On the Relationship Between the Virgo Radial Merger and the Gaia Sausage

THOMAS DONLON II,1 BOKYOUNG KIM,2,3 HEIDI JO NEWBERG,1 AND SEBASTIEN LÉPINE2

1Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, 110 8th St, Troy, NY 12180, USA
2Department of Physics and Astronomy, Georgia State University, 25 Park Place, Suite 605, Atlanta, GA 30303, USA
3Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK

ABSTRACT

We find that low-mass halo stars on radial orbits that are located within 2 kpc of the Sun have at least two distinct components; the velocity and photometrically determined metallicity distributions of these components cannot be explained by a single radial merger event (RME). The first component has [Fe/H] \(\sim -1.6\), accounts for one third of halo stars near the Sun, and is consistent with the Virgo Radial Merger (VRM); it has previously been shown that the VRM was accreted into the Milky Way halo within the past few Gyr. The second component likely includes stars with more than one origin, but about half of these stars could be consistent with a second, early, massive contribution to the halo with [Fe/H] \(\sim -1.0\) and low energy, as has been proposed for the origin of the “Gaia Sausage” and “Gaia-Enceladus” halo stars. These stars which comprise the “Gaia Sausage” velocity structure are a combination of VRM and other stars on radial orbits.

1. INTRODUCTION

The Milky Way (MW) halo was primarily built up by accretion events (Helmi 2020). Some evidence of the MW’s accretion history comes from streams of stars stripped from satellites that are currently in the process of being accreted (Newberg & Carlin 2016). Recently, the Gaia mission (Gaia Collaboration et al. 2016), has allowed us to explore the past accretion history of the stellar halo in ways that were previously impossible (Helmi 2020), using precise positions and motions for billions of stars in the local solar region.

Perhaps the most surprising discovery in the Gaia era has been the proposal that the stellar halo is primarily made of a single massive, ancient accretion event (Deason et al. 2013; Belokurov et al. 2018). This accretion event, discovered simultaneously by multiple groups as structures in velocity and chemical abundances, is known as the Gaia Sausage/Gaia-Enceladus merger (GSE, Belokurov et al. 2018; Helmi et al. 2018). GSE stars have a wide spread in radial velocity and near-zero rotational velocities, which creates a “sausage” shape in plots of \(v_r\) vs. \(v_\phi\).

Corresponding author: Thomas Donlon II
donlot@rpi.edu

It has been claimed that the GSE debris fell into the proto-MW between 8 and 11 Gyr ago, causing the formation of the MW’s thick disk and inner stellar halo (Helmi et al. 2018; Helmi 2020). The large age of the GSE merger event is required to explain the age of the thick disk (Belokurov et al. 2018). In order to obtain the observed high metallicity of [Fe/H] = -1.2 (Helmi et al. 2018) at early times, the GSE progenitor must have had a stellar mass of \(5 \times 10^9 M_\odot\) (Vincenzo et al. 2019).

While the majority of the literature is in agreement regarding the properties of the GSE event, an alternative interpretation of the observed Gaia Sausage/Gaia-Enceladus phenomena has been proposed. Donlon et al. (2019) found that a young (2 Gyr ago) radial merger event (RME) could explain a portion of the “sausage” velocity structure, and Donlon et al. (2020) determined that the distribution of radial merger debris shells in the stellar halo was consistent with a dwarf galaxy colliding with the Galactic center 2.7 Gyr ago. This recent RME is known as the Virgo Radial Merger (VRM).

In this work we will show that the local VRM stars, with metallicity [Fe/H] \(\sim -1.6\), are responsible for the “sausage” shape in velocity plots due to their wide spread in radial velocity. The higher metallicity stars in our sample have radial velocities closer to zero. This leads to the conclusion that the “sausage” velocity structure is made up of at least two major components, and
therefore the halo cannot have been formed by a single massive major merger event at early times.

2. DWARF STARS IN THE LOCAL SOLAR NEIGHBORHOOD

2.1. The Catalog

We select dwarf stars in the local stellar halo from the \textit{Gaia}-EDR3 survey (\textit{Gaia} Collaboration \textit{et al.} 2021) using the the set of conditions given in \S 2.3.1 of Kim \textit{et al.} (2020). In addition to these conditions, we require that stars in our sample have low parallax uncertainties ($\sigma_\pi/\pi < 0.15$), and we also restrict our sample to only stars near the Galactic poles by requiring that $|b| > 70^\circ$. This halo sample contains 36,410 dwarf stars. 71\% (99\%) of these stars are located within 1 (2) kpc of the Sun.

The majority of the stars in our sample have accurate parallax and proper motion measurements, but do not have the line-of-sight velocity measurements required to calculate full 3-dimensional velocities. However, if one selects only stars that are located roughly in the direction of one of the Galactic Cartesion Cartesian axes, then the tangential velocities of each star are aligned with the other two Galactocentric Cartesian coordinates. Therefore, those two Galactocentric Cartesian velocities can be measured using only the proper motions.

In the local solar neighborhood, radial and rotational velocity are roughly equivalent to the Galactocentric $v_X$ and $v_Y$, respectively. To select the radial portions of the stellar halo, we compute each star’s $v_X$ and $v_Y$, or equivalently their Local Standard of Rest velocities $U$ and $V$. This is done using the procedure in \S 2.2 of Kim \textit{et al.} (2020) to compute each star’s $v_T$, which is perpendicular to the direction of disk rotation, and $v_\|$, which is parallel to the direction of disk rotation. Our selection is limited to only stars near the galactic poles, so $v_T$ corresponds to $U_\|$ and $v_\|$ corresponds to $V_\|$. The double-bar subscript on a velocity indicates that it does not contain any radial velocity contributions ($U_\|, V_\| = U, V$ near the Galactic poles). Positive $U_\|$ is in the direction of the Galactic center, and positive $V_\|$ is in the direction of the disk’s rotation.

In addition to $U_\|$ and $V_\|$ velocities, our sample of dwarf stars includes photometric metallicity estimations for each star (Kim & Lepine, subm.). These measurements are calibrated using stars with precisely measured metallicities from various surveys. Each dwarf star’s [Fe/H] abundance is inferred from its \textit{Gaia} ($G - G_{RP}$) color and absolute $G$ magnitude.

The dwarf star sample contains a large number of thick disk stars and stars on very retrograde orbits. In order to isolate stars that are potential members of radial structures, we restrict our sample to only include stars with $-300 \text{ km s}^{-1} < V_\| < -220 \text{ km s}^{-1}$. This radial sample contains 2257 dwarf stars in the stellar halo with low Galactocentric rotational velocity.

2.2. Velocities of Nearby Dwarf stars

Figure 1 shows the $U_\|$ and $V_\|$ velocities of our dwarf star sample split up by metallicity. The elongated “sausage” structure is clearly seen at $V_\| \sim -220 \text{ km s}^{-1}$, particularly at metallicities between -2.2 and -1.4. Note the two lobes of stars with $U_\| \sim \pm 200 \text{ km s}^{-1}$; these excesses were previously identified by Belokurov \textit{et al.} (2018). Excluding thick disk stars, the double-lobed structure appears to dominate the sample near $V_\| = -220 \text{ km s}^{-1}$ at low metallicities, while a central single-lobed structure appears to make up the majority of the sample at high metallicities. When the two structures are superimposed, the result is a “sausage”-like shape.

Other substructure is apparent in Figure 1 besides the radial stars. At lower metallicity and very counter-rotating velocities ($V_\| \sim -350 \text{ km s}^{-1}$) a cluster of stars is visible, possibly related to the Sequoia structure (Myeong \textit{et al.} 2019). At nearly all metallicities, an excess can be found at ($U_\|, V_\| = (125, -200)$ km s$^{-1}$ that is not mirrored at negative $U_\|$. Similarly, at most metallicities, the negative $U_\|$ side of the thick disk (moving outwards from the Galactic center) has substantially more stars than the positive $U_\|$ portion of the thick disk. It is possible that these latter features are related in some way to the MW disk disequilibrium (e.g. Antoja \textit{et al.} 2018).

To determine whether any velocity asymmetries in the dataset are due to substructure that varies over the volume sampled, a two-sample Kolmogorov-Smirnov test (Kolmogorov 1933) was used to evaluate whether the radial sample stars in the north and south were drawn from the same underlying distribution. Overall the north and south distributions appeared to be statistically uniform, although the lowest metallicity bin had a two-sigma significance ($p=0.056$) of stars in each pole being drawn from a different distribution.

3. RADIAL MERGER SIMULATIONS

We modeled the velocity distribution of the debris of a single RME in the local solar region using the suite of $N$-body simulations of RMEs in a static MW-like potential from Donlon \textit{et al.} (2020). These simulations were characterized by initial inclination of the progenitor with respect to the Galactic disk ($i$), final apogalacticon distance from the center of the Galaxy ($r_0$), and mass of the progenitor ($M$). Each simulation was evolved forwards in time for 10 Gyr; snapshots of the radial merger
debris were taken every 100 Myr to study how the RMEs evolve over time.

We cut the simulated data to include only stars with $6 < R/\text{kpc} < 8$ and $|Z| < 2 \text{ kpc}$ in order to roughly match the solar region, and then plotted $v_\phi$ vs. $v_r$ for many RME simulations. Figure 2 shows some of these simulations, selected to illustrate trends in the simulated data. Generic trends showing how the characteristics of each RME impact its velocity plot were identified in the simulations; increasing the initial distance of the RME progenitor from the Galactic center increased the separation of the $v_r$ lobes, and increasing the progenitor mass increased the width of the lobes. Overall, the inclination of the progenitor with respect to the Galactic plane didn’t have a substantial effect. For recent merger times ($< 2$ Gyr since the beginning of the simulation), the RME debris did not have time to phase mix, and the amount of material in each lobe depended strongly on the orientation of the debris. After $\sim 2$ Gyr, the simulation time did not change the appearance of the velocity lobes.

4. FITTING RME MODELS TO THE DATA

4.1. Model & Optimization

Histograms of $v_r$ in the simulated data are dominated by a double-lobed structure (Figure 2). The lobe with $v_r > 0$ represents stars in the merger that are moving away from the Galactic center at the solar position, and the lobe with $v_r < 0$ represents those falling back towards the Galactic center. RME stars with $v_r \sim 0$ must be at the apogalacticon of their (radial) orbits, and therefore have lower energy than the stars in the lobes.

Each lobe appears to have a roughly Gaussian distribution in $v_r$, so we model the total distribution of $v_r$ for a single RME as the sum of two Gaussians. For most of the simulations, the two lobes appear to have the same amplitude, dispersion, and distance from $v_r = 0$. With these assumptions, our model is:

$$f(v_r) = \frac{a}{\sqrt{2\pi}c} \left[ \exp \left( \frac{-(v_r - b)^2}{2c^2} \right) + \exp \left( \frac{-(v_r + b)^2}{2c^2} \right) \right],$$

being Each panel of Figure 2 shows a model distribution (blue) fit to the simulated data (red). The model was fit to the data by minimizing the residual sum of squares ($\text{RSS}$), given by

$$\text{RSS} = \sum_i^N \left( \int_{v_r,i}^{v_r,i+1} f(v_r) \, dv_r - n_i \right)^2,$$

where $N$ is the number of bins in the histogram, $v_{r,i}$ and $v_{r,i+1}$ give the bounds of the $i$th bin, and

Figure 1. Heliocentric Cartesian velocities of 36,410 dwarf stars in the halo sample. Each panel represents a different metallicity range. The extent of the thick disk is shown as a red circle, and black dashed lines show the Galactic Standard of Rest. One can see the characteristic elongated “Sausage” structure in the stars with $V_\parallel \sim -250 \text{ km s}^{-1}$. Note that there are two lobes of material at $U_\parallel = \pm 200 \text{ km s}^{-1}$ in the stars with $-2.2 < [\text{Fe/H}] < -1.0$. Stars that lie in the shaded gray region make up our radial sample.
Figure 2. Velocities of solar neighborhood particles from RME N-body simulations. Each panel shows a different simulation: the conditions for each panel are $i = 30^\circ$, $M = 10^8 M_\odot$, $r_0 = 30$ kpc, and $t = 5$ Gyr, except for the parameter provided above each panel. The top row shows that increasing progenitor mass makes the lobes wider and closer to $v_r \sim 0$. The middle row shows increasing $r_0$ moves the lobes farther apart. The bottom row shows the lobes are asymmetric at the beginning of the simulation. The bottom half of each panel is a heatmap of $v_\phi$ vs. $v_r$ for the simulated stars within $6 < R/<kpc < 10$ and $|Z| < 2$ kpc. The top half of each panel shows the radial merger velocity model (blue) fit to a histogram of the $v_r$ data (red). The data is fit well by our model, except for very recent collisions (e.g. the bottom-left panel) where our model is not able to fit the different amplitudes of the lobes, and a small number of stars between lobes.

$n_i$ is the number of stars in the $i$th bin of the histogram. The value of the RSS was minimized using the scipy.optimize.minimize() routine (Pedregosa et al. 2011).

4.2. Fitting the Observed Data

We assume that all of the stars in our radial sample are from RMEs, and can therefore be decomposed into individual double-lobed structures. Each merger is characterized by three variables (Equation 1). While the amplitude ($a$) varies for each metallicity bin, the position ($b$) and width ($c$) are kept fixed for a given component of the halo.

We optimized a mixture model containing $N$ double-Gaussian models to the observed data, where $N$ was incremented from 1 to 6. Each mixture model has $10 \cdot N$ free parameters. The procedure from §4 was used to optimize each mixture model to the observed data, except the minimized quantity $L$ was now the sum of the RSS for each metallicity slice,

$$L = \sum_i^8 RSS_i.$$  \hspace{1cm} (3)

For each value of $N$, a Bayesian information criterion (BIC, Schwarz 1978) was used to judge the quality of
The BIC was defined as

$$BIC = 10N \ln(n) + n \ln(L/n),$$

where $n$ is the number of bins in each histogram, e.g., the number of observed data points. The mixture model with the lowest value of the BIC was the model with $N = 2$, which had an improvement of $|\Delta BIC| > 20$ over each other model.

5. RESULTS

Figure 3 shows the fitted $N = 2$ mixture model to the observed data; the best fit model parameters are provided in Table 1. The fitted model appears to match the observed data well, although the model residual still contains some substructure.

We tried fitting the nearby ($d < 600$ pc) and more distant ($d > 600$ pc) stars separately. The single-lobed component was wider in the more distant sample, but the single-lobed component remained unchanged. Changing the size of the metallicity bins did not change the fit for either component.

The fitted metallicity distribution functions (MDFs) of the two components are shown in Figure 4. The two components are described in detail in the following subsections.

5.1. The Lobes at $U_\parallel = \pm 230$ km s$^{-1}$

| Parameter     | Component 1 | Component 2 |
|---------------|-------------|-------------|
| $U_\parallel$ | (km s$^{-1}$) | (km s$^{-1}$) |
| b             | 229.1       | 66.9        |
| c             | 75.2        | 121.5       |
| a (-3.0 < [Fe/H] < -2.6) | 94.0       | 178.0       |
| a (-2.6 < [Fe/H] < -2.2) | 250.2      | 379.4       |
| a (-2.2 < [Fe/H] < -1.8) | 531.5      | 447.8       |
| a (-1.8 < [Fe/H] < -1.4) | 616.5      | 450.7       |
| a (-1.4 < [Fe/H] < -1.0) | 327.5      | 490.2       |
| a (-1.0 < [Fe/H] < -0.6) | 61.9       | 571.1       |
| a (-0.6 < [Fe/H] < -0.2) | 0.0        | 482.2       |
| a (-0.2 < [Fe/H] < +0.2) | 0.0        | 276.1       |

The blue MDF in Figure 4 corresponds to the double Gaussian with lobes at $U_\parallel \sim 230$ km s$^{-1}$ in Figure 3. This component makes up over one third of the stars in the sample (1882 stars out of 5157 total).

The blue MDF appears similar to the expected MDF for a luminous dwarf galaxy (Kirby et al. 2013), and matches the metallicity of the Virgo Overdensity (Dufau et al. 2006; An et al. 2009), so it is natural to assign...
the double-lobed stars to the VRM. This supports the claim of Donlon et al. (2020) that the Virgo Overdensity is composed of VRM debris. In our model, the observed velocity dispersion of the lobes was reproduced with a total progenitor mass of $10^9$ to $10^{10} \, M_\odot$. This is larger than previous estimates of $<10^9 \, M_\odot$ (Donlon et al. 2019, 2020).

5.2. The Lobes at $U_\parallel = \pm65$ km s$^{-1}$

The orange distribution in Figure 4 contains a large range of metallicities that peaks at $[\text{Fe/H}] \sim -1.0$. This MDF corresponds to the single-lobed velocity component near $U_\parallel = 0$.

We note that the MDF for the orange component is not similar to that expected MDF for a single dwarf galaxy, possibly due to contamination of the sample with other substructure. On the high metallicity end, we expect thick disk stars to bleed into the sample near $U_\parallel = 0$ (see Figure 1). The lower metallicity range of the orange MDF could be populated by a series of minor accretion events. If the minor accretion events are well-mixed and were randomly oriented before being accreted, they would have a velocity distribution centered on $(U_\parallel, V_\parallel) = (0, -220)$ km s$^{-1}$.

Neither thick disk contamination nor radial accretion of minor dwarf galaxies can explain the large number of stars with $-1.5 < [\text{Fe/H}] < -1.0$ in the orange MDF, since the thick disk does not have many stars with metallicities that low, and smaller dwarf galaxies cannot make stars with metallicities that high. To explain the stars with this range of metallicities, the halo could potentially include a second significant merger with a metallicity distribution similar to the blue MDF but shifted to higher $[\text{Fe/H}]$ (much like the bottom-center panel in Figure 11 of Naidu et al. 2020). In order to match the shape of this MDF in Naidu et al. (2020), the second possible merger would contribute roughly the same number of stars as the VRM to the local solar region. As the stars on radial orbits with small $v_r$ have lower energy than the double-lobed VRM stars, it is natural to propose that the higher metallicity, single-lobed radial merger happened at earlier times.

Alternatively, an older merger could populate the entire metallicity range observed in the single-lobed component, as was produced in the MDF model of Vincenzo et al. (2019). In Figure 2b of Vincenzo et al. (2019), there is an additional peak in the MDF around $[\text{Fe/H}] \sim -1.5$ that could correspond to VRM debris, as the metallicity and shape of that peak look similar to the blue MDF in Figure 4. Adopting this picture would make the stellar mass of an ancient metal-rich merger in the local solar region closer to twice that of the VRM.

Most of our RME simulations had double-lobed velocity distributions that were well-separated in $v_r$. The single-lobed velocity distribution could be explained by an ancient merger event that initially had two velocity lobes at the time of accretion, but were pushed together as the MW gained mass. Alternatively, the progenitor of an ancient merger could have been a substantial fraction of the MW mass at the time of accretion (i.e. the top-right panel of Figure 2).

It is also possible that the metal-rich end of the orange MDF contains stars from the Splash (Belokurov et al. 2020), which is composed of stars with high metallicities and small $v_\phi$. It is thought that these Splash stars are heated from the MW disk early on, but it is not yet clear whether an early merger event is responsible for the structure (Belokurov et al. 2020), or if the Splash is the result of lumps in the proto-MW’s disk (Amarante et al. 2020).

Yet another possibility is that some of the metal-rich stars in the second component could have been formed in outflows. Yu et al. (2020) show that in-situ outflow stars can comprise as much as 40% of the metal-rich stellar halo in MW-like cosmological zoom-in simulations. Outflow stars are predicted to have metallicities similar to that of thick disk stars, so they could populate the metal-rich end of the orange MDF.

6. CONCLUSIONS

We find that the dwarf stars in the local stellar halo with photometrically determined metallicities and velocities consistent with the “Gaia Sausage” velocity structure are actually built up from debris from the VRM, as well as a second component with different kinematic and chemical properties. The VRM makes up roughly a third of the radial sample, has an MDF that peaks at $[\text{Fe/H}] \sim -1.6$, and has a double-lobed velocity distri-
The high energy and separate velocity lobes of this component are consistent with the VRM adding its stars to the halo relatively recently.

The second halo component leaves open the possibility of an ancient, metal-rich ([Fe/H] ∼ −1.0), massive RME, along with some thick disk stars and possibly a background of old minor accretion events. Alternatively, outflow stars and/or Splash stars could also contribute to this component. This component contributes a total of twice as many dwarf stars to the solar neighborhood as the VRM.

The halo sample of dwarf stars also contains strongly retrograde material that is possibly related to the Sequoia. Additionally, the distribution of thick disk stars in the halo sample is asymmetric in $U_\parallel (\approx v_r)$, which may imply that the thick disk is out of equilibrium.

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