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Streams and the Milky Way dark matter halo

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Abstract. We describe an algorithm that can fit the properties of the dwarf galaxy progenitor of a tidal stream, given the properties of that stream. We show that under ideal conditions (the Milky Way potential, the orbit of the dwarf galaxy progenitor, and the functional form of the dwarf galaxy progenitor are known exactly), the density and angular width of stars along the stream can be used to constrain the mass and radial profile of both the stellar and dark matter components of the progenitor dwarf galaxy that was ripped apart to create the stream. Our provisional fit for the parameters of the dwarf galaxy progenitor of the Orphan Stream indicates that it is less massive and has fewer stars than previous works have indicated.

Keywords. Galaxy: halo, cosmology: dark matter, methods: n-body simulations

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1. Introduction

When dwarf galaxies fall into the Milky Way, they are ripped apart by tidal forces into long streams of stars that can encircle the Milky Way. If the dwarf galaxy comes in on a radial orbit, the stripped stars can form cloud-like structures at the apogalacticon points. The Sagittarius dwarf tidal stream was the first large tidal stream to be found (Yanny *et al.* 2000; Ibata *et al.* 2001). By 2015, there were 26 known tidal streams and clouds in the Milky Way (Newberg & Carlin 2016). The rate of finding streams has increased in recent years, including the discovery of 11 streams in DES data (Shipp *et al.* 2018) and 5 or more streams in *Gaia* data (Malhan *et al.* 2018). There are now in the neighborhood of 70 identified tidal streams.

The stars associated with tidal streams are special among stars in the Galaxy, because we have some information about their past location and velocity. Because we know the stars in tidal streams were once all in the same progenitor dwarf galaxy, we have some information about the potential through which they have come. By mapping the potential of the Milky Way, we are mapping the density distribution of matter in our galaxy. If we can map the density of baryons, then the difference between the two distributions tells us about the density distribution of dark matter.

Broadly, two different methods have been used to understand the substructure that we see in the Milky Way and other galaxies in the Universe. One way is to simulate the growth of the Universe from random fluctuations in the early universe. This way creates galaxies and structure that can be compared with what we see in a statistical sense, but does not tell us directly about the particular galaxy in which we live. The other way is to run N-body simulations in a potential that mimics the actual Milky Way, and vary the parameters of the potential, the dwarf galaxy, and the orbit to match the tidal streams that we observe.

In this paper we will describe the use this second method to determine the dark matter content of a dwarf galaxy progenitor of the Orphan Stream, which is the first step towards the long term goal of extending the described techniques to map the dark matter distribution in the Milky Way.

2. MilkyWay@home

MilkyWay@home (Cole *et al.* 2008) uses volunteered computers to fit parameters to data. The infrastructure is built using software originally designed to process radio observations from the SETI project using volunteered computer processors. We have built an optimization layer on top of that, which is designed to find the model parameters that best fit a dataset given a metric that determines numerically how well a given set of model parameters matches the data. The primary method we have used for optimizations is differential evolution. MilkyWay@home uses processors from $\sim 20,000$ volunteers from all over the world at any given time.

We have used this infrastructure to determine the parameters in the density distribution of turnoff stars in the halo, including multiple tidal streams (Weiss *et al.* 2018). The angular positions and apparent magnitudes of $\sim 100,000$ turnoff stars in a single SDSS stripe have been fit with a model that includes 20 or more parameters, thus demonstrating our ability to fit large numbers of parameters to complex datasets in our highly heterogeneous, asynchronous parallel computing environment.

3. Using tidal streams to determine the spatial distribution of dark matter

We would like to use the optimization capability of MilkyWay@home to constrain the spatial distribution of dark matter. Each stream is formed from a dwarf galaxy (4 or more parameters describe each dwarf galaxy) that is coming into the Milky Way on a particular orbit (5 parameters per stream) and has been on that orbit for a particular amount of time (1 parameter). The dwarf galaxy moves on that orbit through the potential of the Milky Way galaxy (any number of parameters).

Imagine we measure the spatial density and velocities of stars in at least a dozen tidal streams. This would give us a large number of constraints that could in principle allow us to determine a large number of Galactic parameters. We can run N-body simulations of the dwarf galaxies disrupting in the Milky Way to make tidal streams, and compare the properties of the simulated streams with the actual streams to optimize the parameters that describe the Milky Way potential and the dwarf galaxies that have fallen into it.

We expect the parameters of the Milky Way potential, dwarf galaxy, and orbit are partially separable. For example, Newberg *et al.* (2010) estimated the parameters for the orbit of the dwarf galaxy progenitor of the Orphan Stream using the line-of-sight velocity, distance, and angular position in the sky of the center of the tidal stream. We also showed that the path of this stream was sensitive to the overall mass of the Milky Way.

Table 1. Recovered parameters of the simulated dwarf galaxy progenitor.

Parameters	**Evolve Time**	R_B**(kpc)**	$R_B/(R_D + R_B)$	$M_B(M_{sim})$	$M_B/(M_D + M_B)$	**Likelihood**
Correct	3.950	0.200	0.200	12.000	0.200	−30.265
Search Range	[2.0−6.0]	[0.05−0.5]	[0.1−0.6]	[1.0−100.0]	[0.001−0.95]	
Trial 1	4.175	0.199	0.216	12.070	0.226	−13.905
Trial 2	4.117	0.198	0.220	12.111	0.239	−14.163
Trial 3	4.089	0.196	0.211	12.045	0.221	−14.337

Table 2. The recovered simulated dwarf galaxy progenitor in physical units.

Parameters	**Time (Gyr)**	$M_B(M_\odot)$	R_B**(kpc)**	$M_D(M_\odot)$	R_D
Correct	3.95	2.67×10^6	0.20	1.07×10^7	0.80
Trial 1	4.18	2.68×10^6	0.20	9.16×10^6	0.74
Trial 2	4.12	2.69×10^6	0.20	8.59×10^6	0.70
Trial 3	4.09	2.68×10^6	0.20	9.42×10^6	0.73
Accuracy	$\sim 3\%$	$\sim 1\%$	$\sim 1\%$	$\sim 10\%$	$\sim 10\%$

Bonaca & Hogg (2018) studied the accuracy with which the dark matter distribution in the Milky Way could be constrained by the positions of stars in cold tidal streams in the Milky Way halo. By calculating derivatives of measurable stream properties as a function of halo and stream model parameters, in an ideal system and for eleven cold streams roughly corresponding to actual streams found in the Milky Way, they calculated that dark matter parameters can be determined at the 1% level.

In this proceedings, we use the density and angular width of the stars along the Orphan Stream to constrain the properties of the dwarf galaxy progenitor of this stream.

Different stream properties are used to determine the dwarf galaxy properties, the orbits, and the Milky Way potential. However, we know that all of these parameters are not fully separable; for instance the mass and rotation speed of the dwarf galaxy will affect the offset of the leading and trailing streams from the path of the dwarf galaxy progenitor. In the end we will need to optimize all of the parameters simultaneously.

4. Optimization of dwarf galaxy progenitor properties

We made a simulated tidal stream with properties similar to those of the Orphan Stream. The dwarf galaxy progenitor was simulated as a dark matter component of 10,000 bodies with a Plummer sphere profile and a stellar (baryonic) component of 10,000 bodies, also with a Plummer sphere profile. The velocities are generated so that both components are stable when the dwarf galaxy is evolved in a null potential. The Plummer sphere parameters of the dwarf galaxy and the time through which the N-body simulation was evolved are given in Tables 1 and 2. The dwarf galaxy was evolved through a fixed Galactic potential with a Miyamoto-Nagai disk, a spherical bulge, and a logarithmic halo. The parameters for the Milky Way model and the parameters for the orbit are from the best fit model in Newberg *et al.* (2010). The distribution of dark matter and baryonic matter in the simulated tidal stream are shown in Figure 1.

We then wanted to know whether, given only the stellar stream width and the density of stars as a function of angle along the stream, MilkyWay@home could correctly determine the dwarf galaxy parameters and evolution time used in the simulation. MilkyWay@home was given the exact parameters for the orbit and the Milky Way potential, but had to determine the evolution time and the four parameters that were used to create the

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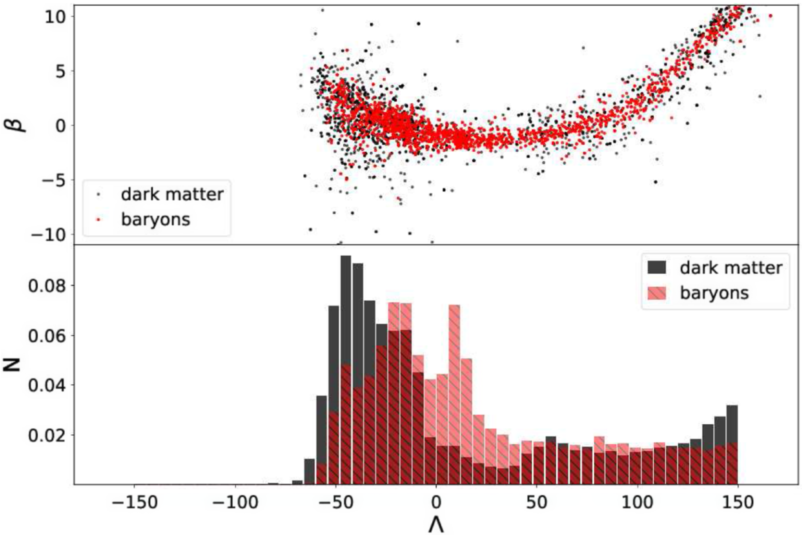

Figure 1. The simulated data histogram. The upper panel shows a sub-sampled plot of the positions on the sky of the dark matter (black) and stars (red) in the simulated tidal stream. Λ is the angle along the stream and β is the angle across the stream. The lower panel shows the density distribution of stars and dark matter as a function of angle along the stream.

dwarf galaxy progenitor: the baryon mass, M_B; the Plummer radius of the baryons, R_B; the dark matter mass, M_D; and the Plummer radius of the dark matter, M_D. MilkyWay@home used a different random seed to create its simulations, so it could not generate *exactly* the same tidal stream and know the exact parameters.

Each volunteered MilkyWay@home CPU was given a different set of five parameters to try. So that the simulated tidal stream ends up at its current location, the simulation is run by first placing a body at the current stream location and running it backwards along the orbit for the simulation time. Then the double Plummer sphere dwarf galaxy is placed where the single body ended up, and then the dwarf galaxy is evolved along the forward orbit for approximately the same amount of time; the forward time is adjusted within a small range to the value that produces the best likelihood. At the end of the simulation with each set of parameters, MilkyWay@home constructs a density histogram and a stream width histogram to compare to the original simulated histogram.

The log likelihood that the current parameter set is the same as the one that was used to create the original histogram is calculated as the sum of three different components. The first component measures how well the shape of the stellar density distributions along the streams match, using an Earth Mover Distance (EMD). The shape of the density distribution is related to the evolution time and the density profile of the dwarf galaxy progenitor. The second component measures how similar the total stellar masses in the two simulations are. This component is required because the EMD comparison is done with normalized histograms, and therefore is insensitive to the total mass of stars in the stream. The third component compares the stream widths in the two simulations. This component was added because without this information it was difficult for MilkyWay@home to determine the total amount of dark matter in the dwarf galaxy progenitor. The stream width can also vary as a function of the evolution time.

MilkyWay@home sent different sets of parameters out to each volunteered CPU, which returned the log likelihood that the given set of parameters matched the originally simulated stream. Each optimization takes of order 30 minutes on one CPU, but it can run in parallel on multiple cores so the actual latency can be shorter. The maximum likelihood was found by a differential evolution technique. Each optimization requres $\sim 50,000$ parameter evaluations and takes a couple of weeks to a month on MilkyWay@home. Multiple optimizations can be run simultaneously without substantially increasing the time of a single optimization; if multiple optimizations are running simultaneously then fewer cores are being used per optimization, but the choice of parameters for each work unit that is run is informed by more previous work unit results, so the number of work units required to complete the optimization is reduced.

Table 1 gives the search range for each parameter, and the optimization results for each of three trials. In order to avoid unusual combinations of dark matter and baryonic matter masses and radii, the optimization operates on a radius ratio and a mass ratio instead of the straight dark matter mass and scale radius. Table 2 gives the same results, but converted to physical units. A comparison of the correct values to the results of the three trials shows that under ideal conditions where the orbit, Milky Way potential, and the form of the dwarf galaxy are known exactly, it is possible to recover the evolution time to $\sim 3\%$, the mass and radial profile of the stars to $\sim 1\%$, and the mass and radial profile of the dark matter to $\sim 10\%$.

The dark matter content of dwarf galaxies is usually determined from the velocity dispersion of the stars in the dwarf galaxy. However, this one number cannot determine both a mass and a radial profile of the dark matter. Generally it is correlated with the dark matter mass within the stellar half light radius. But even this measurement relies on the assumption that the dwarf galaxy is in equilibrium, which is questionable – especially for ultrafaint dwarf galaxies. Our results are encouraging because they indicate that the properties of the progenitor dwarf galaxy are encoded in the distribution of stars along and across a tidal stream. With this algorithm we are able to probe the distribution of dark matter in the progenitor dwarf galaxy that was ripped apart to make the tidal stream, without the assumption of equilibrium.

Figure 2 shows that there is a ridge in the likelihood surface along the set of parameters that correspond to a constant mass within the half light radius of the progenitor dwarf galaxy. The fact that the likelihood surface is not constant along the ridge means that we are measuring more than one parameter in the dark matter distribution of the progenitor dwarf galaxy. We get useful information about both the mass and the radial profile of the dark matter. Because of this, we were able to fit both parameters in the optimization.

5. The progenitor of the Orphan Stream

We have made a first attempt to fit the parameters for the progenitor dwarf galaxy of the Orphan Stream to the actual data for the Orphan Stream. Figure 3 shows the density of SDSS turnoff stars along the Orphan Stream, following the selection proceedure from Newberg *et al.* (2010). There is a gap where there is no data in the SDSS footprint. It has been suspected in the past that what is left of the core of the progenitor is roughly at the edge of the SDSS footprint, where the density increases, or in the gap (Grillmair *et al.* 2015). We use the shaded histogram in Figure 3 as the actual number density of stars along the Orphan Stream. In order to compare this density with the stellar density in the MilkyWay@home simulations, we need to assess how much stellar mass each turnoff star represents. By comparing the number of turnoff stars in Pal 5 to the estimated total stellar mass of the cluster, we estimate that each turnoff star represents about $13 M_{\odot}$ of stars in the original dwarf galaxy.

Figure 4 shows four cross sections through the SDSS turnoff star data, for four different ranges of Λ, the angle along the Orphan Stream. These cross sections have been fit with a linear function representing the background, and a Gaussian representing the stream.

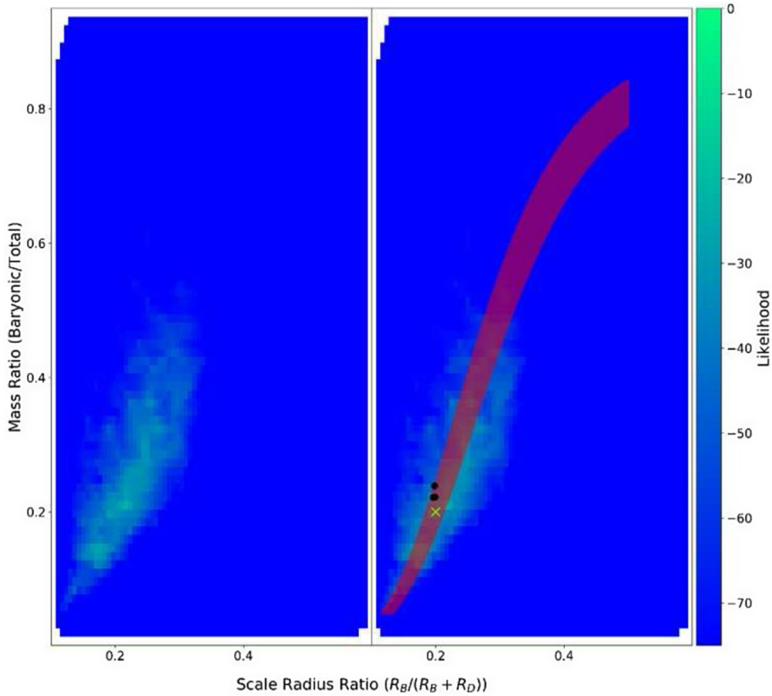

Figure 2. Likelihood surface for simulated data. We show the likelihood as a function of the scale radius ratio and the mass ratio, holding the other three parameters (evolve time, baryon mass, and baryon scale radius) fixed at the simulated values. The dark matter mass and scale radius vary with position in the diagram. The left panel shows that there is a ridge in the likelihood surface. In the right panel, the black points show the results of the three trials and the X marks the simulated value. Purple shows the region where the mass within the half light radius of the simulated dwarf galaxy would be about the same as the actual simulated dwarf galaxy; it is positioned along the ridge, supporting the idea that the tidal stream is most sensitive to the dark matter mass within the half light radius. The fact that the likelihood surface is not constant along the purple region means that there is also sensitivity to the radial distribution of the dark matter.

The width of these fit Gaussians are used as the width of the stream at the center Λ value of each of these datasets. These four widths are compared to the simulated stream widths at these locations for each of set of parameters.

We have completed three optimization trials with this data on MilkyWay@home. Two of the trials support an evolution time of ~ 3 Gyr, a stellar mass of $\sim 8 \times 10^5 M_\odot$ with a Plummer scale radius of 30 pc, and a dark matter mass that is roughly the same mass and profile as the stars. This makes the progenitor seem like it is almost a globular cluster. However, these solutions put a strong stellar core in the gap in the SDSS data, that we know from other surveys is not present (Fardal *et al.* 2019). What we have learned from this is that we need to have data near the progenitor to better constrain our models.

The third trial gave us a more physically plausible result. The evolution time was 3.5 Gyr, the stellar mass was $5.5 \times 10^4 M_\odot$ with a Plummer radius of 0.11 kpc, and the dark matter mass was $3.1 \times 10^6 M_\odot$ with a Plummer scale radius of 0.27 kpc. The inferred mass-to-light ratio for this dwarf galaxy is 56. All of these parameters are reasonable; they are roughly like Leo T (Simon & Geha 2007) with a little less dark matter.

The total mass of the dwarf galaxy progenitor is very similar to the mass of $3.2 \times 10^6 M_\odot$ suggested by Newberg *et al.* (2010), but much smaller than other authors, who

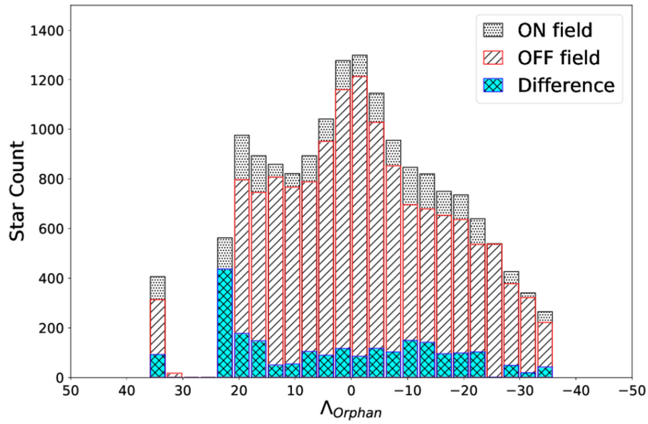

Figure 3. Histogram of the turnoff star counts as a function of angle along the Orphan stream. The data in this figure is the same as in Figure 5 of Newberg *et al.* (2010). The black histogram shows the star counts on the Orphan Stream, the red the star counts in a region of the sky around the Orphan Stream, and the filled histogram shows the difference. The difference histogram is used in our optimization as the number of stars as a function of angle along the stream.

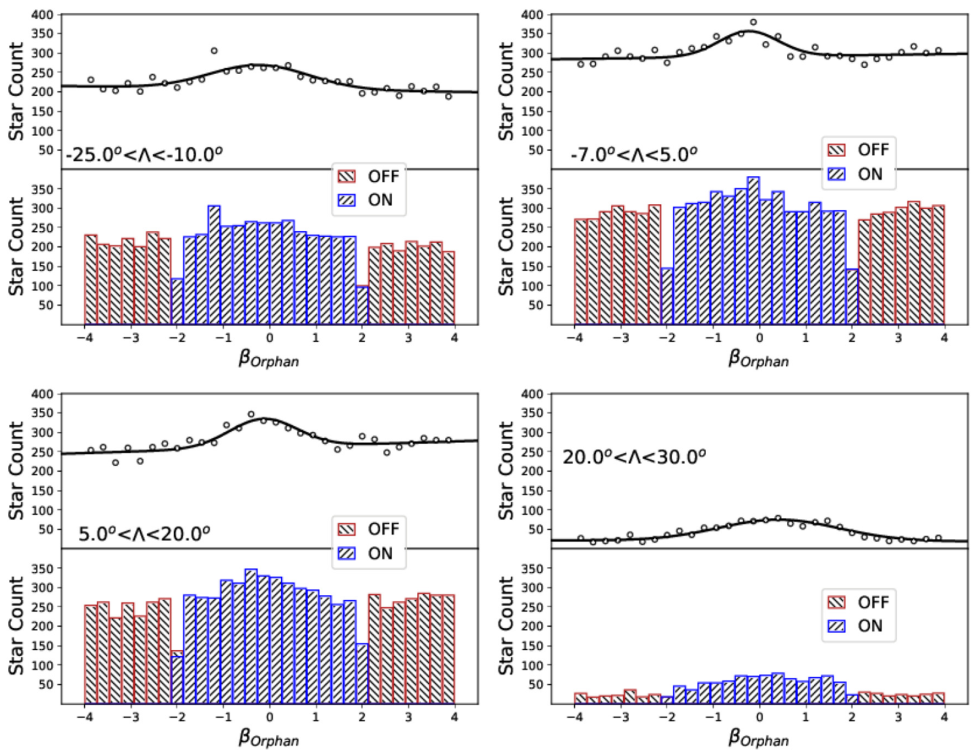

Figure 4. Histograms of the star counts perpendicular to the path of the Orphan Stream, at four different angles along the stream. The region on the Orphan Stream is shown in blue and the region around the Orphan Stream is shown in red. The best line-plus-Gaussian model fit to the combined distribution is shown by the black curve. A differential evolution algorithm was used to minimize the sum of squares of the residuals between the model and data. The widths of this Gaussian fit to the stream cross section is used as the stream width in the optimization.

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suggested masses in the $10^8 - 10^9$ range (Sales *et al.* 2008; Hendel *et al.* 2018; Fardal *et al.* 2019). The best fit stellar mass of the progenitor is $5.5 \times 10^4 M_\odot$, which is significantly smaller than previous estimates of $1.0 \times 10^5 M_\odot$ (Belokurov *et al.* 2007) and $7.5 \times 10^5 M_\odot$ (Sales *et al.* 2008).

6. Conclusion

We have developed N-body software that will generate two component dwarf galaxies, integrate any number of bodies in a large range of Milky Way potentials, and calculate the likelihoods that two streams match based on histograms of stream properties. We have used this code to show that under ideal conditions (the Milky Way potential, the orbit of the dwarf galaxy progenitor, and the functional form of the dwarf galaxy progenitor are known exactly), the density and angular width of stars along the stream can be used to constrain the mass and radial profile of both the stellar and dark matter components of the progenitor dwarf galaxy that was ripped apart to create the stream. Our first attempt to fit for the parameters of the dwarf galaxy progenitor of the Orphan Stream suggest that it is less massive and has fewer stars than previous works suggest. We are able to fit the observed stream with a dwarf galaxy progenitor with a stellar mass of $5.5 \times 10^4 M_\odot$, a Plummer radius of 0.11 kpc, a dark matter mass of $3.1 \times 10^6 M_\odot$, and a Plummer scale radius of 0.27 kpc.

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