An old, metal-rich accreted stellar component in the Milky Way stellar disk

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ABSTRACT

We study the possibility that the Milky Way’s cool stellar disc includes mergers with ancient stars. Galaxies are understood to form in a hierarchical manner, where smaller (proto-)galaxies merge into larger ones. Stars in galaxies, like the Milky Way, contain in their motions and elemental abundances tracers of past events and can be used to disentangle merger remnants from stars that formed in the main galaxy. The merger history of the Milky Way is generally understood to be particularly easy to study in the stellar halo. The advent of the ESA astrometric satellite Gaia has enabled the detection of completely new structures in the halo such as the Gaia-Enceladus-Sausage. However, simulations also show that mergers may be important for the build-up of the cool stellar disks. Combining elemental abundances for 100 giant branch stars from APOGEE DR17 and astrometric data from Gaia we use elemental abundance ratios to find an hitherto unknown, old stellar component in the cool stellar disk in the Milky Way. We further identify a small sample of RR Lyrae variables with disk kinematics that also show the same chemical signature as the accreted red giant stars in the disk. These stars allows us to date the stars in the accreted component. We find that they are exclusively old.

Keywords: The Galaxy: disk, abundances, stellar content

1. INTRODUCTION

Galaxies are understood to form in a hierarchical manner, where smaller (proto-)galaxies/haloes merge into larger ones (Lacey & Cole 1993; Naab & Ostriker 2017). Each galaxy will have a unique star formation history and hence also a unique chemical evolution history. Different elements are released to the inter-stellar medium by stars with different masses and therefore on different timescales (Arnett 1996; Nomoto et al. 1997). This means that the elemental abundances are able to tell us about the past history of the gas that the stars formed out of. Low-mass stars retain, in their outer atmospheres, an imprint of the composition of the gas from which they formed (Lambert 1989; Freeman & Bland-Hawthorn 2002). By analysing the spectra of such stars we can trace the chemical evolution of a stellar population over time. One important aspect of star formation is that it proceeds faster in heavier systems and slower in smaller systems (Matteucci & Greggio 1986). This in turn means that smaller galaxies that merged with the Milky Way have different elemental abundance patterns compared to the stars that formed in situ in the large galaxy. Several elements are affected but it has been shown that the abundance of aluminum relative to iron is empirically lower in local dwarf galaxy or accreted stellar populations over a range of iron abundances \( -2.0 < [\text{Fe/H}] < 0.0 \), Hawkins et al. 2015; Hasselquist et al. 2019, 2021). Thus, we infer that stars in galaxies, like the Milky Way, contain in their motions and elemental abundances tracers of past events and can be used to disentangle merger remnants from stars that formed in the main galaxy.

The merger history of the Milky Way is generally understood to be more visible in the stellar halo as the fraction of in situ stars is lower than in the disk (Helmi 2020). The advent of the ESA astrometric satellite Gaia (Gaia Collaboration et al. 2018) has enabled astronomers to find completely new structures in the halo, such as the Gaia-Enceladus-Sausage that is believed to be the dissolved stellar population of a massive accretion event (Helmi et al. 2018; Belokurov et al. 2018; Myeong et al. 2019; Feuillet et al. 2020).

However, simulations show that mergers may be important also for the build-up of the cool stellar disks (Read et al. 2008; Gómez et al. 2017). So far, the empirical evidence for
Table 1. APOGEE fields removed from consideration

| Field          | DRACU |
|---------------|-------|
| 47TUC         |       |
| FL_2020       |       |
| LMC           |       |
| M22           |       |
| M53           |       |
| M92           |       |
| M2420         |       |
| N5634SRG2-RV-btx |      |
| N752_btx      |       |
| ORPHAN-       |       |
| Sgr           |       |

Note. — Strings corresponding to the APOGEE DR17 parameter FIELD. The asterisk (*) is used as a wild card character, indicating multiple possible names.

Table 2. APOGEE programs removed from consideration

| Program Name         | Programs Removed |
|----------------------|------------------|
| Drout_18b            | Fernandez_20a    |
| clusters_gc2        | clusters_gc3     |
| halo_stream          | kollmeier_19b    |
| stutz_18b            | magclouds        |

Note. — Strings corresponding to the APOGEE DR17 parameter PROGRAMNAME. We list only unique programs but some stars belong to multiple programs.

significant merger remnants present in the Milky Way stellar disk is inconclusive (Ruchti et al. 2014, 2015). With the arrival of the Gaia parallaxes and proper motions for over a billion stars (Gaia Collaboration et al. 2018) in combination with radial velocity data for bright stars from Gaia and for fainter stars from ground-based stellar spectroscopic surveys, it is now feasible to study how stars move in the Milky Way. Such studies have successfully found accreted populations in the stellar halo, such as Gaia-Enceladus-Sausage and many smaller systems, as well as new streams in the disk (Necib et al. 2020; Ratzenbäck et al. 2020). These potential mergers present in the disk are either on non-circular orbits, very young, or present only in the outer parts of the disk. To find mature merger remnants in the stellar disk with disk-like, circular orbits is a more subtle task where we need additional information in the form of elemental abundances (Ruchti et al. 2015; Necib et al. 2020). Such data is provided by large ground-based, high-resolution, spectroscopic surveys, such as APOGEE (Majewski et al. 2017), the Gaia-ESO Survey (Gilmore et al. 2012; Randich et al. 2013), and GALAH (De Silva et al. 2015).

In this paper we make use of the astrometric data from the Gaia satellite in combination with data from APOGEE and the literature to hunt for accreted populations in the stellar disk. We supplement the APOGEE observations with a small sample of disk RR Lyrae stars, which are known to be old, that have low measured aluminum abundances and so may be associated with an accreted population, giving an estimate of age (Liu et al. 2013).

2. DATA AND METHODS

2.1. Stellar data from APOGEE DR17

2.1.1. Spectroscopic data

We make use of high-quality elemental abundances for 136701 red giant star from APOGEE Data Release 17 (APOGEE DR17, Majewski et al. 2016; Abdurro’uf et al. 2022) and Gaia Early Data Release 3 (Gaia EDR3, Gaia Collaboration et al. 2016, 2021) to hunt for merger remnants in the Milky Way stellar disk. The sample was selected to contain only stars with \( \sigma_\pi / \pi < 0.2 \). For quality control of the stellar parameters and elemental abundances, the following selection criteria for the spectroscopic data were applied:

- \( \text{SNREV} > 80 \)
- \( \text{AL_FE_FLAG} = 0 \)
- \( \text{TEFF} < 6000 \text{ K} \)
- \( \text{TEFF} > 4000 \text{ K} \)
- \( \text{LOGG} < 2.8 \)
- Remove any \( \text{VERY_BRIGHT_NEIGHBOR} \) and \( \text{PER-SIST_HIGH} \) bit set in STARFLAG
- Remove any \( \text{STAR_BAD} \), \( \text{CHI2_BAD} \), \( \text{M_H_BAD} \), and \( \text{CHI2_WARN} \) bit set in ASPCAPFLAG
- Remove duplicate observations of a single target that have bit 4 of \( \text{EXTRATARG} \) set

The upper effective temperature limit was imposed to remove stars at the hot edge of the main stellar atmospheric model grids used in the APOGEE analysis. For some of
these stars, the effective temperatures derived have preferentially discrete values. The lower effective temperature limit was imposed to remove cool red giant stars with suspected problems with the derivation of the aluminium and magnesium elemental abundances. The sample was further limited to giant stars in order to avoid any possible effects of an over-density of stars seen in the [Al/Fe] of metal-rich dwarfs stars. For more details on the APOGEE DR17 data quality see the SDSS DR17 documentation available on the web\(^1\) and a detailed discussion of DR16 in Jönsson et al. (2020).

The dataset has been cleared of all fields and programs targeting known stellar clusters, accreted stellar populations, and stars outside the Milky Way (Santana et al. 2021; Beaton et al. 2021). The full lists of the removed fields and program names are given in Tables 1 and 2, respectively.

2.1.2. Calculation of kinematic data

Astrometric measurements from Gaia EDR3 are available for the APOGEE sample and the RR Lyrae stars (see Sect. 2.2). We use the more precise APOGEE spectroscopic radial velocity measurements when calculating kinematics for the APOGEE sample. Galactic positions and velocities are calculated for all stars using Astropy (Astropy Collaboration et al. 2013a, 2018a) and galpy (Bovy 2015). We use the actionAngleStaeckel approximation (Bovy & Rix 2013; Binney 2012) with the MWPotential14 Milky Way potential (Bovy & Rix 2013), delta of 0.4, and default values for other parameters. The mean uncertainties for our sample are 0.030 km s\(^{-1}\) in radial velocity, 0.020 mas year\(^{-1}\) in RA proper motion, and 0.018 mas year\(^{-1}\) in Dec proper motion. We expect the resulting uncertainties on the calculated kinematics to be small, specifically the uncertainty in rotational velocity (V), which we use as a selection parameter, is \(\sim 10\) km s\(^{-1}\). The photogeometric distance from Bailer-Jones et al. (2021) is used for all stars.

2.1.3. Identification of the population

Through the following investigation, we have identified “disk” stars to have [Fe/H] \(\sim -0.8\) and V \(> 110\) km s\(^{-1}\). We first looked for stars with low-[Al/Fe] and disk-like metallicities ([Fe/H] \(\sim -0.8\)). Fig. 1a shows that such stars exist and are identified as black points. We define a low-[Al/Fe] star to have [Al/Fe] \(< -0.2\). This cut is somewhat arbitrary but is informed by the locus of accreted stars at lower metallicities found in previous studies (Hawkins et al. 2015; Das et al. 2020; Feuillet et al. 2021).

The properties of these stars are further explored in Fig. 1b,c and Fig. 2. In these figures, the cleaned APOGEE DR17 data is shown as the orange-scale density and yellow points; low-[Al/Fe], low metallicity stars ([Al/Fe] \(< -0.2\), [Fe/H] \(\sim -0.8\) are shown as gray triangles; low-[Al/Fe] disk-like stars are shown as black points; low-[Al/Fe] stars with disk-like metallicity but halo-like velocity are shown as pink points; and the RR Lyrae sample is shown as blue points.

We see that stars identified as “disk-stars” using a cut in the V - metallicity plane (V \(> 110\) km s\(^{-1}\), Fig. 2a) follow the typical thin disk trend for [Mg/Fe] (Fig. 1b) and that they are essentially confined to the plane of the Milky Way (Fig. 2b).

\(^1\) https://www.sdss.org/dr17/
These stars are also separate from the halo-like accreted stars in [Mg/Mn]-[Al/Fe] space, Fig. 1c. Known accreted halo stellar populations, such as Gaia-Sausage-Enceladus, have been found to occupy a distinct region of this elemental abundance space (e.g. Das et al. 2020). The dotted lines in Fig. 1c show the approximate separation of accreted, thick disk, and thin disk stars in this space. We note that previous studies have included only the halo-like stars with [Mg/Mn] > 0.1 as the accreted region. These chemical, spatial, and kinematics properties give us confidence that we have identified a sample of stars that are kinematically integrated with the disk, have anomalously low aluminum abundances, but are chemically distinct from previously identified accreted halo populations.

2.1.4. Checking that the low-[Al/Fe] abundances are real

To check if the low-[Al/Fe] measurements for stars with disk-like metallicities are robust and not the product of problems in the elemental abundance determination we performed an ocular inspection of the stellar spectra of all the low-[Al/Fe] stars with [Fe/H] > −0.8. We compared each low-[Al/Fe] spectrum with the spectrum of another star with the same stellar atmospheric parameters but with ordinary [Al/Fe] values. Fig. 3 shows two examples of these comparisons. They show that indeed the aluminum lines in the low-[Al/Fe] stars, marked by the vertical dotted lines, are shallower than in the stars with ordinary [Al/Fe] values. This comparison also shows that our finding is not the result of NLTE effects that may not have been accounted for by the APOGEE DR17 analysis. The direct comparison of stars with the same stellar parameters shows the difference to be real.

In Fig. 4 we show the APOGEE stars identified as low-[Al/Fe] stars ([Al/Fe] < −0.2) in the log g − Teff plane with the full APOGEE sample in gray for comparison. It is clear that the more metal-rich disk-like stars have cooler temperatures whilst the halo like stars are warmer, indicating a color-difference such that the halo is blue and the disk red. The color-coding indicates the signal-to-noise ratio (SNR) in the APOGEE spectra used for the abundance analysis. As can be seen, the spectra have good SNR.

We have also inspected the derived abundances as a function of Teff, log g, SNR, and microturbulence and find no obvious trends for any of the APOGEE subsamples used.

To summarize, the spectra for the low-[Al/Fe] stars are of good quality and we have no reason to believe that the results are the result of poor quality spectra. Combined with the visual inspection of all the metal-rich low-[Al/Fe] stars, we have weeded out all spectra that were not reliable and what remains is a clean sample.

2.2. Sample of RR Lyrae variables

2.2.1. Spectroscopic data and population identification

RR Lyrae variable stars are known to be old and are often used to characterize accreted populations in the Milky Way (Dambis et al. 2013). Liu et al. (2013) identify a sample of 23 RR Lyrae stars belonging to the disk of the Milky Way. To complement the sample of low-[Al/Fe] APOGEE disk stars, we make use of this RR Lyrae sample. We select the nine stars with aluminum measurements to use in our analysis. Table 3 lists the sub-sample and compiled parameters used in this work. The [Fe/H], [Mg/Fe], [Al/Fe], and [Mn/Fe] abundance ratios are derived by Liu et al. (2013). For comparison, we include [Fe/H] and [α/Fe] values compiled in Marsakov et al. (2019). Four of the stars have identical [Fe/H] in the two studies. In those cases, the magnesium and α abundances (calculated as the average of magnesium, calcium, silicon, and titanium) are also almost identical. For four stars there is
Figure 3. Observed spectra for two pairs of stars illustrating the reality that the aluminum lines are weaker in the stars with low-[Al/Fe]. In each panel we show two stars with similar stellar parameters. The red spectra have [Al/Fe] values typical of the stellar disk, whilst the black spectra have low [Al/Fe] values. The blue line shows the spectrum of the low-[Al/Fe] star divided by that of the [Al/Fe]-normal star, emphasizing the difference in the strength of the aluminum lines, indicated by the vertical dotted lines, that are otherwise remarkably similar.

Table 3. Summary of available data for the nine known RR Lyrae variables with measured aluminum abundances. Elemental abundances are from Liu et al. (2013) (Liu) and Marsakov et al. (2019) (Marsakov). Masses are taken from (Marsakov et al. 2019). We indicate which stars have Gaia radial velocities available. For those without Gaia radial velocities we use values from Layden (1994). The last column indicates if we identify the star as an accreted star based on elemental abundance criteria.

| Star    | [Fe/H]  | [Mg/Fe] | [Al/Fe] | [Mn/Fe] | Mass [M⊙] | Gaia RV | Layden RV | Accr. |
|---------|---------|---------|---------|---------|-----------|---------|-----------|-------|
| Aa Aql | −0.32   | −0.32   | 0.21    | 0.18    | −0.18     | −0.31   | 0.56      | ✓     |
| CN Lyr  | −0.04   | −0.04   | −0.05   | −0.01   | −0.14     | −0.20   | 0.54      | ✓     |
| DM Cyg  | 0.03    | 0.03    | −0.01   | −0.06   | −0.23     | −0.13   | 0.54      | ✓     |
| DX Del  | −0.14   | −0.31   | 0.08    | −0.02   | −0.19     | −0.18   | 0.54      | ✓     |
| KX Lyr  | −0.27   | −0.42   | 0.12    | 0.09    | −0.04     | −0.17   | 0.58      | ✓     |
| RS Boo  | −0.12   | −0.21   | 0.07    | 0.03    | −0.16     | −0.16   | 0.53      | ✓     |
| SW And  | −0.07   | −0.22   | 0.07    | 0.00    | −0.11     | −0.15   | 0.53      | ✓     | (√)    |
| TV Lib  | −0.43   | −0.43   | 0.30    | 0.29    | 0.23      | −0.23   | 0.54      | ✓     |
| V445 Oph | 0.14    | 0.11    | 0.04    | −0.05   | −0.20     | −0.09   | 0.52      | ✓     |

Table 3. Summary of available data for the nine known RR Lyrae variables with measured aluminum abundances. Elemental abundances are from Liu et al. (2013) (Liu) and Marsakov et al. (2019) (Marsakov). Masses are taken from (Marsakov et al. 2019). We indicate which stars have Gaia radial velocities available. For those without Gaia radial velocities we use values from Layden (1994). The last column indicates if we identify the star as an accreted star based on elemental abundance criteria.

| Star    | [Fe/H]  | [Mg/Fe] | [Al/Fe] | [Mn/Fe] | Mass [M⊙] | Gaia RV | Layden RV | Accr. |
|---------|---------|---------|---------|---------|-----------|---------|-----------|-------|
| AA Aql  | −0.32   | −0.32   | 0.21    | 0.18    | −0.18     | −0.31   | 0.56      | ✓     |
| CN Lyr  | −0.04   | −0.04   | −0.05   | −0.01   | −0.14     | −0.20   | 0.54      | ✓     |
| DM Cyg  | 0.03    | 0.03    | −0.01   | −0.06   | −0.23     | −0.13   | 0.54      | ✓     |
| DX Del  | −0.14   | −0.31   | 0.08    | −0.02   | −0.19     | −0.18   | 0.54      | ✓     |
| KX Lyr  | −0.27   | −0.42   | 0.12    | 0.09    | −0.04     | −0.17   | 0.58      | ✓     |
| RS Boo  | −0.12   | −0.21   | 0.07    | 0.03    | −0.16     | −0.16   | 0.53      | ✓     |
| SW And  | −0.07   | −0.22   | 0.07    | 0.00    | −0.11     | −0.15   | 0.53      | ✓     | (√)    |
| TV Lib  | −0.43   | −0.43   | 0.30    | 0.29    | 0.23      | −0.23   | 0.54      | ✓     |
| V445 Oph | 0.14    | 0.11    | 0.04    | −0.05   | −0.20     | −0.09   | 0.52      | ✓     |

a large difference in the [Fe/H] values in the two studies. In this work we use exclusively the data from Liu et al. (2013), which presents data from an homogeneous analysis.

To investigate if any of the selected RR Lyrae variables are accreted disk stars we make use of two elemental abundance diagnostics: 1) A cut in [Al/Fe] at −0.14 dex, Fig. 1a, and 2) the diagnostic plot in the [Mg/Mn] - [Al/Fe] plane, Fig. 1c, proposed by Hawkins et al. (2015). The exact cut in [Al/Fe] must remain arbitrary, in particular since we have no way of knowing if the APOGEE DR17 and the data from Liu et al. (2013) are on the same absolute scale. We have chosen to set the cut at −0.14 dex for the RR Lyrae variables. Accreted stellar populations have been empirically found to occupy a different region of the [Mg/Mn] - [Al/Fe] abundance plane.
than Milky Way stellar populations (Das et al. 2020). There is some theoretical motivation for this (see Hawkins et al. 2015) and initial chemical evolution models confirm a different evolutionary sequence through this space for a population similar to the Gaia-Sausage-Enceladus (Horta et al. 2021).

It should be noted that some elemental abundances can change in RR Lyrae variables as a function of the pulsation phase (For et al. 2011; Liu et al. 2013). Examining Table 6 in Liu et al. (2013) we see that some abundances, for example manganese and magnesium, remain stable throughout the phases whilst others may have some changes, notably aluminum. In the two stars with [Al/Fe] measurements at different phases, the variation in [Al/Fe] is as large as 0.15 dex. Our understanding of this effect is that the change in abundance, if anything, makes it harder to identify the accreted stars (i.e. they may have higher [Al/Fe] in one phase). Thus our identification of low-[Al/Fe] variable stars should be conservative.

A few of the RR Lyrae in Table 3 are not included in our sample of accreted stars. Of the nine stars one, TV Lib, shows thick disk elemental abundances with elevated [Mg/Fe] and [Al/Fe]. We do not associate KX Lyr with the accreted sample as it has approximately solar [Al/Fe]. The [Al/Fe] value for SW And falls just short of our (arbitrary) cut at −0.14 dex, we therefore include it in our accreted sample, but use caution when drawing conclusions that may be influenced by its presence. AA Aql, has low [Al/Fe] but higher [Mg/Fe]. When examined in the [Mg/Mn]-[Al/Fe] plane the star clearly falls in the accreted halo region (see Fig. 1c). This star also has a rotational velocity (V) more associated with thick disk/halo kinematics than with thin disk kinematics (Table 3). The remaining five stars have a high [Fe/H], centered near solar values and all have low-[Al/Fe] and fall in the disk region in Fig. 2a. Our final classification of accreted and non-accreted for the nine RR Lyrae stars can be found in Table 3. In total we are able to identify six stars with low-[Al/Fe], suggesting they could be accreted, with a seventh very close to the cut in [Al/Fe]. Six of the seven have kinematics consistent with the thin disk.

2.2.2. Estimating masses of RR Lyrae variable stars

RR Lyrae variables are stars that have evolved from the main sequence, along the giant branch and have descended onto the horizontal branch and are currently crossing the instability strip (a good explanation of this from the point of view of population synthesis is given in Savino et al. 2020). If we know the mass of an RR Lyrae variable and how much mass it loses along the red giant branch then we can infer its mass on the main-sequence. This mass relates directly to the age of the stellar population of which that the RR Lyrae variable is a member.

Mass-loss along the red giant branch is difficult to measure, but recent studies enabled by a large data-set for globular clusters and dwarf spheroidal galaxies have been able to show that the mass-loss along the red giant branch measured empirically is dramatically different from many of the older theoretical estimates (Tailo et al. 2020; Savino et al. 2020).

Current mass estimates are available for all stars from Marsakov et al. (2019). We note that the [Fe/H] values for two of the accreted stars are not the same in the study that derived the elemental abundances and the compilation used to derive the stellar masses (compare Table 3). However, the differences are not large enough to change the masses of these stars drastically and certainly not large enough to make the stars much heavier (Marsakov et al. 2019).

The current masses for the RR Lyrae variables in our sample are all around 0.5 to 0.6 M_☉ (Table 3). Using the recent mass-loss laws by Tailo et al. (2020) we estimate the mass-loss for our low-[Al/Fe] RR Lyrae variables and find that their turn-off masses are not in excess of 0.85 M_☉. Such masses indicate an old stellar population, approximately 10-12 Gyr.

2.3. Kinematic data

All nine RR Lyrae stars have astrometric measurements from Gaia EDR3 are available. Six of the RR Lyrae stars have Gaia RVS measurements. We prefer to use Gaia RV measurements when possible to keep the dataset homogeneous and because multiple measurements, such as done by Gaia, reduces the uncertainty in the mean RV of these pulsating stars. The RV uncertainty is 4-5 km s⁻¹. For the remaining three RR Lyrae, the radial velocities are taken from...
new data table of Layden (1994), which uses at least two measurements. The RV uncertainty is 15-20 km s\(^{-1}\). The distance for all RR Lyrae is calculated from the Gaia parallax measurement using the astropy Distance function.

Fig. 2b shows the Galactic positions of the low-[Al/Fe] stars in comparison to the full sample. We see that the stars with disk-like kinematics (Fig. 2a) are spread across the whole disk, but are mainly confined to the plane. Of the APOGEE stars with disk-like kinematics, 12 stars out of 92 low-[Al/Fe] have current vertical positions larger than 1 kpc from the Galactic plane. For low-[Al/Fe] stars with halo kinematics these numbers are 1873 stars out of 2077 stars.

The orbits for the low-[Al/Fe] stars were integrated using galpy in the MWPotential14 Milky Way potential (Bovy & Rix 2013) for 500 Myr. The orbital trajectories of the low-[Al/Fe] stars are shown in Fig. 5a with disk stars (blue) and halo stars (black) compared to the RR Lyrae stars (red). Fig. 5 also shows cumulative histograms of the orbital eccentricity (b) and z max (c) of the APOGEE sub-samples as well as the RR Lyrae. The orbits of the low-[Al/Fe] stars identified as belonging to the cool disk are confined to the Galactic plane, further strengthening their association with the disk. These stars are seen to be on mainly circular orbits with no orbits reaching inside about \(R_{\text{Gal}} = 4\) kpc.

3. RESULTS AND DISCUSSION

3.1. Accreted disk stars identified in APOGEE DR17

Fig. 1 shows three plots of elemental abundance data for our sample as well as the RR Lyrae stars with likely accreted origins. Panel a in Fig. 1 shows [Al/Fe] as a function of [Fe/H]. This plot is used to define the low-[Al/Fe] stars, which we propose may have accreted origins. Empirically, several dwarf galaxies and known accreted stellar populations in the Milky Way have low [Al/Fe] abundances. This is nicely demonstrated in Hasselquist et al. (2021, see their Fig. 5), which shows APOGEE elemental abundances of the Large Magellanic Cloud, Small Magellanic Cloud, Gaia-Sausage-Enceladus accreted population, Sagittarius dwarf galaxy, and Fornax dwarf galaxy in comparison to Milky Way disk stars with a similar range of effective temperature and surface gravity. These five ex situ stellar populations all have [Al/Fe] abundance ratios well below the Milky Way at a given [Fe/H]. Of particular relevance to our study is the Sagittarius dwarf galaxy, which maintains a low [Al/Fe], \(-0.4\) dex, even at metallicities approaching solar values. This supports the possibility of low-[Al/Fe] stars forming at high [Fe/H] in a dwarf galaxy environment.

Beyond using [Al/Fe] alone as an indicator of ex situ origins, the [Mg/Mn] vs [Al/Fe] space has been identified as holding high diagnostic power in this effort (Das et al. 2020; Hawkins et al. 2015; Horta et al. 2021). Although the cause of the low [Al/Fe] abundance ratios found in ex situ populations is not well understood, the theoretical motivation for using the [Mg/Mn] vs [Al/Fe] elemental abundance space as detailed by Hawkins et al. (2015) and Das et al. (2020) can inform our discussion. We therefore seek some understanding in the known formation channels of aluminum, magnesium, and manganese (see Kobayashi et al. (2020) for a detailed modeling of element production in a Milky Way environ-
Magnesium is produced primarily in type II supernovae (SNII) and in a small amount by Asymptotic Giant Branch (AGB) stars. Manganese is primarily produced in type Ia supernovae (SNIa), with small contributions from SNII and AGB stars. Aluminum is produced primarily in SNII with small contributions from AGB stars. In contrast to the low-[Al/Fe] disk stars presented in this work, the five dwarf galaxy or accreted populations discussed in Hasselquist et al. (2021) maintain [Mg/Fe] abundance ratios below that of the Milky Way disk at any given [Fe/H]. McWilliam et al. (2013) conclude that the low [α/Fe] abundance ratios in the Sagittarius dwarf galaxies are an indication of a lack of high-mass stars or a top-light initial mass function. They argue that the low [Al/Fe] supports this finding as aluminum is formed during hydrostatic carbon and neon burning in massive stars. Woosley & Weaver (1995).

Panel b of Fig. 1 shows [Mg/Fe] as a function of [Fe/H]. The low-[Al/Fe] stars with [Fe/H] less than about -0.6 dex essentially all fall on the lower [Mg/Fe] sequence, which has been associated with accreted populations generally (Nissen & Schuster 2010; Hayes et al. 2018) and specifically the Gaia-Enceladus-Sausage and Sequoia merger events (Helmi 2020; Matsumo et al. 2020; Feuillet et al. 2021). At higher [Fe/H] the low-[Al/Fe] stars either fall on the thin disk sequence or below the main sample. Only two APOGEE stars and one RR Lyrae fall on what is commonly referred to as the thick disk trend ([Mg/Fe] > 0.2 dex). Hasselquist et al. (2021) find that the Sagittarius population reaches similarly high [Fe/H] and low [Al/Fe], but does not have [Mg/Fe] consistent with the Milky Way thin disk.

Fig. 2 shows [Fe/H] as a function of the tangential velocity (V) for all low-[Al/Fe] stars. The low-[Al/Fe] stars fall into two groups; one with typical disk-like kinematics and one with halo-like kinematics. The latter are centered around \( V = 0 \) km s\(^{-1}\), in fact they are somewhat retrograde, consistent with findings of the kinematics of the major remnants in the Milky Way halo (Helmi 2020; Feuillet et al. 2020). We have calculated the orbits of the low-[Al/Fe] stars and find that the stars with [Fe/H] greater than about –0.8 dex all have orbits that are kinematically cool, i.e., confined to the Galactic plane, and with mainly circular orbits, see Fig. 5.

The fraction of accreted stars sitting in the disk is a very difficult parameter to estimate because of selection effects in the APOGEE survey and our selection of this particular dataset. In addition, although we have identified a population of stars that are likely accreted based on their low-[Al/Fe], there is an unknown number of merger events contributing to this population. Given the small number of stars we have robustly identified as low-[Al/Fe] and disk-like out of the full APOGEE sample, the fraction of accreted stars in the Milky Way disk that can be identified through [Al/Fe] is likely very small.

To roughly estimate this fraction, we consider only stars with \( 6 < R < 11 \) kpc and \( |z| < 0.5 \) kpc in order to reduce possible spatial biases from the APOGEE lines of sight. Within this spatial region, we limit our estimate to stars with [Fe/H] > –0.8 and \( V > 110 \) km s\(^{-1}\), as was required of the low-[Al/Fe] disk stars. The fraction of these stars that have [Al/Fe] < –0.2 is 0.073%. We tested how this fraction changes as a function of galactocentric radius and [Fe/H] as well as effects of removing any z constraint. The resulting low-[Al/Fe] fraction varies between 0.11% and 0.046%, with no continuous trends. We stress that these fractions are calculated with very small numbers of low-[Al/Fe] stars and so are very uncertain. The conclude that the stars we identify as accreted disk stars represent approximately 0.07% of the APOGEE disk sample.

3.2. Age dating the accreted component and the time of the merging

Our main sample consists of red giant branch stars. Such stars are difficult to determine an age for without access to asteroseismology (Montalbán et al. 2021). Another possibility to obtain an age for the newly identified population would be to find stars associated with this population but currently in an evolutionary stage that allow for them to be dated (Soderblom 2010). Instead of directly calculating ages for the red giant stars in our main sample, we have found a sample of intrinsically old stars that are kinematically and chemically associated with the low-[Al/Fe] disk giants.

Recent studies have found RR Lyrae variables with kinematics typical of the cool thin disk and metallicities ranging from a tenth of that of the sun to solar values (Marsakov et al. 2019; Prudil et al. 2020; Iorio & Belokurov 2021). In Sect. 2.2.1 we describe the construction of a small sample of RR Lyrae variables that are associated with the kinematic thin disk and have elemental abundances available in the literature. Some of these stars show the low-[Al/Fe] characteristic for our disk-like accreted sample.

In Sect. 2.2.2 we derive the masses at turn-off for the RR Lyrae variables. We find that they all have masses consistent with an old stellar population with an age around 10 Gyr. With an extreme mass-loss of 0.5 M\(_{\odot}\) the stars would be somewhat younger, but still several billion years old (Bono et al. 1997). We should expect fewer metal-rich RR Lyrae variables than metal-poor as the mass-range for when a star is in the instability strip is dependent on metallicity, being very small for the metal-rich stars and requiring significant mass-loss, perhaps as extreme as 0.5 M\(_{\odot}\) to become a variable star (see Taam et al. 1976).

By using kinematic data and elemental abundances we have been able to associate stars of known ages (i.e. our RR Lyrae sample) with our newly identified accreted stellar population (i.e. our disk-like, low-[Al/Fe] sample). These RR Lyrae
stars are all old. This implies that the stellar population that was accreted formed its stars before that time.

Another way to age-date a stellar population in the stellar disk is to study the velocity dispersions (Nordström et al. 2004; Sharma et al. 2021). The idea is that stars that formed in the stellar disk and via encounters with other objects, their velocities change over time such that older stars have more “heated” orbits. Using the largest kinematic-only (i.e. no elemental abundances) sample of RR Lyrae variables it has been shown that their velocity dispersions are consistent with models indicating that the sample has an age of about 2 billion years (Iorio & Belokurov 2021). This finding appears incompatible with our new accreted disk stellar population. However, what is measured based on the kinematics is not the age of the stars but the age of the population since it became part of a cool stellar disk. Thus, we argue that the two findings are compatible in a scenario where a stellar population consisting of stars formed up to 10 billion years ago merged with the Milky Way stellar disk about 2 billion years ago. The population was dragged into the plane, onto very circular orbits and has since been heated.

Is such a scenario plausible? Simulations show that it is possible to accrete stellar systems into the Milky Way and, given the right inclination of the merger, via plane-dragging deposit the stars into the stellar disk on disk-like, essentially circular orbits (Read et al. 2008; Gómez et al. 2017). However, it is difficult to make a quantitative comparison between our data and such models due to the small observational sample and the resolution of the models.

Donlon et al. (2020) present evidence from stellar overdensity shell structures of a dwarf galaxy passage through the Milky Way center 2.7 billion years ago, suggesting the progenitor galaxy could have been the Gaia-Sausage-Enceladus or another unknown galaxy. Such timing is compatible with the “heating age” of the RR Lyrae.

It is difficult to assess the size of the galaxy that merged with ours and later deposited its stars into the local stellar disk. Mass-metallicity relations that evolve with redshift would, because of the high metallicity of the stars, indicate a merger as massive as $M_*=10^{11}$ to $10^{12} \, M_\odot$ (Ma et al. 2016). This assumes that the merging galaxy retained all of its stars at the time of the merger. Assuming that the merger took place about 2 billion years ago and the stars are up to 10 billion years old, this leaves about 8 billion years of evolution from formation to merger. This means that the merging galaxy continued to evolve in the Local Group and thanks to its proximity to the Milky Way it may have been stripped of some of its stars and only a smaller portion of it merged with the Milky Way disk.

4. CONCLUSIONS AND OUTLOOK

Using elemental abundances from APOGEE DR17 (Majewski et al. 2016; Abdurro’uf et al. 2022) we have identified a sample of stars that have chemical signatures of an accreted origin and also have kinematics similar to the Milky Way stellar disk. We have further identified a small sample of RR Lyrae variables that share the properties with this possibly-accreted component. The RR Lyrae variables offer the possibility to obtain an independent age estimate of this new stellar component. We find that most likely we are looking at an ancient stellar population that formed outside the Milky Way and was later accreted and dragged into the stellar disk. Only by combining elemental abundances, kinematics and different age dating techniques are we able to confirm its existence.

Looking forward there are both on-going and up-coming large massive spectroscopic surveys that will enable us to identify larger samples of stars with chemical signatures of an accreted origin. In particular, the 4MOST survey will target several million disk stars, including a specific survey to target RR Lyrae stars. At the same time, theoretical models of aluminum enrichment are needed to improve our understanding of how a galactic system might maintain low [Al/Fe] at high [Fe/H].

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