of the same order of magnitude, with an average value of $d_{av} = 4.5 \pm 4.6$ kpc ($\mu = 13.2$). Two stars (C2222241-094912 and C2242408-024953) have very large distances but the errors are also large. If we exclude the largest of these but retain the other for consistency with the isochrone distance average, the mean distance reduces to $d_{av} = 3.6 \pm 3.4$ kpc ($\mu = 12.8$), which is very similar to the value found for the isochrones.

4.5. Comparison with Other Distances

In Table 3 we also list distances derived in Breddels et al. (2010) ($d_B$), Zwitter et al. (2010) ($d_Z$), and Burnett & Binney (2010) ($d_{BB}$), where these distances are all derived from RAVE stellar parameters, employing various methodology. Comparing the above $d_1$ and $d_9$ to the distances calculated in Zwitter et al. (2010), for which 11 of the 15 Aquarius stars have an entry, we find that the isochrone distances agree better with a $\mu \pm \sigma$ for the difference $(d_Z - d_1)/d_Z$ of $23\% \pm 20\%$, while for $(d_Z - R)/d_Z$ we have $-10\% \pm 100\%$. This is somewhat unsurprising given that the Zwitter distances and the isochrone distances are both based on RAVE stellar parameters. Interestingly, however, for six stars that have distances calculated by the method of Burnett & Binney (2010), the RPM distances fare better: $(d_{BB} - d_1)/d_{BB}$ gives $-100\% \pm 170\%$ while $(d_{BB} - d_Z)/d_{BB}$ yields $-30\% \pm 70\%$. For the six Breddels et al. (2010) entries we have much larger discrepancies of $(d_B - d_1)/d_B$ of $-200\% \pm 40\%$ and $(d_B - d_Z)/d_B$ of $330\% \pm 60\%$. Clearly, all these discrepancies imply that the individual distances listed in Table 3 have large uncertainties. In general, however, the RPM distances give more consistent kinematics than the isochrone distances as we will see below in Section 5.

5. POSSIBLY RELATED SUBSTRUCTURE

In this section, we seek connections between the Aquarius stream and other known kinematic and spatial substructures nearby in the Galaxy. We start with the spatially detected substructures before returning to kinematically detected solar neighborhood features.

5.1. Large Stellar Streams and Features

The nearest companion of the Milky Way, the Sgr dSph (Ibata, Gilmore & Irwin 1994), has shed significant debris on its polar orbit around our Galaxy. The all-sky mapping of this debris by Breddels et al. (2006) has revealed further branches and details within the debris wraps. Recently, Yanny et al. (2009a) used M and K giants selected from SDSS and SEGUE data (Yanny et al. 2009b) to provide additional observational constraints on the stream.

The Aquarius stars fall fairly close to the orbital plane of the Sgr dwarf. Also, the isochrone fit from Section 4 is consistent with a population of 10 Gyr, $[M/H] = -1$. Layden & Sarajedini (2000) obtained color–magnitude diagrams of Sgr field populations, finding a dominant old and intermediate age population of 11 Gyr, $[M/H] = -1.3$ and 5 Gyr, $[M/H] = -0.7$. Giuffrida et al. (2010) find a range of populations in the periphery of Sagittarius, with $[M/H] = -2.34$ to $-0.6$, while the dominant population has a similar metallicity to 47 Tuc with $[M/H] = -0.6$. Given the errors, the isochrone fit for the Aquarius stream is consistent with the Sgr dwarf. We thus investigated a possible link between the Aquarius stream and the Sagittarius dwarf debris. The details of this investigation are given in the Appendix.

The overall result is that the Aquarius stream’s kinematics do not match those of the Sagittarius dwarf debris, calculated using a variety of potential models (oblate, spheroid, prolate, triaxial) from Law et al. (2005, 2009). The oblate model shows a potential match for a small section of nearby debris when considering the line-of-sight velocity in the Galactic rest-frame, $V_{gal}$, alone. However, the full kinematics of $V_u$, $V_b$, $V_z$ display that the kinematics of the Aquarius stream and this nearby section are actually quite different.\textsuperscript{20} The possible connection is further ruled out by the fact that the oblate halo potential model does not compare well with other observational data for Sgr dwarf debris.

Since the Aquarius stream lies in the southern part of the RAVE data, it could not be discovered in the main, northern SDSS survey. Thus, the stream is far removed from the SDSS-discovered substructures, including the Canis Major overdensity at $(l, b) = (240^\circ, -8^\circ)$ (Martínez et al. 2005) and the Virgo overdensity at $(l, b) = (300^\circ, +60^\circ)$; Juric et al. 2008). Further, the stream is located between the southern SEGUE SDSS stripes so it is unsurprising that this has not been detected in this survey. The stream’s Galactic latitude of $b = -60^\circ$ rules out a relation to the more planar Monoceros stream ($b < 40^\circ$; Penarrubia et al. 2005). Its velocities and latitude are also inconsistent with the thick disk asymmetries detected by Parker et al. (2003, 2004).

The Hercules–Aquila cloud, again detected using SDSS photometry, is located at $l = 40^\circ$ and extends above and below the plane by $50^\circ$ (Belokurov et al. 2007). The velocities of the $b > 0^\circ$ segment are $V_{gal} = +180$ km s$^{-1}$ and the structure ranges over heliocentric distances of $d = 10–20$ kpc. The Hercules–Aquila cloud is near the Aquarius stream on the sky. However, despite the lack of velocity data below the plane, it can be clearly seen that the two entities are separate: the centering in $(l, b)$ for the two are shifted from each other and their distance ranges are clearly incompatible. Additionally, in Section 6.1 we trace the orbit of a simple model for the Aquarius stream and the resulting region of phase space that the debris inhabits does not overlap with the Hercules–Aquila cloud in $(l, b, V_{gal})$.

5.2. Solar Neighborhood Streams

We have calculated orbits for candidate stars in the potential of Helmi et al. (2006), which has contributions from a disk, bulge, and dark halo. Table 4 gives averages for various quantities derived from these orbits as well as the median quantities for the overall kinematics, using both sets of distances. Note that we chose the median as it gives more consistent results, and for this reason we also excluded the two most distant stars with $d > 9$ kpc as their kinematics differed greatly from the others. Also, the values for the pericenter and apocenter only include non-radial orbits.

Figure 6 shows the $L_c$–$L_{z, perp}$ and $L_c$–Energy (Lindblad) planes for orbits based on both distance estimates, where to aid comparison to other studies we use here energies as calculated in Dinescu et al. (1999). Note that the scatter of the isochrone distance results is large so the majority of these points lie off the plot, as do some of the RPM distance results. We plot for reference stars in the Geneva Copenhagen survey (Nordström et al. 2004), which is comprised mainly of thin and some thick

\textsuperscript{20} We use the Dehnen & Binney (1998) values for the solar peculiar velocity of $(U, V, W) = 10, 5, 7$ km s$^{-1}$ with respect to the LSR, which we set at a rotation velocity of 220 km s$^{-1}$.
Figure 6. (a) $L_z$–$L_{\text{perp}}$ and (b) $L_z$–Energy (Lindblad) planes for the Aquarius stars with the solid red points calculated using $d_L$ and the open red points $d_t$. In the background the mostly thin-disk Geneva Copenhagen Survey stars are shown as black points. The uncertainty in the solid red points are shown via the clouds of small colored dots, which give the 1σ spread for the MC simulation. Each color shows the spread for a single solid red point. A high degree of covariance in the large errors is evident, though the retrograde nature of the Aquarius stream stars is clear. The solid curves in the Lindblad diagram represent the circular orbit loci for this potential. (A color version of this figure is available in the online journal.)

Table 4
Orbital Properties of the Aquarius Stream Using (A) Isochrone Distances, (B) RPM Distances, and (C) the Satellite Model in Section 6.1, Selected Between $-70 < b < -50$, $d < 5$ kpc, $t_s = -700$ Myr

<table>
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<th>Method</th>
<th>$V_p$ (km s$^{-1}$)</th>
<th>$\sigma(V_p)$ (km s$^{-1}$)</th>
<th>$V_\phi$ (km s$^{-1}$)</th>
<th>$\sigma(V_\phi)$ (km s$^{-1}$)</th>
<th>$V_z$ (km s$^{-1}$)</th>
<th>$\sigma(V_z)$ (km s$^{-1}$)</th>
<th>$L_z$ (kpc km s$^{-1}$)</th>
<th>$L_{\text{perp}}$ (kpc km s$^{-1}$)</th>
<th>Energy (kpc$^2$ s$^{-2}$)</th>
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</thead>
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<td>$-50$</td>
<td>$110$</td>
<td>$110$</td>
<td>$110$</td>
<td>$80$</td>
<td>$-360 \pm 710$</td>
<td>$1000 \pm 400$</td>
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<tr>
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<td>$170$</td>
<td>$-50$</td>
<td>$70$</td>
<td>$90$</td>
<td>$60$</td>
<td>$30$</td>
<td>$-330 \pm 500$</td>
<td>$710 \pm 320$</td>
</tr>
<tr>
<td>C</td>
<td>$0$</td>
<td>$40$</td>
<td>$-75$</td>
<td>$5$</td>
<td>$60$</td>
<td>$30$</td>
<td>$50$</td>
<td>$-590 \pm 30$</td>
<td>$480 \pm 100$</td>
</tr>
</tbody>
</table>

$\epsilon_{\text{peri}}$, $\epsilon_{\text{apo}}$, $\zeta_{\text{max}}$ (kpc), $\epsilon$ (kpc), $\epsilon$ (kpc), $\epsilon$ (kpc)

$\epsilon_{\text{peri}}$ = 1.5, $\epsilon_{\text{apo}}$ = 9, $\zeta_{\text{max}}$ = 6, $\epsilon$ = 0.8
$\epsilon_{\text{peri}}$ = 1.8, $\epsilon_{\text{apo}}$ = 9, $\zeta_{\text{max}}$ = 5, $\epsilon$ = 0.7
$\epsilon_{\text{peri}}$ = 1.8, $\epsilon_{\text{apo}}$ = 9, $\zeta_{\text{max}}$ = 4, $\epsilon$ = 0.7

disk stars. The circular orbit loci for this potential are also shown in the Lindblad diagram. To show the typical error covariance we also ran a Monte Carlo (MC) simulation for each star (with the RPM distances). From the errors in distances, proper motion and radial velocity we generated a sample of 1000 points representative of each distribution, which were then propagated through into the momenta and energy. Following Wylie-de Boer et al. (2010), in Figure 6 we plot the resulting distributions within 1σ of each of the average values. These demonstrate the large non-Gaussian errors and covariances in $L_z$, $L_{\text{perp}}$, Energy: the Aquarius stream could not be found initially in these planes. Indeed, all three values are quite ill constrained with the current uncertainties in the stellar distances.

Nevertheless, we can at least say that the stars are retrograde and that they are away from the notable halo feature of Helmi et al. (1999) at ($L_z$, $L_{\text{perp}}$) = (1000, 2000) kpc km s$^{-1}$. The Aquarius stream is also not near the prograde and retrograde features of Kepley et al. (2007) at ($L_z$, $L_{\text{perp}}$) ~ (2500, 500) kpc km s$^{-1}$ and ($L_z$, $L_{\text{perp}}$) ~ (−2500, 1700) kpc km s$^{-1}$. Also, with values of $(V_{\phi}, V_{\phi}, \psi) = (125 \text{ km s}^{-1}, 205 \text{ km s}^{-1}, -15 ^\circ)$ it is not one of the newly detected solar neighborhood streams listed in Table 2 of Klement et al. (2009). Another solar neighborhood stream is the Kapteyn group, which Wylie-de Boer et al. (2010) suggests is stripped from ω Centauri (also see Meza et al. 2005), which in turn is thought to be the surviving nucleus of an ancient dwarf galaxy (Bekki & Freeman 2003). Wylie-de Boer et al. (2010) employ the same potential as we do here, finding $L_z$ = −413 kpc km s$^{-1}$, $E$ = $-1.3 \times 10^5$ km$^2$ s$^{-2}$ for ω Cent and $L_z$ ~ −200 kpc km s$^{-1}$, $E$ ~ $-9.5 \times 10^4$ km$^2$ s$^{-2}$ for the Kapteyn group. The Aquarius stream is somewhat similar to the distribution in $L_z$–Energy for the Kapteyn group/ω Cent. However, in Section 6.2 we will see that our model for the stream rules against an association. Another significant halo clumping found by Majewski et al. (1996) toward the north Galactic pole has a retrograde orbit with $V_\phi$ ~ −55 km s$^{-1}$, which is consistent with that of Aquarius. The mean $|z|$ for this moving group of $|z|_{\text{median}} = 4.5$ kpc is rather high when compared to ($|z|_{\text{median}}$), $|z|_{\text{median}}$ ~ (2, 3.5) kpc for Aquarius, as well as the $z_{\text{max}}$ values in Table 4. Moreover, our model for the Aquarius stream in Section 6.2 does not overlap with the north Galactic pole, again ruling against an association.

6. Nature of the Stream

The distances calculated for Aquarius stream stars place it fairly close to the sun. If they are of the correct order of magnitude then we could possibly expect additional stream members in other areas of the sky. However, our exploration of the two bounding latitude ranges in Section 3.4 yielded no striking overdensities that we can immediately associate with the Aquarius stream. Two other regions had overdensities detected for $J > 10.3$, though they are not as conspicuous as Aquarius: the region around $-50^\circ < b < -30^\circ$, $320^\circ < l < 350^\circ$, 150 km s$^{-1} < V_{\phi} < 300$ km s$^{-1}$ (Region A) and the region

21 Klement et al. (2009) define $V_{\phi} = \sqrt{(V + V_{\phi \text{SR}})^2 + W^2}$, $V_{\phi \text{SR}} = \sqrt{U^2 + 2(V + V_{\phi \text{SR}})^2}$ and $\psi = \arctan((V + V_{\phi \text{SR}})/W)$. 

$C1.8940.7$ $B1.8950.7$ $B0170−50$ $220$ $110$ $110$ $80$ $-360 \pm 710$ $1000 \pm 400$ $-8 \pm 6 \times 10^4$ $-50$ $70$ $90$ $60$ $-330 \pm 500$ $710 \pm 320$ $-9 \pm 3 \times 10^4$ $0$ $-75$ $5$ $60$ $30$ $-590 \pm 30$ $480 \pm 100$ $-9.3 \pm 0.6 \times 10^4$ 

$A$ $1.5$ $9$ $6$ $0.8$
$B$ $1.8$ $9$ $5$ $0.7$
$C$ $1.8$ $9$ $4$ $0.7$
internal velocity dispersion, \( r_c \) traced by the orbits falls within this sample volume. However, the majority of Aquarius (and RA VE) stars are within a few kpc of the sun, and only a small portion of the total volume could be associated with the Aquarius stream, and if not, how the stream’s localization arises, we created a simple model of a satellite dissolving in the potential of the Galaxy.

6.1. Model Satellite Disruption

To generate a simple satellite dissolution, we first chose one of the average, stable orbits—that using \( d_R \) for the star C2322499-135351—and integrated the orbit back in time. Centering on the orbital positions at various times in the past, \( t_s \), we generated \( 10^4 \) test particles from a Gaussian sphere with core radius and internal velocity dispersion, \( r_c = 300 \text{ pc} \) and \( \sigma_V = 10 \text{ km s}^{-1} \). Neglecting self-gravity we then integrated the orbits of the satellite forward in time until the present day. This approximate approach suffices as our aim here is illustrative rather than finding the definitive orbit for the Aquarius stream.

Figure 7 shows the distribution of particles for two different starting times: \( t_s = -700 \text{ Myr} \) (a, c, left) and \( t_s = -5 \text{ Gyr} \) (b, d, right). The position of the sun is marked as a yellow point and the Aquarius stars (using \( d_R \)) as red points.

In Figure 8, we plot \( l-b \) and \( l-V_{\text{los}} \) planes for test particles within \( d < 5 \text{ kpc} \) of the sun for the simulations with the two different starting times, where we chose this distance limit as it encompasses \(~70\%\) of the Aquarius stars. We also plot the Aquarius candidates and the stars that fall within Regions A and B, as well as the background population of RAVE stars. The distribution of particles for the simulation with \( t_s = -700 \text{ Myr} \) occupy a small region in \( l-b-V_{\text{los}} \) that does not coincide with the locations of Regions A and B. Furthermore, the distribution in \( l-V_{\text{los}} \) remarkably mimics that of the Aquarius stream and a picture emerges of how the stream can be so localized: with the RAVE survey data we miss portions of the stream due to the location of the survey boundary in some regions and in others, because \( V_{\text{los}} \) overlaps with that of the main distribution so the stream is difficult to detect.

In the phase-mixed \( (t_s = -5 \text{ Gyr}) \) scenario we see that there is overlap between the region in \( l-b \) plane occupied by the test particles with Regions A and B with Aquarius without others regions being populated. In particular, we could expect overdensities at \(-50^\circ < b < -30^\circ\), \( l > 240^\circ\), \( V_{\text{los}} = +200 \text{ km s}^{-1} \) as well as a population at \(-30^\circ < b < -50^\circ\), \( l < 60^\circ \) out to \( V_{\text{los}} = -200 \text{ km s}^{-1} \). Such overdensities are not observed in the data.

These simple models of a dissolving satellite therefore suggest that the localization of Aquarius is due to further regions of phase space not yet being populated: the region in \( (l, b, V_{\text{los}}) \) space occupied by the \( t_s = -700 \text{ Myr} \) simulation is more consistent with the observed population than that of the \( t_s = -5 \text{ Gyr} \) simulation. This suggests that the stream is most likely dynamically young, resulting from a recent disruption of a
progenitor, and has not yet undergone phase mixing. Indeed, our simple model of a recently disrupted satellite is very successful in reproducing the main features of the Aquarius stream. In Table 4 we therefore list the parameters found for test particles from this model in the Aquarius stream’s latitude range. These are quite similar to those found using $d_1$ and $d_2$. The results also corroborate our observation from the RPMD in Section 4.3 that the stream stars have a constant transverse velocity, a fact which was used in Section 4.4 to derive $d_2$. Test particles for the $t_s = -700$ Myr simulation within the Aquarius stream’s latitude range and distance range, i.e., $-70^\circ < b < 50^\circ$ and $d < 5$ kpc have $v_r = 250 \pm 100$ km s$^{-1}$. This agrees with the value of $v_t = 250 \pm 100$ km s$^{-1}$ from the RPMD.

From Figure 8, we see that the recent-disruption model suggests that at $-10^\circ < b < +30^\circ$, $330^\circ < l < 270^\circ$ we can expect a smaller population of stars associated with the Aquarius stream out to $V_{los} = 350$ km s$^{-1}$. This begins to overlap at $+20^\circ < b$ with the RAVE survey area, though we do not detect such a population in the data. Future releases of RAVE data with more observations in this area, combined with more careful modeling of the stream, will enable a better understanding of whether this area is indeed populated by Aquarius stream stars.

6.2. Progenitor of Aquarius

The above scenario of a dynamically young stream is not inconsistent with an age of 10 Gyr for the Aquarius candidates, as estimated from the isochrone fit in Section 4.1: the stream can be seen as a remnant of an old satellite that has been recently disrupted. As to the nature of the progenitor of the Aquarius stream, it could either be a dwarf galaxy or a globular cluster. The survival of this progenitor would depend on its concentration: it could either have been tidally stripped or have undergone complete disruption.

To search for possible globular clusters that the Aquarius stream could have been tidally stripped from, we performed a search of the Harris (1996) catalog of known globular clusters, selecting those with $-1.5 < [\text{Fe/H}] < -0.5$, $1.5 < R_{GC} < 9$ kpc, and $Z < 4$ kpc, where the latter limits are taken from the model satellite orbit in Table 4. We then compared the distribution of the clusters in $l$, $b$, $V_{los}$ to that of the model satellite stream ($t_s = -700$ Myr), and found no globular clusters that match the simulation. Also, $\omega$ Cen, with an $l$, $b$, $V_{los}$ of $(309^\circ, +15^\circ, 233$ km s$^{-1}$) and $L_c = -413$ kpc km s$^{-1}$, is not consistent with not-yet-phased-mixed scenario in Figure 8 and Table 4. With our uncalibrated metallicities, it is difficult to compare the MDF to that of $\omega$ Cen. A high-resolution spectroscopic abundance study, such as in Wylie-de Boer et al. (2010), is required (as well as further modeling of Aquarius) to definitively understand if Aquarius is related to $\omega$ Cen.

The progenitor of the Aquarius stream therefore is currently unknown.

7. CONCLUSION

In this paper we report the detection of a new halo stream found as an overdensity of stars with large heliocentric radial velocities in the RAVE data set. The detection is enabled by RAVE’s selection criteria creating no kinematic biases. The 15 member stars detected have $V_{los} = -199 \pm 27$ km s$^{-1}$ and lie between $-70^\circ < b < -50^\circ$, $30^\circ < l < 75^\circ$, $J > 10.3$ in the constellation of Aquarius. We established the statistical
isochrone fit in the $T_{\text{eff}}$, $\log g$, space of nearby tracer particles at the present day to potential. We presented simulations for two timescales, one localized on the sky, we performed simple dynamical identifications. Monoceros stream, Hercules–Aquila cloud) yielded no positive in the solar suburb (e.g., Canis Major and Virgo overdensities, tures both in the solar neighborhood (e.g., Kapteyn group) and with the Sagittarius dwarf. A search of other known substruc-

For most of the Aquarius stars RAVE stellar parameter estimates are also available. The member stars are metal-poor with [M/H] = $-1 \pm 0.4$ and we derive a preliminary isochrone fit in the $T_{\text{eff}}$–$\log g$ plane with an population age of 10 Gyr. Both the $V_{\text{los}}$ and metallicity are consistent with the group being within the stellar halo. We further use an RPMD to derive the transverse velocity for the stream, finding $v_T = 250 \pm 100$ km s$^{-1}$ for the group. This again places it within the Galaxy’s halo. We use the isochrone fits and the RPMD to provide distance estimates to the stars, where we prefer the latter as they give more consistent kinematics.

We investigated the relation of the stream to known substructures. We first discussed the probability of the stream being with debris from the Sagittarius dwarf. This is a priori plausible because the stream does not fall far from the orbital plane of the Sgr dwarf and the stream’s metallicity is consistent with that of the dwarf. A comparison to the models of Sagittarius dwarf debris from Law et al. (2005) and Law et al. (2009), shows that although the majority of models do not yield a good fit, a certain selection of nearby stars in the oblate model provides a reasonable fit in the $\Lambda_\odot$–$V_{\text{gal}}$ plane. This is most likely just coincidental however: the distributions in both distance and $V_{\phi}$ are clearly inconsistent with those of the Sgr stream. Also, the oblate model is the least favored of all the models when compared to the most recent data for the Sagittarius stream. We thus conclude that the Aquarius stream is most likely not associated with the Sagittarius dwarf. A search of other known substructures both in the solar neighborhood (e.g., Kapteyn group) and in the solar suburb (e.g., Canis Major and Virgo overdensities, Monoceros stream, Hercules–Aquila cloud) yielded no positive identifications.

Finally, to understand better how the stream is both local and localized on the sky, we performed simple dynamical simulations of a model satellite galaxy dissolving in the Galactic potential. We presented simulations for two timescales, one where the satellite is dissolving and the other when it is completely phase mixed. We compared the distribution in $l$, $b$, $V_{\text{los}}$ space of nearby tracer particles at the present day to that of the Aquarius stream stars plus the two other marginally overdense regions found in the RAVE data. The model in which the progenitor has had time to become phase mixed predicts overdensities in places where the data show none. By contrast, the dissolving, not-yet-phase-mixed scenario was able to account for the localization as well as reproducing the observed structure of the Aquarius stream. We therefore suggest that the stream is dynamically young: the localization could be explained as a recent disruption event of a progenitor whereby the stream has yet to occupy the available phase space. The progenitor could either be a globular cluster or a dwarf galaxy, which may or may not have survived to the present day. We make no positive identification of the Aquarius stream with any globular clusters, though there could be a possible link with likely dwarf galaxy remnant, $\omega$ Cen, and the associated Kapteyn group. Follow-up high-resolution abundances would elucidate this possible connection. Further, more sophisticated simulations of Aquarius are required. This will enable a better understanding of this interesting new halo stream which places hierarchical formation right on our proverbial doorstep.

Figure 9. Longitude in the Sagittarius orbital plane, $\Lambda_\odot$, vs. galactocentric radial velocity for the Aquarius stream stars (red points) compared to the Law models. Stars in the models with $d < 15$ kpc, $b < 0^\circ$, $l < 0^\circ$, $V_{\text{gal}} > -50$ km s$^{-1}$ are labeled green while $d < 15$ kpc, $b < 0^\circ$, $l < 0^\circ$, $V_{\text{gal}} < -50$ km s$^{-1}$ are blue. In this plot the blue points in the oblate model show a possible match to the Aquarius stream stars.

(A color version of this figure is available in the online journal.)

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Facilities: UKST
We compared the kinematic properties of the Aquarius stream stars to models of the Sagittarius dwarf debris, using the prolate \((q = 0.9)\), spherical \((q = 1.0)\), and oblate \((q = 1.25)\) models of Law et al. (2005, hereafter L05).\(^{22}\) We also used the triaxial model of Law & Majewski (2010, hereafter LM10) which uses a halo potential with \(c/a \approx 0.67, b/a \approx 0.83\) within 60 kpc.\(^{23}\) We follow convention and use the parameter \(\Lambda_\odot\) (defined in Figure 1 of L05) in our plots, which is the longitude from the Sgr dSph in the plane of its orbit increasing away from the Galactic plane. Figure 9 plots \(\Lambda_\odot\) against Galactocentric radial velocity for the Aquarius stream stars and the different Law models. We highlight those stars from the models that have the following properties:

1. Distance to Sun < 15 kpc
2. Declination < 0°
3. Galactic latitude < 0°

We are generous with the distance and Galactic latitude criteria to allow for uncertainties in the models (as well as the observational distances). Figure 9 shows \(V_{\text{gal}}\) as a function of \(\Lambda_\odot\). Those stars that fit the above selection criteria and that have \(V_{\text{gal}} > -50\) km s\(^{-1}\) are marked in green while those that have \(V_{\text{gal}} < -50\) km s\(^{-1}\) are marked in blue. The reason for this delineation will become evident below.

\(^{22}\) Available from http://www.astro.virginia.edu/srm4n/Sgr/

\(^{23}\) Kindly provided before public release by D. Law.

The velocities show a main feature at \(V_{\text{gal}} = +200 - 250\) km s\(^{-1}\), which corresponds to the leading arm, which the models predict is vertically streaming through the solar neighborhood. This stream gets stronger going from the prolate toward the oblate models. This large signal is not present in the RAVE data, as the heliocentric radial velocity is of the order of \(V_{\text{los}} = -270\) km s\(^{-1}\) or \(W = -300\) km s\(^{-1}\). Seabroke et al. (2008) showed that there is no such large asymmetry detectable in the distribution of radial velocities for stars with \(l < -45°\). We do see, however, that a faint signal of stars is present for the oblate models with \(V_{\text{gal}} = -100\) km s\(^{-1}\), which is associated with an extra wrap of the leading arm passing south of the solar neighborhood in this model. A value of \(V_{\text{gal}} = -50\) km s\(^{-1}\) separates this extra, fainter wrap from the main leading arm component predicted by the oblate model. The triaxial model does not exhibit this feature and indeed the \(V_{\text{gal}} = +300\) km s\(^{-1}\) stream is weaker as the leading arm misses the solar neighborhood.

We concentrate on the oblate model with its possible curl of the leading arm fitting the Aquarius stream stars, as this is the only possible match. In Figure 10 we show the \(X-Z\) plane as well as the \(V_R-V_\phi-V_Z\) planes for the stream stars and the solar neighborhood stars from the oblate model. The space velocities were calculated using the radial velocities and proper motions in the RAVE catalog as well as the distances derived via the two different methods (isochrone and RPMD). There is some overlap between the velocities from the two different distance derivations but in general we see that the space velocities are affected by the uncertainties in the distances. The RPM distances give a much tighter grouping in velocity for the stars and we take these

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\(\Lambda\) We follow convention and use the parameter \(\Lambda_\odot\) (defined in Figure 1 of L05) in our plots, which is the longitude from the Sgr dSph in the plane of its orbit increasing away from the Galactic plane. Figure 9 plots \(\Lambda_\odot\) against Galactocentric radial velocity for the Aquarius stream stars and the oblate model of L05. The solid red points show the values for Aquarius stream stars using the RPM distances while the open red points use the isochrone-derived distances. Median errors bars for the RPM distance-derived values are also shown. The blue and green points are as in Figure 9, where we see that with the full six-dimensional phase-space information the possible match with the blue points from the oblate model is ruled out.

(A color version of this figure is available in the online journal.)

**APPENDIX**

**RULING OUT SAGITTARIUS DWARF DEBRIS**

We compared the kinematic properties of the Aquarius stream stars to models of the Sagittarius dwarf debris, using the prolate \((q = 0.9)\), spherical \((q = 1.0)\), and oblate \((q = 1.25)\) models of Law et al. (2005, hereafter L05).\(^{22}\) We also used the triaxial model of Law & Majewski (2010, hereafter LM10) which uses a halo potential with \(c/a \approx 0.67, b/a \approx 0.83\) within 60 kpc.\(^{23}\) We follow convention and use the parameter \(\Lambda_\odot\) (defined in Figure 1 of L05) in our plots, which is the longitude from the Sgr dSph in the plane of its orbit increasing away from the Galactic plane. Figure 9 plots \(\Lambda_\odot\) against Galactocentric radial velocity for the Aquarius stream stars and the different Law models. We highlight those stars from the models that have the following properties:

1. Distance to Sun < 15 kpc
2. Declination < 0°
3. Galactic latitude < 0°

We are generous with the distance and Galactic latitude criteria to allow for uncertainties in the models (as well as the observational distances). Figure 9 shows \(V_{\text{gal}}\) as a function of \(\Lambda_\odot\). Those stars that fit the above selection criteria and that have \(V_{\text{gal}} > -50\) km s\(^{-1}\) are marked in green while those that have \(V_{\text{gal}} < -50\) km s\(^{-1}\) are marked in blue. The reason for this delineation will become evident below.

\(^{22}\) Available from http://www.astro.virginia.edu/srm4n/Sgr/

\(^{23}\) Kindly provided before public release by D. Law.
results to be more indicative of the group’s properties, plotting median error bars for these values.

The first thing to note is that the \( V_{gal} < -50 \, \text{km s}^{-1} \) simulation particles do not fit the positions of the Aquarius stream stars in the X-Z plane. Even accounting for distance errors the distribution is strikingly different. Rather, the group stars tend to be aligned spatially with the \( V_{gal} > -50 \, \text{km s}^{-1} \) simulation particles. Secondly, while the \( V_X \) and \( V_Z \) values for the \( V_{gal} < -50 \, \text{km s}^{-1} \) simulation particles are similar to that of the group, the values for \( V_Y \) very much differ from those of the Aquarius stream stars. For while the errors for the stream’s \( V_Y \) values are larger than the other velocity components, a significant (\( \sim 2\sigma \)) and systematic shift would be required in this component for the stream and \( V_{gal} < -50 \, \text{km s}^{-1} \) particles to agree. So, while there does appear to be some overlap between this faint wrap and the group in a couple of variables, both the spatial distribution and the velocity distribution do not match. This is further borne out by the proper motions: the average value for the Aquarius stream stars is 28 mas yr\(^{-1}\) while for the \( V_{gal} < -50 \, \text{km s}^{-1} \) particles it is 4 mas yr\(^{-1}\).

It is further worth noting that the oblate halo potential model does not compare well to Sagittarius dwarf debris data. As noted by Fellhauer et al. (2006), the Belokurov et al. (2006) data set traces dynamically old Sgr stream stars around the North Galactic Cap, where the oblate and prolate dark halos give different predictions. These data do not favor the oblate model with Fellhauer et al. (2006) arguing for a spherical dark halo, while LM10 favor a triaxial halo. Furthermore, the absence of the Sgr stream near the Sun (Seabroke et al. 2008; Newberg et al. 2009) is consistent with simulations of the disruption of Sgr in nearly spherical and prolate Galactic potentials. Thus, the only model that has a passing resemblance to the Aquarius stream stars is the least likely of all those presented. On the strength of all the evidence, we conclude that the Aquarius and Sagittarius streams are unrelated.

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