Dark Matter Content of Dwarf Galaxies, Measured from Tidal Debris

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ABSTRACT

We use maximum likelihood estimation (MLE) to find the best parameters for the mass, size, and mass/light ratio of dwarf galaxies that are the progenitors of tidal streams. An N-body simulation, including both dark matter and stars, is run for each set of candidate parameters. The distribution of stars in the resulting tidal stream is compared to either a simulated tidal stream with known progenitor properties, or observations of stars in a tidal stream. Massively parallelized sets of n-body simulations using the BOINC computing project, MilkyWay@Home, allow probing of an extensive likelihood surface. We show evidence that this approach is feasible, and report the results of initial trials on real streams. This research is supported by NSF grant AST AST 10-09670.

Introduction

A treasure trove of information is contained within stellar streams, the remnants of tidally disrupted dwarf galaxies. The long, tube-like structures exist far out in the Galactic halo, acting as orbital tracers for a past collision. What is proposed here is the feasibility of measuring the potential that such disruptions occurred in, revealing the nature of the Milky Way's dark matter distribution via Poisson's equation:

$$\nabla^2\Phi = 4\pi G\rho \tag{1}$$

The method used is a maximum likelihood estimation algorithm that models the collisional process between a dwarf galaxy and the Milky Way, and attempts to fit collision parameters by a massive application of asynchronous optimization algorithms. We find that given a dwarf spheroidal model to be discussed, that it is possible to fit the masses and scale radii for the baryonic and dark matter components of the colliding dwarf galaxies. This has the implication that it should be possible to extend the number of variables fit to include static potential parameters, and the future determination of the Milky Way's mass distribution.

Dwarf Galaxy Model

We use Monte-Carlo methods to model the progenitors of stellar streams as 2 component baryonic core and dark matter halo Plummer spheres.

$$\rho(\mathbf{r},t)|_{t=0} = \frac{3M_{core}}{4\pi a_{core}^3}\frac{1}{(1+r^2/a_{core}^2)^{5/2}} + \frac{3M_{halo}}{4\pi a_{halo}^3}\frac{1}{(1+r^2/a_{halo}^2)^{5/2}} \tag{2}$$

and particles are assigned circular orbits via:

$$v = \sqrt{\Phi_{Plummer}} \tag{3}$$

We are currently implementing a model with the velocity distribution one would expect from the phase density. When modeled in a null external potential, the distribution keeps its form over time after adjustment of the softening length to fit our simulation. It is believed that circular orbits should suffice in modeling the system, but an a priori dispersion will soon be added.

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N-Body Simulation

We employ a Barnes-Hut algorithm to solve the n-body problem for a dwarf galaxy colliding with the Milky Way. The Galactic potential is modeled by a spherical bulge, Miyamoto-Nagai disk, and a logarithmic halo. The dwarf galaxy is a dual-component model with particles following two nested Plummer profiles of different masses and scale radii to represent the baryonic core and dark matter halo. The resultant tidal stream stars created from the simulation can be binned and compared to data.

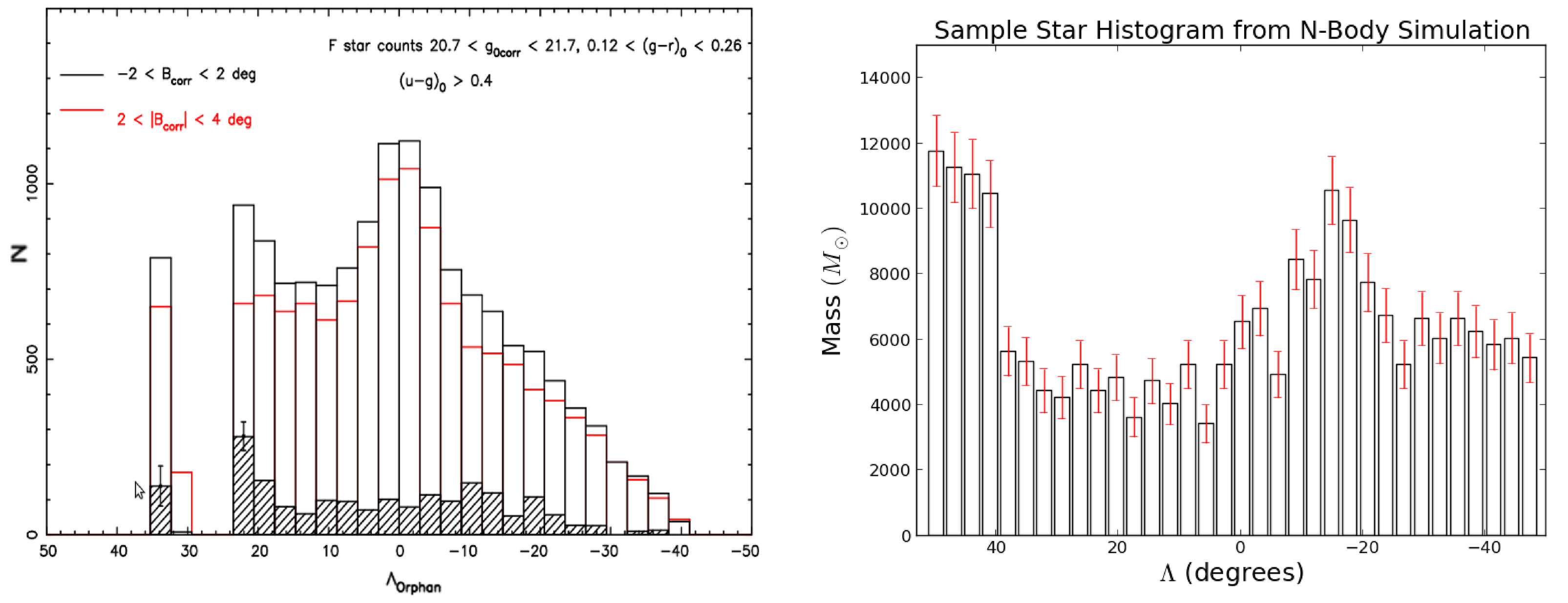

Figure 1: The left image (a) is raw data from Newberg et al. 2010 detailing the stream density distribution. The right image (b) is a simulated fit to this data. The distinct empty bins in (a) are a result of there being a lack of data in SDSS DR7. The data are only F-Turnoff stars, but they may be adjusted to represent total baryonic denisty.

Figure 1b shows the simulated data which can be compared to Figure 1a by a combination of an Earth-Mover Distance metric and a binomial PMF. We compute the distance between the histograms by the following metric:

$$\ln[\mathcal{L}] = \ln\left[\left(1-\frac{EMD}{EMD_{MAX}}\right)\left(1-\frac{B(x;n,k)}{B(x;n,nr)}\right)\right] \tag{4}$$

Here, EMD is the Earth-Mover Distance metric, a special solution to the transport problem which compares the geometry of the histograms. The function B is the binomial PMF. The binomial terms are a function of the ratio of the number of particles in the data histogram to the total number simulated in the simulation. The value n is the total number simulated, k is the ratio of masses per particle, and $r = nx$.

Parameter Optimization Results

Using the distributed computing project, MilkyWay@Home, with a total computing power of 0.5 petaFLOPs, we can use two asynchronous optimization algorithms (differential evolution and particle swarm) to fit the parameters of a progenitor dwarf galaxy by minimizing the distance function (4). N-body simulations with histograms to compare are sent to users contributing 350000 computers. As results are returned, better fits are sent out to replace the completed units. The optimizations take approximately a month to run. We have confirmed results for "fake" dwarf galaxies which take input parameters that are known a priori. The results are presented here in Table 1.

Table 1: Presented here are the results for multidimensional parameter optimizations for a dwarf galaxy with a known baryonic scale radius of 0.2 kpc, dark halo scale radius of 0.4 kpc, baryonic mass of $4 \times 10^5 M_\odot$, and a dark mass of $1.6 \times 10^6 M_\odot$ (80 percent) evolved for 4 Gy. The reverse time is the time a particle evolved back from the current stream's center of mass takes to reach the progenitor starting position. Masses are measured in units of 222248.42 $M_\odot$, radii are measured in kiloparsecs, and times are measured in Gy.

	t_f	$\frac{t_f}{t_{orbit}}$	a_{core}	$\frac{a_{core}}{a_{halo}}$	M_{total}	$\frac{M_{core}}{M_{total}}$
Range:	[3.00,5.00]	[0.75, 1.25]	[0.05, 1.00]	[0.05,1.00]	[0.10,100]	[0.00,1.00]
DE:	4.318	0.972	0.312	0.652	38.746	0.116
PS:	3.667	0.939	0.307	0.278	29.752	0.159

In addition to the created dwarfs, initial results from the Orphan Stream data in Newberg et al. 2010 suggest that the mass of the Orphan Stream is $10^7 M_\odot$, about 5% of which is baryonic matter distributed in a dense core surrounded by a diffuse dark matter halo. To add some confidence to this method beyond optimization testing, we plot the partial curves, or "parameter sweeps" of each input variable in Figure 2.

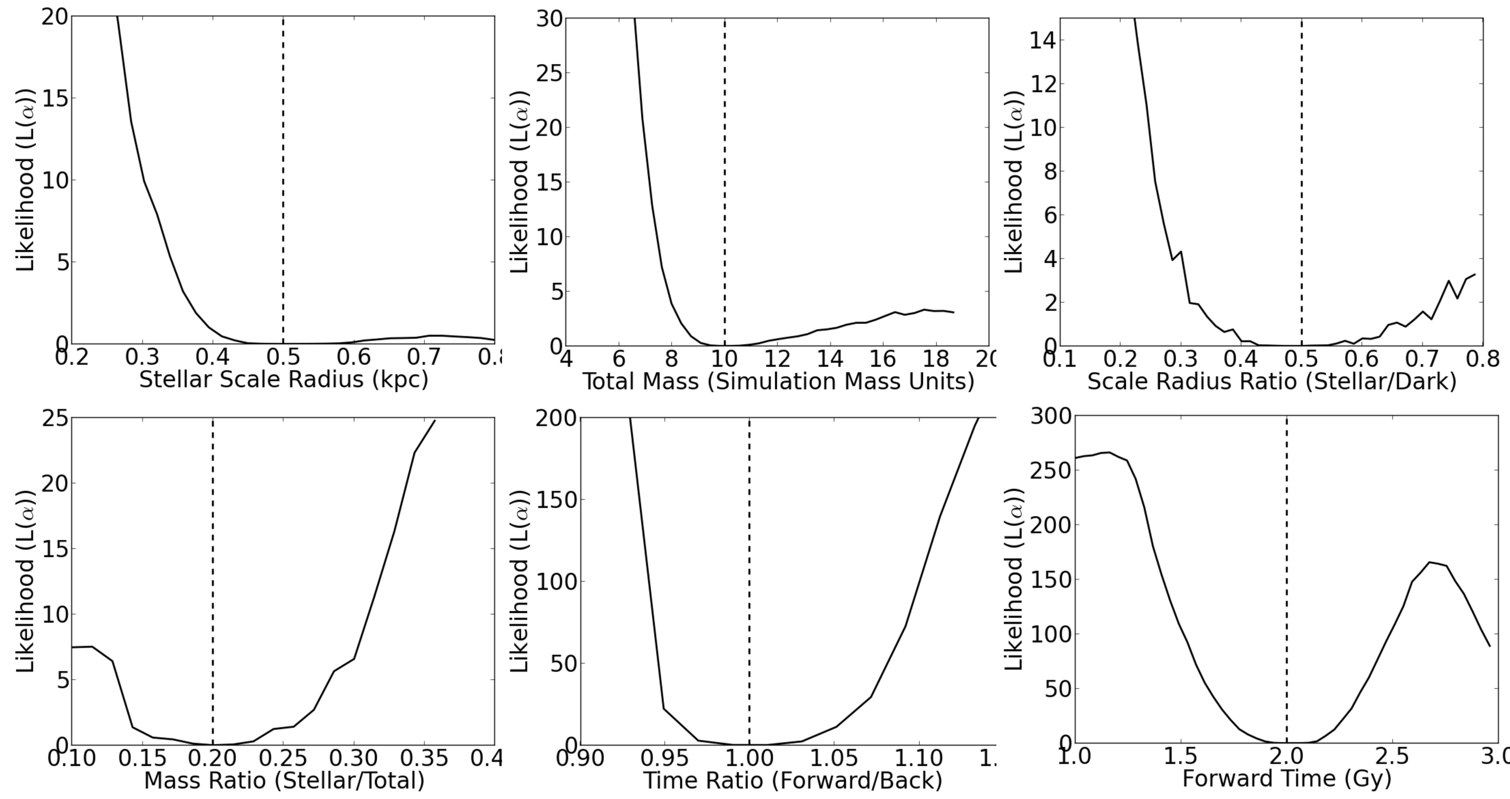

Figure 2: Plots of partial curves for each of the input parameters for an arbitrary dwarf galaxy. The expected values are indicated by dashed lines.

We conclude that this method has a high probability of success for application to deducing properties of stellar streams. Future work will include analysis of the likelihood surface and application to more stellar streams. We also have plans to fit the Milky Way potential to an arbitrary number of scale parameters.

References

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