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The Inner Structure and Kinematics of the Sagittarius Dwarf Galaxy as a Product of Tidal Stirring — [Source link](#)

Ewa L. Łokas, Stelios Kazantzidis, Steven R. Majewski, David R. Law ...+2 more authors

Institutions: Ohio State University, University of Virginia, University of California, Los Angeles, University of Zurich ...+1 more institutions

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The inner structure and kinematics of the Sagittarius dwarf galaxy as a product of tidal stirring

Lokas, E L ; Kazantzidis, S ; Majewski, S R ; Law, D R ; Mayer, L ; Frinchaboy, P M

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THE INNER STRUCTURE AND KINEMATICS OF THE SAGITTARIUS DWARF GALAXY AS A PRODUCT OF TIDAL STIRRING

EWA L. LOKAS¹, STELIOS KAZANTZIDIS², STEVEN R. MAJEWSKI³,
DAVID R. LAW⁴, LUCIO MAYER⁵ AND PETER M. FRINCHABOY⁶

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ABSTRACT

The tidal stirring model envisions the formation of dwarf spheroidal (dSph) galaxies in the Local Group and similar environments via the tidal interaction of disk dwarf systems with a larger host galaxy like the Milky Way. These progenitor disks are embedded in extended dark halos and during the evolution both components suffer strong mass loss. In addition, the disks undergo the morphological transformation into spheroids and the transition from ordered to random motion of their stars. Using collisionless N -body simulations we construct a model for the nearby and highly elongated Sagittarius (Sgr) dSph galaxy within the framework of the tidal stirring scenario. Constrained by the present orbit of the dwarf, which is fairly well known, the model suggests that in order to produce the majority of tidal debris observed as the Sgr stream, but not yet transform the core of the dwarf into a spherical shape, Sgr must have just passed the second pericenter of its current orbit around the Milky Way. In the model, the stellar component of Sgr is still very elongated after the second pericenter and morphologically intermediate between the strong bar formed at the first pericenter and the almost spherical shape existing after the third pericenter. This is thus the first model of the evolution of the Sgr dwarf that accounts for its observed very elliptical shape. At the present time there is very little intrinsic rotation left and the velocity gradient detected along the major axis is almost entirely of tidal origin. We model the recently measured velocity dispersion profile for Sgr assuming that mass traces light and estimate its current total mass within 5 kpc to be $5.2 \times 10^8 M_{\odot}$. To have this mass at present, the model requires that the initial virial mass of Sgr must have been as high as $1.6 \times 10^{10} M_{\odot}$, comparable to that of the Large Magellanic Cloud, which may serve as a suitable analog for the pre-interaction, Sgr progenitor.

Subject headings: galaxies: dwarf – galaxies: individual (Sagittarius) – galaxies: Local Group – galaxies: fundamental parameters – galaxies: kinematics and dynamics – galaxies: structure

1. INTRODUCTION

The tidal stirring scenario (Mayer et al. 2001; Klimentowski et al. 2007, 2009; Kazantzidis et al. 2010) proposes that the population of dwarf spheroidal (dSph) satellite galaxies around the Milky Way and Andromeda galaxies were transformed into their present morphology via tidal interaction of late type progenitors — initially small disks embedded in extended dark matter halos — with their respective host. Due to tidal forces the dwarfs are substantially stripped of their mass and their stellar component undergoes strong dynamical and morphological evolution. This evolution manifests itself in the morphological transformation of the disk into a bar and then an ellipsoid or spheroid, with the commensurate transition from ordered (rotation in the disk) to random motion of the stars. In the transitory bar-like stage the

orbits are mostly radial and become more isotropic as the stellar shape evolves toward spherical. The effectiveness of the tidal transformation depends crucially on the orbital parameters (the orbital time and the pericenter distance) and also to some extent on the initial structure of the dwarf (Kazantzidis et al. 2010).

An interesting example of a dSph galaxy strongly affected by tidal forces from the Milky Way is the Sagittarius (Sgr) dwarf discovered by Ibata et al. (1994). A convincing proof of such interaction was provided by the identification within the 2MASS survey of the Sgr stream, which spans a 360° great circle on the sky (Majewski et al. 2003). Until now, modeling of the Sgr system by N -body simulations has focused on reproducing the properties of the tidal stream, especially the velocities, velocity dispersions, positions and distances of the stellar debris in the leading and trailing arm (Johnston et al. 1995, 1999; Helmi & White 2001; Helmi 2004; Martinez-Delgado et al. 2004; Johnston et al. 2005; Law et al. 2005; Fellhauer et al. 2006; Peñarrubia et al. 2010). Only recently, however, have models been developed that are able simultaneously to satisfy all angular position, distance, and radial velocity constraints on both the leading and trailing tidal streams (Law et al. 2009; Law & Majewski 2010). Nevertheless, in most such numerical models the dwarf was initially assumed to be spherical and one-component, with the distribution of stars and dark matter approximated by a single

¹ Nicolaus Copernicus Astronomical Center, 00-716 Warsaw, Poland; lokas@camk.edu.pl

² Center for Cosmology and Astro-Particle Physics; and Department of Physics; and Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA; stelios@mps.ohio-state.edu

³ Department of Astronomy, University of Virginia, Charlottesville, VA 22904-4325, USA; srm4n@virginia.edu

⁴ Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA; Hubble Fellow; dr-law@astro.ucla.edu

⁵ Institute for Theoretical Physics, University of Zürich, CH-8057 Zürich, Switzerland; lucio@phys.ethz.ch

⁶ Department of Physics and Astronomy, Texas Christian University, Fort Worth, TX 76129, USA; p.frinchaboy@tcu.edu

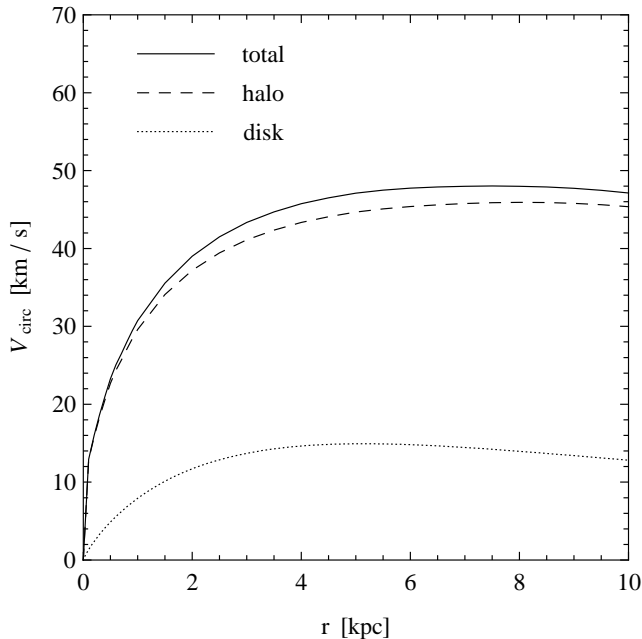


FIG. 1.— The circular velocity curve of the simulated dwarf galaxy in the initial state. The dotted, dashed and solid lines correspond, respectively, to the disk, the dark halo and the sum of the two.

Plummer sphere.

However, it has been known since the time of the discovery of Sgr that the shape of the dwarf is strongly non-spherical. Ibata et al. (1997) estimated the shape to be bar-like with axis ratios 3:1:1 and this was later confirmed by observations of the distribution of Sgr M giant stars with the 2MASS survey (Majewski et al. 2003). The elongation of the dwarf is usually interpreted as due to tidal deformation (e.g., Johnston et al. 1995). However, if a satellite that is initially spherical is required to survive long enough to produce the observed amount of tidal debris, the observed degree of elongation would be difficult to obtain through tides. Even at pericenter, where tidal forces are the strongest, the surface density contours will likely be elongated only in the outer part of the dwarf (where the transition to the tidal tails occurs) but remain rather circular in the central parts.

In this work we demonstrate that the observed shape of the Sgr core can be reproduced if the stellar component was initially in the form of a disk, slightly inclined with respect to the orbital plane. As such, the Sgr dwarf might have previously resembled the Large Magellanic Cloud, a conjecture that is actually consistent with other observations, such as Sgr’s chemistry (Chou et al. 2010) and star formation history (Siegel et al. 2007). In our model, we embed the disk in a massive dark matter halo, place it at an apocenter of a probable orbit of Sgr, determined from previous work, and evolve the system for a few orbital times. The dwarf undergoes a characteristic evolution on such a tight orbit: the stellar component forms a bar at the first pericenter that survives until after the second. By that time a sufficient number of stars are stripped to reproduce most of the observed Sgr stream (although see Correnti et al. 2010). Unlike previous studies that focused on the Sgr tidal tails, here we use constraints from the shape of the Sgr core to estimate the time Sgr has

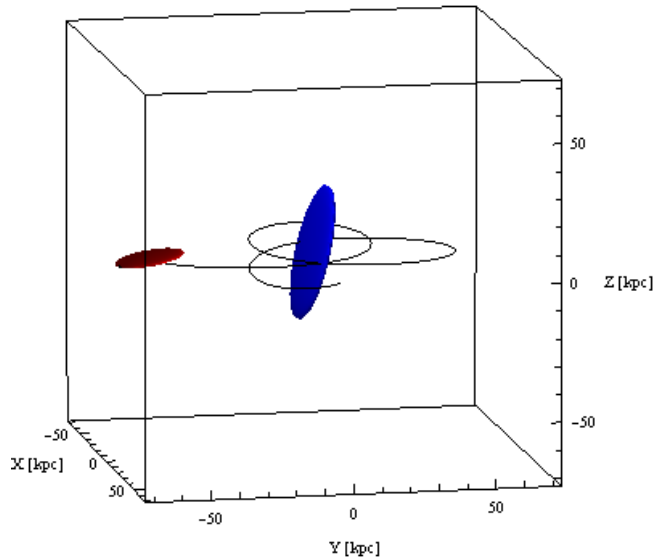


FIG. 2.— A schematic view of the initial simulation setup. The dwarf galaxy, indicated by the smaller, red disk on the left, is located at the orbit apocenter and is inclined by 10° with respect to the orbital plane. The bigger, blue disk on the right shows the Milky Way disk. The orbit, plotted with the solid black line, is coplanar with the XY plane of the coordinate system and is inclined by 76° to the Galactic plane. The dwarf galaxy starts orbiting towards the positive X coordinate and the dwarf disk is prograde with respect to the orbit so that both the orbital motion of the dwarf and the rotation of the stars in the dwarf are counterclockwise when viewed from the top of the figure. The Milky Way disk rotates clockwise when viewed from the right side of the figure.

spent on its current orbit around the Milky Way and the number of pericenters it has passed while on that orbit.

The paper is organized as follows. In Section 2 we describe the N -body simulations used in this study. In the next section we study the evolution of the simulated Sgr dwarf. Section 4 is devoted to the modeling of the stellar kinematics in the simulated Sgr system and a comparison to those in the real Sgr. The discussion of the implications of our model follows in Section 5.

2. THE SIMULATIONS

We performed collisionless N -body simulations of rotationally supported, disk dwarf galaxies orbiting inside a Milky Way-sized host. All simulations were carried out with the multisteping, parallel, tree N -body code PKDGRAV (Stadel 2001).

Given existing uncertainties about the exact shape of the Milky Way halo (i.e., whether it is prolate, oblate or triaxial; see, e.g., Helmi 2004; Law et al. 2005, 2009; Law & Majewski 2010) and the fact that our purpose here is not to reproduce perfectly the shape and kinematics of the Sgr stream but rather the shape and kinematics of the Sgr core, we decided to employ a simple Milky Way model with a spherical dark matter halo. Because the dominant aspect affecting the evolution of the core is the strength of the tidal force, dictated primarily by the perigalacticon distance of the dwarf and the radial mass distribution of the Milky Way but not its detailed shape, we do not expect this simplification to affect our general results.

The adopted model is based on the dynamical mass model A1 for the Milky Way from Klypin et al. (2002),

which consists of a Navarro et al. (1997, hereafter NFW) halo with a virial mass of $M_{\text{vir}} = 10^{12} M_{\odot}$ and concentration $c = 12$, a stellar disk with a mass of $M_{\text{D}} = 4 \times 10^{10} M_{\odot}$, scale length of $R_{\text{d}} = 3.5$ kpc, and scale height of $z_{\text{d}} = 0.35$ kpc, as well as a bulge with a mass of $M_{\text{b}} = 0.008 M_{\text{vir}}$ and scale-length of $a_{\text{b}} = 0.2 R_{\text{d}}$. The host galaxy model is live, which allows us to take into account the effect of dynamical friction on the satellite. The N -body realization of the Milky Way model contains $N_{\text{h}} = 10^6$ particles in the halo and $N_{\text{d}} = 2 \times 10^5$ in the disk and bulge and is built using the technique developed by Hernquist (1993). We used a fairly large gravitational softening for the dark matter particles, $\epsilon = 2$ kpc, to minimize spurious two-body heating between massive halo particles and those of the disk in the dwarf. The softening in the stars of the Milky Way was set to $\epsilon = 100$ pc.

We employ the method of Widrow & Dubinski (2005) to construct numerical realizations of self-consistent, multi-component dwarf galaxies built of exponential stellar disks embedded in NFW dark matter halos. The Widrow & Dubinski (2005) models represent axisymmetric, equilibrium solutions to the coupled collisionless Boltzmann and Poisson equations, and are thus ideal to confirm both the tidal heating and the tidally-induced non-axisymmetric instabilities that are required for the transformation of the dwarf.

In the simulation described below that reproduced best the observed properties of Sgr, the dwarf progenitor initially had a dark halo with a virial mass $M = 1.6 \times 10^{10} M_{\odot}$ and a concentration of $c = 15$. The mass and radial scale length of the disk were $3.2 \times 10^8 M_{\odot}$ and $R_{\text{d}} = 2.3$ kpc, respectively. According to Mo et al. (1998), this disk scale-length corresponds to an angular momentum parameter $\lambda = J/G\sqrt{|E|}/M_{\text{vir}}^5 = 0.08$ (where J and E are the total halo angular momentum and energy, respectively), which is typical of dwarf galaxies (Jimenez et al. 2003). We note that this value of R_{d} is derived without considering the effect of halo adiabatic contraction in response to the accretion of baryons. For the disk vertical structure we assumed an isothermal sheet with scale height of $z_{\text{d}} = 0.3 R_{\text{d}}$, which is higher compared to that appropriate for massive galaxies. Such choice is motivated by the greater importance of turbulent motions in dwarf galaxies which results in thicker systems (e.g., Schombert 2006). This disk thickness parameter corresponds to the axis ratio $c/a = 0.18$ calculated from the moments of the inertia tensor for all stars in the disk. The initial central value of the velocity dispersion associated with the vertical structure of the disk was $\sigma_z = 19.5 \text{ km s}^{-1}$. The decomposition of the circular velocity curve into the different components of the dwarf is shown in Figure 1.

We sampled the dwarf galaxy with 10^6 dark matter particles and 1.2×10^6 stellar disk particles. The gravitational softening length was set to $\epsilon = 60$ and 15 pc, for the dark matter and stellar particles, respectively. Evolution of the dwarf model in isolation confirmed its stability against bar formation for 10 Gyr, and demonstrated the excellent quality of the initial conditions as well as adequate resolution of the simulations.

The dwarf galaxy was evolved on an eccentric orbit with an initial apocenter and pericenter of $r_{\text{a}} = 58$ kpc

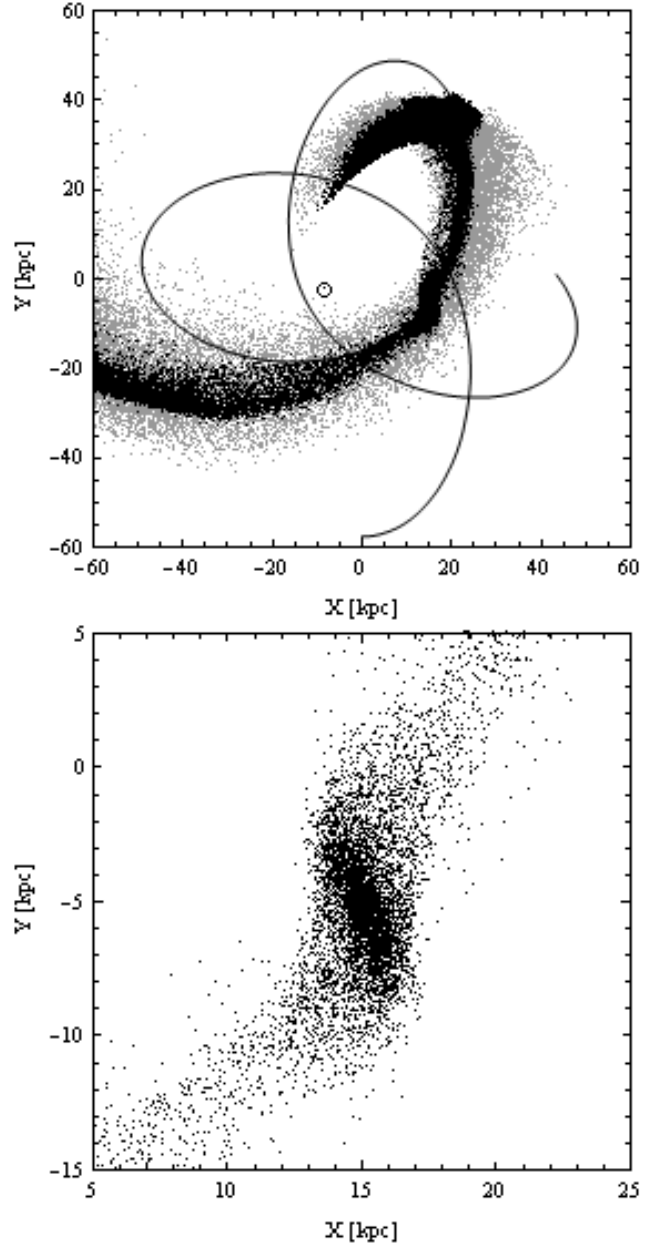


FIG. 3.— (*Upper panel*) Overview of the simulated Sgr projected onto the orbital plane. The gray dots show the dark matter particles, the black ones the stars. The solid line plots the orbit of the galaxy during 2.5 Gyr of evolution with the starting position at the bottom of the plot. The Milky Way disk intersects the orbital plane at $y = 0$. The Sun symbol shows the position of the Sun. (*Lower panel*) The magnified view of the stellar component of the simulated Sgr.

and $r_{\text{p}} = 17$ kpc, respectively. We placed the dwarf initially at the apocenter and followed its evolution for 2.5 Gyr, which corresponds to more than three orbital periods. The orbit was inclined by 76° to the Galactic plane and the dwarf galaxy disk was inclined by 10° with respect to the orbital plane. The rotation in the disk was prograde with respect to the orbital motion. Our choice of the orbital parameters was motivated by the study of Law et al. (2005) for the spherical Milky Way halo case (with small modifications due to the fact that we use a slightly different model of the Milky Way). The

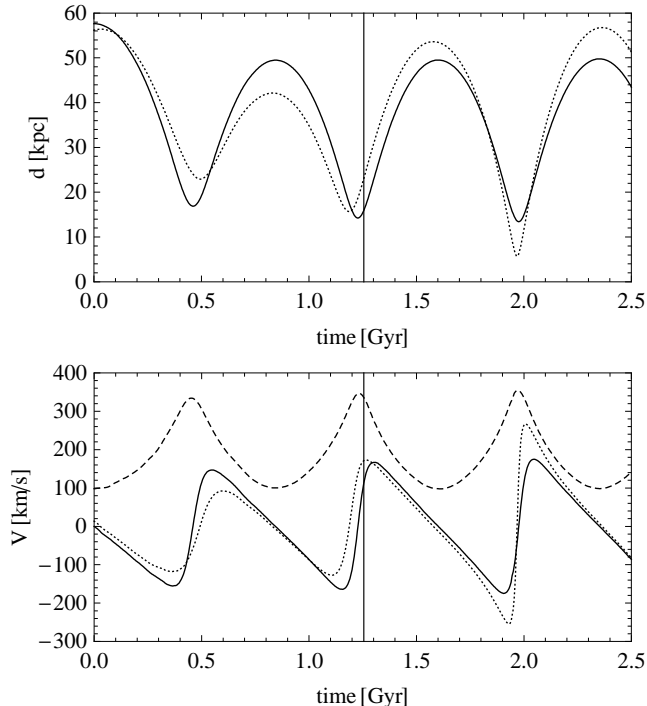


FIG. 4.— (*Top panel*) The distance of the Sgr center from the Galactic Center (GC; solid line) and from the Sun (dotted line). (*Bottom panel*) The total velocity of the Sgr center with respect to the GC (dashed line) and the radial velocities with respect to the GC (solid line) and the Sun (dotted line). In both panels the vertical line indicates the present position of Sgr after 1.255 Gyr of evolution, which corresponds to the output shown in Figure 3.

inclination of the dwarf galaxy disk and the direction of its rotation were adjusted to reproduce the inclination of the observed Sgr image with respect to the orbit and the observed rotation curve, respectively (see the next sections). The initial simulation setup is illustrated in Figure 2.

We note that for such a massive dwarf the initial dark halo is very extended, with a virial radius of ~ 65 kpc. Therefore, we started the simulation after imposing a smooth Gaussian cut-off in density which sets in at ~ 7.3 kpc. The latter value corresponds to the nominal Jacobi tidal radius of the model at the apocenter of the orbit.

The parameters of the best dwarf galaxy model were chosen after a number of trial simulations. In those simulations we varied slightly the orbit, the initial mass and the other halo and disk parameters but tried to keep them as close as possible to the general trends in cold dark matter cosmologies, such as those concerning the relation between the virial mass and concentration of the halo (e.g., Bullock et al. 2001) and the relations between the different disk parameters (Mo et al. 1998). In summary, we considered dark halo virial masses in the range $(0.8 - 1.6) \times 10^{10} M_{\odot}$, concentrations of the dark halo $c = 4 - 30$, different inner slopes of the dark halo $\alpha = 0.6 - 1$, λ parameters $0.04 - 0.08$, disk mass fractions $m_d = 0.01 - 0.04$, disk thicknesses $z_d/R_d = 0.2 - 0.3$, pericenter distances $r_p = (14 - 21)$ kpc and apocenters $r_a = (58 - 60)$ kpc. We only used some combinations of these parameters and in adjusting them we relied on the knowledge of their effect on the evolution gained from the systematic study by Kazantzidis et al. (2010).

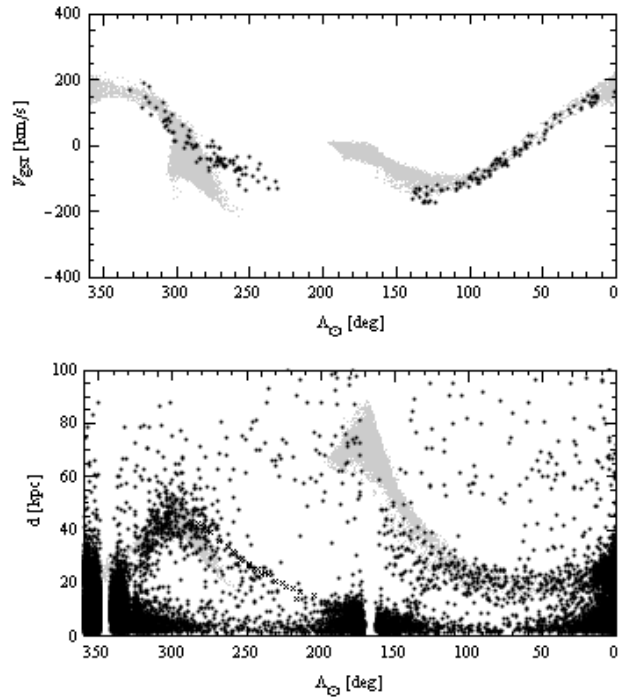


FIG. 5.— Radial velocities (*upper panel*) and distances from the Sun (*lower panel*) of the simulated debris (gray points) compared to the data for M giants (black points) from Majewski et al. (2003, 2004) and Law et al. (2005). The crosses in the lower panel show the distance measurements for the stars in the leading tail from Belokurov et al. (2006). The Λ_{\odot} coordinate measures the angular distance from Sgr in the direction of the trailing tail (see Majewski et al. 2003).

3. EVOLUTION OF THE SIMULATED DWARF

Figure 3 shows the simulation output projected onto the orbital plane after 1.255 Gyr of evolution when the dwarf galaxy position corresponds to the present position of Sgr. The Sun was placed at a distance of 8 kpc from the Galactic Center (GC) and the simulated Sgr is then at 23 kpc from the Sun (within the range 22-28 kpc of current best estimates, see e.g., Table 2 in Kunder & Chaboyer 2009). The distances of the Sgr center from the GC and from the Sun are plotted in the upper panel of Figure 4 as a function of time. Note that our orbit is decaying (the apocenter and pericenter distances decrease slightly) due to dynamical friction, because we use a live Galaxy model. The total velocity and the radial velocities of the dwarf measured in the Galactic Standard of Rest frame at the Sun and at the GC are shown in the lower panel of Figure 4.

To check if our model is consistent with the available data on the leading and trailing Sgr debris, in Figure 5 we compare the radial velocities (upper panel) and distances (lower panel) of the stars in the leading and trailing tails to the data. We can see that the simulated trailing tail matches the observed velocities very well, while in the leading tail the velocities are slightly too large. A similar discrepancy is seen in the distances of the tails. This behavior is in agreement with the expectations for the spherical Milky Way halo model assumed here, which cannot account perfectly for all properties of the tails (Law et al. 2005). However, our purpose here was not to reproduce the tails exactly, but rather to demonstrate that at the time we chose as corresponding to the present

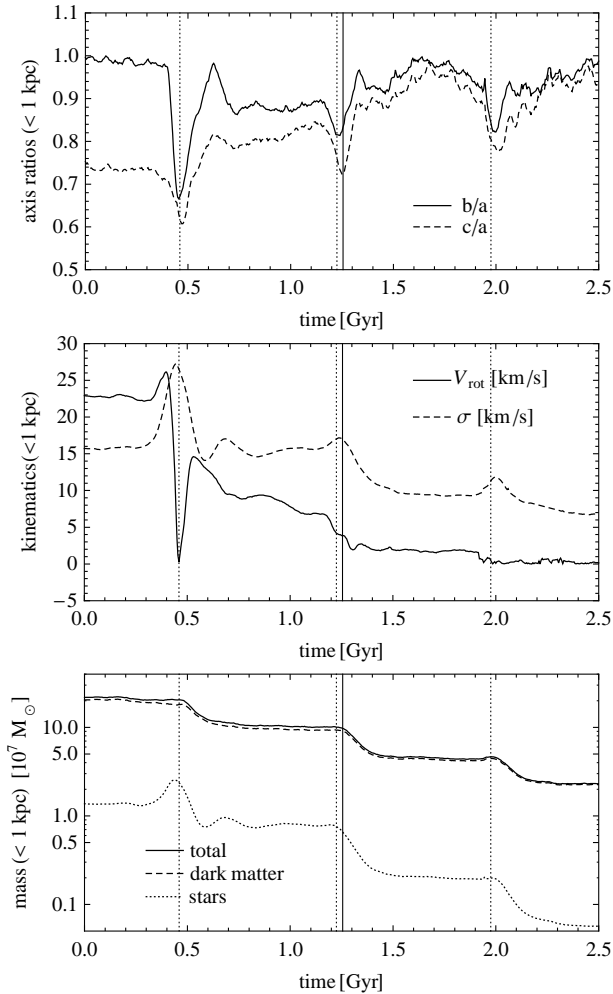


FIG. 6.— Evolution of the simulated dwarf. The panels from top to bottom show the following quantities as a function of time: the axis ratios, kinematical properties (the rotation velocity around the shortest axis V_{rot} and 1D velocity dispersion σ), and mass. All quantities were measured on particles within a distance $r < 1$ kpc from the center of the dwarf. Except for the mass, all measurements refer to the stellar component of the dwarf. The vertical solid lines indicate the presumed present state of Sgr while the dotted lines mark the pericenter passages.

phase of Sgr evolution, the dwarf has already produced most of the debris required to account for the observed extent of the trailing and leading arm.

Figure 6 illustrates the evolution of the dwarf in time up to 2.5 Gyr from the start of the simulation. All quantities shown in this Figure were estimated using stars (or dark matter particles) within a fixed radius of 1 kpc from the center of the dwarf. By adopting this rather low value we make sure that only particles inside the Sgr core are included at all times — i.e., we measure the intrinsic properties of the dwarf avoiding the contamination by tidally stripped material (the adopted scale of 1 kpc is dictated by late evolutionary stages when the dwarf is heavily stripped and therefore much reduced in size; see Figure 7).

The most interesting and relevant parameter for us here is the evolution of the shape of the satellite, which we quantify by the axis ratios b/a and c/a where a , b and c are the longest, intermediate and the shortest axis

of the distribution of the stars. To estimate them, for all simulation outputs (saved every 0.005 Gyr) we determine the directions of the principal axes of the stellar component using the moments of the inertia tensor. The evolution of the axis ratios is shown in the top panel of Figure 6.

Other interesting aspects of the evolution of the dwarf are related to its kinematics. To measure the kinematics we introduce a spherical coordinate system (r, θ, ϕ) centered on the dwarf so that the z -axis is along the shortest axis of the stellar distribution and the angle ϕ is measured in the xy plane. We then calculate the rotation velocity around the shortest axis $V_{\text{rot}} = V_{\phi}$ and the dispersions σ_r , σ_{θ} and σ_{ϕ} around the mean values. We combine the dispersions into the 1D dispersion parameter $\sigma = [(\sigma_r^2 + \sigma_{\theta}^2 + \sigma_{\phi}^2)/3]^{1/2}$, which measures the amount of random motion in the stars. The evolution of these two quantities is illustrated in the middle panel of Figure 6.

The bottom panel of the figure shows the evolution of the stellar, dark and total mass of the dwarf contained inside a radius of 1 kpc. The strongest decrease in all of the masses occurs around pericenters, i.e., after 0.46, 1.225 and 1.975 Gyr from the start of the simulation (vertical dotted lines in Figure 6). We note that the mass loss in stars follows that in dark matter.

The evolution of the shape is further illustrated in Figure 7. Here we plot the surface density distribution of the stars selected within $r < 6$ kpc from the center of the dwarf as seen along the longest (x), intermediate (y) and shortest (z) axis (from the top to the bottom row) of the stellar distribution. In columns we show the results right after the first, second and third pericenter. The second column corresponds to the simulation output shown in Figure 3 which we choose as best corresponding to the present time.

The analysis of the evolution of different quantities in Figure 6 and the surface density plots in Figure 7 reveals a clear picture of the fate of the dwarf. The shape of the dwarf galaxy disk evolves so that after the first pericenter a bar is formed ($b/a = c/a$). This bar soon transforms into a triaxial, but still prolate shape. At the second pericenter the bar becomes stronger again and at the moment shown in Figure 3, which corresponds to the present state of Sgr, the dwarf is still quite elongated with $b/a = 0.83$ and $c/a = 0.72$ inside the inner 1 kpc. Note that these values depend on radius and would be $b/a = 0.64$ and $c/a = 0.57$ when measured within the disk initial scalelength $r < R_d = 2.3$ kpc. Right after the second pericenter the stellar component becomes almost spherical with b/a and c/a both very close to unity. The shape becomes a little elongated again at the third pericenter because the tidal forces are at their maximum.

The changes of the shape of the stellar component are accompanied by a strong mass loss and decreasing rotation velocity V_{rot} of the stars. The velocity dispersion also decreases with time (except for peaks at pericenters due to tidal heating) because of mass loss. However, the ratio V_{rot}/σ drops below unity already at the first pericenter and remains like that until the end. At the time we chose as corresponding to the present evolutionary stage of the dwarf, after 1.255 Gyr from the start of the simulation, the remnant rotation in the core ($r < 1$ kpc) is

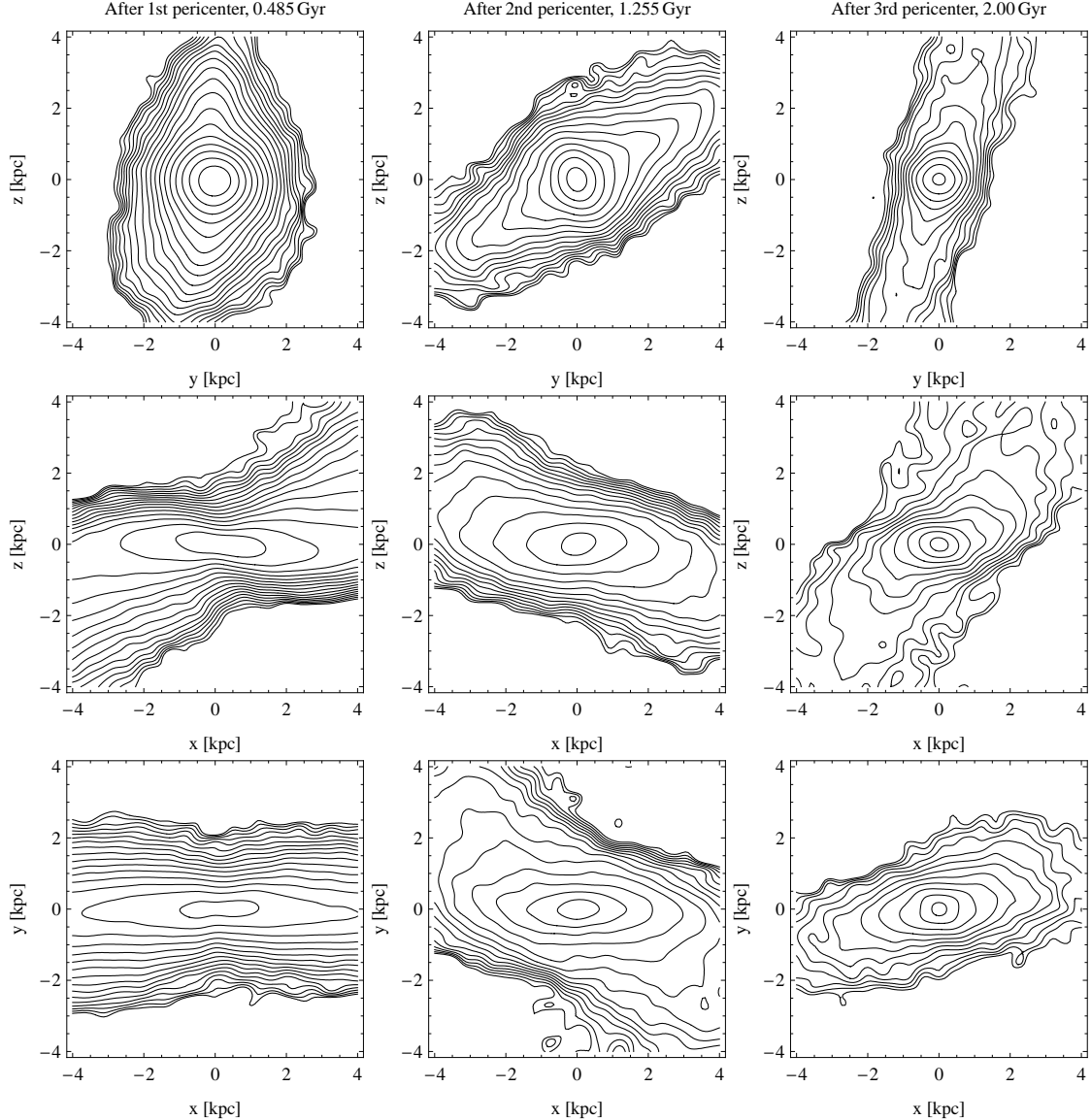


FIG. 7.— Surface density of stars in the simulated dwarf as seen by an observer located at infinity along its longest, intermediate and the shortest axis (from the upper to the lower row) after the first, second and third pericenter passage (from the left to the right column).

very low, of the order of 4 km s^{-1} with $V_{\text{rot}}/\sigma = 0.22$ (0.4 at the scale of $R_{\text{d}} = 2.3 \text{ kpc}$). Note that at the first pericenter, when the bar forms, the rotation velocity drops to zero. Right after this pericenter the orientation of the bar is such that there is a strong tidal torque from the Milky Way that speeds up the bar in the same direction the disk was initially rotating. This phenomenon is similar to the one discussed by Kazantzidis et al. (2010, see their section 5.2 and figure 13) in a similar context.

During the whole evolution the shortest axis of the stellar component of the dwarf is almost perpendicular to the orbital plane because the initial disk was inclined by only 10° to the orbital plane. Since the bar forms in the plane of the disk the longest axis lies almost in the orbital plane. Because the tidal tails also lie in this plane we see them clearly in the bottom row of Figure 7. The bar happens to be oriented almost perpendicular to the line of sight of the observer at the Sun (see Figure 3) at the present time so such an observer sees Sgr almost along the intermediate axis (the latter as shown in the

middle row of Figure 7). This observer's view of the simulated dwarf is shown in the middle panel of Figure 8. For comparison, in the upper panel we plot the surface density of the real Sgr M giants from Majewski et al. (2003). The inner isodensity shapes are very similar: strongly elongated, both with ellipticity $e = 1 - b/a$ of the order of 0.6, where b and a are now measured along the major and minor axis of the image from the projected surface density contours at the radius of 5° . Note that the outer isodensity shapes for the actually observed Sgr are perturbed by contamination of stars from the Milky Way disk.

The coordinate system chosen for these images measures the angles along the Λ_\odot and B_\odot coordinates associated with the orbital plane of Sgr projected on the sky (Majewski et al. 2003). Thus the orbital plane lies in the horizontal direction of the plots and both images show slight inclination with respect to this plane. The inclination of the simulated dwarf measured to be about 6° at the radius of 5° from the center agrees very well

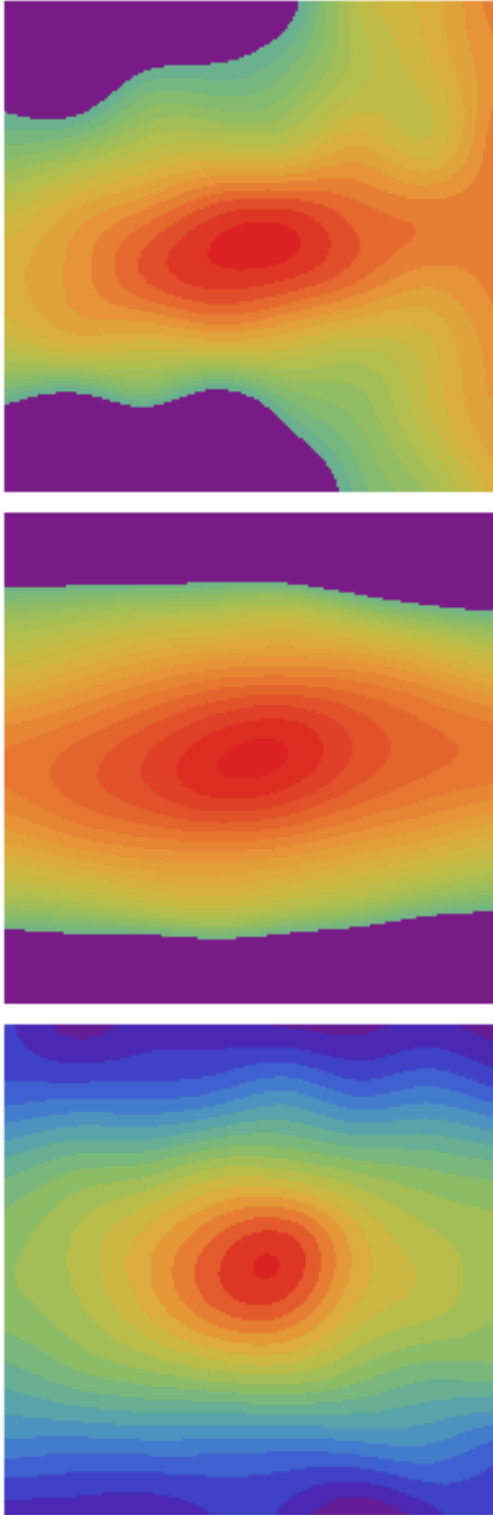


FIG. 8.— (*Upper panel*) The surface density of M giant stars as seen by an observer at the Sun in the real Sgr (from Figure 4 of Majewski et al. 2003). The flaring overdensity of stars toward the right part of the image is due to contamination from Milky Way disk M giants. (*Middle panel*) The surface density of the simulated dwarf at the present time, 1.255 Gyr from the start of the simulation, right after the second pericenter. (*Lower panel*) The surface density of the dwarf’s dark matter halo which was initially spherical. The horizontal direction is the projection of the Sgr orbital plane. The image size in all panels is 14° .

with the “canting angle” of the Sgr main body with respect to its orbital plane measured for the real data by Majewski et al. (2003). The inclination of the simulated image was reproduced by adopting the initial inclination of the dwarf disk of 10° with respect to the orbital plane (by rotating the disk around the X axis of Figure 3 so that the half of the disk closer to the Galactic center is above the plane of Figure 3; see also Figure 2). The angle seen at the present time is expected to be lower than the initially adopted value because in the observed image the intrinsic surface density contours of the core are affected by the tidally distorted distribution of stars at larger projected radii. These tidal extensions are obviously along the orbit and therefore decrease the observed inclination. Note, however, that the initial inclination angle cannot be much higher than the 10° we adopt since then the core would be more inclined and would form a pronounced S-shape with the tails that is not seen in the data.

In summary, since the formation of the bar can only occur in disks, if one starts with a spherical dwarf model the observed elongated shape of Sgr is very difficult to reproduce. To further support this statement, in the lower panel of Figure 8 we show the surface density distribution of dark matter as it would be seen at present by an observer at the Sun. The dark matter halo of the dwarf was initially spherical and, clearly, the surface density contours remain spherical in the center at present and are very different in shape from the contours of the distribution of the stars. This strongly suggests that the stellar component of Sgr must have been very different from spherical when the dwarf entered its orbit around the Galaxy. In addition, right after the second pericenter the stellar component quickly transforms into a much more spherical shape; thus, according to this model, Sgr could not have been a satellite for much more than 1.5 orbital times in its *present* orbit, in which it must have just passed its second pericenter around the Milky Way.

4. MODELING OF THE KINEMATICS

Recently Frinchaboy et al. (2010) have measured the radial velocities and velocity dispersions of stars in a number of pointings in the field of the Sgr main body. We model these data later in this section. First, we produce similar mock kinematical data sets by probing the simulated dwarf in the same way as Frinchaboy et al. Figure 9 shows the positions of a fraction of stars in the simulated dwarf as they would be observed from the Sun. The coordinate system adopted here was such that the x axis is along the major axis of the image of the dwarf’s stellar component and the y axis is along the minor axis (in analogy with the Λ'_{Sgr} and B'_{Sgr} coordinates adopted in the real observations by Frinchaboy et al.). The black circles indicate the model-sampled fields, which are analogous to those applied in the real Frinchaboy et al. observations and are listed in the first column of Table 1 with the same names as in that reference. Because there are no multiple tidal streams in our simulation, in this direction of the sky only the main body of Sgr is seen and there is almost no contamination from tidal debris along the line of sight (except for the stars presently being stripped). By using only the stellar particles of the simulated dwarf we also avoid the contamination from the Milky Way. Thus there is no need to introduce any cut-off in velocity for the model kinematical measurements, as was done in

TABLE 1
KINEMATICS OF THE SIMULATED SGR

Field	N_{tot}	N_{sel}	R [deg]	$\langle V_{\text{gsr}} \rangle$ [km s $^{-1}$]	$\sigma_{V_{\text{gsr}}}$ [km s $^{-1}$]
Major+00	1577	102	0.29	171.81 \pm 1.94	19.64 \pm 1.38
Major-04	608	110	3.98	172.06 \pm 1.49	15.66 \pm 1.06
Major-02	930	86	1.81	170.23 \pm 1.87	17.33 \pm 1.33
Major+02	931	182	1.98	172.79 \pm 1.45	19.60 \pm 1.03
Major+04	680	82	3.91	170.03 \pm 1.65	14.91 \pm 1.17
Major+06	433	57	6.03	166.21 \pm 2.07	15.62 \pm 1.48
Major+08	249	45	8.00	160.51 \pm 2.32	15.55 \pm 1.66
Major+10	159	24	10.01	154.61 \pm 3.14	15.39 \pm 2.27
Major+12	101	14	12.08	152.94 \pm 4.58	17.15 \pm 3.36
Minor-03	208	31	2.91	167.79 \pm 3.22	17.95 \pm 2.32
Minor-02	533	56	1.79	166.05 \pm 2.32	17.36 \pm 1.65
Minor-01	1008	89	0.97	167.70 \pm 2.06	19.47 \pm 1.47
Minor+01	1112	56	0.93	175.55 \pm 2.61	19.55 \pm 1.86
Minor+02	405	48	2.05	174.33 \pm 2.25	15.62 \pm 1.61
Minor+03	224	49	2.82	172.41 \pm 2.53	17.70 \pm 1.81
Minor+05	6	6	4.85	167.49 \pm 3.15	7.71 \pm 2.44
NW+02	671	62	1.96	167.62 \pm 2.02	15.90 \pm 1.44
SW+02	669	60	1.83	167.69 \pm 2.21	17.09 \pm 1.57
SE+02	724	88	1.88	174.66 \pm 1.53	14.38 \pm 1.09
NE+02	550	37	2.18	179.11 \pm 2.62	15.95 \pm 1.88
NW+04	195	17	3.86	169.48 \pm 3.47	14.30 \pm 2.53
SW+04	175	12	3.96	155.50 \pm 4.40	15.24 \pm 3.25
SE+04	193	34	3.86	170.95 \pm 2.49	14.49 \pm 1.78
ESE+07	67	25	6.28	168.27 \pm 2.58	12.88 \pm 1.86

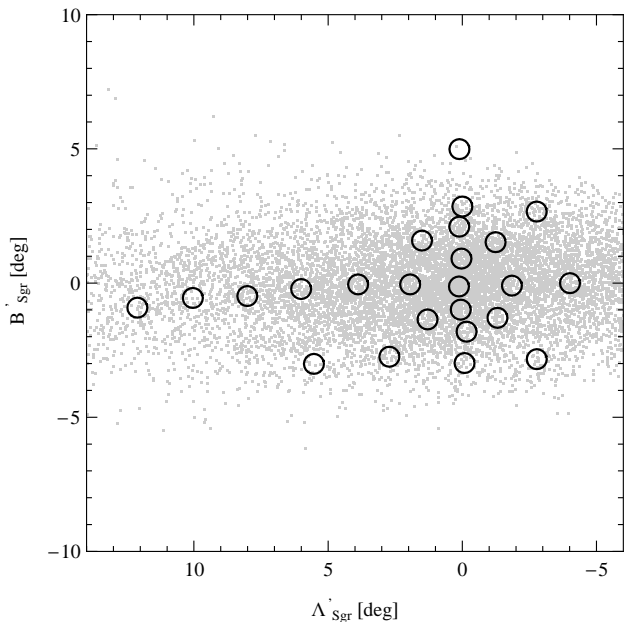


FIG. 9.— View of the simulated Sgr core (*gray dots*) and the positions of the fields analogous to those in the real observations of Sgr kinematics by Frinchaboy et al. (2010; *black circles*). The coordinate system is that of Λ'_{Sgr} and B'_{Sgr} , where Λ'_{Sgr} is measured along the major axis of the Sgr image, i.e. the positions of the stars were rotated clockwise by the angle of 6° with respect to those used in Figure 8.

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The total numbers of stars selected within the fields, N_{tot} , are listed in the second column of Table 1. Only in the case of the field Minor+05 is the number of stars smaller than observed (6 versus 9). This turns out to be understandable in the light of the fact that this field is

likely the one most contaminated by Milky Way stars (see below and Frinchaboy et al. 2010). In all other fields the number of stars in the simulated Sgr is much larger than in the actually observed samples. To create mock data sets as similar as possible to the real ones for all fields (except Minor+05 where we take all 6 stars available) we randomly select a number of stars exactly the same as in the real data. The numbers of selected stars N_{sel} are listed in the third column of Table 1. The next columns of the Table list the mean projected distance of the stars in a given field from the center of the dwarf and the mean velocity and velocity dispersion obtained in the field with their respective standard errors.

The velocity dispersion profile of the simulated dwarf obtained in this way is shown in the upper panel of Figure 10. We model the profile using solutions of the Jeans equation (see, e.g., Lokas 2002; Lokas et al. 2005; Lokas 2009), assuming that mass follows light and that the anisotropy parameter β is constant with radius. The anisotropy parameter measures the amount of radial versus circular orbits in the stellar population and we define it in the standard way as $\beta = 1 - (\sigma_\theta^2 + \sigma_\phi^2)/(2\sigma_r^2)$. By adjusting the solutions to the measured profile we estimate the total mass M and the anisotropy parameter β . The mass-follows-light assumption is well justified by the measurements of the density profiles of stars and dark matter within 5 kpc (corresponding to the angular scale of 12° in the data). The density profiles are plotted in Figure 11, where one can see that they follow each other. We have also verified that the anisotropy parameter does not strongly vary with radius and is contained within $0 < \beta < 0.4$ for radii $0 \text{ kpc} < r < 5 \text{ kpc}$ with the average value $\beta = 0.17 \pm 0.13$.

To perform this analysis we adopt the density profile of the stars as obtained by deprojection of their surface

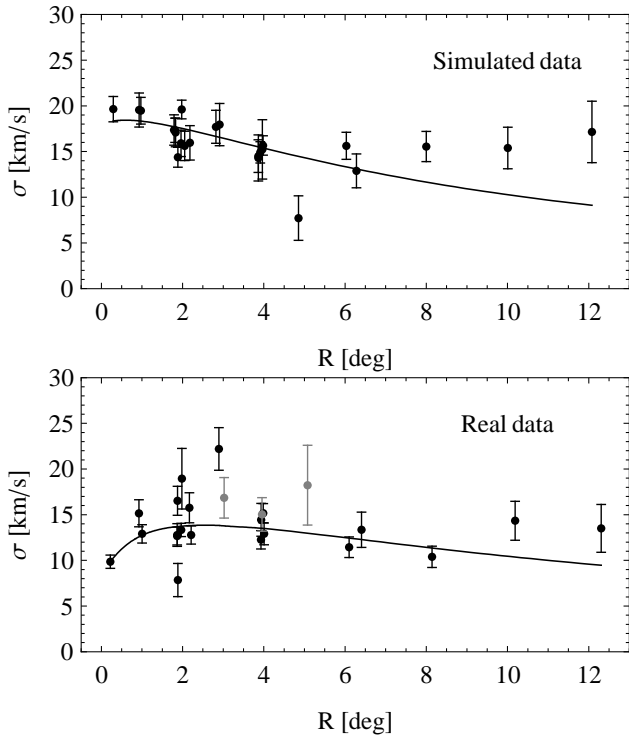


FIG. 10.— The line-of-sight velocity dispersion of the simulated dwarf (upper panel) and the real Sgr (lower panel) as a function of radial distance from the center R . Solid lines show the best-fitting solutions of the Jeans equation. The data points marked in gray in the lower panel are most contaminated by the Milky Way stars and were excluded from the fit.

number density profile. This profile measured from the simulation is shown as gray points in Figure 12. The measurements were done up to projected $R < 12^\circ$, the distance of the furthest kinematical measurement along the major axis by Frinchaboy et al. (2010). Interestingly, the profile does not yet flatten at these largest distances; such flattening would signify the transition to tidal streams. The model profile is well fitted by the Sérsic (1968) formula $N(R) = N_0 \exp[-(R/R_S)^{1/m}]$ with the Sérsic radius $R_S = 1.7^\circ$ and shape parameter $m = 1.2$.

The best-fitting solution of the Jeans equation is shown in the upper panel of Figure 10 as the solid line. The best-fitting parameters are $M = (8.1 \pm 0.5) \times 10^8 M_\odot$ and $\beta = 0.12_{-0.16}^{+0.12}$. Note that the quality of the fit is quite poor, with $\chi^2/N = 46/22$. The 1σ errors were estimated from $\Delta\chi^2$ statistics. The anisotropy estimate agrees very well (within errors) with the averaged value $\beta = 0.17$ measured from the simulation. The mass within $R < 12^\circ$ (which corresponds to 5 kpc) of this best-fitting model is $M = 7.3 \times 10^8 M_\odot$, significantly higher than the mass actually contained within this radius in the simulated dwarf, $M = 4.1 \times 10^8 M_\odot$. Note that for objects observed perpendicular to the bar we actually expect to underestimate the mass from the Jeans analysis rather than overestimate it (Łokas et al. 2010). This is not the case for the present state of Sgr since it is close to pericenter and therefore departs strongly from equilibrium. These departures manifest themselves in the strong mean radial velocity signal (in the spherical coordinates related to the dwarf, introduced in section 3, i.e. the dwarf is ex-

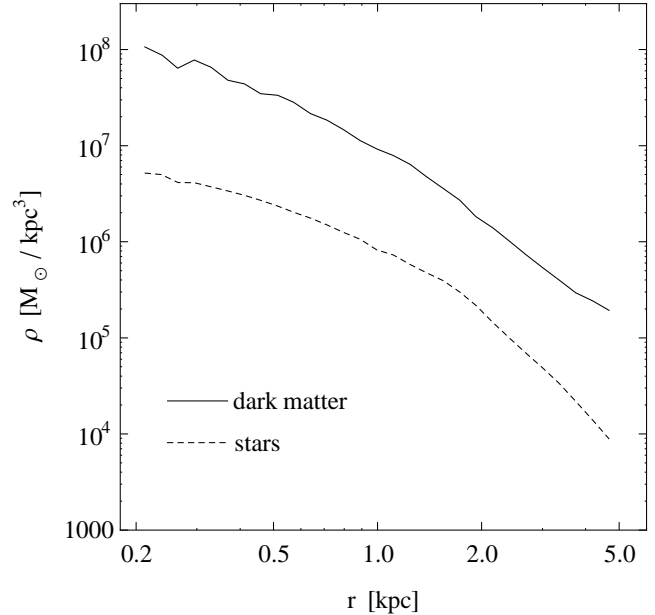


FIG. 11.— The density profiles of stars (*dashed line*) and dark matter (*solid line*) in the simulated dwarf up to $r = 5$ kpc, which corresponds to the angular scale of 12° probed by the Frinchaboy et al. (2010) kinematical measurements.

panding due to the action of strong tidal forces) and the increasing velocity dispersion at the outer parts, which are affected by tidally stripped material.

We proceed in an analogous way to fit the velocity dispersion profile obtained from the real data for Sgr, shown in the lower panel of Figure 10. In gray we marked the data points corresponding to the fields Minor-03, Minor+05 and NW+04 where the contamination by Milky Way stars exceeds 50% according to the estimates by Frinchaboy et al. (2010). The surface density profile of the stars measured from the M giants (Majewski et al. 2003) is shown in Figure 12 as black dots. To obtain an estimate of the profile out to circular radii of $R < 12^\circ$ and yet avoid the contamination from the Milky Way disk (seen as the flaring of the outer contours in the right side of Figure 8, top panel) we measured the density of stars only on one side (that at higher Galactic latitude) of the dwarf, as illustrated in Figure 13: only the stars shown in black were used for the measurements. The rejected stars, shown in gray, were separated by a line parallel to the Milky Way disk. A Sérsic profile has been fitted to the data and the best-fitting parameters are: $R_S = 1.2^\circ$ and $m = 1.4$. Note that in spite of the different parameters (the Sérsic profile is strongly degenerate for R_S and m) the shapes of the density profiles of the stars in the simulated and real Sgr are very similar.

Assuming that mass follows light we fit the velocity dispersion profile of Sgr by adjusting the total mass and anisotropy. When performing this fit we have excluded the data points marked in gray in the lower panel of Figure 10. The best-fitting parameters are $M = (6.1 \pm 0.5) \times 10^8 M_\odot$ and $\beta = -0.68_{-0.32}^{+0.24}$. The corresponding best-fitting dispersion profile is shown with a solid line in the lower panel of Figure 10. The mass within $R < 12^\circ$ of this best-fitting model is $M = 5.2 \times 10^8 M_\odot$, similar to the one of the simulated dwarf. The quality of the

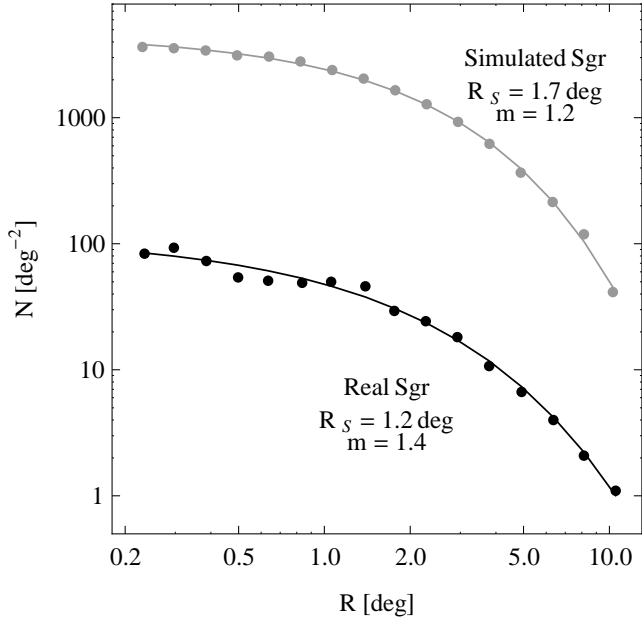


FIG. 12.— Surface density profiles of the simulated dwarf (*gray points*) and the real Sgr (*black points*) measured within circular projected radii. Solid lines show the best-fitting Sérsic profiles.

fit is also poor this time, with $\chi^2/N = 49/19$. This is due to the fact that the dispersion data points are very scattered around the mean fit, which may be due to some contamination from the Milky Way stars (still likely present in some fields, as shown by Frinchaboy et al., in spite of the 3σ clipping applied to the velocity measurements by those authors and our rejection of most contaminated data points) and the tidally stripped stars, as mentioned above. The total mass we find is about 40% lower than the early rough estimate of Ibata et al. (1997) who found the mass to be of the order of $10^9 M_\odot$. Our estimate is however very close to the more precise value $M = (5.8 \pm 0.5) \times 10^8 M_\odot$ obtained by Majewski et al. (2003) from a single velocity dispersion measurement by following the Richstone & Tremaine (1986) version of the King (1966) formalism. Our value agrees also very well with the one recently obtained by Law & Majewski (2010) from the dispersion of velocities in the tidal tails. Within 4° they find $M = 2.5^{+1.3}_{-1.0} \times 10^8 M_\odot$ while our mass profile gives $2.1 \times 10^8 M_\odot$.

Figure 14 compares the rotation curves of the simulated and real Sgr. The points with error bars are the measurements of the mean velocity of the stars along the major axis in the real Sgr from Frinchaboy et al. (2010). The solid line connects analogous values measured in the simulation and listed in Table 1, but without the errors. The match is very good. Note that at the stage of the evolution selected as corresponding to the present state of Sgr, the stellar component of the simulated dwarf had very little remnant rotation, of the order of 4 km s^{-1} (see the second panel of Figure 6). This intrinsic rotation is very much obscured in Figure 14 by the velocity gradient due to tidal tails pointed in the opposite direction. This reversal of the intrinsic rotation is similar to the effect seen in Leo I (Łokas et al. 2008). Note that the observed velocity trend shown in Figure 14 could not be reproduced by the model proposed by Peñarrubia et al.

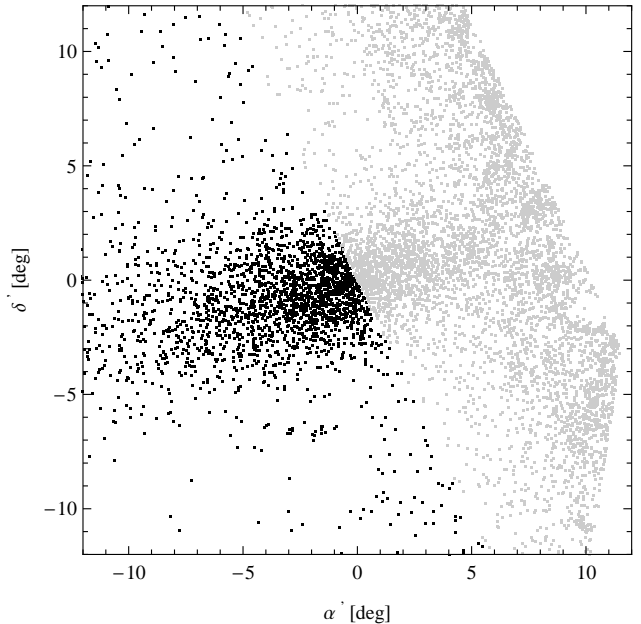


FIG. 13.— Positions of the stars from the 2MASS survey of Sgr. The coordinates α' and δ' are measured along the RA and Dec with respect to the Sgr's center. Black dots indicate the stars used for the calculation of the surface number density profile shown in Figure 12. Stars marked in gray were rejected due to the contamination by the Milky Way disk.

(2010) where the intrinsic rotation is still very high (of the order of 20 km s^{-1}). We have also verified that the observed velocity trend cannot be reproduced by a similar model as presented here but with the disk spinning in a retrograde manner. In such a case the stars stripped from the dwarf form tidal tails of similar length but with a much wider distribution of stars in distance and velocity than observed. In addition, a disk on a retrograde orbit does not form a bar and it is more difficult to remove rotation from it. Such significant remnant rotation is then clearly seen in the velocity trend right from the center of Sgr and has the same sign as the tidally induced velocity shear seen in Figure 14.

5. SUMMARY AND DISCUSSION

We presented a plausible model for the inner structure and kinematics of the Sgr dwarf galaxy. By adopting an initial stellar distribution in the form of a disk rather than a spheroid, this model reproduces for the first time the present, very elongated shape of the Sgr stellar core. The satellite orbit around the Milky Way was chosen so that its present distance and velocity with respect to the Sun agree well with the observed values. Our model also has a total mass similar to that estimated from the velocity dispersion profile of the real Sgr as well as a velocity gradient along the major axis that matches that seen in the real data. By requiring the dwarf to produce enough tidally stripped debris to match most of the observed extent of the Sgr stream and at the same time still preserve its highly non-spherical shape we put constraints on the number of pericenters Sgr could have passed until the present in its current orbit. For the present model to work, Sgr must have had only two perigalacticon passages. Indeed, if there had only been one pass not enough tidal debris would be produced, whereas after three passages the Sgr core would have already be-

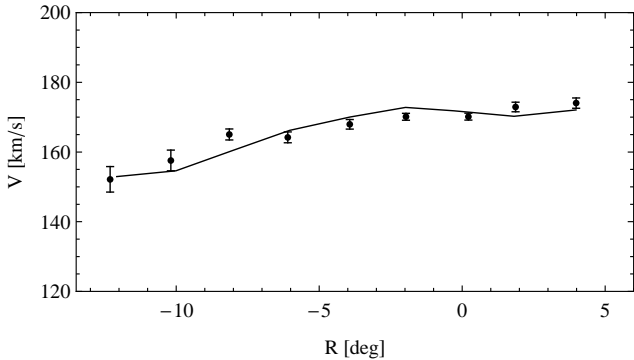


FIG. 14.— The rotation curve measured along the major axis of the Sgr image. The points with error bars show the kinematic measurements for real Sgr from Frinchaboy et al. (2010). The solid line shows the measurements in the simulated dwarf performed in the same way as in the real observations, as shown in Figure 9.

come significantly more spherical and thus inconsistent with observations.

Let us note that although the parameter space we explored was quite wide, we cannot absolutely exclude the possibility that the Sgr dwarf entered its orbit around the Milky Way with a spherical stellar component. The numerical experiments we performed strongly suggest, however, that it is very difficult to reproduce its present, elongated shape through the action of tidal forces on a spherical stellar distribution. For this to occur, the tidal forces would have to distort the dwarf down to the very center implying that it was weakly self-bound. Whenever we tried to significantly lower the self-gravity of the dwarf, e.g. by adopting a dark matter halo of low concentration, we found it to be very quickly destroyed by tidal forces; such an object would not survive long enough on its present orbit to produce enough tidal debris.

Our model also reproduces in a satisfactory way the density profile of the stars, the total luminosity and the mass-to-light ratio of the Sgr core. For the real Sgr in its present state, using our total mass estimate and adopting the luminosity of $2 \times 10^7 L_{\odot}$ (Mateo et al. 1998; Majewski et al. 2003), we get M/L of the order of 30 in solar units. As in the case of the mass, this is significantly lower than the estimate of M/L of 50 by Ibata et al. (1997) but agrees well with the estimate by Majewski et al. (2003) based on core-fitting. To find the corresponding value for the simulated dwarf we need to translate the mass of stars into luminosity. Since the stellar M/L are poorly known, especially for systems containing many stellar populations of different age, we can conservatively adopt M/L in the range of $(1 - 3)M_{\odot}/L_{\odot}$ for the stars. The mass of stars within 5 kpc is $3.2 \times 10^7 M_{\odot}$ so the luminosity is in the range $(1.1 - 3.2) \times 10^7 L_{\odot}$ in good agreement with the true present luminosity of Sgr. The mass-to-light ratio is then in the range $(13 - 39)M_{\odot}/L_{\odot}$, which includes our value obtained for the real Sgr.

The present shape of Sgr must be bar-like with the bar major axis almost perpendicular to our line of sight. If it were a disk seen almost edge on, its rotation curve would be very different: we would see a strong rotation signal at the very center of the dwarf which could become dominated by the velocity gradient of tidal origin only at the outer parts. What is observed is the rotation velocity increasing very slowly with distance along the major axis (Frinchaboy et al. 2010). This is almost

entirely caused by the tidally induced velocity gradient of stripped debris, which obscures the remnant intrinsic rotation if any is present. Such a low intrinsic rotation is only possible in a prolate shape, where radial orbits dominate the motion of the stars. In the case of Sgr seen from the Sun, this motion is almost perpendicular to the line of sight.

Recently, Peñarrubia et al. (2010) proposed a model of Sgr that also initially contained a disk, with the purpose of addressing the origin of the bifurcation in the leading Sgr arm visible in Sloan Digital Sky Survey data (e.g., Belokurov et al. 2006; Yanny et al. 2009). They showed that if their initial disk was inclined by about 20° with respect to the orbital plane then the bifurcation would be reproduced. While an intriguing hypothesis for the origin of the enigmatic bifurcation, our work suggests that the initial inclination of the disk was probably about a factor of two lower since otherwise the stellar component forms a pronounced S-shape that is not observed in the real data. In addition, at the stage corresponding to the present time their disk retains a significant amount of rotation, of the order of 20 km s^{-1} which does not match the rotation curve measured by Frinchaboy et al. (2010) along the Sgr major axis and reproduced by our model in Figure 14. The Peñarrubia et al. (2010) model also does not include the effect of dynamical friction, which may significantly change the structure of the leading arm. It is therefore not obvious whether a disk model that accurately reproduces the core structure of Sgr might also be able to produce a bifurcation similar to that observed.

The orbit that we chose for the progenitor of Sgr is not supposed to simulate its initial cosmological infall into the Milky Way halo. It is instead meant to model the time over which the transformation of the stellar component has occurred. Constrained cosmological simulations of the Local Group (Klimentowski et al. 2010) show that the wide majority of satellites surviving to $z = 0$ are on orbits with apocenters exceeding 100 kpc, namely larger than what we have assumed for the orbit of Sgr. Likewise, most satellites, especially those accreting after $z = 1$ (as is implicitly required for the case of Sgr by the fact that our model suggests that it should have performed only two pericenter passages in its current orbit by now), have virial masses an order of magnitude below the initial mass of the progenitor of Sgr (Klimentowski et al. 2010). However, the apparently unusual orbit and rather high mass are mutually explained once we try to place Sgr in the more general context of satellite accretion.

It is likely that Sgr was indeed accreted on an orbit having an apocenter exceeding 100 kpc, but this orbit was rapidly eroded by dynamical friction owing to Sgr's large mass, which enabled Sgr to acquire the apocenter that we have assumed. During this early time tidal mass loss occurred mostly in the halo, as shown by N -body simulations (e.g., Mayer et al. 2001). Hence, such mass loss would not change the results of our work concerning the evolution of the stellar component of the core. Note however, that some mass loss in stars and the formation of stellar streams could take place even before the phases of evolution we study in this paper. Thus, more pericenter passages than two may have occurred in total, but the earlier ones at large radii will have minimal effect on the internal structure of Sgr (Kazantzidis et al. 2010).

Figure 4 shows that the effect of dynamical friction is moderate for our initial mass of $1.6 \times 10^{10} M_\odot$, but if the mass of Sgr before infall was only a factor of a few times larger ($\sim 3 - 5 \times 10^{10} M_\odot$), dynamical friction could have reduced its apocenter by at least a factor of 2 after the first actual pericenter (see, e.g., Colpi et al. 1999; Jiang & Binney 2000; Taffoni et al. 2003 — once the mass ratio between primary and secondary approaches 20:1 or less the dynamical friction timescale becomes much shorter than the Hubble time). Therefore in this scenario Sgr would have its current, unusually tight orbit by the present time exactly because of the rather large mass of its progenitor, which implies much more dynamical friction than for typical satellites.

A higher initial virial mass before infall is also strongly suggested by the quantitative relation between stellar mass and halo mass suggested by statistical methods, such as halo abundance matching using stellar masses from SDSS (Guo et al. 2009; Sawala et al. 2010), as well as by structural analysis of individual dwarfs in the Local Group and, more generally, in the nearby Universe (Mayer & Moore 2004; Oh et al. 2008; McGaugh & Wolf 2010). Indeed, the first of the cited methods implies that typical stellar masses are $< 0.05 - 1\%$ of the halo mass for halos with virial masses close to $10^{10} M_\odot$, while the second line of evidence, which has less statistical power but does not suffer from incompleteness problems due to the low surface brightness of typical dwarfs, would suggest $\sim 1 - 2\%$ of the halo mass to be typical (with significant scatter present); this places our choice of the initial condition $m_d = 0.02$ towards the high end of allowed values. For comparison, detailed mass modeling of two of the best studied, isolated dIrr galaxies in the Local Group, NGC 6822 and NGC 3109, with circular velocities close to that assumed for the progenitor of Sgr ($40 - 60 \text{ km s}^{-1}$), would also yield $m_d \sim 0.01$ (Valenzuela et al. 2007). This marginal discrepancy is easily resolved if one assumes that the initial halo mass before infall was at least a factor of 2 larger than what we have assumed here, thus placing Sgr among the typical disk dwarfs in terms of the initial stellar to halo mass ratio.

Although our disk mass fraction $m_d = 0.02$ may appear high in terms of stellar mass, the whole baryonic mass of dIrr galaxies (including gas) is a factor of a few higher. Since our simulation is collisionless we could not model explicitly the gas component and our intermediate value reflects the baryonic disk mass after it has been affected by the tidal field. There are convincing arguments, both observational and theoretical, that not all of the gas initially present in the dwarf was converted into stars; some of it must have been lost soon after the dwarf had become a satellite of the Milky Way. Simulations including hydrodynamics (e.g., Mayer et al. 2006, 2007) suggest that this gas is stripped immediately due to ram pressure. The discovery of a possible neutral hydrogen component of the Sgr stream towards the Galactic anticenter by Putman et al. (2004) suggests that this may indeed be the last source of star formation fuel for the dwarf that was probably stripped at the pericenter passage that corresponds in our model to that which occurred about 0.8 Gyr ago. Interestingly, this is also about when the last significant star formation activity in Sgr took place (Siegel et al. 2007).

The only significant feature of the Sgr core that our

model does not reproduce very well is the shape of its velocity dispersion profile. Although the observed kinematics may still be contaminated, e.g., by Milky Way stars or tidally stripped material, such contamination would most probably affect the outer parts, while we also witness some discrepancy in the very center. While the observed velocity dispersion profile decreases towards the center down to 10 km s^{-1} , the simulated one increases up to about 20 km s^{-1} . The observed value is actually very robust and has been established in an extensive study of the Sgr center by Bellazzini et al. (2008). The velocity dispersion profile of the simulated dwarf is characteristic of the cuspy, rather concentrated dark matter halo that we use here in the initial conditions. It has been recently demonstrated by Governato et al. (2010), however, that the presence of gas and star formation processes can modify the dark matter halos of isolated dwarfs and cause them to produce cores. Such cores would manifest themselves in flatter dispersion profiles of the stars, as observed in Sgr. Mayer et al. (2007) have also shown that the presence of gas can induce stronger bars, which could further reduce the remnant intrinsic rotation seen in the simulated dwarf. It seems therefore that including gas and star formation processes may significantly improve the agreement between the observed and simulated properties of Sgr. However, because only very few hydrodynamical simulations of dwarf galaxies evolving in the tidal field of their hosts have been performed until now, very little is known about the effect of additional parameters on the tidal evolution of satellites. We postpone this much more complex form of study for future work.

The picture of the evolution of the Sgr dwarf we propose in this work fits well within the scenario of the formation and evolution of dSph galaxies in the Local Group as predicted by the tidal stirring model (Mayer et al. 2001). This model accounts very well for the observed morphology-density relation for the dwarfs (e.g., Grebel 1999): those closer to the Milky Way are more affected by tidal forces and have become more spherical, those further away are still dwarf irregulars. Sgr seems to be in an intermediate stage between objects that have evolved only very little, like NGC 6822, and those objects that have apparently been substantially evolved by tidal stirring, like the classical dSph galaxies Draco or Sculptor. The rather tight orbit of Sgr has allowed it to significantly transform over a short timescale of 1.3 Gyr and only two pericenter passages. Soon after the recent, second perigalactic passage Sgr will become more spherical, and more closely resemble a typical, classical dSph galaxy.

On the other hand, the Large Magellanic Cloud (LMC), whose mass is similar to the initial mass we estimate here for Sgr, has probably just passed its first pericenter around the Milky Way (Besla et al. 2007). Given that its pericenter distance is rather large, of the order 50 kpc, and its orbit is eccentric, the LMC core has been little affected by tidal forces. As shown by Kazantzidis et al. (2010), on such an orbit a satellite disk gets distorted and a bar can form, but the orbit is too extended and the tidal force therefore too weak to transform the disk into a spheroid, even over a Hubble time. That the LMC does in fact presently contain a bar is consistent with this general picture of dwarf spheroidal satellites

being simply the end stage of tidally stirred dwarf disks. Other evidence supports the notion of the LMC as a viable prototype for the pre-interaction Sgr progenitor. Both systems have very extended star formation histories including recent star formation (e.g., Siegel et al. 2007; Harris & Zaritsky 2009). Moreover, Chou et al. (2010) have shown that the LMC and Sgr share very similar chemical enrichment histories for several α and s-process elements explored, only with Sgr slightly more advanced in its overall chemical evolution. The primary difference in the present appearance of these two systems may well be driven primarily by differences in their current orbital radii and the time they have been bound to the Milky Way.

In this work we have not endeavored to account for the structure and dynamics of the Sgr tidal arms. The models that have focused on the tidal arms of Sgr (e.g., Ibata et al. 2001; Helmi 2004; Martinez-Delgado et al. 2004; Law et al. 2005; Law & Majewski 2010) have tended to attribute more than two perigalacticon passes to Sgr to account for the length of the arms. The scenario we propose here, with just two pericenter passages, does not necessarily mean that we are in conflict with these other models for the tails. It simply means that the number of passes that affected the core structure of Sgr through tidal stirring is most probably limited to two. This however does not preclude the possibility of previous passes on an orbit of larger size where the core is unaffected but tails can begin to be generated. It is obvious that Sgr's orbit must have evolved, both due to dynamical friction and the growth in mass of the Milky Way (Peñarrubia et al. 2006). More comprehensive models that simultaneously account for both the evolution of the Sgr core and the Sgr tidal debris in a more realistic, growing Milky Way potential and with an evolving Sgr orbit from in-

fall to the present state is obviously a goal for future efforts, and one that must be guided by more complete and precise mapping of the phase space distribution of the extended debris tails.

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REFERENCES

- Bellazzini, M., Ibata, R. A., Chapman, S. C., Mackey, A. D., Monaco, L., Irwin, M. J., Martin, N. F., Lewis, G. F., & Dalessandro, E. 2008, *AJ*, 136, 1147
- Belokurov, V., et al. 2006, *ApJ*, 642, L137
- Besla, G., Kallivayalil, N., Hernquist, L., Robertson, B., Cox, T. J., van der Marel, R. P., & Alcock, C. 2007, *ApJ*, 668, 949
- Bullock, J. S., Kolatt, T. S., Sigad, Y., Somerville, R. S., Kravtsov, A. V., Klypin, A. A., Primack, J. R., & Dekel, A. 2001, *MNRAS*, 321, 559
- Chou, M.-Y., Cunha, K., Majewski, S. R., Smith, V. V., Patterson, R. J., Martinez-Delgado, D., & Geisler, D. 2010, *ApJ*, 708, 1290
- Colpi, M., Mayer, L., & Governato, F. 1999, *ApJ*, 525, 720
- Correnti, M., Bellazzini, M., Ibata, R. A., Ferraro, F. R., & Varghese, A. 2010, *ApJ*, 721, 329
- Fellhauer, M., et al. 2006, *ApJ*, 651, 167
- Frinchaboy, P. M., Majewski, S. R., Muñoz, R. R., & Patterson, R. J. 2010, in preparation
- Governato, F., et al. 2010, *Nature*, 463, 203
- Grebel, E. K. 1999, in *IAU Symp. 192, The Stellar Content of Local Group Galaxies*, ed. P. Whitelock & R. Cannon (San Francisco: ASP), 17
- Guo, Y., McIntosh, D. H., Mo, H. J., Katz, N., van den Bosch, F. C., Weinberg, M., Weinmann, S. M., Pasquali, A., & Yang, X. 2009, *MNRAS*, 398, 1129
- Harris, J., & Zaritsky, D. 2009, *AJ*, 138, 1243
- Helmi, A. 2004, *ApJ*, 610, L97
- Helmi, A., & White, S. D. M. 2001, *MNRAS*, 323, 529
- Hernquist, L. 1993, *ApJS*, 86, 389
- Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, *Nature*, 370, 194
- Ibata, R. A., Wyse, R. F. G., Gilmore, G., Irwin, M. J., & Suntzeff, N. B. 1997, *AJ*, 113, 634
- Ibata, R., Lewis, G. F., Irwin, M., Totten, E., & Quinn, T. 2001, *ApJ*, 551, 294
- Jiang, I.-G., & Binney, J. 2000, *MNRAS*, 314, 468
- Jimenez, R., Verde, L., Oh, S. P. 2003, *MNRAS*, 339, 243
- Johnston, K. V., Spergel, D. N., & Hernquist, L. 1995, *ApJ*, 451, 598
- Johnston, K. V., Majewski, S. R., Siegel, M. H., Reid, I. N., Kunkel, W. E. 1999, *AJ*, 118, 1719
- Johnston, K. V., Law, D. R., & Majewski, S. R. 2005, *ApJ*, 619, 800
- Kazantzidis, S., Lokas, E. L., Callegari, S., Mayer, L., & Moustakas, L. A., 2010, submitted to *ApJ*, arXiv:1009.2499
- King, I. 1966, *AJ*, 71, 64
- Klimontowski, J., Lokas, E. L., Kazantzidis, S., Prada, F., Mayer, L., & Mamon, G. A. 2007, *MNRAS*, 378, 353
- Klimontowski, J., Lokas, E. L., Kazantzidis, S., Mayer, L., & Mamon, G. A. 2009, *MNRAS*, 397, 2015
- Klimontowski, J., Lokas, E. L., Knebe, A., Gottlöber, S., Martinez-Vaquero, L. A., Yepes, G., & Hoffman, Y. 2010, *MNRAS*, 402, 1899
- Klypin, A., Zhao, H., & Somerville, R. S., 2002, *ApJ*, 573, 597
- Kunder, A., & Chaboyer, B. 2009, *AJ*, 137, 4478
- Law, D. R., Johnston, K. V., & Majewski, S. R. 2005, *ApJ*, 619, 807
- Law, D. R., Majewski, S. R., & Johnston, K. V. 2009, *ApJ*, 703, L67
- Law, D. R., & Majewski, S. R. 2010, *ApJ*, 714, 229
- Lokas, E. L. 2002, *MNRAS*, 333, 697
- Lokas, E. L. 2009, *MNRAS*, 394, L102
- Lokas, E. L., Mamon, G. A., & Prada, F. 2005, *MNRAS*, 363, 918
- Lokas, E. L., Klimontowski, J., Kazantzidis, S., & Mayer, L. 2008, *MNRAS*, 390, 625
- Lokas, E. L., Kazantzidis, S., Klimontowski, J., Mayer, L., & Callegari, S. 2010, *ApJ*, 708, 1032

- Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, *ApJ*, 599, 1082
- Majewski, S. R., et al. 2004, *AJ*, 128, 245
- Martinez-Delgado, D., Gomez-Flechoso, M. A., Aparicio, A., Carrera, R. 2004, *ApJ*, 601, 242
- Mateo, M., Olszewski, E. W., & Morrison, H. L. 1998, *ApJ*, 508, L55
- Mayer, L., & Moore, B. 2004, *MNRAS*, 354, 477
- Mayer, L., Governato, F., Colpi, M., Moore, B., Quinn, T., Wadsley, J., Stadel, J., & Lake, G. 2001, *ApJ*, 559, 754
- Mayer, L., Mastropietro, C., Wadsley, J., Stadel, J. & Moore, B. 2006, *MNRAS*, 369, 1021
- Mayer, L., Kazantzidis, S., Mastropietro, C., & Wadsley, J. 2007, *Nature*, 445, 738
- McGaugh, S. S., & Wolf, J. 2010, *ApJ*, 722, 248
- Mo, H. J., Mao, S., & White, S. D. M. 1998, *MNRAS*, 295, 319
- Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, *ApJ*, 490, 493 (NFW)
- Oh, S.-H., de Blok, W. J. G., Walter, F., Brinks, E., & Kennicutt, R. C. 2008, *AJ*, 136, 2761
- Peñarrubia, J., Benson, A. J., Martinez-Delgado, D., & Rix, H. W. 2006, *ApJ*, 645, 240
- Peñarrubia, J., Belokurov, V., Evans, W. N., Martinez-Delgado, D., Gilmore, G., Irwin, M., Niederste-Ostholt, M., & Zucker, D. B. 2010, *MNRAS*, 408, L26
- Putman, M. E., Thom, C., Gibson, B. K., & Staveley-Smith, L. 2004, *ApJ*, 603, L77
- Richstone, D. O., & Tremaine, S. 1986, *AJ*, 92, 72
- Sérsic, J. L. 1968, *Atlas de Galaxies Australes*, Observatorio Astronomico, Cordoba
- Sawala, T., Scannapieco, C., Maio, U., & White, S. 2010, *MNRAS*, 402, 1599
- Schombert, J. M. 2006, *AJ*, 131, 296
- Siegel, M. H., et al. 2007, *ApJ*, 667, L57
- Stadel, J. G. 2001, PhD thesis, Univ. of Washington
- Taffoni, G., Mayer, L., Colpi, M., & Governato, F. 2003, *MNRAS*, 341, 434
- Valenzuela, O., Rhee, G., Klypin, A., Governato, F., Stinson, G., Quinn, T., & Wadsley, J. 2007, *ApJ*, 657, 773
- Widrow, L. M., & Dubinski, J. 2005, *ApJ*, 631, 838
- Yanny, B., et al. 2009, *ApJ*, 700, 1282