DWARF SPHEROIDAL SATELLITE GALAXIES WITHOUT DARK MATTER: RESULTS FROM TWO DIFFERENT NUMERICAL TECHNIQUES

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ABSTRACT

Self-consistent simulations of the dynamical evolution of a low-mass satellite galaxy without dark matter are reported. The orbits have eccentricities of 0.41 ≤ e ≤ 0.96 in a Galactic dark halo with a mass of 2.85 × 10^{12} M_{\odot} and 4.5 × 10^{11} M_{\odot}. A particle-mesh code with nested subgrids and a direct-summation N-body code running with the special-purpose hardware device GRAPE are used for the simulations. Initially, the satellite is spherical with an isotropic velocity distribution and a mass of 10^{7} M_{\odot}. Simulations with 1.3 × 10^{5} up to 2 × 10^{6} satellite particles are performed. The calculations proceed for many orbital periods, until well after the satellite disrupts. In all cases, the dynamical evolution converges to a remnant that contains roughly 1% of the initial satellite mass. The stable remnant results from severe tidal shaping of the initial satellite. To an observer from Earth, these remnants appear strikingly similar to the Galactic dwarf spheroidal satellite galaxies. Their apparent mass-to-light ratios are very large, despite the fact that they contain no dark matter. These computations show that a remnant without dark matter displays larger line-of-sight velocity dispersions, σ, for more eccentric orbits, as a result of projection onto the observational plane. Assuming that they are not dark matter dominated, it follows that the Galactic dSph satellites with σ > 6 km s^{-1} should have orbital eccentricities of e > 0.5. Some remnants have substructure along the line of sight that may be apparent in the morphology of the horizontal branch.

Subject headings: dark matter — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: structure — methods: numerical

1. INTRODUCTION

At least nine dwarf spheroidal (dSph) galaxies are known to orbit the Milky Way at distances ranging from a few tens to a few hundred kpc. On the sky these are barely discernible stellar density enhancements. Some have internal substructure and appear flattened. Their velocity dispersions are similar to those seen in globular clusters, and they have approximately the same stellar mass. However, they are about 2 orders of magnitude more extended. For spherical systems in virial equilibrium with isotropic velocity dispersions, the overall mass of the system can be determined from the observed velocity dispersion. Comparing this gravitational mass to the luminosity of the system determines the mass-to-light ratio, M/L (in the following always given in solar units, M_{\odot}/L_{\odot}). In the solar neighborhood this ratio is 3 < M/L < 5 (e.g., Tsujimoto et al. 1997). Values for M/L of 10 or larger are usually taken to imply the presence of dark matter in a stellar system. For the dSph satellites, M/L values as large as a few hundred are inferred, implying that these systems may be completely dark matter dominated (for a review, see Mateo 1997).

A careful compilation of the observed structural parameters and kinematical data for the Galactic dSph satellite galaxies can be found in Irwin & Hatzidimitriou (1995). More general reviews are given in Ferguson & Binggeli (1994), Gallagher & Wyse (1994), Meylan & Prugniel (1994), Grebel (1997), and Da Costa (1997).

There are in principle two possible ways to attain an apparent high mass-to-light ratio without dark matter. First, unresolved binary stars may inflate the measured velocity dispersion, thus increasing M/L. However, this effect is not large enough for a reasonable population of binary systems (Hargreaves, Gilmore, & Annan 1996; Olszewski et al. 1996). Assuming that Newtonian gravity is valid in dSph galaxies, an alternative may be that the assumption of virial equilibrium is violated; the satellite galaxies may be significantly perturbed by Galactic tides. The structural, kinematical, and photometric data of the dSph satellites show correlations that may be interpreted as the result of significant tidal shaping (Bellazzini, Fusi Pecci, & Ferraro 1996). Extragalactic stars indicate that some dSph satellites may be losing mass (Irwin & Hatzidimitriou 1995; Kuhn, Smith, & Hawley 1996; Smith, Kuhn, & Hawley 1997), and Burkert (1997) points out that if the tidal radii derived from the Irwin & Hatzidimitriou (1995) profiles (assuming King models) are correct, then these radii are smaller than expected from the observed large M/L values.

The “tidal scenario” has been studied in detail by a variety of authors; Oh, Lin, & Aarseth (1995), for example, modeled the evolution of dSph galaxies on different orbits for a set of rigid spherical Galactic potentials. The satellites are represented by 10^{3} particles and are evolved using a softened direct N-body program over many orbital periods, until disruption. Their work gives important insights into the tidal stability of such systems. Piasek & Pryor (1995) concentrate on one perigalactic passage of a dSph galaxy for different rigid spherical Galactic potentials. Their satellite consists of 10^{4} particles and is modeled using a TREE-CODE scheme. They find that a single perigalactic passage cannot perturb a satellite enough for an observer to
measure a high $M/L$ ratio, a conclusion similar to that of Oh et al. (1995). Johnston, Spergel, & Hernquist (1995), who apply their simulations to the dynamical evolution of the Sagittarius satellite galaxy, also arrive at similar conclusions.

Self-consistent simulations of the long-term evolution of a low-mass satellite galaxy on two different orbits interacting with an extended Galactic dark halo are presented by Kroupa (1997; hereafter K97). The satellite consists of $3 \times 10^5$ particles, and the whole system is evolved by applying a particle-mesh scheme with nested subgrids, the aim being to study the system well after the satellite has mostly dissolved and to "observe" its properties as they would be seen from Earth. The satellite is projected onto the sky, and its brightness profile, line-of-sight velocity dispersion, and apparent $M/L$ ratio are determined. These quantities can be directly compared to the observed values for Galactic dSph satellites.

Kroupa’s main finding is that a remnant containing about 1% of the initial satellite mass remains as a long-lived and distinguishable entity after the major disruption event. To an observer from Earth, this remnant looks strikingly similar to a dSph galaxy. The remnant consists of particles with phase-space characteristics that reduce spreading along the orbit. That this is a possibility to be considered has been pointed out by Kuhn (1993). However, projection effects are also important. An observer whose line of sight subtends a small angle with the orbital path of the remnant sees an apparently brighter satellite possibly with internal sublumps and an inflated velocity dispersion. The flattened structure that may be apparent to the observer need not have a major axis oriented along the orbital path. The observer derives values for $(M/L)_\text{obs}$ that are much larger than the true mass-to-light ratio $(M/L)_\text{true}$ of the particles, because the object is far from virial equilibrium and has a velocity dispersion tensor that is significantly anisotropic.

The aim of the present study is to investigate whether the conclusions of K97 can be arrived at using higher resolution simulations with more particles and a different numerical scheme altogether. We hope to confirm that the high $M/L$ values of the dSph satellite galaxies can be explained without the need for dark matter. We furthermore suggest possible observational discriminants, and continue the analysis of the two snapshots studied in K97.

In addition to the particle-mesh method applied in K97 and here, we use a direct $N$-body integrator in connection with the special-purpose hardware device GRAPE, which allows the integration of systems with 10$^5$ or more particles. It is therefore a useful tool for studying the evolution of dSph galaxies in a Galactic dark halo.

Using two different numerical schemes enables us to determine where the models agree, i.e., which conclusions are firm and where they show deviations. This allows us to quantify uncertainties inherent in the numerical method, but we do not aim at an in-depth discussion of the detailed differences between the two numerical schemes. We will show that the general conclusions agree for both methods, and that they can both be used equivalently to explore further regions in parameter space. The simulations described here are part of an extensive study of parameter space designed to investigate which orbits and which assumption for the Galactic dark halo might lead to dSph-like objects on the sky. Detailed reports of this survey will be presented elsewhere.

In the next section we give a short introduction to the two numerical schemes applied here, followed by a description of the data analysis used to evaluate the simulations. Section 3 treats the initial conditions, and in § 4 we discuss our results. Possible discriminants between dark matter and tidal models are presented in § 5. We conclude with § 6.

2. TWO NUMERICAL SCHEMES AND DATA ANALYSIS

A short description of both numerical schemes used for the simulations is provided in §§ 2.1 and 2.2, and the data reduction method is described in § 2.3.

2.1. Direct Integration Scheme with GRAPE

GRAPE (for “GRAvity PipE”) is a special-purpose hardware device that solves the Poisson and force equations for a gravitational $N$-body system by direct summation on a specially designed chip, thus leading to a considerable speed-up (Sugimoto et al. 1990; Ebisuzaki et al. 1993). We use the currently distributed version, GRAPE-3AF, which contains eight chips on one board and can therefore compute the forces on eight particles in parallel. The board is connected via a standard VME interface to the host computer, in our case a SUN Sparcstation C and FORTRAN libraries provide the software interface between the user’s program and the board. The computational speed of GRAPE-3AF is approximately 5 Gflops.

The force law is hardwired to be a Plummer law,

$$F_i = -G \sum_{j=1}^{N} \frac{m_j m_i (r_i - r_j)}{(r_i - r_j)^2 + \epsilon_i^2)^{3/2}}. \tag{1}$$

Here $i$ is the index of the particle for which the force is calculated and $j$ enumerates the particles that exert the force; $\epsilon_i$ is the gravitational smoothing length of particle $i$, and $G$, $m_i$, and $m_j$ are Newton’s constant and the particle masses, respectively. We chose all particles to have the same masses and smoothing lengths.

To increase speed, concessions in the accuracy of the force calculations had to be made. GRAPE works internally with a 20 bit fixed-point number format for particle positions, with a 56 bit fixed-point number format for the forces and a 14 bit logarithmic number format for the masses (Okumura et al. 1993). Conversion to and from this internal number representation is handled by the interface software. The number format limits the spatial resolution in a simulation and constrains the force accuracy. However, for collisionless $N$-body systems, the forces on a single particle need not be known to better than about 1%. In that respect, GRAPE is comparable to the widely used TREECODE schemes (e.g., Barnes & Hut 1986).

We utilize GRAPE by implementing the direct summation approach. This essentially involves two nested loops: an outer loop over all the particles for which forces are calculated and an inner loop for the interaction of each of these with all other particles in the system. Therefore, the number of operations scales as $O(N^2)$ with the particle number $N$. Typically, this scaling law limits the particle number to a few thousand. However, GRAPE substitutes the inner loop, and thus a considerable speed-up is gained. We also implement variable time steps and interpolate the particle accelerations when no new force calculations are needed within the required accuracy. Once the accelerations are obtained in each time step, the particles are advanced using the leapfrog scheme. The satellite galaxy is described
with 131,072 particles. To give an example of the computational time needed, a simulation with 5500 time steps (e.g., run Sat-M2 in Table 1) typically takes three days on a Sun Sparcstation with the GRAPE board.

2.2. SUPERBOX: A Particle-Mesh Code with Nested Subgrids

SUPERBOX is a conventional particle-mesh code (see, e.g., Sellwood 1987), but it allows high spatial resolution of density maxima by employing three levels of nested grids. Each active grid has \( N_{\text{grid}} = (2K)^3 \) cells, where \( K \) is a positive integer. The outermost, coarsest grid contains the local universe. The subgrids of the two lower levels are positioned at the density maximum of a galaxy and follow its motion through the coarse outer grid. In principle, any number of interacting galaxies can be treated. The force acting on each particle is obtained by first solving Poisson’s equation using the leapfrog integration scheme is used to advance the particles differentiating the potential at the position of the particle. The particle is obtained by first solving Poisson’s equation using the fast Fourier transform technique, then numerically differentiating the potential at the position of the particle. The leapfrog integration scheme is used to advance the particles along their orbits (for a brief description of the code see a detailed account will be provided elsewhere).

For the present purpose, SUPERBOX is used to simulate the interaction of two galaxies, namely, the Galactic dark halo and the satellite galaxy. Typically, \( N_{\text{grid}} = 32^3 \) cells per grid and a total of \( 1.3 \times 10^6 \) particles are used. In addition, two simulations with \( N_{\text{grid}} = 64^3 \) cells on each level and a total of \( 4 \times 10^6 \) particles are run to test the numerical resolution of SUPERBOX. An 8000 time step simulation takes 5 CPU days on an IBM RISC/6000 350 workstation in the first case, and 55 CPU days on a SUN Sparcstation 10/514 in the latter case.

2.3. Data Evaluation

The model satellite is analyzed by reproducing terrestrial observations of a dSph galaxy, as in K97.

At each time step in the simulation, the position of the density maximum of the satellite and of its remnant are determined using the full set of \( N_{\text{sat}} \) particles. Every prechosen number \( n \) of integration steps, a subset of \( N_{\text{sat}} \) satellite particles is stored on disk for detailed analysis by the hypothetical observer on Earth. In the adopted Cartesian coordinate system, this observer is located at \( R_0 = (0, 8.5, 0) \) kpc, where the origin is the Galactic center.

For further analysis, only stored particles that have a distance modulus \( M \) satisfying

\[
M_{\text{cod}} - \frac{\Delta M}{2} \leq M \leq M_{\text{cod}} + \frac{\Delta M}{2}
\]

are used, where \( M_{\text{cod}} = 5 \log_{10} D_{\text{cod}} - 5 \) is the distance modulus of the satellite’s density maximum, lying at a distance \( D_{\text{cod}} \) from the Sun, and \( \Delta M \) is the magnitude range covered by the observations. This reduced sample is the model observational sample. Throughout this paper, \( \Delta M = 0.8 \) mag is used, except in § 5.2, where \( \Delta M \) is varied for a detailed study of two snapshots.

Unless stated otherwise (as in § 5.2), the observational plane is subdivided into \( k = 20 \) circular annuli within a projected radial distance \( r_{\text{bin}} = 1.5 \) kpc from the density maximum of the satellite. These are used to evaluate the line-of-sight velocity dispersions and the surface brightness profile. The velocity dispersions are calculated using the iterated biweight scale estimator, which is the estimated dispersion about the biweight mean velocity of the sample. The biweight location (i.e., mean) and scale (i.e., dispersion) estimators are described by Beers, Flynn, & Gebhardt (1990), and are robust to outlying velocity data.

The apparent mass-to-light ratio an observer deduces is estimated from the King formula (see Piatek & Pryor 1995):

\[
\left( \frac{M}{L}_\text{obs} \right) = \frac{9}{2\pi G} \frac{\sigma_0^2}{\mu_0 r_{1/2}},
\]

where \( G \) is the gravitational constant and \( r_{1/2} \) is the half-light radius, i.e., the radius at which the projected surface brightness density decreases by 0.75 mag pc\(^{-2}\). The central line-of-sight velocity dispersion, \( \sigma_0 \), is calculated within the central bin. The central surface brightness, \( \mu_0 \), is estimated by fitting an exponential surface density profile to the “observed” radial model profile, which is obtained by counting the number of particles in the model observational sample in the above-mentioned projected radial bins, each particle having an intrinsic \( (M/L)_{\text{true}} = 3 \) comparable to the values derived for the solar neighborhood. Other values may be used to change the luminosity of the satellite.

3. THE MODELS AND INITIAL CONDITIONS

The Milky Way is a highly complex stellar and gaseous system. It can be subdivided into four major components: bulge, disk, stellar halo, and a nonluminous dark component required to fit the rotation curve. The latter dominates the total mass of the system by far. We thus simplify the problem by examining the dynamical interaction of a satellite galaxy with this dark halo alone. The next subsection details the models adopted for these two components, and § 3.2 discusses the initial conditions for the numerical experiments.

3.1. Galaxy Models

The dark halo of the Galaxy is taken to be an isothermal sphere with a total mass of \( M_{\text{halo}} = 2.85 \times 10^{12} M_\odot \) within 250 kpc. This follows for a halo that is truncated at 250 kpc

| Simulation | \( N_{\text{grid}} \) | \( N_{\text{halo}} \) | \( N_{\text{sat}} \) | \( N_{\text{st}} \) | \( n_{\text{sat}} \) | \( n \) | \( \Delta t \) (Gyr) | \( r_0 \) (x, y, z) (kpc) | \( v_0 \) (x, y, z) (km s\(^{-1}\)) | \( e \) | \( M_{\text{halo}} \) (x, y, z) \( M_\odot \) |
|------------|----------------|-------------|----------------|-------------|--------------|-------------|----------------|----------------|----------------|------------|----------------|
| RS1-10     | 32\(^3\)     | 1E6         | 3E5           | 5E4         | 8000         | 30          | 8.8            | 60, 0, 0       | 0, 60, 0, 0    | 0.71        | 0.45           |
| Sat-M1     | 32\(^3\)     | 1E6         | 3E5           | 5E4         | 3000         | 15          | 4.5            | 60, 0, 0       | 0, 60, 0, 0    | 0.71        | 0.45           |
| RS1-113    | 64\(^3\)     | 2E6         | 2E6           | 1E5         | 4500         | 15          | 8.25           | 60, 0, 0       | 0, 120, 0, 0   | 0.46        | 0.45           |
| Sat-M2     | 32\(^3\)     | 1E6         | 3E5           | 5E4         | 5500         | 15          | 5.5            | 100, 0, 0      | 0, 25, 0       | 0.96        | 2.85           |
| RS1-1L     | 64\(^3\)     | 2E6         | 2E6           | 1E5         | 7500         | 40          | 8.3            | 60, 0, 0       | 0, 175, 0, 0   | 0.41        | 2.85           |
| RS1-24     | 32\(^3\)     | 1E6         | 3E5           | 5E4         | 10,000       | 60          | 11             | 60, 0, 0       | 0, 175, 0, 0   | 0.41        | 2.85           |
| RS1-24L    | 64\(^3\)     | 2E6         | 2E6           | 1E5         | 7500         | 40          | 8.3            | 60, 0, 0       | 0, 175, 0, 0   | 0.41        | 2.85           |
and has a circular velocity of 220 km s\(^{-1}\). The crossing time of the diameter containing 33% of the halo mass, \(d_{33} = 137.2\) kpc, is \(t_{33} = 588\) Myr. We also adopt a core radius of 5 kpc.

In the simulations with SUPERBOX, the dark halo is treated as a live component consisting of \(N_{\text{halo}}\) particles, with \(N_{\text{halo}} = 1 \times 10^6\) or \(2 \times 10^6\). The simulations made for a comparison with GRAPE have a halo cutoff at \(R_c = 40\) kpc, with a total mass of \(M_{\text{halo}} = 4.5 \times 10^{11} M_\odot\). In this case, the inner and middle grids have dimensions of \(30^3\) kpc\(^3\) and \(122^3\) kpc\(^3\), respectively. For a comparison of SUPERBOX simulations with different numbers of grid cells and particles, \(R_s = 250\) kpc is used, in which case the inner and middle grids have dimensions of \(50^3\) kpc\(^3\) and \(188^3\) kpc\(^3\), respectively. The initial velocity dispersion is always isotropic. The isolated halo with \(R_c = 40\) kpc is allowed to relax to dynamical equilibrium by integrating it for \(9 \times t_{13}\), with a time step of 1.7 Myr. The halo with \(R_c = 250\) kpc is integrated in isolation for \(25 \times t_{13}\), with a time step of 7 Myr. Further details and a brief discussion of the final slightly prolate shape of the halo with \(R_c = 250\) kpc is provided in K97. The halo with \(R_c = 40\) kpc remains spherical after attaining dynamical equilibrium. Bothcontract slightly during relaxation into equilibrium.

In the simulations with GRAPE, the dark halo of the Galaxy is a rigid sphere with a core radius of 4 kpc, a cutoff radius of 40 kpc, and a total mass of \(M_{\text{halo}} = 4.5 \times 10^{11} M_\odot\). In all cases, the satellite is initially assumed to be a Plummer sphere with a Plummer radius of \(R_{\text{pl}} = 0.3\) kpc, a cutoff radius \(R_s = 1.5\) kpc, and a mass \(M_{\text{sat}} = 10^7 M_\odot\). The initial velocity dispersion is isotropic, and the crossing time of the diameter containing 33% of the mass, \(d_{33} = 0.56\) kpc, is 84 Myr. The satellite model is allowed to relax to dynamical equilibrium for typically eight such crossing times, with a time step of 1.1 Myr (SUPERBOX) and 1.5 Myr (GRAPE). The final, dynamically relaxed satellite is spherical.

In the SUPERBOX simulation, the inner and middle grids have dimensions of \(3.6^3\) kpc\(^3\) and \(8^3\) kpc\(^3\), respectively. The spatial resolution is thus \(50 (25)\) pc per cell length within a distance of 0.8 kpc from the satellite’s density maximum, and \(250 (125)\) pc per cell length between 0.8 kpc and 4 kpc from the satellite’s density maximum in the \(32^3\) (\(64^3\)) cell simulations. There are two sets of calculations, one with \(N_{\text{sat}} = 3 \times 10^5\) and \(N_{\text{grid}} = 32^3\), and one with \(N_{\text{sat}} = 2 \times 10^6\) and \(N_{\text{grid}} = 64^3\).

The calculations with GRAPE use \(N_{\text{sat}} = 131,072\) and \(\epsilon = 50\) pc (eq. [1]), equal for all particles.

### 3.2. Initial Conditions

As stated in the introduction, the aim of the present paper is to investigate, using different numerical realizations, the robustness of the results of K97. Simulations with SUPERBOX are compared with equivalent simulations running on GRAPE. In addition, SUPERBOX simulations with a total of \(1.3 \times 10^6\) particles and \(N_{\text{grid}} = 32^3\) cells are compared with simulations with a total of \(4 \times 10^6\) particles and \(N_{\text{grid}} = 64^3\) cells. In each case, the integration time step is 1.1 Myr for simulations with SUPERBOX and 1.5 Myr is the lowest time step bin for simulations using direct summation on GRAPE.

In all simulations presented here, the satellite is initially positioned on the \(x\)-axis at an apogalactic distance \(R_{\text{apo}}\) from the Galactic center, with an initial velocity vector \(v_0\) along the \(y\)-direction. The eccentricity of the orbit is \(e = (R_{\text{apo}} - R_{\text{peri}})/(R_{\text{apo}} + R_{\text{peri}})\), where \(R_{\text{peri}}\) is the perigalactic distance.

An overview of the initial conditions for the eight simulations described here is given in Table 1. The first column contains the name of the simulation, and the second column \((N_{\text{grid}})\) lists the number of grid cells used with SUPERBOX (G indicates runs with GRAPE). \(N_{\text{halo}}, N_{\text{sat}}, \) and \(N_{\text{sat}}\) are the number of halo, satellite, and stored satellite particles used in the data evaluation, respectively; \(n_{\text{tot}}\) is the total number of time steps, and every \(n\) steps \(N_{\text{sat}}\) particles are written to computer disk. The column \(\Delta t\) lists the total time interval simulated. The next two columns give the initial center-of-mass position, \(r_0\), and velocity, \(v_0\), vectors of the satellite in a Cartesian coordinate system centered on the Galaxy. The last two columns list the orbital eccentricity, \(e\), and the mass of the Galactic dark halo (see § 3.1).

### 4. RESULTS

Equivalent simulations with SUPERBOX and GRAPE are compared in § 4.1. The dependence of the results obtained with SUPERBOX on the number of grid cells and particle number is discussed in § 4.2.

#### 4.1. SUPERBOX versus GRAPE

The initial conditions for the two pairs of SUPERBOX-GRASE simulations are listed in the top four lines of Table 1. The evolution of the satellite galaxy in an orbit with eccentricity \(e = 0.71\) (simulations RS1-109 and Sat-M1) and an orbit with \(e = 0.46\) (RS1-113 and Sat-M2) are compared using the two different numerical schemes. In both cases the apogalactic distance is \(R_{\text{apo}} = 60\) kpc.

Three snapshots of the satellite in simulation Sat-M1 are shown in Figure 1. At each particular time, the satellite is plotted as seen from outside the Galaxy (the solid line traces its density maximum). Enclosed in the circle at the left is a magnification of the central region of the satellite and its remnant. The upper panel shows the satellite shortly after the start of the calculation. The middle panel shows the dwarf galaxy shortly after its first apogalacticon. Considerable tidal tails have developed, and there is a well-bounded core. The bottom panel shows the galaxy shortly after its third apogalactic passage. The satellite has disrupted. However, there still exists a measurable density enhancement, the remnant, which might be identified as a dSph satellite galaxy. This behavior is found in all simulations studied here and in K97.

In Figure 2 we show the path of the satellite in simulations RS1-109 and Sat-M1 looking perpendicularly onto the orbital plane. The satellite disrupts after the second perigalactic passage. Similarly, Figure 3 depicts the orbit in simulations RS1-113 and Sat-M2 for the first four perigalactic passages.

During passage through perigalacticon, the satellite is heated and particles escape. An insightful discussion of the processes involved is presented in § 4 of Piatek & Pryor (1995). Plotting the Lagrange radii as a function of time conveniently summarizes the overall evolution of the structure of the satellite. The effects of the periodic passages through perigalacticon on the mass budget of the satellite are shown in Figure 4 for the eccentric orbit and in Figure 5 for the orbit with \(e = 0.46\). Tidal shocks expel the outer regions of the satellites in both cases and excite damped
oscillations in those mass shells that remain bound. High values of $(M/L)_{\text{obs}}$ result only after the satellite is completely disrupted and has reached the remnant phase. This is similar to the simulation discussed by Kuhn & Miller (1989, see their Fig. 2). In their simulation, which is a simplified treatment of a satellite in a circular orbit in a constant tidal field, the observed mass-to-light ratio exceeds the true value by more than a factor of 5 only during the disruption phase at the end. The essential difference is that we find long-lived remnants with significantly inflated $(M/L)_{\text{obs}}$ after the disruption event.

Comparing both numerical schemes, the evolution of the satellites are very similar; for the eccentric orbit, the induced oscillations of the mass shells are evident in both the SUPERBOX and the GRAPE simulations, and both satellites lose more than 90% of their initial mass at dis-

Fig. 1.—Snapshot of the evolution of the satellite in GRAPE simulation Sat-M1 at three different times. The right side of each panel plots the distribution of satellite particles at the given time in the Galactic coordinate system. Each of the axes is 140 kpc long. Solid line shows the trajectory of the density maximum of the satellite until the time of the snapshot. On the left, the central part of the satellite is shown enlarged (the total length of each axis is 5 kpc).

Fig. 2.—Orbital path of the satellite in simulations RS1-109 and Sat-M1.

Fig. 3.—Orbital path of the satellite in simulations RS1-113 and Sat-M2.
Fig. 4.—Upper panel shows the evolution of the radii containing 10%, 20%, ..., 90% of the total mass of the satellite; lower panel shows the Galactocentric distance as a function of time. In both panels the solid lines show simulation RS1-109 (SUPERBOX), and the dashed lines show Sat-M1 (GRAPE).

ruption time $t \approx 1.3$ Gyr. The tidal forces are milder for the less eccentric orbit ($e = 0.46$), and in the SUPERBOX simulation RS1-113, the satellite disrupts at $t = 3.6$ Gyr, as is evident in Figure 5. Disruption occurs one orbital time (i.e., about 1.2 Gyr) later in the GRAPE simulation. However, both simulations lead to the same overall evolution of the satellite. A difference in disruption time between the two simulations is to be expected, as the Galactic dark halo is taken into account in very different ways (live and self-consistent in simulation RS1-113, rigid in simulation Sat-M2), leading to differences in the tidal forces that accumulate.

Applying the data reduction described in § 2.3, the measured mass-to-light ratio $(M/L)_{\text{obs}}$ for the satellite remnant is very large, despite the fact that the true mass-to-light ratio was chosen to agree with the value obtained in the solar neighborhood. Figures 6 and 7 plot $(M/L)_{\text{obs}}$ for both sets of simulations with SUPERBOX and GRAPE. These figures also show the evolution of the central surface brightness, $\mu_0$, and of the line-of-sight velocity dispersion, $\sigma_{1/2}$, evaluated within $r_{1/2}$, which is largely indistinguishable from $\sigma_0$ (see § 5.1).

A comparison of the SUPERBOX simulation RS1-109 with the GRAPE simulation Sat-M1 shows excellent agreement. The apparent mass-to-light ratio is not inflated prior to disruption, despite the forced oscillations of the Lagrange radii apparent in Figures 4 and 5. After disruption, the remnant stabilizes with $k_{\text{obs}} \sim 2\times 10^4$. The velocity dispersion that the observer measures for the largest fraction of the time after satellite disruption has a value in the range of $\sigma_{1/2} \approx 10$–30 km s$^{-1}$, and $(M/L)_{\text{obs}}$ ranges from a few hundred to a few thousand. Similarly, the satellite in the initially less eccentric orbit ($e = 0.46$) behaves alike in the SUPERBOX (RS1-113) and GRAPE (Sat-M2) simulations. With both numerical techniques, the remnant stabilizes

Fig. 5.—Same as Fig. 4, but for SUPERBOX simulation RS1-113 (solid lines) and GRAPE simulation Sat-M2 (dashed lines).

Fig. 6.—Upper panel: Evolution of the central surface brightness. Center panel: Evolution of the line-of-sight velocity dispersion within the half-light radius, $r_{1/2}$. Bottom panel: Evolution of the apparent mass-to-light ratio evaluated using eq. (3). In all panels, solid line shows SUPERBOX simulation RS1-109, dashed line shows GRAPE simulation Sat-M1.
These have central surface luminosities ranging from low when compared to the Galactic dSph satellite galaxies. Our simulations are, with $kpc_l$ observed central surface brightnesses of the remnants in above.

One cautionary remark is necessary at this point: the “observed” central surface brightnesses of the remnants in our simulations are, with $\mu_0 \approx 10^{4.5} \ L_\odot \ kpc^{-2}$, relatively low when compared to the Galactic dSph satellite galaxies. These have central surface luminosities ranging from $\mu_0 \approx 7 \times 10^5 \ L_\odot \ kpc^{-2}$ for Sextans to $\mu_0 \approx 3 \times 10^7 \ L_\odot \ kpc^{-2}$ for Leo I (Irwin & Hatzidimitriou 1995), and are thus at least $\approx 1$ order of magnitude larger than our values.

However, so far we have only scanned a very small range of initial parameters; we have limited the present study to an initial satellite mass of $10^8 \ M_\odot$. One possible way to arrive at the observed central surface brightness is to use a satellite galaxy with an initial mass that is approximately 1 order of magnitude larger. A simulation of a satellite galaxy with $M_{sat} = 10^8 \ M_\odot$ in an orbit with $e = 0.85$ but with properties otherwise identical to those of the satellite modeled here (§ 3.1) shows that its behavior is similar to the lower mass satellites. Because of its higher binding energy, it needs many more orbital periods until it is disrupted, and thus the computational cost is severe. In the remnant phase it has $\mu_0 \approx 10^{5.5} \ L_\odot \ kpc^{-2}$, much closer to the observed values. Its appearance on the sky closely resembles a dSph galaxy. Thus, if the size of the satellite is scaled up to have the same (relative) binding energy, the evolution is expected to be almost identical to the lower mass cases presented here.

All values discussed here are derived adopting $(M/L)_{true} = 3$. Another way to reconcile the central surface brightness of the models presented here with the observed values is to decrease this value of $(M/L)_{true}$. If we assume $(M/L)_{true} = 0.3$, then again $\mu_0 \approx 10^{5.5} \ L_\odot \ kpc^{-2}$. However, such a $(M/L)_{true}$ implies rather unusual relative numbers of bright, evolved stars and less luminous, unevolved stars (Dirsch & Richtler 1995).

Finally, it is of interest to evaluate the number of particles contributing to the central part of the remnant. To this end, the number $N$ of particles is counted in a volume with a radius of 0.8 kpc, centered on the density maximum of the remnant. While not an exact quantification, this is a reasonable assessment of the number of particles that are either bound energetically or have phase-space variables that inhibit spreading away from the remnant’s density maximum. A detailed investigation of the relative contribution of each type of particle to $N$ awaits simulations with initially $10^7$ to $10^8$ particles per satellite galaxy. The evolution of $N$ with time is shown in Figure 8 for all four runs discussed here. As can be seen from the figure, both the SUPERBOX and the GRAPE simulations lead to remnants that stabilize with 0.3% to 3% of the initial number of particles. The later disruption time of the satellite in the GRAPE simulation Sat-M2 is evident, but the outcome is the same as in the SUPERBOX run.

4.2. Different Number of Cells and Particles

The comparison of SUPERBOX and GRAPE simulations in the last section shows that both yield the same conclusions concerning the evolution and fate of a low-mass satellite galaxy without dark matter. Small differences

![Figure 7](image1.png)

**Fig. 7.**—Same as Fig. 6, but for SUPERBOX simulation RS1-113 (solid line) and GRAPE simulation Sat-M2 (dashed line).

![Figure 8](image2.png)

**Fig. 8.**—Number of particles $N(t)$ in the volume with radius 0.8 kpc centered on the density maximum of the satellite. Upper panel: Solid line shows SUPERBOX simulation RS1-109, dashed line shows GRAPE simulation Sat-M1. Lower panel: Solid line shows SUPERBOX simulation RS1-113, dashed line shows GRAPE simulation Sat-M2. In both panels, the number of GRAPE particles is scaled up by a factor of $(3 \times 10^7)/131072$, where the numerator and denominator are the initial number of particles in the SUPERBOX and GRAPE simulations, respectively.
Fig. 9.—Orbital path of the satellite in the $32^3$ cell simulation RS1-1 and the $64^3$ cell simulation RS1-1L. Owing to the slight prolate form of the live Galactic dark halo, the orbital plane flips after perigalacticon. This renders the projection of the orbital plane onto the $x$-$y$ plane somewhat irregular.

occur, but only in as much as the time of disruption differs by an orbital period. The satellite in the less eccentric orbit arrives at the remnant phase one orbital period later in the GRAPE simulation. The presence of a center to the mesh moving with the satellite therefore does not artificially promote the survival of a denser core in the remnant.

In this section, SUPERBOX simulations with $N_{\text{grid}} = 32^3$ cells per grid, $N_{\text{halo}} = 1 \times 10^6$ particles in the Galactic dark halo, and $N_{\text{sat}} = 3 \times 10^5$ particles in the satellite are compared with SUPERBOX simulations with $N_{\text{grid}} = 64^3$, $N_{\text{halo}} = 2 \times 10^6$, and $N_{\text{sat}} = 2 \times 10^6$. The structure and mass of the Galactic dark halo and the satellite are described in § 3.1. Two pairs of simulations are compared, for which the initial conditions are listed in the bottom four lines of Table 1. Runs RS1-1 and RS1-1L simulate the satellite galaxy on an extremely eccentric orbit ($e = 0.96$), the path of which is shown in Figure 9. Runs RS1-24 and RS1-24L are simulations with the satellite galaxy in an orbit with $e = 0.41$. Its trajectory is shown in Figure 10.

Fig. 10.—Orbital path of the satellite in the $32^3$ cell simulation RS1-24 and $64^3$ cell simulation RS1-24L.

Fig. 11.—Same as Fig. 4, but for the $32^3$ cell simulation RS1-1 (solid lines) and the $64^3$ cell simulation RS1-1L (dashed lines).

Fig. 12.—Same as Fig. 4, but for the $32^3$ cell simulation RS1-24 (solid lines) and the $64^3$ cell simulation RS1-24L (dashed lines).
As is evident from Figures 11 and 12, the overall evolution of the satellite is very similar in all four simulations. As in the SUPERBOX and GRAPE simulations discussed in the last section, the mass shells are induced to oscillate with about the same period by the periodic tidal field. Shedding of mass proceeds on about the same timescale in the $32^3$ and $64^3$ cell simulations, although the final disruption time is uncertain by about one orbital period. In the highly eccentric orbit, the satellite loses more than 90% of its mass at $t = 1.4 \text{ Gyr}$ in the $32^3$ cell simulation (RS1-1). Disruption occurs at $t = 2.4 \text{ Gyr}$ in the $64^3$ cell simulation (RS1-1L). The satellite in the less eccentric orbit is, however, disrupted at about the same time in both simulations RS1-24 and RS1-24L.

The evolution of the central surface brightness, the line-of-sight velocity dispersion within the half-light radius, and the apparent mass-to-light ratio for the four simulations are shown in Figures 13 and 14. The same results are obtained, namely, that satellite evolution leads to a stable remnant with a similar $\mu$, an inflated $\sigma_{1/2}$, and $(M/L)_{\text{obs}} \approx 100$ or more.

It is evident that the highly eccentric orbit leads to a brighter remnant with a larger $\sigma_{1/2}$ than the remnant in the less eccentric orbit. This trend is also observed in § 4.1 and results from projection effects, as described in the introduction.

In Figure 15 the number of particles within the spherical volume with a radius of 0.8 kpc is plotted as a function of time for all four simulations. Again, this agrees with § 4.1; the number of particles in the remnant stabilizes at 0.5% to 3.5% of the initial number of satellite particles.

5. POSSIBLE DISCRIMINANTS

The evidence presented so far shows that dark matter may not be necessary to account for the structural and kinematical properties of at least some of the Galactic dSph
5.1. The Preference for Eccentric Orbits

A perusal of Figures 6, 7, 13, and 14 shows that during the remnant phase the average line-of-sight velocity dispersion increases with orbital eccentricity. To quantify this, the time-averaged central line-of-sight velocity dispersion, $\langle \sigma_0 \rangle$, is computed over a 2.5 Gyr time interval, $t_e - t_b$, where $(M/L)_\text{obs}(t > t_e) > 50$. The time-averaged line-of-sight velocity dispersion within the half-light radius, $\langle \sigma_{0.5} \rangle$, is also computed over the same time interval. The simulations discussed here are augmented by the SUPERBOX simulations RS1-4 and RS1-5 (with $N_{\text{grid}} = 32^3$ cells and $N_{\text{sat}} = 3 \times 10^5$ particles) analyzed in K97. The orbits discussed there have $e = 0.74$ (RS1-4) and 0.60 (RS1-5), with $R_{\text{apo}} = 100$ kpc, and the Galactic dark halo consists of $N_{\text{halo}} = 10^6$ particles, with $R_c = 250$ kpc and $M_{\text{halo}} = 2.85 \times 10^{12} M_\odot$.

The result is plotted in Figure 16. The negligible difference between the central velocity dispersion and the dispersion evaluated within the half-light radius is evident. In this figure, the largest differences result for simulations of nearly radial orbits, where the modeled tidal forces at the Galactic center are most sensitively dependent on the resolution used. The GRAPE and SUPERBOX simulations give essentially the same result, again nicely confirming their independence of the numerical technique used.
5.2. Implications of $\Delta M$

Analysis of the remnants has been based on particles that lie within a magnitude range of $\Delta M = 0.8$ (eq. [2]), centered on the distance modulus of the density maximum. Observational samples used to derive kinematical quantities for dSph galaxies typically rely on a set of giant stars within some limited magnitude range.

Assuming the same intrinsic stellar brightness, this translates into a distance selection. If the satellite is extended and has substructure along the line of sight, as may be the case for tidally modified remnants, its color-magnitude diagram would exhibit a scatter that might mimic populations with different ages or metallicities, and the kinematical properties might depend on the magnitude range considered. This is demonstrated in Figure 12 of K97, where a significant increase of the observed velocity dispersion is seen for increasing $\Delta M = 0.1, \ldots, 3.5$ mag in one of the models. It is important to notice that even for the smallest magnitude bin, the derived mass-to-light ratio is extremely high and exceeds the true value by far.

Structural and photometric properties of Galactic dSph satellite galaxies rely on more inclusive stellar samples, because the stringent constraint on the nature of the stars necessary for kinematical studies (luminous stars with well-defined spectral features) can be relaxed. It is therefore important to quantify the changes of the structural parameter, $r_{1/2}$, and the photometric quantity, $\mu_0$, with $\Delta M$. If the tidal modification theory is to remain valid, then these quantities must not change much with $\Delta M$, or the observer would see such variations for different subpopulations in the H-R diagram of a dSph satellite galaxy.

Given that the two snapshots of satellites RS1-4 and RS1-5 at times $t = 6.27$ Gyr and 8.74 Gyr, respectively, are studied in much detail in §§ 4.2 and 4.3 of K97, we extend that analysis here to quantify the variation of $r_{1/2}$ and $\mu_0$ with $\Delta M$ (§ 5.2.1) and to investigate whether the morphology of the H-R diagram might betray tidal modification (§ 5.2.2). At $t = 6.27$ Gyr, remnant RS1-4 has $M_{\text{cod}} = 19.33$ mag, corresponding to a Galactocentric distance of $R_{\text{GC}} = 70.7$ kpc. At $t = 8.74$ Gyr, remnant RS1-5 has $M_{\text{cod}} = 19.16$ mag, corresponding to a Galactocentric distance of $R_{\text{GC}} = 65.7$ kpc.

5.2.1. Dependence of Structural and Photometric Quantities on $\Delta M$

In Figure 17, the half-light radius $r_{1/2}$ (solid circles) and the central surface brightness $\mu_0$ (open circles) are plotted as a function of $\Delta M$. The two upper curves describe the snapshot of remnant RS1-4 when its trajectory is almost aligned with the observer’s line of sight. The observer sees the remnant and parts of the leading and trailing tidal debris projected onto the same small region of the sky, producing a considerable extension along the line of sight, and thus a large variation of the observed velocity dispersion with $\Delta M$.

However, from Figure 17 it is apparent that the inferred $r_{1/2}$ and $\mu_0$ values are not affected much by the sampling procedure: $r_{1/2} \approx 170$–240 pc and $\mu_0 \approx 10^4$–$10^5 L_\odot$ kpc$^{-2}$. The snapshot of remnant RS1-5 is observed at a larger angle to its orbital trajectory, leading to no significant extension along the line of sight. Consequently, $r_{1/2}$ and $\mu_0$ do not vary much with $\Delta M$ (Fig. 17, lower set of curves).

5.2.2. The Width of the Horizontal Branch

A spread of distances leads to a broadening of the giant and horizontal branches in the H-R diagram. Subclumping along the line of sight will lead to distinct populations that are separated vertically in the H-R diagram. These are important possible observational discriminants, and the horizontal branch is especially well suited to this type of investigation because it is horizontal and blue enough to be less affected by contamination from foreground Galactic field stars, as suggested by C. Pryor (1997, private communication). The significant line-of-sight extension of remnant RS1-4 provides us with a model for examining the effects of this on the horizontal branch.

To this end, all particles are assumed to have the same luminosity, and histograms of the number of particles in bins of distance modulus centered on $M_{\text{cod}}$ are constructed in different regions of the remnant’s face. This is done for remnants RS1-4 and RS1-5 after storing model observational samples using $\Delta M = 3$ mag (eq. [2]). The appearance of the remnants on the sky and the distribution of mean velocities and velocity dispersions are shown in Fig. 9 of K97, which also defines the rectilinear coordinate system $(x_{\text{obs}}, y_{\text{obs}})$ on the observational plane used here. It demonstrates that neither of the two remnants is centered precisely on its density maximum (at position $x_{\text{obs}} = y_{\text{obs}} = 0$ kpc), and that neither the velocity gradient nor the isophotal shape of the remnant need be aligned with the orbital trajectory.

Figures 18 and 19 show the above-mentioned histograms for models RS1-4 and RS1-5, respectively, at three different positions along the velocity gradient across the face of both remnants (upper panels). The solid line indicates the magnitude distribution of particles within a radius of 0.2 kpc of the position of the density maximum of the remnants ($x_{\text{obs}} = y_{\text{obs}} = 0$). The long-dashed line shows the sample within a radial distance of 0.4 kpc of the position $x_{\text{obs}} = y_{\text{obs}} = 0.8$ kpc, and the dash-dotted line shows the sample within a radial distance of 0.4 kpc of the position $x_{\text{obs}} = y_{\text{obs}} = -0.8$ kpc. These three regions are aligned along the line-of-sight velocity gradient observed in both remnants. In
FIG. 18.—Distance-modulus distribution of particles across the face of remnant RS1-4. Both panels show the distribution of distance moduli relative to the distance modulus of the remnant’s density maximum. In the upper panel, the solid histogram shows the distribution at the remnant’s center, and the long-dashed and dot-dashed histograms show the distributions in regions offset from the center by 1.13 kpc along the velocity gradient. The bottom panel shows the distribution for all particles appearing projected within a radial distance of 1.2 kpc from the position on the sky of the remnant’s density maximum. For details, see §5.2.2. This figure complements Figs. 9–12 of K97.

FIG. 19.—Same as Fig. 18, but for the snapshot of remnant RS1-5 each figure, the lower panel samples all particles within a radius of 1.2 kpc of $x_{\text{obs}} = y_{\text{obs}} = 0$, thus including the above three smaller regions. Particles closer to the observer than the density maximum have $\Delta M < 0$.

The large projected depth of the remnant RS1-4, together with its clumpiness, produces a range of observed magnitudes, especially in the lower panel in Figure 18. The three peaks are separated by 0.25 mag and $-0.85$ mag, corresponding to distances of about 8 kpc and $-23$ kpc, respectively, from the position of the density maximum (70.7 kpc). In a color-magnitude diagram (CMD), the apparent scatter might be interpreted as coming from three distinct stellar components of different metallicities. However, the major peak at $\Delta M = 0$ is narrow and well defined, and would be prominent in a CMD. The CMD of remnant RS1-5 would appear featureless and very narrow (Fig. 19).

5.2.3. Words of Caution

As we have argued in §5.1, the tidal model favors eccentric orbits. For an observer on Earth, the angle between the line of sight and the trajectory of the dSph satellite is likely to be small, and the projection phenomena discussed above become important. Therefore, we expect the CMDs of at least some of these galaxies to exhibit some scatter and possibly complex substructure. However, this prediction is still preliminary and must be taken with caution. We have presented a detailed analysis of only two snapshots of the same initial low-mass satellite in two slightly different orbits. More general conclusions will be possible once the parameter study now in progress is finished. The present results do not exclude the possibility that all known Galactic dSph satellite galaxies resemble remnant RS1-5 more than RS1-4, with color-magnitude diagrams that are not affected by a line-of-sight extension.

Spreads in stellar age or metallicity introduce scatter in the CMD. Examples of the variation of the horizontal branch morphology with regard to the dependence of metallicity and age can be found in Lee, Demarque, & Zinn (1994). The width of the theoretical horizontal branches is typically 0.2–0.35 mag, as is true for globular clusters. In this case the horizontal branch morphology could constrain the depth if the particular dSph satellite has a significant extension along the observer’s line of sight. A more complex horizontal branch morphology results if a dSph satellite had a complex star formation history. In this case, depth information will be difficult to extract.

The CMDs of some Galactic dSph satellite galaxies exhibit considerable scatter; this is usually interpreted, along with other evidence in the H-R diagram, to be a sign of a complex star formation history (see Grebel [1997] and Da Costa [1997] for excellent reviews). A long-term aim of the parameter study now under way, in which the orbits and initial satellite masses are varied, is to identify those parameters that lead to remnants that most closely resemble the known dSph satellites in terms of $r_{1/2}$, $\sigma_0$, $\mu_0$, and $(M/L)_{\text{obs}}$. A detailed study of individual remnants will then include the construction of synthetic CMDs.

6. Conclusions

Different numerical schemes are used to compute the evolution of a low-mass satellite galaxy without dark matter for different orbits in different spheroidal Galactic dark halos. The simulations are performed with a particle-mesh code with nested subgrids (SUPERBOX) running on
conventional workstations, and with a direct-summation N-body code using the special-purpose hardware device GRAPE. For the former numerical approach, 32$^3$ cells per hierarchy with 3 $\times$ 10$^5$ satellite particles and 64$^3$ cells per hierarchy with 2 $\times$ 10$^6$ satellite particles are used. In the latter numerical scheme, 131,072 satellite particles are integrated. The evolution is very similar, and thus independent of the numerical scheme employed. In addition, the different number of grid cells and particle numbers in the SUPERBOX simulations leads to the same results, apart from small differences relating to the exact time of satellite disruption.

A comparison shows that in all cases, the satellite evolves to a stable remnant that contains on the order of 1% of the original mass. This remnant phase is achieved at the final disruption event near perigalacticon, during which the remaining 10%–20% of the initial satellite mass is thrown off. The structural parameters and the line-of-sight kinematical properties are similar to values observed for the Galactic dSph satellites. The present model remnants have, with $(M/L)_{\text{true}} = 3$, lower central surface luminosities than the Galactic dSph satellites. However, larger initial satellite masses, or reduced $(M/L)_{\text{true}}$ per particle, could reconcile this difference.

Satellites initially on eccentric orbits lead to apparent brighter remnants with inflated line-of-sight velocity dispersions, owing to the observer’s line of sight being approximately aligned with the orbital path. In this case, particles ahead of and following the remnant add to what the observer may make out to be a dSph galaxy. An observer looking along a very eccentric orbit finds a remnant with a larger $\sigma$ than if its orbit were less eccentric. The apparent $M/L$ an observer deduces from the King formula (eq. [3]) is very large, although the individual particles have $(M/L)_{\text{true}} \lesssim 3$. The line-of-sight velocity dispersion, $\sigma$, can thus be quite unrelated to the true mass of the system.

The projection onto the observational plane has important implications for deducing the dark matter content of Galactic dSph satellite galaxies, if their orbital eccentricities are known. The model data discussed here show that Galactic dSph satellites, which have $\sigma_{1/2} \approx 6$–10 km s$^{-1}$, should be in orbits with eccentricities of $e > 0.5$. Conversely, if future observations confirm $e < 0.3$ for some of these systems, then these must be dark matter dominated, unless they have a very pronounced internal velocity anisotropy (Kuhn 1993). Such anisotropy would appear to be difficult to produce, however, on a nearly circular orbit with currently known galaxy formation mechanisms.

The tidal model furthermore predicts scatter in the CMDs of at least some dSph galaxies. For preferentially eccentric orbits, projection effects enhance the extent of the observed remnant along the line of sight. This translates into a distribution of stellar magnitudes and subsequently a scatter in the CMD, and contributes to the scatter usually interpreted as a sign of a complex star formation history or metallicity variation. The morphology of the horizontal branch is well suited to the study of possible projection effects. The best candidate Galactic dSph satellites to show such an effect are those with internal subclumps, which cannot be expected to be at exactly the same distance. Thus, each subclump may contribute a horizontal branch displaced vertically by a few tenths of a magnitude relative to the horizontal branches of the other subclumps.

This work strengthens the evidence that at least some of the dSph satellite galaxies may not be dark matter dominated, confirming the conclusions of K97. It follows that the interpretation of Kuhn (1993) that at least some of the Galactic dSph satellite galaxies may be systems with special phase-space characteristics that permit long-time survival is to be taken seriously. Self-consistent simulations of the type analyzed here show how a tidally shaped remnant can be obtained through periodic modifications of the phase-space properties of the satellite particles.

The conclusions arrived at here are in agreement with the suggestion that some of the progenitors of dwarf spheroidal galaxies surrounding the Milky Way may have formed as condensations in the tidal arms of past merging events (see, e.g., & Lynden-Bell 1995; Grebel 1997 for a review). The formation of dwarf galaxies in tidal tails is studied in detail by Elmegreen, Kaufman, & Thomasson (1993) and Barnes & Hernquist (1992).

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