Fig. D.7.** Two-dimensional t-SNE projection of the input parameters. The stars belonging to a GMM with 4 components are indicated with different colours.





**Fig. D.8.** Same as fig. 5. Grey points are stars from Bonifacio et al. (2021), stars belonging to the different group of the 4 components of the GMM have different colours.



**Fig. D.9.** Same as Fig. 17. Symbols are coloured as in Fig. D.8. Cluster 0 (bottom-right) and 1 (top-right) correspond to yellow and blue stars in figure D.8 and can be associated to GSE and bulge stars as identified in section 4.

## Appendix E: SpiteF: Further discussion

In this section we provide a more detailed discussion of SpiteF, its selection and its properties.

### E.1. Selection of stars belonging to the bulge and SpiteF

The operational definition of the SpiteF structure is certainly arbitrary to some degree. In appendix D, we saw that the second most prominent cluster among the stars of our sample is a group of stars at low energies which includes the SpiteF.

The SpiteF was initially noticed as a group of stars with a well defined trend in the  $Z_{GC}$  vs  $R_{GC}$  plane. A possible selection of stars belonging to this structure is presented in the top-left panel of Fig.E.1 (magenta large filled circles). The SpiteF stars are also shown as green triangles, while the remaining stars in our sample are shown as blue stars. The inset shows a zoom-in of the region of the selected stars. Fifteen of the sixteen SpiteF stars belong also to the stars we select in this way. This larger sample is composed of 30 stars and we call them 'RZ' in the following.

The two different selections (RZ and SpiteF) are presented in the top-right panel in the  $Z_{max}$  vs  $r_{ap}$  plane. A rotating disc was included in the potential in order to evaluate these quantities. By definition, SpiteF stars are confined to  $r_{ap} < 3.5$  kpc. A group of five stars (filled black squares) extends to large values ( $r_{ap} > 7$  kpc and  $Z_{maz} > 6$  kpc). Excluding these five stars, the RZ is a sample of 25 stars confined to  $r_{ap} < 5.4$  kpc and  $Z_{max} < 3.8$  kpc, as can be better seen in the inset. Fifteen of these 25 stars also belong to the SpiteF. These RZ stars extend, thus, to larger  $Z_{max}$  values than the SpiteF, which is confined to  $Z_{max} < 3$  kpc.

The bottom panel of the figure, presents the RZ and SpiteF stars in the  $[Fe/H]$  vs  $[Mg/Fe]$  plane. Stars extending at large  $r_{ap}$  and  $Z_{maz}$  are also identified (black filled squares). The remaining stars in the sample are also shown as blue stars. As can be seen, 7 out of the 10 stars additional stars confined in the inner region of the Galaxy, have abundances compatible with the SpiteF. Of the remaining 3 stars, two present a lower  $[Mg/Fe]$  ratio, and one has a lower metallicity ( $[Fe/H] = -2.75$ ). Three of the stars extending to large values of  $r_{ap}$  and  $Z_{maz}$  are also compatible with SpiteF, while two are not.

In summary, the 25 stars in the RZ sample confined to the inner Galaxy provide a possible alternative definition for the structure we identified and labelled as SpiteF. All but one of the SpiteF stars are in fact contained in the RZ sample. The kinematics and chemistry of RZ and SpiteF are compatible between each other.

Note that, Lucey et al. (2021) adopted the same criterion we used to define stars belonging to the SpiteF ( $r_{ap} < 3.5$  kpc), to discriminate stars truly confined to the bulge from halo interlopers. They indicate this as the distance usually adopted to define the Galactic bulge in the literature (e.g. Ness et al. 2013b; Arentsen et al. 2020; Kunder et al. 2020).

### E.2. SpiteF and the poor old heart of the Milky Way

Rix et al. (2022) identified a metal-poor structure in the central part of the Milky Way, that they interpret as the result of the coalescence of a few massive progenitor galaxies and they refer to this structure as 'proto-galaxy' or, more poetically, in their title as 'Poor Old Heart of the Milky Way', for short we shall refer to it as POH in the following. We would like to understand if SpiteF could simply be a subset of POH or, more in general, if there is any connection between the two structures.

SpiteF has two young stars, while POH is interpreted by Rix et al. (2022) as an old structure, this would allow us to conclude that the two structures have no connection. Let us, for the sake of discussion, set aside this issue, one can always argue the apparently young stars are just evolved blue stragglers. SpiteF and POH overlap both in the  $(l, b)$  and in the  $Z, R$  planes, as shown in Fig. E.2. However, to conclude that SpiteF is somewhat associated to the POH they should share further properties than their spatial coincidence.

In order to make more meaningful the comparison we select from the sample of Rix et al. (2022) stars with transverse velocity larger than  $500 \text{ km s}^{-1}$ . This is a sample of 11 743 stars and is shown in Fig. E.3. In the left panel we also select a subsample of 2 178 stars (shown as green dots) that occupy the same region in  $(l, b)$  as our SpiteF panel. In the right panel we show the same sets of stars in the  $(R, Z)$  plane. It is obvious that the sample of high transverse speed stars that occupies the same  $(l, b)$  region as SpiteF shows, for any given  $R$ , a wider range in  $Z$ , as we already said in Sect. 6.4.

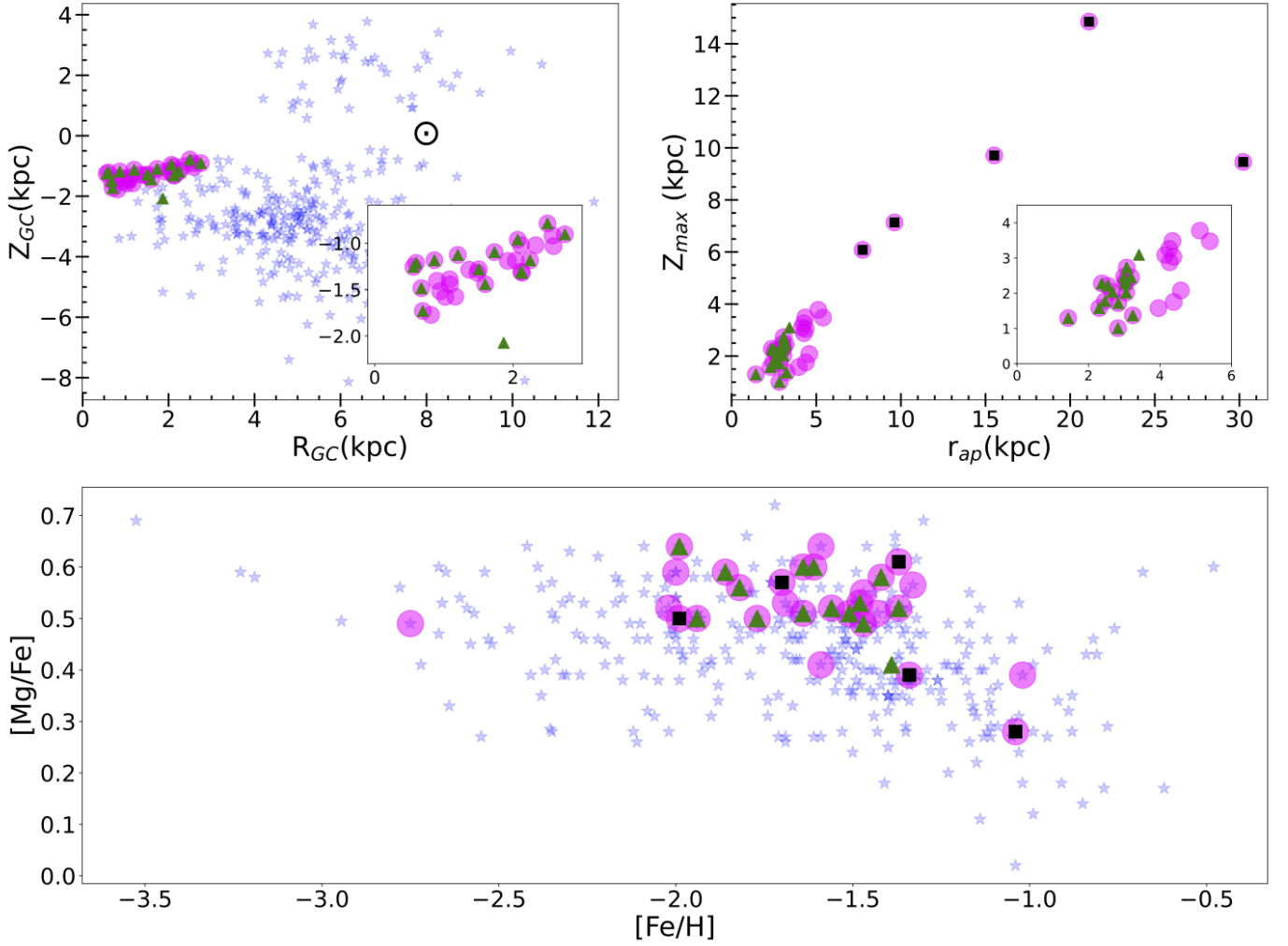
As a preliminary step we try to put the metallicities of Rix et al. (2022) on the same scale as ours. In Fig. E.4 we compare the photometric metallicities of Rix et al. (2022) with our spectroscopic metallicities for 43 stars in common. The correlation coefficient is about 0.93. A linear fit yields a slope of 1.199877 and an intercept of 0.10886344, the root mean square error around this relation is 0.2 dex, fully compatible with the errors involved. It is nevertheless noticeable how the correlation becomes more dispersed below photometric metallicity of  $-2.0$ . This is expected, on the one hand the photometric sensitivity to metallicity diminishes below this value, even for narrow bands, on the other hand the calibration set used by Rix et al. (2022) has very few calibrators at low metallicity (see their figure 1). Let us assume this linear correlation as suitable to put the metallicities of Rix et al. (2022) on the same scale as ours.

In Fig. E.5 we show the histogram of the corrected metallicities for the whole sample for which Rix et al. (2022) computed orbits. In Fig. E.6 we show the normalised metallicity histogram for the high transverse speed stars of Rix et al. (2022) that occupy the same  $(l, b)$  region as SpiteF and identified in Fig. E.3 as green dots. In the same plot we also show the normalised metallicity histogram of SpiteF. The difference in the metallicity distribution of the two sets of stars is obvious, in spite of the fact that they all have transverse speed in excess of  $500 \text{ km s}^{-1}$  and occupy the same region in  $(l, b)$ .

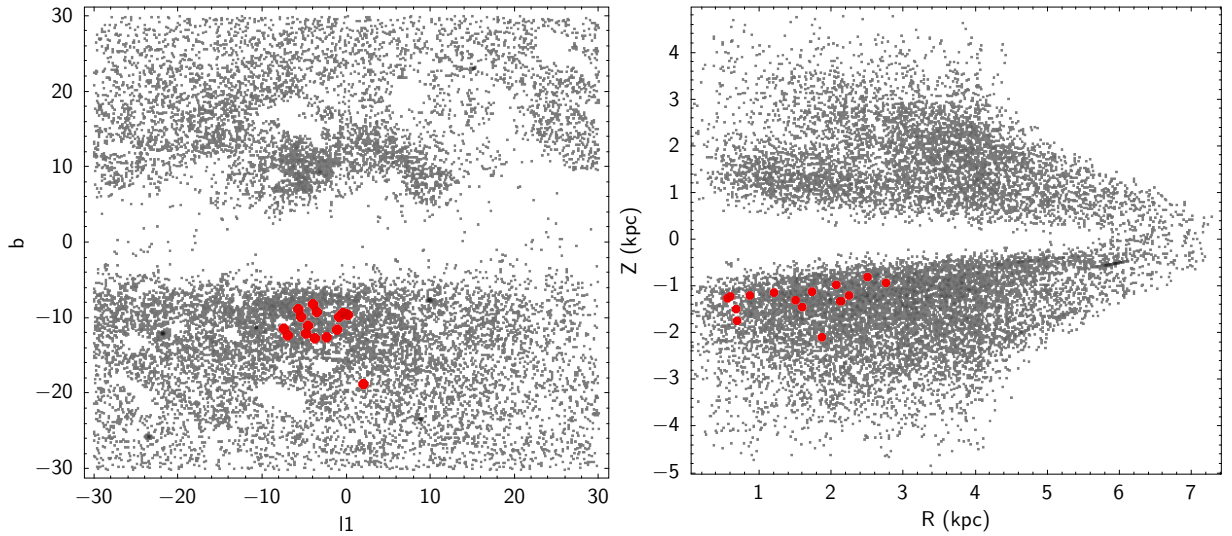
In Fig. E.7 we show the corrected metallicity normalised histogram for the entire sample of the high transverse speed stars of Rix et al. (2022). On the same plot we also show the metallicity distribution of our stars. It is clear that our sample peaks at much lower metallicities than that of Rix et al. (2022).

Let us now restrict the comparison to the sample of stars that we identified as SpiteF, as shown in Fig E.8. It is obvious that the two metallicity distributions are very different. SpiteF spans a much smaller range in metallicity than the high transverse velocity stars selected from the sample of Rix et al. (2022). The sample of Rix et al. (2022) has few but well understood biases: it comprises only stars in a rectangular region of  $60^\circ$  side centred on the Galactic centre, it only selects giant stars, and  $1.0 \leq (G_{BP} - G_{RP}) \leq 3.5$ .

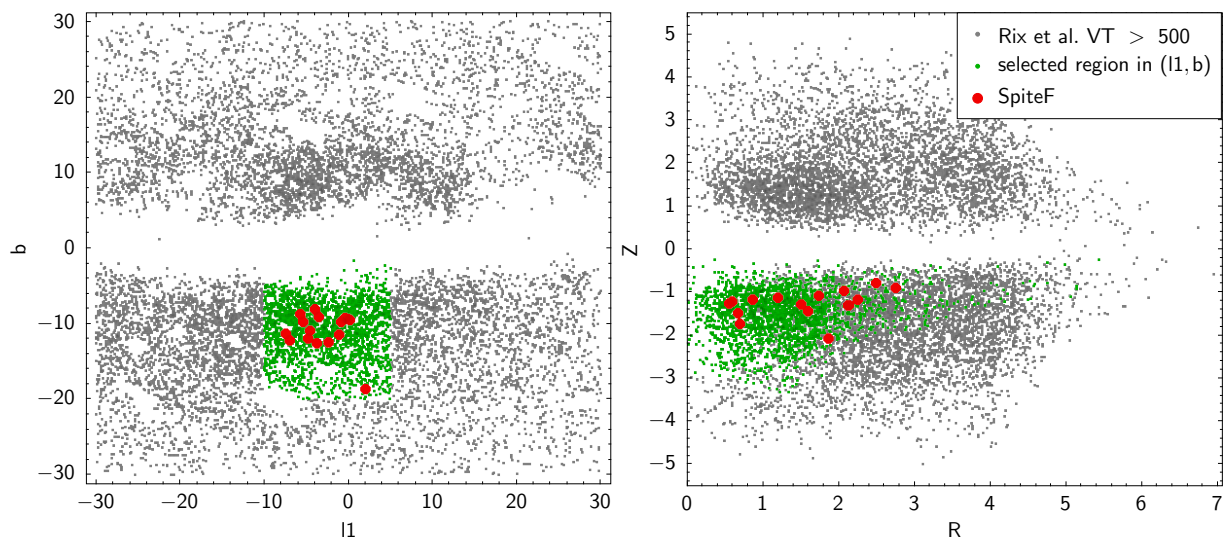
Quite likely the colour selection introduces some metallicity bias, our sample contains bluer stars and we do not observe any of the M giants that are part of the Rix et al. (2022) sample. The difference in colour selection may be at the root of the different metallicity distribution of our sample and that of Rix et al. (2022), even when restricted to the high transverse speed



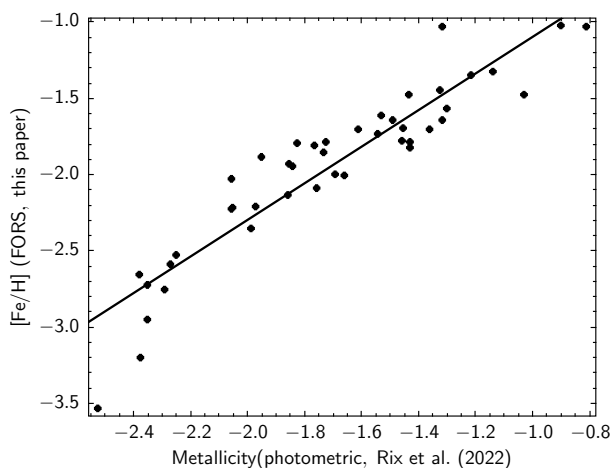
**Fig. E.1.** Possible alternative selection of the SpiteF structure. Top left: in the  $Z_{GC}$  vs  $R_{GC}$  plane (magenta large filled circles). The SpiteF stars as selected in Sect. 6.4 are identified as green triangles, the other stars in our sample are shown as blue stars. Top right: the same in the  $Z_{max}$  vs  $r_{ap}$  plane. Bottom panel: The same in the  $[Mg/Fe]$  vs  $[Fe/H]$  plane. Stars with  $r_{ap} > 7$  kpc are shown as black filled squares in the top-right and bottom panels.



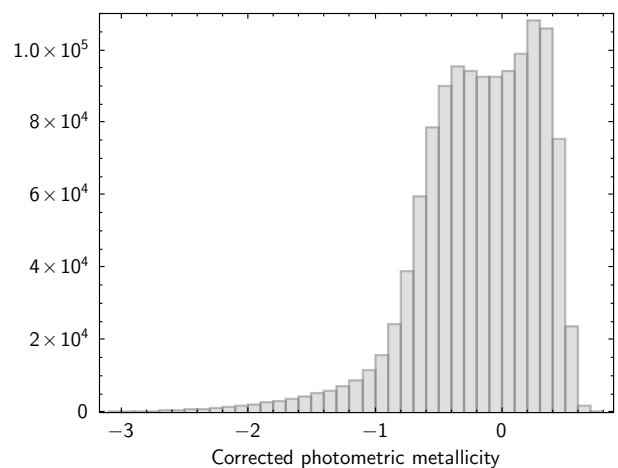
**Fig. E.2.** Stars with  $[M/H] < -1.5$  from the sample of Rix et al. (2022) (grey dots) compared with the SpiteF stars of our stars in the planes  $(l1, b)$  and  $(R, Z)$ . To be consistent with figure 3 of Rix et al. (2022), in the left panel we plot  $l1 = \{l \text{ if } l \leq 180.; l - 360. \text{ if } l > 180.\}$ .



**Fig. E.3.** Stars with transverse speed faster than  $500 \text{ km s}^{-1}$  from the sample of Rix et al. (2022) (grey dots) compared with the SpiteF stars of our stars in the planes  $(l, b)$  and  $(R, Z)$ . The green dots are the subset of high transverse velocity stars from the sample of Rix et al. (2022), selected in the  $(l, b)$  region occupied by our SpiteF stars.



**Fig. E.4.** Comparison of the spectroscopic and photometric metallicities for 43 stars in common between this paper and Rix et al. (2022). The straight line is a linear fit.



**Fig. E.5.** Histogram of the corrected metallicity for the sample of 1 250 764 stars for which Rix et al. (2022) computed orbits.

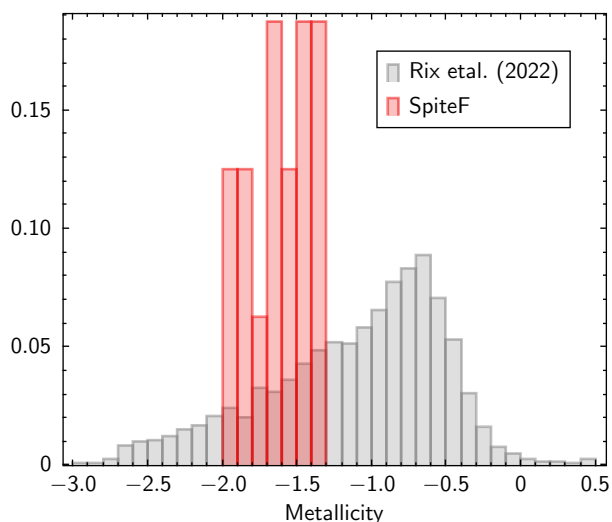
stars (Fig. E.8). A more detailed investigation of the biases is hampered by the inhomogeneous selection of our sample. Even keeping in mind this underlying difference between the two samples, in view of Fig. E.6 and Fig. E.8 it does not seem likely that SpiteF is just a random selection of the population of high transverse velocity stars found in the central part of the Galaxy.

### E.3. Is a recent accretion of a massive galaxy possible?

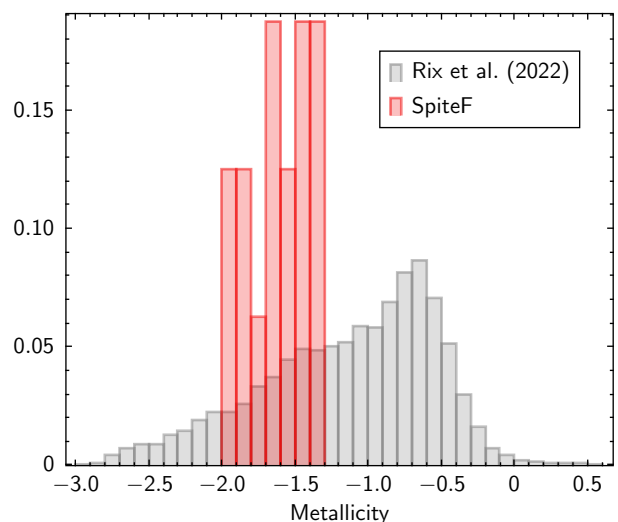
To fully answer this question it is necessary to conduct detailed dynamical simulations, including the presence of gas, both in the accreted satellite and in the Milky Way. One argument in favour of a recent accretion is the fact that stellar debris that has apocentre distances smaller than 3.5 kpc, and therefore relatively short periods, will mix, in phase space, on time-scales of a few Ga. This statement is supported, for example, by the analysis on tidal streams of dwarf galaxies and globular clusters by Amorisco (2015), see specifically his equation 16. Thus the fact that we still see a dynamical coherence among the SpiteF stars implies that the accretion is relatively recent. On the other hand

recent accretion events mostly deposit stars in the outer regions of the halo and not in the inner Galaxy. Dynamical friction can make the stars sink to the central regions of the galaxy, but the process takes time and it may be incompatible with the young age of the stars we observe in SpiteF (Vasiliev et al. 2022). We stress that to make the analysis realistic the effect of gas should be taken into account, which is not the case for the analysis of Vasiliev et al. (2022). Awaiting for specific analysis we can look at the work of Eliche-Moral et al. (2006) who investigated the possible role of mergers in the growth of bulges. It should be stressed that this work is mainly concerned with large accreting satellites and classical bulges, so it may not be directly relevant to the case of SpiteF. However among their results, the one that may be relevant for the present discussion is that the survival of the merging galaxy at the centre of the bulge of the primary galaxy depends on the structural properties of the merging galaxy. Structural properties that Eliche-Moral et al. (2006) quantify through the index of the Tully-Fisher relation,  $\alpha_{TF}$ <sup>13</sup>.

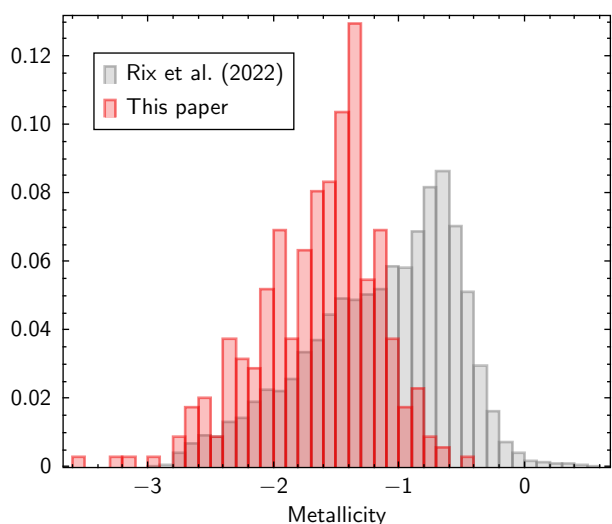
<sup>13</sup> Initially introduced by Tully & Fisher (1977) as a method to estimate distances of galaxies from the widths of H I 21 cm lines, in its mod-



**Fig. E.6.** Histogram of the corrected metallicity for the sample of 2 178 high transverse speed stars of Rix et al. (2022) selected in  $(I, b)$  as shown in Fig. E.3. Our sample of SpiteF stars are also shown. Both histograms have been normalised to the total number of stars.



**Fig. E.8.** Same as Fig. E.7 except that now only our sample of SpiteF stars is shown. Both histograms have been normalised to the total number of stars.



**Fig. E.7.** Normalised histogram of the corrected metallicity for the sample of 11 743 stars from the sample of Rix et al. (2022) with transverse velocities larger than  $500 \text{ km s}^{-1}$  (grey). Superimposed is the metallicity histogram of our sample of stars (red). Both histograms have been normalised to the total number of stars.

In particular they find that if  $\alpha_{TF} \geq 3.5$  the galaxy partially survives at the centre of the bulge, while for  $\alpha_{TF} = 3.0$  the merging galaxy totally disrupts. The time scales are also interesting, in their suite of simulations Eliche-Moral et al. (2006) find a time for full merger of 1.3 Gyr for a merging galaxy with  $\alpha_{TF} = 4.0$  and mass  $1/2$  of the mass of the bulge of the primary galaxy, corresponding to  $1/6$  of the mass of primary galaxy. While we do not claim that these simulations may explain our observations, we believe they show that a recent merger with a massive galaxy with partial survival of the merging galaxy at the centre of the primary galaxy is not implausible. Clearly detailed *ad hoc* simulations should be performed to further explore the issue, and see other secondary effects, such as the localisation of the disrupted debris. We close this subsection by recalling that for external

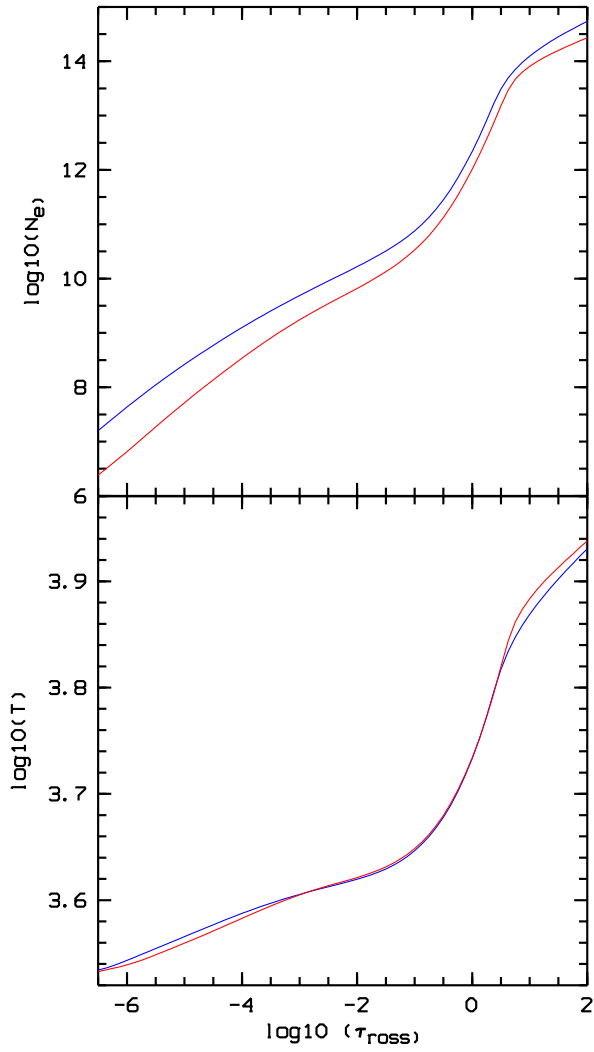
ern accretion the Tully-Fisher relation can be expressed as  $M \propto V_{rot}^{\alpha_{TF}}$ , where  $M$  is the mass of the galaxy and  $V_{rot}$  its rotational velocity.

galaxies there is a general consensus that the bulges grow also through the contributions of mergers (see e.g. Sachdeva et al. 2017, and references therein). Most of the growth is due to secular evolution of disc stars being accreted by the bulge, but this process may also be triggered by accretion events.

## Appendix F: Limitations of MyGIsFOS for ionised species

MyGIsFOS uses grids of synthetic spectra that are computed from models of different metallicity. This implies that when MyGIsFOS fits a spectral feature it interpolates among profiles computed with *different* models. This is different than what is usually done in abundance analysis, where profiles, or equivalent widths, are computed from a given model atmosphere and different abundances of the element under study. While being inconsistent (the model atmosphere had been computed with a fixed abundance of any element) this approach can be justified on the grounds that the element under study is a trace element and the effect of its abundance on the structure of the model atmosphere is negligible. Of course this condition may fail for some specific elements. The classical example is Mg in cool models around solar metallicity. Since Mg is the dominant electron donor in these models, changing its abundance can have a non-negligible effect on the model structure, mainly through the H- number density and associated opacity. The MyGIsFOS approach is also inconsistent, yet in Sbordone et al. (2014) we have shown that for lines of neutral species, it provides essentially the same results as the more traditional approach.

This is not true, in general, for ionised species, or for any feature that has a strong dependence on the electron density, like, for instance the [O I] line at 630 nm. The reason is that two models that differ in metallicity by a significant amount, let us say one order of magnitude to fix the ideas, have a similar T( $\tau$ ) structure but a very different electron density structure. This is illustrated in Fig. F.1. While for neutral trace species, like Fe I the T( $\tau$ ) is the most relevant characteristic of the model in computing the line profile, for dominant ionised species, like Ba II, the run of electron density is also very important in determining the computed profile. We made some experiments with Ba II features and, as a rule of thumb MyGIsFOS gives unreliable



**Fig. F.1.** Structure in temperature and electronic density for two ATLAS 12 models of our grid.  $T_{\text{eff}} = 5000$  K,  $\log g = 2.0$ ,  $\xi = 2 \text{ km s}^{-1}$  and  $[\alpha/\text{Fe}] = +0.4$  and metallicity  $-1.0$  (red) and  $-2.0$  (blue).

quantitative results when  $|[\text{Ba}/\text{Fe}]| > 0.3$ . Qualitatively the result is correct, but the MyGIsFOS abundance cannot be trusted. By extension we assume this limit for any electron density sensitive feature.