MASS ESTIMATES OF TIDAL DWARF GALAXIES IN N-BODY SIMULATIONS OF COLLIDING DISK GALAXIES

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ABSTRACT

N-body simulations of colliding disk galaxies were run and gravitationally bound clumps were identified in the tidal tails. The N-body results were converted to simulated observations (moment maps) and "observable" quantities such as half-light radius, surface brightness and velocity dispersion were extracted from the clumps by fitting a Gaussian profile to them. From these values, the virial or "observed" mass (M_{vir}) and mass-to-light ratio $(M/L)_{obs}$ can be determined, and compared to the true mass (M_{true}) and true mass-to-light ratio $(M/L)_{true}$ of the clumps. We find that the locations of bound regions in tidal tails often do not correspond to projected density peaks in the moment maps, so the Gaussian fitting method does not accurately recover the true properties of these regions. An alternate mass-estimating method is explored using routines that are built into the N-body software, which yields additionally arbitrary results.

1. Introduction

Tidal dwarf galaxies (hereafter TDGs) are thought to be self-gravitating condensations of stars and gas forming within the tidal debris of interacting disk galaxies. Simulations of such interactions (Barnes & Hernquist 1992) show that gravitationally bound structures that develop within tidal tails have properties that are similar to those of some dwarf irregular and dwarf spheroidal galaxies, and retain little dark matter from the halos of their parent galaxies. Recent observational work purports to identify several of these TDGs within tidal debris. However, the observational evidence that these TDGs are distinct, dynamical entities is circumstantial or non-existant.

2. N-Body Simulations

Josh Barnes' Zeno software is a self-consistent N-body simulation package that can be downloaded at http://www.ifa.hawaii.edu/ barnes/treecode/treeguide.html. Zeno simulates encounters of two equal-mass disk galaxies, each composed of a central bulge, an exponential/isothermal disk, and a spheroidal halo (for details, see Barnes (1992)). We ran two simulations with the parameters in Table 1, where N is the total number of particles in each simulation; N_{bulge}, N_{disk}, and N_{halo} are the number of bulge, disk, and halo particles in each galaxy; N_{tot} is the total number of particles in each galaxy; M_{bulge}, M_{disk}, and M_{halo} are the masses of the bulge, disk, and halo of each galaxy; and M_{tot} is the total mass of each galaxy.

3. Gridding the Data and Calculating Moment Maps

In order to turn our N-body data into simulated observations, we grid the data in the x-, y-, and vz-dimensions and compute moment maps using IDL. If i, j, and k represent the indices of the x, y, and vz dimensions, respectively, N_{ijk} is the number of particles in pixel i,j,k of the grid, and V_k is the velocity of the k^{th} channel, then we can calculate moment maps using the following formulae:

$$mom0 = N_{ij} = \sum_k N_{ijk} \tag{1}$$

$$mom1 = V_{ij} = \frac{1}{N_{ij}} \sum_k N_{ijk} V_k \tag{2}$$

$$mom2 = \sigma_{ij} = \sqrt{\frac{1}{N_{ij}} \sum_k (V_k - V_{ij})^2} \tag{3}$$

Mom0 is an integrated “intensity”, or the number of particles in each pixel of the grid. Mom1 is an intensity-weighted velocity, and mom2 is an intensity-weighted velocity dispersion. The mom0,1,2 maps for our N=69632 simulation are shown in Figure 1.

4. Identifying Gravitationally Bound Regions

Barnes' dwarf-finding procedure in Zeno utilizes a friends-of-friends algorithm which identifies bound regions in the tidal tails. We consider only “virialized” regions with $\frac{T}{U} < -0.4$, where T is kinetic energy and U is potential energy. Figure 2 shows the locations of these regions at four different viewing angles. The result of the dwarf-finding procedure for the N=69632 simulation is

Table 1. N-body Simulation Parameters.

N	N_{bulge}	N_{disk}	N_{halo}	N_{tot}	M_{bulge}	M_{disk}	M_{halo}	M_{tot}
69632	2048	24576	8192	34816	0.0625	0.1875	1.00	1.25
139264	4096	49152	16384	69632	0.0625	0.1875	1.00	1.25

tabulated in Table 2, where N is the number of particles in each clump; $Mass$ is the mass of the clump for a Milky Way progenitor in solar units; x, y, and z are the coordinates of each clump in model units; and $\frac{R_m}{R_t}$ is the mean radius divided by the tidal radius; if $\frac{R_m}{R_t} < 1$, the dwarf is expected to lose mass to the parent body as it orbits.

5. Observationally Derived Mass Estimates

In order to calculate the "observed" mass of these clumps, we use the scalar virial theorem $2 < T > + < U >= 0$, where the angle brackets denote time averages. If the kinetic energy is $T = \frac{3}{2}\sigma^2 M$ and the potential energy is $U = \frac{-GM^2}{ar_{1/2}}$, where σ is the one-dimensional velocity dispersion, G is the gravitational constant, a is a geometric factor (for a uniform density sphere, $a = 2.74$), and $r_{1/2}$ is the half-light radius (Binney & Tremaine 1987), the observed, or virial mass, is then:

$$M_{vir} = 3\sigma^2 a r_{1/2} G^{-1} \tag{4}$$

where σ is given by mom2 at the location of a bound region, and $r_{1/2}$ is obtained from fitting a Gaussian profile to a location of a clump in the mom0 map.

The observed mass to light ratio of the clump can be found by the core-fitting formula (King's method):

$$\left(\frac{M}{L}\right)_{obs} = \frac{9}{2\pi G}\frac{\sigma^2}{r_{1/2} I_0} \tag{5}$$

where G, σ, and $r_{1/2}$ are the same as above and I_0 is the central surface brightness of the clump (Richstone & Tremaine 1986).

NOTE: We fit Gaussians to the known locations of bound regions regardless of whether there is a density peak in the mom0 map or not; this is very different from how observers identify TDG candidates.

We find that the locations of some bound regions in the tidal tails of our simulations do not correspond to density peaks in the mom0 maps so a Gaussian fit is not possible. In the regions that do correspond to density peaks, the estimations of $r_{1/2}$ and I_0 are too large, resulting in an estimate of M_{vir} that is orders of magnitude too large. There may be two possible reasons for this overestimate: (1) the clumps are embedded within projected tidal material that is not bound to them, or (2) our Gaussian fitting method is simply not appropriate.

6. Mass Estimates of Isolated Bulges

In order to test whether our method of Gaussian fitting is appropriate, we build simple models of an isolated spherical bulge of a galaxy and apply our Gaussian fitting routine to extract the half-light radius and velocity dispersion. To determine if these values are correct, we use the

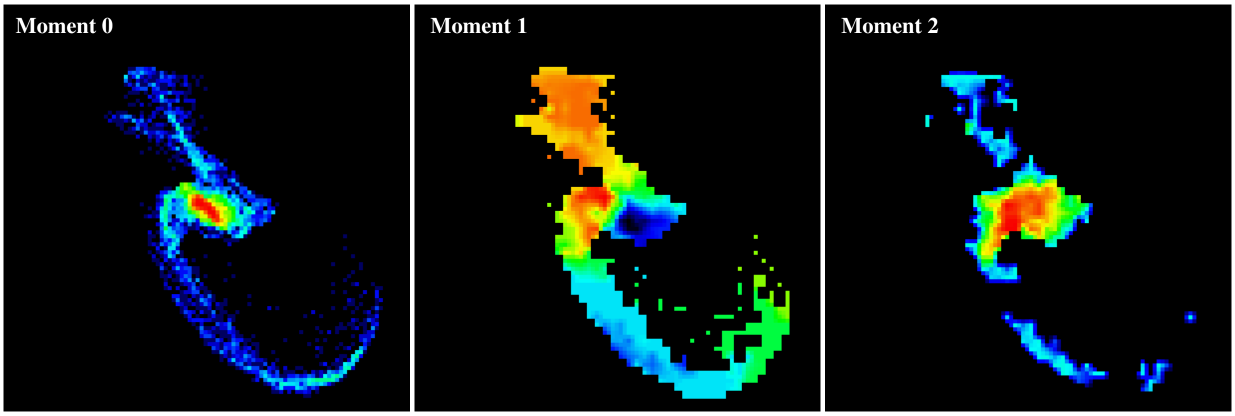

Fig. 1.— Mom0 (left), mom1 (center), and mom2(right) maps of N=69632 simulation.

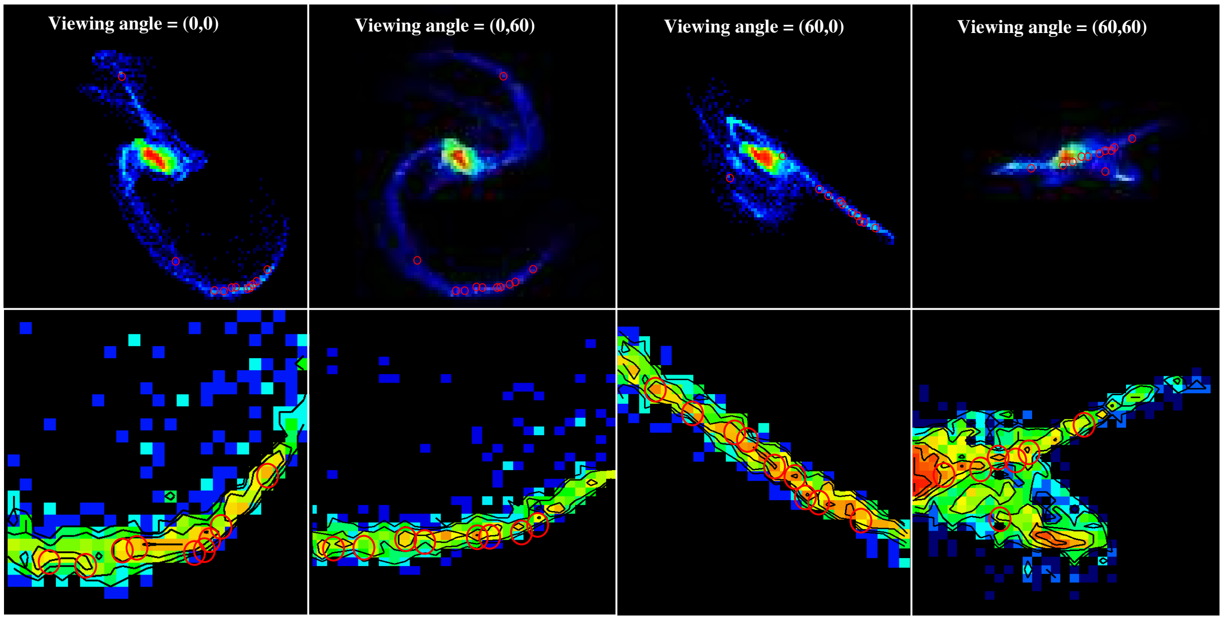

Fig. 2.— Red circles indicate the locations of bound regions in N=69632 simulation (top, left to right). Viewing angles (in degrees) correspond to rotations about the x- and y-axes, respectively. Close-up contour maps of the southern tidal tail at each viewing angle are shown at bottom, left to right.

Zeno routine *listdwarf* to directly calculate the expected projected half-light radius as well as the expected velocity dispersion from $\frac{-E}{m}$ (the total energy divided by the total mass) and $\frac{-T}{U}$, given that $T = \frac{3}{2}\sigma^2$.

The spatial stellar density of a galactic bulge may resemble the de Vaucoleurs (1948) profile in the outer parts, but towards the center can be modeled by

$$\rho(r) = \frac{(3-\gamma)M}{4\pi}\frac{a}{r^{\gamma}(r+a)^{4-\gamma}} \tag{6}$$

where a is a scaling radius and M is the total mass of the bulge (Dehnen 1993). We used Zeno to run a model with $\gamma = 1$, $a = \frac{1}{24}$ and $M = 1$. From Dehnen (1993) and Hernquist (1990) we can calculate the expected, "true" values of $r_{1/2}$ and σ for this model. The cumulative mass distribution corresponding to the density profile in equation (6) is

$$M(r) = M\left(\frac{r}{r+a}\right)^{3-\gamma} \tag{7}$$

The half-light radius can be found by setting $M(r_{1/2}) = M/2$, such that

$$r_{1/2} = a(2^{1/(3-\gamma)} - 1)^{-1} \tag{8}$$

So for $\gamma = 1$, $r_{1/2}(true) = 0.101$. To find σ, the projected velocity dispersion, for $\gamma = 1$, we use the virial theorem, $2T + U = 0$, or $\frac{T}{U} = -0.5$. Using $U = \frac{-GM^2}{6a}$ (Hernquist 1990), and $T = \frac{3}{2}\sigma^2$, we find $\sigma(true) = 1.16$. In Figures 3 and 4 we plot the values obtained by both the Gaussian method and the *listdwarf* method compared to the true values.

We find that the values of M_{vir} obtained by the Gaussian fitting method tend to increase as N increases; this is due to the increasing values of $r_{1/2}$ rather than the values of σ, which appear nearly constant. For the listdwarf method, the σ values are also constant as a function of N, and the $r_{1/2}$ and M_{vir} values become closer to 1 as N increases. Since the TDGs in our simulations typically contain less than 25 particles, we would like to employ a method that gives accurate estimates at small N. Therefore, it appears that the Gaussian method is more appropriate. The deviation at high N is certainly problematic, but there may be several remedies. First of all, a more realistic bulge model may have $\gamma = 0$; the constant-density core and r^{-4} halo of this model may be a better approximation to the expected structure of a TDG. Also, the spatial and velocity resolution of the moment maps may be altered to better resolve the clumps in the tidal tails and produce better estimates for M_{vir}.

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Table 2. Properties of Bound Regions in N=69632 Simulation.

Clump	N	Mass	$-\frac{T}{U}$	x	y	z	$\frac{R_m}{R_t}$
1	17	2.8e7	0.422	2.698	-3.922	-0.284	0.360
2	23	3.9e7	0.400	2.278	-3.935	-0.731	0.868
3	13	2.2e7	0.563	2.380	-3.932	-0.611	1.166
4	24	4.0e7	0.527	2.939	-3.843	-0.018	0.839
5	12	2.0e7	0.412	2.812	-3.880	-0.173	0.399
6	12	2.0e7	0.429	-1.023	2.445	2.098	1.521
7	25	4.2e7	0.490	0.586	-3.080	-1.801	1.495
8	53	8.9e7	0.517	1.716	-4.011	-1.182	1.081
9	37	6.2e7	0.570	1.981	-4.018	-0.962	1.039
10	17	2.9e7	0.595	3.052	-3.713	0.120	0.875
11	38	6.4e7	0.440	3.406	-3.331	0.547	0.936

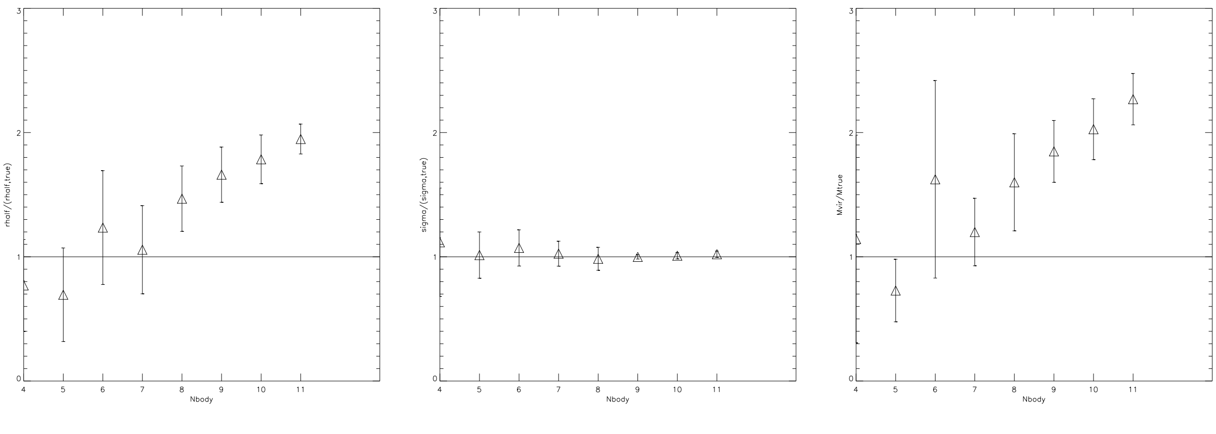

Fig. 3.— Plots of $r_{1/2}$, σ, and M_{vir} values derived from Gaussian fitting compared to true values for $\gamma = 1$ bulge model. Number of particles in simulation is $N = 2^{Nbody}$.

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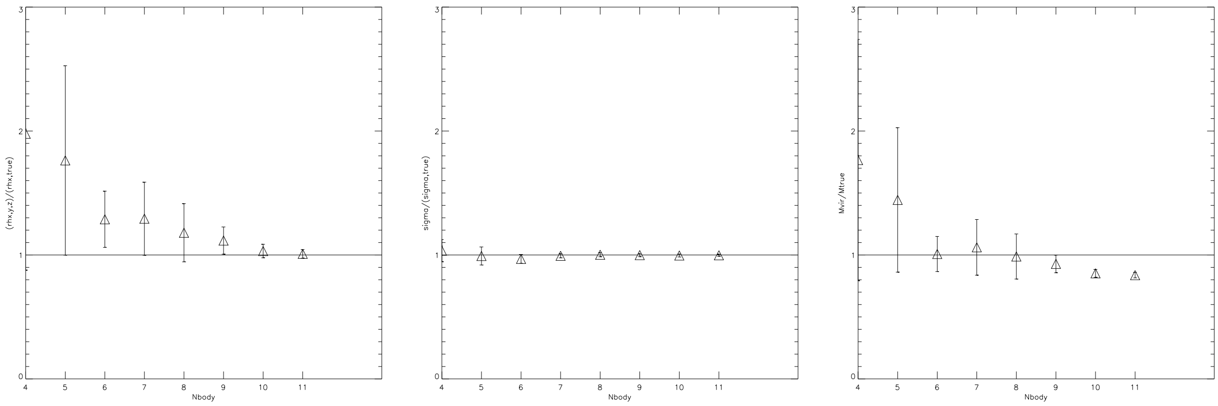

Fig. 4.— Plots of (rhx, y, z), σ, and M_{vir} values derived from Zeno listdwarf routine compared to true values for $\gamma = 1$ bulge model, where (rhx, y, z) is the average of the projected half-light radii on the x-, y-, and z-axes. Number of particles in simulation is $N = 2^{Nbody}$.