The SkyMapper-Gaia RVS view of the Sausage – an investigation of the metallicity and mass of the Milky Way’s last major merger

Diane K. Feuillet,1⋆ Sofia Feltzing,1 Christian L. Sahlholdt,1 Luca Casagrande2,3
1Lund Observatory, Department of Astronomy and Theoretical Physics, Box 43, SE-221 00 Lund, Sweden
2Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, The Australian National University, ACT 2611, Australia
3ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D)

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ABSTRACT

We characterize the Gaia-Sausage kinematic structure recently discovered in the Galactic halo using photometric metallicities from the SkyMapper survey, and kinematics from Gaia radial velocities measurements. By examining the metallicity distribution functions (MDFs) of stars binned in kinematic/action spaces, we find that the $\sqrt{J_R}$ vs $L_z$ space allows for the cleanest selection of Sausage stars with minimal contamination from disc or halo stars formed in situ or in other past mergers. Stars with $30 \leq \sqrt{J_R} \leq 50 \ (\text{kpc km s}^{-1})^{1/2}$ and $-500 \leq L_z \leq 500 \ \text{kpc km s}^{-1}$ have a narrow MDF centered at $[\text{Fe/H}] = -1.17 \ \text{dex}$ with a dispersion of 0.34 dex. This $[\text{Fe/H}]$ estimate is more metal-rich than literature estimates by 0.1–0.3 dex. Based on the MDFs, we find that selection of Sausage stars in other kinematic/action spaces without additional population information leads to contaminated samples. The clean Sausage sample selected according to our criteria is slightly retrograde and lies along the blue sequence of the high $V_T$ halo CMD dual sequence. Using a galaxy mass-metallicity relation derived from cosmological simulations and assuming a mean stellar age of 10 Gyr we estimate the mass of the Sausage progenitor satellite to be $10^{8.85-9.85} \ M_\odot$, which is consistent with literature estimates based on disc dynamic and simulations. Additional information on detailed abundances and ages would be needed for a more sophisticated selection of purely Sausage stars.

Key words:

1 INTRODUCTION

The Milky Way halo contains evidence of past mergers in the form of stellar streams (e.g. Belokurov et al. 2006). These overdensities of stars on the sky move together and are the remnants of dwarf galaxies that accreted onto our Galaxy, contributing to the stellar halo (e.g. Helmi & White 1999). However, the origins of the diffuse stellar halo population remained unclear. Many observational studies have advocated for a dual nature of the halo (e.g. Carollo et al. 2007; Nissen & Schuster 2010), suggesting perhaps there exists a major accreted population (e.g. Hayes et al. 2018) that is spatially integrated into the in situ classical halo (see Eggen et al. 1962). Most cosmological simulations produce Milky Way-like galaxies with halos containing a significant accreted component (e.g. Cooper et al. 2010).

Gaia Data Release 2 (DR2, Gaia Collaboration et al. 2018a) has greatly expanded our view of the Milky Way by providing precise astrometry to millions of stars. Significant substructures, beyond the visual overdensities of the stellar streams, have been identified in kinematic space which suggest at least one major merger event contributed to building the Milky Way halo. The largest kinematic structures recently found are the Gaia-Sausage (hereafter Sausage, Belokurov et al. 2018) and Gaia-Enceladus (Helmi et al. 2018). The extend to which these structures represent the same accretion event is still unclear, however, there are some differences in their initial identification. The Sausage was first identified by Belokurov et al. (2018) in the $V_\phi$ vs $V_R$ velocity space as a ‘Sausage-like’ structure centered around $V_\phi \sim 0$ and extended in $V_R$. Using a suite of cosmologi-
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Gaia-Enceladus was first identified by Helmi et al. (2018) as stars in the inner halo with kinematics ranging from highly eccentric to highly retrograde, selected in $L_\text{z}$ and $E_\text{vir}$. Using APOGEE data, Helmi et al. (2018) find that these stars lie along an $[\alpha/Fe]$ vs $[Fe/H]$ track that is more metal-poor than the thin disc and lower in $[\alpha/Fe]$ than the thick disc. Helmi et al. (2018) find Gaia-Enceladus to have a mean $[Fe/H] \sim -1.6$ from APOGEE data and an age of 10-13 Gyr through color-magnitude isochrone fitting. They argue that a progenitor stellar mass of $6 \times 10^8 M_\odot$ is consistent with the chemical evolution sequence shown in the APOGEE data.

There have also been smaller kinematic substructures identified, such as the Sequoia event identified by Myeong et al. (2019) based on 10 high-energy, high-eccentricity globular clusters (Myeong et al. 2018). Myeong et al. (2019) argue that the Sequoia and Sausage are distinct accretion events that make up Gaia-Enceladus has identified by Helmi et al. (2018). The Sausage stars have high-energy, radial orbits and a mean $[Fe/H] \sim -1.3$ while the Sequoia stars are highly retrograde with a mean $[Fe/H] \sim -1.6$. Koppelman et al. (2019) use a clustering algorithm to identify several kinematic substructures in the high velocity stars. The main structures they identify are Gaia-Enceladus, the Sequoia, the Helmi Streams (Helmi et al. 1999), and two new structures with low-energy, retrograde orbits that they dub Thamnos 1 and 2. The Gaia-Enceladus structure selected with the clustering algorithm of Koppelman et al. (2019) is kinematically more confined than the Helmi et al. (2018) selection. In their Figure 2, the region of the Toomre diagram occupied by Gaia-Enceladus stars in Helmi et al. (2018) is now assigned to four different substructures. The revised Gaia-Enceladus selection by Koppelman et al. (2019) results in stars constrained to large $V_R$ with kinematics consistent with the Belokurov et al. (2018) Sausage. We hereafter refer to this kinematic structure in the Milky Way as the Sausage to avoid confusion with the Helmi et al. (2018) Gaia-Enceladus definition.

GaiaDR2 also revealed the existence of a double sequence in the Hertzsprung-Russell Diagram (HRD) of the high velocity halo (Gaia Collaboration et al. 2018b), which could be associated with the two halo groups noted by Ness & Schuster (2016). The two sequences are easily visible in both the dwarfs and the giants, but are more often studied using the giants, where they are designated as the red and blue sequences. Haywood et al. (2018) find that while the two sequences overlap in kinematic space, it is likely that the blue sequence is composed of accreted stars and the red sequence is composed of kinematically heated Milky Way stars, either the old thick disc (see Di Matteo et al. 2019) or ‘in situ’ halo (e.g. Zolotov et al. 2009). Sahlholdt et al. (2019) characterize the giants of the dual sequences using SkyMapper data and find that the blue sequence has a peak metallicity of $-1.4$ dex and the red sequence has a peak metallicity of $-0.7$ dex.

Most of the kinematic studies have had limited information on the metallicity of the structures. $[Fe/H]$ estimates have been made using small numbers of stars cross-matched with spectroscopic surveys (e.g. Helmi et al. 2018; Myeong et al. 2019) or using color-magnitude isochrone fitting to a population of stars (Gallart et al. 2019). However, to fully characterize a population, metallicities of individual stars in higher numbers are needed to avoid contamination and provide full metallicity distribution functions (MDFs). Another hurdle in studying these kinematic substructures is selecting clean populations. Samples of accreted stars selected using a large region of kinematic space can easily be contaminated by heated disc or ‘in situ’ halo stars. In this paper, we use the SkyMapper photometric metallicities determined by Casagrande et al. (2019), which includes 10 million GaiaDR2 stars, to explore the metallicity variations over the kinematic space containing possible Sausage stars.

2 DATA

The sample presented is a cross match of the SkyMapper Southern Sky Survey (Casagrande et al. 2019) with the GaiaDR2 Radial Velocity Spectrometer (RVS) catalogue (Gaia Collaboration et al. 2018a), resulting in ~900,000 stars with photometric $T_{\text{eff}}$, photometric $[Fe/H]$, and full 6 dimensional phase-space coordinates. Using GaiaRVS limits the sample to $G$-band magnitudes $\lesssim 13$, which limits the volume ($< 3$ kpc for red clump and $< 10$ kpc for luminous giants, assuming no extinction) but allows for full kinematic measurements. The present sample reaches $\sim 3.5$ kpc from the Sun, see Figure 1 panel b.

We use the distance estimates provided by Schönrich et al. (2019) using a parallax offset of 0.054 mas and a parallax error that is increased by 0.043 mas. The Schönrich et al. (2019) catalogue accounts for the full parallax offset, beyond the offset originally reported by the Gaia team at the time of DR2. Although distance catalogues using more complex distance estimation techniques, such as StarHorse (Queiroz et al. 2018), are available for our sample, we feel a simpler distance estimation method is reliable for such a nearby sample.

The extinction and reddening are derived using the $E(B-V)$ provided by SkyMapper (Casagrande et al. 2019) and the coefficients provided by Casagrande & VandenBerg (2018) to convert to Gaia magnitudes and colors. The de-reddened color magnitude diagram (CMD) of the full SkyMapper-RVS sample is shown in Figure 1 panel a. In this sample features such as the binary sequence, red giant branch bump, asymptotic giant branch bump, and red clump are clearly visible.

The photometric metallicities of the SkyMapper survey are known to have offsets for the metal-poor subgiant stars. As we are interested in characterizing the metallicity distribution of the sample in question, we limit our study to the giant stars. The blue line in Figure 1 panel a shows the giant selection. Only stars brighter than this line are used in this study, resulting in a sample of 372,000 stars. The mean $[Fe/H]$ uncertainty for the giant sample is 0.17 dex. Figure 1 also shows the $[Fe/H]$ vs distance distribution (panel b) and the $|z|$ vs $R_{\text{Gal}}$ distribution (panel c) for the giants only. As mentioned above, the $G \lesssim 13$ magnitude limit of GaiaRVS results in a sample reaching $\sim 3.5$ kpc from the Sun.

Full space velocities, actions, and orbits energy were calculated for the giant sample with galpy using the ‘MWPotential2014’ potential (Bovy 2015). Full orbit integrations were only performed for a representative sample of Sausage stars, see Appendix A. Figure 2 shows the kinematic distributions

\begin{figure}[h]
for the giant sample in four phase spaces typically explored in the literature: a) $\sqrt{J_R}$ vs $L_z$, b) $V_\phi$ vs $V_R$, c) $\sqrt{V_R^2 + V_Z^2}$ vs $V_\phi$, and d) $E_n$ vs $L_z$. In $\sqrt{J_R}$ vs $L_z$, the disc substructure can be seen between $L_z$ of 1.0 and 2.5, as discussed by Trick et al. (2019). $V_\phi$ vs $V_R$ is the space in which the ‘Sausage’ was first noted by Belokurov et al. (2018). A Sausage-like structure is clearly visible in the present sample as well. The $\sqrt{V_R^2 + V_Z^2}$ vs $V_\phi$ space is similar to a traditional Toomre diagram and shows an overdensity around $V_\phi = 0$, where Helmi et al. (2018) indicate the Gaia-Enceladus structure lies. $E_n$ vs $L_z$ has been used by several studies to select kinematic structures (e.g. Helmi et al. 2018; Myeong et al. 2018). We note that our $E_n$ values are not the same as other authors, these values are influenced by the choice of MW potential model. If the McMillan (2017) potential is used (as in e.g. Myeong et al. 2018), then the $E_n$ values are consistent with other studies and the shape our $E_n$ vs $L_z$ distribution is the same. Our sample does not include high $E_n$ stars at $L_z < 0$ as are seen in other studies, probably due to the limited volume sampled, therefore we cannot investigate possible Sequoia stars.

We also define a high-velocity sample in order to compare to the two sequences first noted by Gaia Collaboration et al. (2018b) and characterized using SkyMapper data by Sahlholdt et al. (2019). As in Gaia Collaboration et al. (2018b), we define tangential velocity as

$$V_T = 4.74/\sigma \sqrt{\mu_{\alpha*}^2 + \mu_\delta^2}$$

(1)

and select high-velocity stars as those with $V_T > 200 \text{ km s}^{-1}$.

The high velocity subsample contains 5000 stars, 4000 of which meet our giant selection criteria.

We cross match our clean Sausage sample, see selection details below, with the APOGEE (Majewski et al. 2017) and GALAH (De Silva et al. 2015) surveys, but not enough stars were found to provide significant characterization of the population.

3 ANALYSIS

In order to explore the SkyMapper-RVS giant sample and search for kinematic features, we inspect the kinematic distributions shown in Figure 2 binned by [Fe/H]. Figures 3 and 4 show the $\sqrt{J_R}$ vs $L_z$ and $E_n$ vs $L_z$, respectively, for six bins of [Fe/H]. A prominent feature that emerges is the high $J_R$ plume at $L_z \approx 0$ with $-0.7 < [\text{Fe/H}] < -1.7$. The plume can also be seen over a range of $E_n$.

We characterize the metallicity of this feature in Figure 5 by inspecting the cumulative metallicity distribution functions (CFDs) of stars binned in $\sqrt{J_R}$ vs $L_z$ space. The bins are selected with the intention of examining the symmetry around $L_z = 0$ and the contamination of the disc. Panel a shows the positions of the bins in $\sqrt{J_R}$ vs $L_z$ space, while panels b–e show the CDFs of bins with the same $J_R$. We performed this analysis using different $L_z$ limits with almost identical results. from these metallicity CDFs we select a ‘clean Sausage’ sample that is likely to contain minimal disc...
contamination. A similar analysis is done in $V_\phi$ vs $V_R$ velocity space, Figure 6, to characterize the [Fe/H] variations across the Sausage-like feature (Belokurov et al. 2018). Panel a shows bin placement and panels b – g show the CDFs and bins with the same $V_R$. For reference, the same analysis is done in $\sqrt{V^2_R + V^2_z}$ vs $V_\phi$ and $E_n$ vs $L_z$ space, shown in Figures B1 and B2, respectively.

Helmi et al. (2018) note that the Gaia-Enceladus structure is slightly retrograde. To investigate this in our sample, we calculate a running mean $L_z$ for the full SkyMapper-RVS giant sample using a bin of 1500 stars at $\sqrt{J_R} < 30$ (kpc km s$^{-1}$)$^{1/2}$ and 400 stars at $\sqrt{J_R} > 30$ (kpc km s$^{-1}$)$^{1/2}$, Figure 7. There is a small offset in mean $L_z$ at the transition from $\sqrt{J_R} < 30$ to $\sqrt{J_R} > 30$ due to the smaller bin size, but this offset is quite small and the trends of the two lines are consistent.

The SkyMapper survey does not have any selection limitations that would bias our sample. We do not impose a parallax cut, but the RVS magnitude limit will exclude metal-poor dwarfs from our sample as they are too faint. However, we have limited our analysis to the giants, therefore any metallicity bias should be minimal.
Figure 3. $\sqrt{J_R}$ vs $L_z$ action space log(density) distribution for single [Fe/H] subsamples. The [Fe/H] range of each panel is shown in the upper right corner.

Figure 4. $E_n$ vs $L_z$ log(density) distribution for single [Fe/H] subsamples. The [Fe/H] range of each panel is shown in the upper right corner.
4 RESULTS & EXPLORATION

4.1 SkyMapper-RVS giants

The full sample of SkyMapper-RVS giants is composed primarily of disc stars, as can be seen from the kinematics in Figure 2. This is expected from the limited volume of the sample. However, there are also a significant number of stars with retrograde motions and non-disc-like orbital properties. We focus our attention on these non-disc-like stars. We find a large Sausage-like structure present in the $V_φ$ vs $V_R$ space (panel b of Figure 2) around $V_φ \sim 0$, as first found by Belokurov et al. (2018). Similarly elongated features with non-rotating kinematics are present in the other panels of Figure 2. We therefore explore the characteristics of potential Sausage stars.

At [Fe/H] below $-1.2$ the kinematically cold disc population is no longer present while the retrograde and non-discy stars are present only below [Fe/H] of $-0.2$, see Figures 3 and 4. It is interesting that the distribution of our sample looks quite different from that of Myeong et al. (2018). This is likely because our sample does not extend very far into the halo. We again note that the $E_n$ values are different due to a different choice of MW potential model.

In both $\sqrt{J_R}$ vs $L_z$ and $E_n$ vs $L_z$ space there is a structure around $L_z \sim 0$ that covers a large range of $\sqrt{J_R}$ and $E_n$ and is most prominent in $-1.7 < [\text{Fe/H}] < -0.7$. The most metal-poor stars have a range of kinematic parameters and do not clump into any structures.

4.2 Selecting the Sausage

We start by exploring the [Fe/H] distributions of stars in $L_z$ vs $\sqrt{J_R}$ space in order to characterize the properties of the Sausage. In Figure 5 we find that at high $J_R$, the retrograde and prograde stars, bins 1 and 2 respectively, have nearly identical CDFs, suggesting that these stars are likely from the same population. The median [Fe/H] of both bins 1 and 2 is $-1.17$. To compare the [Fe/H] distributions of all the bins, [Fe/H] $= -1.17$ and the 50th percentile are indicated by the dotted lines in panels b-e of Figure 5.

Bins at $\sqrt{J_R} < 30$ (kpc km s$^{-1}$)$^{1/2}$ are more metal-rich than bins 1 and 2, with the exception of bin 7, and the retrograde stars have different [Fe/H] distributions from the prograde stars. The prograde stars, in blue, are more metal-rich than the retrograde stars, in red, at a given $V_R$. In both red and blue bins, $-100 < V_φ < 30$ km s$^{-1}$, the lower $|V_R|$ bins have a higher median [Fe/H] than the higher $|V_R|$ bins at the same $V_φ$. Bins 1, 6, 7, 8, 11, and 12 have median [Fe/H] values $\sim -1.17$, like bins 1 and 2 in Figure 5.

Based on the [Fe/H] CDFs in both $L_z$ vs $\sqrt{J_R}$ and $V_φ$ vs $V_R$ space, we select the stars in bins 1 and 2 of Figure 5 ($L_z$ vs $\sqrt{J_R}$) to be our clean Sausage sample, resulting in 679 stars with a median [Fe/H] $= -1.17$.

4.3 Characterizing the Sausage

To characterize the Sausage, we use the clean Sausage sample, see Section 4.2. We explore the mean $L_z$ of the sample, the [Fe/H] distribution, the color-magnitude diagram (CMD), and where the clean Sausage stars lie in other kinematic parameter space. Figure 7 shows the $L_z$ vs $\sqrt{J_R}$ distribution of the giant sample in gray scale with the running mean $L_z$ shown in red. The black outline is present merely to highlight the mean line. We find that the mean $L_z$ decreases with $\sqrt{J_R}$ across the whole $\sqrt{J_R}$ range. Above $\sqrt{J_R} \sim 25$ (kpc km s$^{-1}$)$^{1/2}$ the change in mean $L_z$ is very small and $L_z \sim 0$.

Helmi et al. (2018) claim that Gaia-Enceladus is a slightly retrograde feature. From Figure 7, we find that the mean $L_z$ is very slightly retrograde above $\sqrt{J_R} \sim 40$ (kpc km s$^{-1}$)$^{1/2}$. Using the clean Sausage selection, we can see that bin 1 in Figure 5, the retrograde bin, has $\sim 100$ more stars in it that bin 2, the prograde bin.

While the median [Fe/H] of the clean Sausage stars is metal-poor, $-1.17$, the [Fe/H] spread of both bin 1 and bin 2 in Figure 5 extends to metal-rich and very metal-poor. In Figure 8 we examine the metallicity distribution function (MDF) of the clean Sausage stars. The red histogram shows the MDF of the clean Sausage stars using the SkyMapper photometric [Fe/H]. The green and blue histograms show a random normal distribution of 680 stars with a mean of $-1.17$ and a dispersion of one and two times the mean [Fe/H] uncertainty of the clean Sausage stars, respectively. The $2\sigma$ distribution is in excellent agreement with the clean Sausage sample while the $1\sigma$ distribution is too narrow. This suggests that the clean Sausage sample is not a single [Fe/H] population, but has a small spread in [Fe/H].
In Figure 9, we compare the CMD of the clean Sausage sample (red points) with the high $V_T$ stars ($V_T > 200 \text{ km s}^{-1}$) in the SkyMapper-RVS sample (black points). The dual sequence revealed by Gaia DR2 (Gaia Collaboration et al. 2018b) can be seen in the high $V_T$ stars. The blue boxes show the locations of the two sequences seen by Sahlholdt et al. (2019) in the full SkyMapper sample. The clean Sausage stars fall mainly along the blue sequence, although most stars in our sample are farther up the giant branch. We note that the clean Sausage stars shown here have not been limited to high $V_T$.

The mean [Fe/H] of our clean Sausage sample is $-1.17$. Estimates of the mean metallicity of the Gaia-Enceladus-Sausage structure from previous studies have been more metal-poor; Helmi et al. (2018) find $\sim -1.6$ and Myeong et al. (2019) find $\sim -1.3$. Sahlholdt et al. (2019) find the blue sequence of the high velocity HRD has [Fe/H] $\sim -1.4$ dex. We discuss possible reasons for this different in [Fe/H] in Section 5.

Full orbits for 10 stars randomly selected from the clean Sausage sample were calculated, see Section A. These orbits clearly visualize the highly radial nature of the stars, admitted by design of the selection. They are extremely non-disc-like orbits with perihelions at $R_{\text{Gal}} \lesssim 2$ kpc and aphelions between 15 and 30 kpc. They vary significantly in $z$, some staying close to the disc mid-plane, some wandering far from the mid-plane over time, and some orbiting at an angle to the disc.

### 4.4 Other Kinematic Spaces

Although we selected the clean Sausage sample in $L_z$ vs $\sqrt{J_R}$, most studies have identified these kinematic features in other spaces. Figure 10 shows the distribution of the clean Sausage stars (red points) in $\sqrt{J_R}$ vs $L_z$ (panel a), $V_\phi$ vs $V_R$ (panel b), $\sqrt{V_R^2 + V_Z^2}$ vs $V_\phi$ (panel c), and $E_n$ vs $L_z$ (panel d). The full SkyMapper-RVS giant sample is shown in gray scale. For comparison, the stars in bin 3 and bin 4 from Figure 5 are also shown in each panel as cyan points. We will refer to these stars as the sub-Sausage sample. From Figure 10 it is clear that stars selected to be separate in one kinematic space may overlap significantly in other parameters.

The distribution of clean Sausage stars in $V_\phi$ vs $V_R$ (panel b) is consistent with the [Fe/H] CDFs in this space. Figure 6, lying mainly in bins 1, 6, 7, and 12. Bins 8 and 11 of Figure 6 have CDFs consistent with the clean Sausage stars, but these regions of $V_\phi$ vs $V_R$ space are dominated by the sub-Sausage stars. This suggests that the sub-Sausage sample contains some true Sausage stars. However, the extended distribution of the sub-Sausage stars in other kinematic spaces and the corresponding CDFs in Figure 6 suggest that including the sub-Sausage stars would introduce significant contamination into a clean Sausage sample.

While it is possible to imagine defining Sausage selection regions in panels a and b of Figure 10, panels c and d appear to be more complex. The 'V' shaped distributions of the clean Sausage and sub-Sausage stars, especially in panel...
Figure 6. The cumulative metallicity distribution functions of bins in $V_\phi$ vs $V_R$ velocity space. The top panel shows the bins positioned to examine the region originally noted by Belokurov et al. (2018) to have a ‘Sausage-like’ shape. The bottom panels show the CDFs of [Fe/H]. Each CDF panel shows bins with the same $V_R$. The red line indicates stars with $30 < V_\phi < 0$ km s$^{-1}$, the blue line indicates stars with $0 < V_\phi < -100$ km s$^{-1}$, and the green line indicates stars with $-100 < V_\phi < -200$ km s$^{-1}$. The bin and number of stars within the bin are indicated. The dotted lines indicate an [Fe/H] = −1.17, the median [Fe/H] of bins 1 and 2, and the 50th percentile.
Figure 7. $\sqrt{J_R}$ vs $L_z$ action space for the SkyMapper-RVS RGB sample. The red line with black outline shows the running mean $L_z$ using a bin of 1500 stars at $\sqrt{J_R} < 30$ (kpc km s$^{-1}$)$^{1/2}$ and 400 stars at $\sqrt{J_R} > 30$ (kpc km s$^{-1}$)$^{1/2}$.

Figure 8. The MDF of the clean Sausage sample (red) compared to a random Gaussian distribution of the same number of stars with a $\sigma$ of one (green) and two (blue) times the mean [Fe/H] uncertainty of the clean Sausage stars. The random Gaussian distributions are centered on the clean Sausage 50% [Fe/H] from Figure 5, shown as the dotted line.

d, illustrate the delicate nature of selecting these kinematic features. The overlap between the clean Sausage and sub-Sausage stars in $\sqrt{V_R^2 + V_Z^2}$ (panel c) and $E_n$ (panel d) again suggests that the sub-Sausage sample may in fact include some true Sausage stars. Likewise the clean Sausage sample may have some contamination from non-Sausage stars. To visualize the potential contamination of a sample selected in different kinematic spaces, Figure C1 shows the distribution of all $\sqrt{J_R}$ bins from Figure 5 in all four kinematic spaces used in this paper.

The distribution of our clean Sausage sample is remarkably consistent with the revised Gaia-Enceladus selection from Koppelman et al. (2019), see their figures 3 and 5, in all kinematic spaces. We again note that the $E_n$ values are different due to the choice of Galactic potential model.

4.5 Weighting the Sausage

Next we turn to the question of estimating the mass of the progenitor of the Sausage stars. In this work we find that the merging galaxy has a narrowly defined metallicity distribution function with a clear peak at $\sim -1.2$ dex (see, e.g., Figure 8). There is some intrinsic spread in the distribution but it is small. Given the narrowness of the distribution we can attempt to use the relation between a galaxy’s mass and its metallicity to estimate how heavy the Sausage progenitor was when it merged with the Milky Way. The mass-metallicity relation is a function of redshift.

To derive the (stellar) mass of the Sausage requires us to have a rough idea about when the merger happened (and assume that all stars we now see in this structure had formed in the merging galaxy prior to the merger). Several studies have addressed the age of the stars in Gaia-Enceladus-Sausage and/or the high velocity stars in the Milky Way halo as seen in Gaia DR2 (Gaia Collaboration et al. 2018b; Sahlholdt et al. 2019). From Figure 9 we may infer that the Sausage is essentially associated with the blue sequence in the high-velocity CMD from Gaia DR2 (Gaia Collaboration et al. 2018b). Turning to Sahlholdt et al. (2019) we note that they find that this particular sequence is all old, in fact all stars can be fit by stellar isochrones of 10 Gyr or older. Thus it appears safe to assume that the merger did not happen earlier than 10 Gyr ago.

Ma et al. (2016) studied the evolution of the galaxy mass-metallicity relation. In their Section 3.2 they provide
two formulas that quantify the mass-metallicity relation as a function of redshift.

\[
\log\left(\frac{Z_\star}{Z_\odot}\right) = [\text{Fe/H}] + 0.2 = \gamma_*\left[\log\left(\frac{M_\star}{M_\odot}\right) - 10\right] + Z_{\star,10} \tag{2}
\]

\[
Z_{\star,10} = 0.67\exp(-0.50z) - 1.04
\tag{3}
\]

These relations should be valid for the range of masses and redshifts of interest to us. Ma et al. (2016) note that their relations do not capture the relations well for stellar masses above \(\sim 10^{11} M_\odot\) at \(z < 1\). All indications so far is that the merger happened before \(z \sim 1\) and that the mass of the merging galaxy is less than \(\sim 10^{11} M_\odot\). It thus appears safe to use these relations to derive the mass of the merging galaxy at the time of the merger.

Combining Equations 2 and 3 and inverting the equation we get a relation between redshift and stellar mass for a given iron abundance. Figure 11 shows this relation for \([\text{Fe/H}] = -1.4, -1.2, -1.0\). Assuming that the merger takes place no later than 10 Gyr ago then our merging galaxy can not be heavier than \(\sim 10^{9.4} M_\odot\). Given that these relations are not exact and that the \([\text{Fe/H}]\) used by us and by Ma et al. (2016) are not necessarily on exactly the same scale, it appears safe to give the range of possible masses as \(10^{8.45} - 10^{9.85} M_\odot\) (i.e. by varying \([\text{Fe/H}]\) by \(\pm 0.2\) dex).

Our independent stellar mass estimate based on the
The mass-metallicity relation obtained for a large number of high probability Sausage members is well aligned with other estimates in the literature, which find that \( \log(M/M_\odot) \) is in the range of 9 to 10. We discuss this result in the context of some of the most recent studies in Section 5.

5 DISCUSSION AND CONCLUSIONS

Using a sample of 900,000 stars cross-matched between SkyMapper and Gaia DR2 RVS, we define a selection of Sausage stars in action space that minimizes contamination from Milky Way disc (or other accreted) stars based on the MDFs. Our clean Sausage selection results in a sample of 679 stars that were likely accreted during the merger event of Gaia-Enceladus-Sausage. We find that the Sausage stars are fairly centered around \( L_z = 0 \), with a slightly retrograde bias, and are on highly radial orbits. These kinematics, while more constrained, are consistent with previous studies of this structure (e.g. Belokurov et al. 2018; Helmi et al. 2018; Koppelman et al. 2019).

The real advantage of the current sample is the photometric metallicities that are available from the SkyMapper survey. We find that the Sausage stars have a peak \([\text{Fe}/\text{H}] \sim -1.17\) with a mean uncertainty of 0.17 dex and a relatively small \([\text{Fe}/\text{H}]\) spread, consistent with a \( 2\sigma_{[\text{Fe}/\text{H}]} \) Gaussian distribution. When comparing to the dual CMD sequences in the high \( V_T \) halo we find that the Sausage stars lie mainly along the blue sequence, consistent with previous work suggesting the blue sequence is comprised of accreted stars (e.g. Gallart et al. 2019).

Our \([\text{Fe}/\text{H}]\) measurement is slightly more metal-rich than previous \([\text{Fe}/\text{H}]\) estimates of Gaia-Enceladus-Sausage stars and the blue sequence (e.g. Helmi et al. 2018; Myeong et al. 2019; Sahlholdt et al. 2019), however, these studies used a broader selection in kinematic or CMD space. Based on our characterization of the MDFs of bins in kinematic space, see Figures 5, 6, B1, and B2, this likely results in samples contaminated by non-Sausage stars. As shown by Myeong et al. (2019) and Koppelman et al. (2019), the Helmi et al. (2018) estimate is likely contaminated by the Sequoia, Thamnos, and possibly other smaller kinematics structures that have since been identified and found to be more metal-poor than the larger Sausage structure. Similarly, the selection of the blue sequence in the CMD by Sahlholdt et al. (2019) likely includes stars from other accreted structures besides the Sausage.

Figures 10 and C1 show how the regions of kinematic space used in other studies to select stars belonging to Gaia-Enceladus-Sausage contain significant numbers of stars that we show have a different MDF from the clean Sausage sample. While it is almost certain that stars accreted from the Sausage lie outside our clean selection region, these regions also contain significant numbers of non-Sausage stars, making a robust study of the Sausage characteristics difficult. This emphasizes the need for detailed chemical abundance and age measurements in order to robustly identify accreted populations in the halo, especially for ancient mergers that are no longer dynamically distinct.

Using the galaxy mass-metallicity relation of Ma et al. (2016), we estimate the mass of the Sausage progenitor to be between \( 10^{8.85} \) and \( 10^{9.85} \) \( M_\odot \). Helmi et al. (2018) find that the Gaia-Enceladus stars in APOGEE have a large spread in metallicity and argue that this means a longer time of star formation. They find that the stellar mass of the progenitor was about \( 6 \times 10^8 \) \( M_\odot \). This mass estimate is consistent with our findings from the mass-metallicity relation, although we do not find as large of a spread in \([\text{Fe}/\text{H}]\).

Vincenzo et al. (2019) uses the APOGEE sample from Helmi et al. (2018) to explore the chemical evolution of Gaia-Enceladus-Sausage. Their fiducial model arrives at a galaxy with a large spread in metallicity \( -1.26 + 0.82/-1.06 \) dex, a median age of 12.33 + 0.92/-1.26 Gyr, a stellar mass of \( 10^{10} \) \( M_\odot \) at infall, and a gas fraction of \( 0.67 \). Again, the stellar sample used to infer this model has a much larger spread in metallicity than our clean sample and it also has two peaks in the metallicity distribution function (their Figure 2b). Nevertheless, the agreement in stellar mass is good, albeit their model appears to predict a somewhat heavier galaxy than our analysis.

Grand et al. (2020) analyzed twenty two simulations of Milky Way-like galaxies taken from the Auriga simulations in order to study the effects of a Gaia-Enceladus-Sausage on the formation of a Milky Way-like galaxy (see Grand et al. 2020, for a discussion of how the simulations were selected). Analyzing their simulations they find it likely that the Sausage and the splash (Belokurov et al. 2019) are intimately connected, the impact of the Sausage resulting in the splashing of pre-existing Milky Way stars. The merger also causes a star-burst, partly fueled by the gas the merging galaxy brought with it. Here, we are mainly interested in the mass of the merger rather than the impact on the disc formation and subsequent evolution. Helmi et al. (2018) found the merger to be a 1:4 ratio merger, whilst Grand et al. (2020) analysis of their simulations infer a much smaller mass-ratio of the merging galaxy and the Milky Way at the time of the merger. They found that the merging galaxy might be as small as 5% of the mass of the Milky Way at that time. On
the other hand, Amarante et al. (2019) instead find that no merger is needed to account for the presence of the Splash.

Deason et al. (2019) derived the total mass of the current stellar halo to be \( \sim 1.4 \cdot 10^8 \, M_\odot \). Our estimate of the mass of Sausage progenitor at the time of the merger does not contradict this finding.

From this work we conclude:

1) Selection of Sausage stars using the following criteria results in the least contaminated sample based on the homogeneity of the MDFs: \( 30 \leq \sqrt{J_R} \leq 50 \) (kpc km s\(^{-1}\)) and \(-500 \leq L_\phi \leq 500 \) kpc km s\(^{-1}\).

2) The Sausage stars have a relatively narrow [Fe/H] distribution centered at \(-1.17\).

3) The Sausage stars are consistent with the blue sequence of the high velocity dual sequence halo.

4) From the metallicity and likely age of the stars we predict a stellar mass of \( 10^{8.85} - 10^{9.85} \, M_\odot \) for the progenitor satellite.

For future work investigating the stellar populations that make up the Milky Way halo we stress that the MDF of the Sausage (and other populations) depends on the chosen selection criteria. Therefore detailed elemental abundances combined with kinematics, ages, etc for large samples are required for a well-defined separation of the populations.

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APPENDIX A: ORBITS

Full orbits were calculated and visually inspected for \( \sim 200 \) stars in the clean Sausage sample using galpy with the ‘MW-Potential2014’ potential (Bovy 2015). Figure A1 shows the orbital path of 10 representative stars in \( z \) and \( R \). All orbits are highly radial, which is expected from the selection criteria. However, some stars are confined to the disc, while other reach large \( z \).

APPENDIX B: ADDITIONAL [FE/H] CDFS

Here we show the metallicity CDFs of stars binned in \( \sqrt{V_R^2 + V_\phi^2} \) vs \( V_R \) velocity space, Figure B1, and \( E_z \) vs \( L_z \) action space, Figure B2, similarly to Figures 5 and 6. While we find these do not add significantly to the determination of our Sausage selection, they are of interest in characterizing the stars with non-disc kinematics. They also demonstrate the difficulty in selecting a single population of stars based on kinematics alone.

APPENDIX C: CORRESPONDING KINEMATIC DISTRIBUTIONS

Figure 10 proved an interesting demonstration of the potential contamination of the Sausage population when selected in different kinematic spaces. We provide here a similar figure showing where the stars in all bins of Figure 5 in the other three kinematic spaces examined in the work. We find

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Figure A1. Orbits of 10 stars in the clean Sausage sample

this figure is a useful tool for connecting the different kinematic and action spaces.

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Figure B1. The cumulative metallicity distribution functions of bins in $\sqrt{V_R^2 + V_Z^2}$ vs $V_\phi$ velocity space. The top panel (a) shows the bins positioned across the space occupied by the Gaia-Enceladus stars as determined by Helmi et al. (2018). The bottom panels (b-e) show the CDFs of [Fe/H]. Each CDF panel shows bins with the same $V_\phi$. The purple lines indicate stars with $250 < \sqrt{V_R^2 + V_Z^2} < 400$ km s$^{-1}$, the yellow lines indicate stars with $200 < \sqrt{V_R^2 + V_Z^2} < 250$ km s$^{-1}$, the red lines indicate stars with $150 < \sqrt{V_R^2 + V_Z^2} < 200$ km s$^{-1}$, the blue lines indicate stars with $100 < \sqrt{V_R^2 + V_Z^2} < 150$ km s$^{-1}$, and the green lines indicate stars with $50 < \sqrt{V_R^2 + V_Z^2} < 100$ km s$^{-1}$. The bin and number of stars within the bin are indicated. The dotted lines indicate an [Fe/H] = $-1.17$, the median [Fe/H] of bins 1 and 2, and the 50th percentile.
Figure B2. The cumulative metallicity distribution functions of bins in $E_n$ vs $L_z$ action space. Panel a shows the bins positioned over the structure occupied by the Sausage stars. Panels b-e show the CDFs for bins with the same $L_z$. The purple lines indicate stars with $-0.2 < E_n < 0.0$ km$^2$ s$^{-2}$, the yellow lines indicate stars with $-0.3 < E_n < -0.2$ km$^2$ s$^{-2}$, the red lines indicate stars with $-0.4 < E_n < -0.3$ km$^2$ s$^{-2}$, the blue lines indicate stars with $-0.5 < E_n < -0.4$ km$^2$ s$^{-2}$, and the green lines indicate stars with $-0.6 < E_n < -0.5$ km$^2$ s$^{-2}$. The bin and number of stars within the bin are indicated. The dotted lines indicate an [Fe/H] = -1.17, the median [Fe/H] of bins 1 and 2, and the 50th percentile.
Figure C1. The kinematic/action space distributions of stars in ‘slices’ of $\sqrt{J_R}$ corresponding to the $\sqrt{J_R}$ bin pairs in Figure 5. The gray scale background shows the full SkyMapper-RVS giant sample. The red points show stars in bins 1 and 2, blue points show stars in bins 3 and 4, green points show stars in bin 5 and 6, and purple points show stars in bins 7 and 8.