



Measuring Dark Matter With MilkyWay@home

Siddhartha Shelton, Heidi Jo Newberg, Matthew Arsenault, Jacob Bauer, Travis Desell, Roland Judd, Malik Magdon-Ismail, Matthew Newby, Colin Rice, Jeffrey Thompson, Steve Ulin, Jake Weiss, and Larry Widrow



Abstract

We perform N-body simulations of two component dwarf galaxies (dark matter and stars follow separate distributions) falling into the Milky Way and the forming of tidal streams. Using MilkyWay@home we optimize the parameters of the progenitor dwarf galaxy and the orbital time to fit the simulated distribution of stars along the tidal stream to the observed distribution of stars. Our initial dwarf galaxy models are constructed with two separate Plummer profiles (one for the dark matter and one for the baryonic matter), sampled using a generalized distribution function for spherically symmetric systems. We perform rigorous testing to ensure that our simulated galaxies are in virial equilibrium, and stable over a simulation time. The N-body simulations are performed using a Barnes-Hut Tree algorithm. Optimization traverses the likelihood surface from our six model parameters using particle swarm and differential evolution methods. We have generated simulated data with known model parameters that are similar to those of the Orphan Stream. We show that we are able to recover a majority of our model parameters, and most importantly the mass-to-light ratio of the now disrupted progenitor galaxy, using MilkyWay@home. This research is supported by generous gifts from the Marvin Clan, Babette Josephs, Mani Limlaimai, and the MilkyWay@home volunteers.

Model

We use a two component dwarf galaxy model made from Plummer Spheres. One component will represent baryonic matter while the other represents dark matter. We can then compare the light matter component to observed data. The combined potential for this model is:

$$\Phi(r) = -\frac{GM_d}{a_d} \left(1 + \frac{r^2}{a_d^2}\right)^{-\frac{1}{2}} - \frac{GM_l}{a_l} \left(1 + \frac{r^2}{a_l^2}\right)^{-\frac{1}{2}}$$

Where a_d and a_l are the dark matter and baryonic matter scale lengths respectively. We use units where $G=1$. In these units, 1 Simulation Mass unit is equal to 222284.28 Solar Masses. Using Poisson's equation for gravity we can derive a value for the combined density distribution. The combined density distribution for this model is:

$$\rho(r) = \frac{3M_d}{4\pi a_d^3} \left(1 + \frac{r^2}{a_d^2}\right)^{-\frac{5}{2}} + \frac{3M_l}{4\pi a_l^3} \left(1 + \frac{r^2}{a_l^2}\right)^{-\frac{5}{2}}$$

We use this density distribution to assign particle positions. Our model assigns velocities to bodies by sampling a distribution function for spherically symmetric systems. This is a probability density yielding the probability of finding a body at a particular phase space coordinate.

$$f(\epsilon) = \frac{1}{\sqrt{8\pi^2}} \int_0^\epsilon \frac{d\Psi}{\sqrt{\epsilon - \Psi}} \frac{d^2\rho}{d\Psi^2}$$

Social Media

<https://www.facebook.com/Milkywayathome>
<https://www.youtube.com/MilkywayAtHomeRPI>
<https://twitter.com/MilkyWayatHome>
<https://www.instagram.com/milkywayathomerpi>

Stability

We use our two component algorithm to generate a single component dwarf galaxy in order to test against theoretical values.

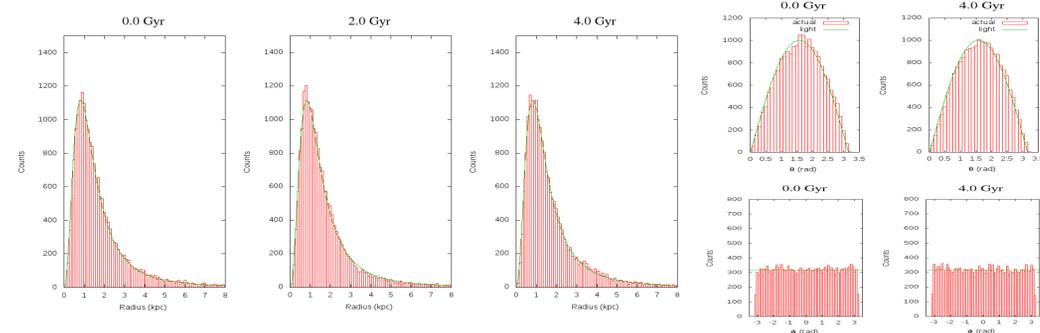


Figure 1: Spatial Stability.

These are histograms of different components of the dwarf galaxy's spacial distribution. The green lines show theoretical expectations. The three plots on the left show the radial profile of the dwarf galaxy after 0.0 Gyr, 2.0 Gyr, and 4.0 Gyr, respectively. The two plots on the top right show the inclination angle distribution after 0.0 Gyr and 4.0 Gyr, respectively. The two plots on the bottom right show the azimuthal angle distribution after 0.0 Gyr and 4.0 Gyr, respectively. As these plots show, the generated dwarf galaxy match theoretical models and retain their distribution over 4.0 Gyr.

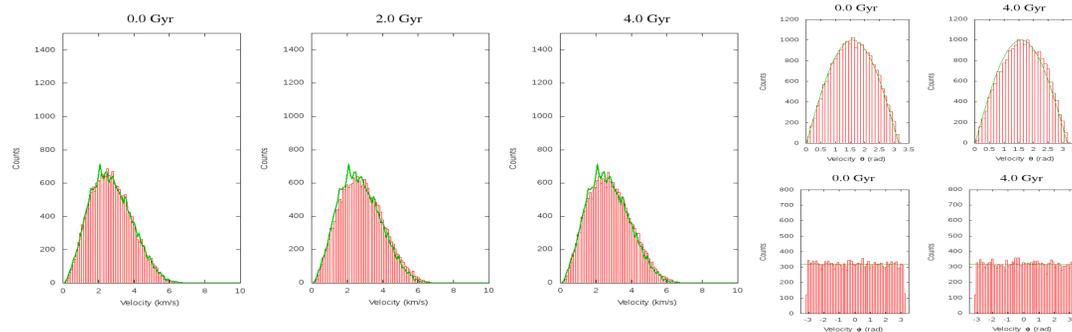


Figure 2: Velocity Space Stability.

We compare our single component dwarf galaxy's velocity distributions against theoretical models. The green lines in the left plots are velocity distributions that have been sampled from the theoretically known single component distribution function. The green lines in the right plots are theoretical expectations. The three plots on the left show the velocity profile of the dwarf galaxy after 0.0 Gyr, 2.0 Gyr, and 4.0 Gyr, respectively. The two plots on the top right show the velocity space inclination angle distribution after 0.0 Gyr and 4.0 Gyr, respectively. The two plots on the bottom right show the velocity space azimuthal angle distribution after 0.0 Gyr and 4.0 Gyr, respectively. As these plots show, the generated dwarf galaxy match both theoretical models and retain their distribution over 4.0 Gyr.

Virial Equilibrium

We test for virial equilibrium by calculating the virial ratio. That is, we want $2K/U = 1$ where K is the total kinetic energy and U is the total potential energy. We calculate the virial ratio using two different methods. In both methods we calculate the total kinetic energy by:

$$K_T = \sum_i \frac{1}{2} m_i v_i^2$$

We use two different methods of calculating total potential energy:

Method 1:

$$U_T = \sum_i m_i \Phi(r_i)$$

Method 2:

$$U_T = \sum_{ij} \frac{m_i m_j}{r_{ij}}$$

Simulation Time (Gyr)	Virial Ratio Method 1	Virial Ratio Method 2
0.0	0.954778	0.953758
0.2	0.973882	0.967526
0.5	1.009558	0.991711
0.75	1.038808	1.011387
1.0	1.047782	1.017715
2.0	1.023762	1.004786
3.0	1.015467	1.00247
4.0	1.010117	1.00108

Likelihood Surfaces

Our algorithm creates a histogram of the baryonic mass density along the tidal stream. This histogram is then compared to one created from observational data. Our likelihood calculation determines the similarity between these two histograms. We are able to explore the likelihood surface of our parameters by plotting likelihood as a function of individual parameters as compared to a test histogram. These plots give us insight into the difficulty associated with fitting these parameters.

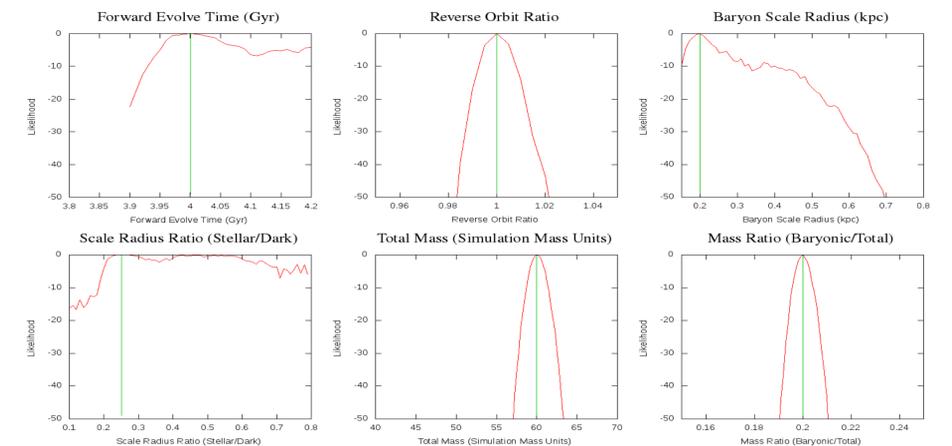


Figure 3: Likelihood Surfaces

The likelihood surfaces of the parameters fit by MilkyWay@home. They are compared to a test histogram. The green line shows the correct value for those parameters. As the plots show, the forward evolve time, the reverse orbit ratio, the baryonic scale radius, the total mass and the mass ratio have well defined peaks. The most important parameters are the mass and mass ratio as they, together, determine the amount of dark matter in the dwarf galaxy.

Preliminary Results

MilkyWay@home allows us to optimize our model parameters. We are currently using test histograms with a distribution similar to the Orphan Stream. We are able to recover the forward simulation time, the reverse orbit ratio, and the mass of the baryonic component of the dwarf galaxy. Below is a table of recovered parameters from a recent optimization using MilkyWay@home. As it shows we have yet to recover the mass ratio.

Parameter	Simulation Result	Correct Value	Percent Difference
Forward Evolve Time	3.6989	3.945	6.23
Backward Evolve Ratio	0.9871	0.9862	0.09
Light Matter Mass	11.9238	12.0	0.6
Mass Ratio	0.4435	0.2	121

We would like to recover the other parameters: baryonic matter scale radius, radius ratio and, most importantly, the mass ratio. Although the likelihood surfaces for the total mass and mass ratio have distinct peaks, we believe them to be coupled. Using the best fit parameters from previous runs on MilkyWay@home, we find that the total mass and mass ratio parameters, together, fit the baryonic matter mass. By fitting the baryonic matter mass directly we may be able to break this coupling. We would also like to explore changing the way the mass ratio is defined and its effect on the likelihood surface. Finally, we would like to explore ways of fitting the baryonic matter radius and the radius ratio.

