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THE SURVIVAL OF THE SAGITTARIUS DWARF GALAXY AND THE FLATNESS OF THE ROTATION CURVE OF THE GALAXY

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ABSTRACT

How has the "fluffy" Sgr dwarf galaxy survived its 10–20 pericentric passages in the halo of the Milky Way for a Hubble time? The scenario that Sgr was deflected to its current orbit by the Magellanic Clouds after a rendezvous on the north Galactic pole 2–3 Gyr ago is examined. It is shown that the conditions of the collision fix both the sense of circulation of Sgr and the Large Magellanic Cloud around the Galaxy and the slope of the Galactic rotation curve. The model argues that the two orthogonal polar circles traced by a dozen or so Galactic halo dwarf galaxies and globular clusters (LMC–SMC–Magellanic Stream–Draco–Ursa Minor along $l \approx 270^\circ$ and M54–Ter 7–Ter 8–Arp 2–NGC 2419–Pal 15 along $l \approx 0^\circ$) are streams of tidal relics from two ancient galaxies that were captured on two intersecting polar rosette orbits by the Galaxy. Our results favor the interpretation of microlensing toward the LMC being due to source or lens stars in tidal features of the Magellanic Clouds. We discuss direct and indirect observations to test the collision scenario.

Subject headings: galaxies: individual (Sagittarius) — Galaxy: halo — Galaxy: kinematics and dynamics — Magellanic Clouds — galaxies: interactions — methods: analytical

1. INTRODUCTION

The recently discovered dwarf galaxy at about 25 kpc from the Sun in the direction of the constellation Sagittarius (Ibata, Gilmore, & Irwin 1994) is the closest galaxy known to us. It is traced by two long trailing/leading tails on the sky (together more than $8^\circ \times 22^\circ$ in solid angle), with most of its stars still clustered around a low-density luminous core (roughly 0.001 $L_\odot$ pc^{-3} with semiaxes 1:1:3 kpc). It is puzzling that stars have not fully dispersed out of this fluffy core despite the severe pericentric tidal shocks of the Galaxy (about 10–100 times stronger than that experienced by satellites in the outer halo, the Magellanic Clouds and the Fornax dwarf galaxy included). The best fit to Sgr's morphology and space velocity yields an orbit with a pericenter-to-pericenter period of about 0.8 Gyr and a pericenter and an apocenter at about 10 and 50 kpc, respectively (Velázquez & White 1995). Simulations show that if a typical Galactic dwarf galaxy (such as Fornax) were replaced on Sgr's orbit, it would dissolve in no more than two pericentric passages by the strong pericentric tidal shock of the Galaxy near 10 kpc (Velázquez & White 1995; Johnston, Spergel, & Hernquist 1995; Johnston, Hernquist, & Bolte 1996; Edelsohn & Elmegreen 1997). This apparently contradicts the observation that the dominant stellar population in the core is older than 10 Gyr (Mateo et al. 1995; Fahlman et al. 1996), which implies that Sgr has survived 10–20 pericentric tidal shocks of the Galaxy.

To circumvent this dilemma, we need to abandon either one or both of the following hidden assumptions: (1) the light distribution of Sgr traces its mass, and (2) Sgr has always been on the same low pericentric orbit in a rigid Galactic potential during the past 5–10 Gyr. Ibata et al. (1997) postulate a dense dark halo of Sgr surrounding the luminous part to hold the system together; they require Sgr's mass density to be uniform inside about 3 kpc of its core with a value (~0.03 $M_\odot$ pc^{-3}) that is several times the mean Galactic halo density inside 10 kpc (0.013 $M_\odot$ pc^{-3}). An inspection of Sgr's rosette-like orbit in relation to that of the Magellanic Clouds (MCs) offers a completely different line of thought. They are on nearly orthogonal planes intersecting along the poles, with their Galactocentric radii overlapping at about 50 kpc. Thus, an encounter at the north or south pole at some time in the past or future is quite inevitable. In a recent preprint, which appeared shortly after the completion of the work reported in this Letter, Ibata & Lewis (1998) also remarked on the small probability of an interaction after noticing in their simulations a weak perturbation to Sgr's orbit when they turned on the moving gravitational field of the massive MCs. Unfortunately, the effect was in the end neglected on grounds of low probability without thoroughly exploring the parameter space (of satellite velocities and the Galactic potential) and the important consequences of a rare strong interaction. So, like Ibata et al. (1997), they were thus left with no alternative but to conclude that a massive dark halo of Sgr is the only explanation for Sgr's presence on a low pericentric orbit after a Hubble time.

In this Letter, we examine the encounter scenario (as illustrated in Fig. 1), in which Sgr has been pulled back from an originally high angular momentum/energy orbit to the present low angular momentum/energy orbit by the massive MCs. A recent encounter would have the advantage of allowing Sgr to spend most of its lifetime on a "safe" orbit with a pericenter (say 20 kpc) too high to be harassed by the sharply declining tidal force of the Galaxy (e.g., Kroupa 1997); in a halo with an r^{-2} density profile, the pericentric shock would drop by a factor of 4 from 10 to 20 kpc. Various interesting aspects of this scenario will be discussed in § 3. But the aim of this Letter is to report an independent constraint on the rotation curve of the Galaxy as imposed purely by *the timing of the collision*. The essence is as follows. The random chance of the LMC and Sgr meeting each other is obviously low, about 1% for a 10 kpc closest approach in the past 3 Gyr for a general set of Galactic potentials and initial conditions of the satellites. So the same argument could be inverted: once we accept the de-

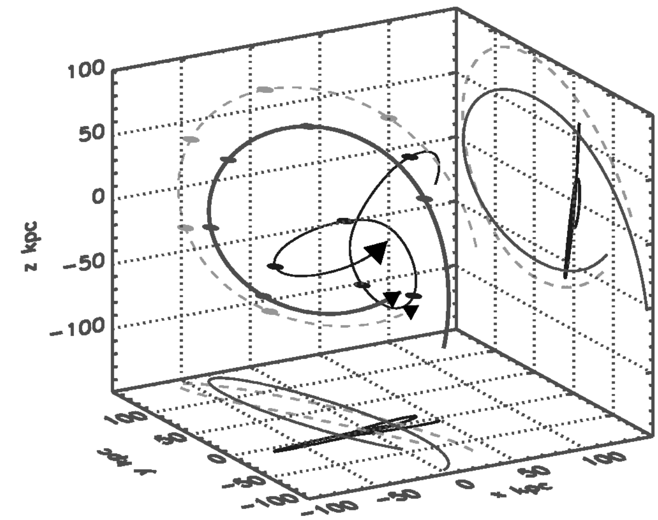

FIG. 1.—Three-dimensional view and *x-y*, *y-z* projections of the orbits of the LMC/SMC (thick/dashed lines near the $x = 0$ plane) and the orbit of Sgr (thin line near the $y = 0$ plane); the Sun is at $(x, y, z) = (-8, 0, 0)$ kpc. The three systems are integrated backward for 3 Gyr (with ellipses marking steps of 0.5 Gyr) from the present epoch (with velocity vectors marked by arrows) inside the Galactic potential.

flection by the MCs as a plausible way out of Sgr's dilemma, a stringent set of conditions on the potential of the halo and the proper motions of the satellites must follow.

2. "MEASURING" THE POTENTIAL OF THE MILKY WAY AND PROPER MOTIONS OF THE LMC AND SGR BY TIMING

Consider the following timing argument for when and where the collision happens. The collision is most likely to happen when Sgr is near its apocenter and the LMC is again near its pericenter, which means that Sgr was $(n + 1/2)$ epicycles back and the LMC was k epicycles back, where n and k are integers. The angles by which the LMC and Sgr have rotated away from the site of the collision are related to the epicycles by $\beta \approx (360^\circ k/\theta_{\rm LMC}) \approx [360^\circ(n + 0.5)/\theta_{\rm Sgr}]$, where $1 < \beta < 2$ is the ratio of the period of one rotation around the Galaxy to that of one radial epicycle; it is essentially a constant for all orbits in a nearly power-law potential (Binney & Tremaine 1987; Johnston 1997). Since Sgr ($l = 5\overset{\circ}{.}6$, $b = -14\overset{\circ}{.}1$) and the LMC ($280^\circ$, -33°) are presently 250° and 240° from the north Galactic pole, respectively, to meet at the poles requires $[(\pm\theta_{\rm LMC} - 240^\circ)/360^\circ,\ (\pm\theta_{\rm Sgr} - 250^\circ)/360^\circ]$ to approximate to a pair of integers if the collision was on the north pole or half integers if it was on the south pole, where the plus sign corresponds to Sgr and the LMC moving toward the plane and the minus sign corresponds to their moving away. In solving the above equations, we allow $\pm 20^\circ$ angular offset from the poles and $\pm 45^\circ$ phase offset (equivalent to one-eighth of an epicycle) from the pericenters or apocenters at the time of collision. This roughly puts both satellites at around 10 kpc from each other and at about 40–60 kpc from the Galactic center. The dynamical friction with the halo can offset the sky position of the massive LMC at the time of the encounter, but the amount $\Delta\theta \sim [M_{\rm LMC} k/M_{\rm MW}(r < 50\ {\rm kpc})] \sim [(1.5 \pm 1.0) \times 10^{10}\ M_\odot/5 \times 10^{11}\ M_\odot]\, k \sim (0.03 \pm 0.02) \sim 3^\circ$ is negligibly small compared to the allowed error of 20°. With a similar argument, any slight flattening in the Galactic potential can be neglected; squashing the Galactic potential to an axis ratio of $q = 0.9$ would change the orbit by a tolerable amount of $\Delta\theta \sim (1 - q) \sim 0.1 \sim 6^\circ$.

It is easy to show that as far as recent collisions are concerned (say $n < 3$), the only possible solution is that $n = 2$, $k = 1$, $\theta_{\rm LMC} = (240^\circ \pm 20^\circ)$, and $\theta_{\rm Sgr} = (610^\circ \pm 20^\circ)$. This means that the collision happened on the *north Galactic pole*, the LMC is presently leading the Magellanic Stream, and the Sgr is moving *toward* the Galactic plane (exactly in the same sense as the observed proper motion of Sgr by Ibata et al. 1997). The timing argument also predicts that the ratio of the epicycle periods of the LMC and the Sgr $T_{\rm LMC}/T_{\rm Sgr} \approx \theta_{\rm Sgr}/\theta_{\rm LMC} = (2.54 \pm 0.23)$, which matches very well with 2 and 0.8 Gyr epicycle periods for the LMC (e.g., Murai & Fujimoto 1980; Moore & Davis 1994; Gardiner, Sawa, & Fujimoto 1994; Lin, Jones, & Klemola 1995; and references therein) and Sgr, respectively, from previous models. Now Sgr has circulated around the Galaxy ($610^\circ \pm 20^\circ$) from the start of the collision and in the meantime advanced (2.5 ± 0.125) epicycles, which is equivalent to a phase angle ($900^\circ \pm 45^\circ$). Thus, an estimate can also be made of β, the ratio of the rotation period to the epicycle period in the Galactic potential: $\beta = (900^\circ \pm 45^\circ)/(610^\circ \pm 20^\circ) = (1.475 \pm 0.088)$. Combined with a similar estimate from the LMC's position, we have $\beta = (1.48 \pm 0.08)$, which is close to the value ($\sqrt{2}$) for a logarithmic potential. This provides a fully *independent* argument for a dark halo of the Milky Way at intermediate radius (10–100 kpc), where the constraints from traditional data sets are weak.

An indirect "measure" of the velocities of the Magellanic Clouds and Sgr can also be made with similar analytical arguments. The velocity of a satellite at radius r is related to the characteristic size (R) of its orbit simply by $V = \{2[\Phi(R) - \Phi(r)]\}^{1/2} = V_{c,\,{\rm MW}}\,[2\ln(R/r)]^{1/2}$ in a logarithmic potential $\Phi(r) = V_{c,\,{\rm MW}}^2 \ln(r)$; for an exactly radial orbit, R is the apocenter radius. Thus a close encounter of the LMC and Sgr requires

$$\frac{V_{\rm LMC}}{V_{c,\,{\rm MW}}} = \sqrt{2\ln\left(\frac{R_{\rm LMC}}{r_{\rm LMC}}\right)} = (1.37 \pm 0.27),$$
$$\frac{V_{\rm Sgr}}{V_{c,\,{\rm MW}}} = \sqrt{2\ln\left(\frac{R_{\rm Sgr}}{r_{\rm Sgr}}\right)} = (1.51 \pm 0.15). \qquad (1)$$

In the above estimation, we have adopted $r_{\rm Sgr} = (16 \pm 1)$ and $r_{\rm LMC} = (50 \pm 1)$ kpc for the present radii of the two satellites. For Sgr to reach the LMC, $R_{\rm Sgr}$ should equal $r_{\rm LMC}$ with a 10 kpc uncertainty, thus $R_{\rm Sgr} = (50 \pm 10)$ kpc. To estimate $R_{\rm LMC}$, we note that the orbital period and the orbital size are nearly proportional to each other in a logarithmic potential (Johnston 1997) with $R_{\rm LMC}/R_{\rm Sgr} \approx T_{\rm LMC}/T_{\rm Sgr} = (2.54 \pm 0.23)$; thus $R_{\rm LMC} = (127 \pm 40)$ kpc.

Two interesting results follow from the above condition. First, the transverse velocity of Sgr can be estimated from that of the LMC (Jones, Klemola, & Lin 1994; *Hipparcos* measurements from Kroupa & Bastian 1997) from the velocity ratios after taking into account the radial velocities. The result, $V_{t,\,{\rm Sgr}} = (237 \pm 60)\ {\rm km\ s^{-1}}$, is consistent with $V_{t,\,{\rm Sgr}} = (250 \pm 90)\ {\rm km\ s^{-1}}$ from direct measurement of Sgr's latitudinal proper motion with respect to the Galactic bulge (Ibata et al. 1997).

Second, the observed space velocities of Sgr and the LMC translate to a circular rotation speed of the Milky Way $V_{c,\,{\rm MW}} = (200 \pm 53)$ and $(194 \pm 45)\ {\rm km\ s^{-1}}$, respectively. Approximating the rotation curve as a power law with a slope $d\log V_{c,\,{\rm MW}}/d\log r = \beta^2/2 - 1 = 0.09 \pm 0.08$ and an ampli-

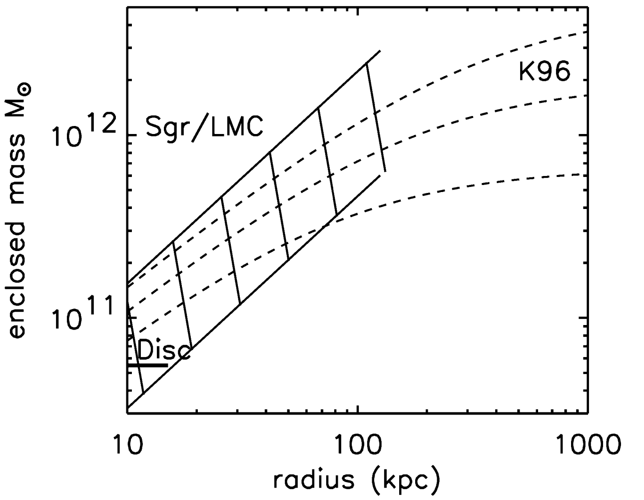

FIG. 2.—Comparison of radial distributions of the dynamical mass of the Galaxy derived from timing the collision of Sgr and the LMC (shaded region with 2 σ limits) and from Kochanek (1996), which synthesizes well-known constraints from several data sets (the median and 2 σ limits, *dashed lines*). Our model predicts a dynamical mass of the Galaxy 10–40 times greater than the mass of a standard disk (*heavy solid line segments*).

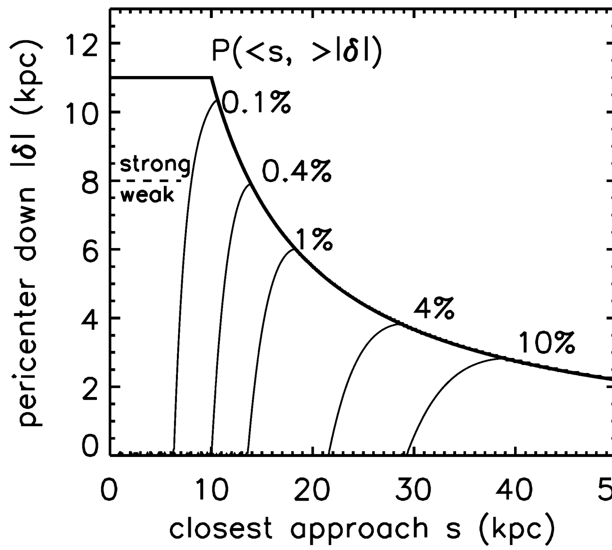

FIG. 3.—Probability $P(<s, >|\delta|)$ of the LMC coming closer than s kpc to Sgr and knocking its pericenter down by more than $|\delta|$ kpc. The "shoe-shaped" boundary, which is reminiscent of the rotation curve of the LMC with its tidal radius $a = 10$ kpc, is set by the scattering power of the LMC $\propto V^2_{c,\,\mathrm{LMC}}(s) \sim (80\ \mathrm{km\ s^{-1}})^2\,[1,\ a/s]_{\min}$. Strong encounters typically involve Sgr coming inside the LMC's tidal radius (~10 kpc).

tude normalized to (197 ± 34) km s^{-1} at 50 kpc, we find that the collision requires the dynamical mass of the Milky Way to increase as

$$\log\left[\frac{M_{\mathrm{MW}}(<r)}{4.55\times10^{11}\ M_\odot}\right] = (1.2 \pm 0.3) \times \log\left[\frac{r}{50\ \mathrm{kpc}}\right] \pm 0.3 \qquad (2)$$

(2 σ error bars are given) in the radii from 10 to 127 kpc as spanned by the orbits of Sgr and the LMC.

3. IMPLICATIONS OF THE COLLISION AND ITS PROBABILITY

In summary, Sgr is proposed to have spent most of its lifetime on a high pericentric orbit based on the theoretical consideration that its "fluffy" core cannot sustain the repeated strong tidal shocks of a low pericentric orbit for 10 Gyr. A natural mechanism to bring Sgr down to its present low orbit is a recent deflection by the passing LMC. By timing such a collision, we get as a by-product an indirect "measure" of the $\log r - \log M$ relation of the Galaxy, both the mean slope and zero point (see eq. [2]). Figure 2 compares our results with a previous comprehensive analysis by Kochanek (1996). Our analysis strengthens the case for a nearly isothermal dark halo of the Galaxy with an argument independent of previous Galactic models. It also makes a unique addition to the handful of estimators for the mass of the Galaxy (Fich & Tremaine 1991). Statistical approaches such as fitting velocity distributions of halo satellites and local escaping stars both rely on a large sample and make assumptions about dynamical equilibrium and the distribution function for the ensemble. The Local Group timing method depends on the Hubble constant, and like models fitting the kinematics of the Magellanic stream, it lacks sensitivity to the slope of the $\log r - \log M$ relation. Our model also confirms the direct measurements of the proper motions of Sgr and the LMC.

On broader aspects, the current model provides a platform to piece together two ancient galaxies that fell into our halo: the Ancient Magellanic Galaxy (AMG) of Lynden-Bell (1976, 1982) and the Ancient Sagittarius Galaxy (ASG). The two ancient galaxies have been torn apart by the strong tidal field of the Galaxy and have produced two grand polar streams of tidal debris: remnants of the ASG along $l \approx 0°$ may include the globular clusters M54 ($l = 5.6°$, $b = -14.°1$), Terzan 7 (3.°4, −20.°1), Arp 2 (8.°5, −20.°8), and Terzan 8 (5.°8, −24.°6) below the plane, NGC 2419 ($l = 180.°4$, $b = 25.°2$) and Palomar 15 (18.°9, 24.°3) above the plane, and many newly found carbon stars all along the polar great circle in the Automatic Plate Measuring survey (M. Irwin 1998, private communication); remnants of the AMG along $l \approx 270°$ may include the LMC, the SMC, Carina (260.°1, −22.°2), Draco (86.°4, 34.°7), Ursa Minor (105°, 44.°8), and the Magellanic stream. Curiously enough, if Sculptor, Sextans, and perhaps Fornax are also on polar orbits with radii in the range 30–150 kpc (Lynden-Bell & Lynden-Bell 1995), then these might have interacted with the ASG and the AMG sometime in the past. Besides constraining the Galactic potential and the proper motions of these remnants as demonstrated, the current model can help reconstruct the merging history and star formation history of these satellites and globular clusters, which are the building blocks of the Galactic halo.

The model also provides a test bed for theories that explain the newly discovered polar ring feature of carbon stars around the LMC disk (Kunkel et al. 1997), microlensing events toward the LMC (Alcock et al. 1997), and the well-known warp of the Galaxy, all with stars or gas stirred up by the strong tidal forces among the LMC–SMC–Milky Way triple system (Zhao 1998a and references therein; Weinberg 1995). Particularly promising is a configuration in which some stars belonging to a polar ring or a tidal tail of the Magellanic Clouds are placed at $D \sim$ (2–10) kpc behind the LMC disk. These stars would have a high probability of being microlensed by the numerous stellar lenses in the LMC disk (Zhao 1998a); the optical depth is boosted from a pure LMC disk self-lensing with a probability of about $0.1\tau_{obs}$ (e.g., Sahu 1994) to about $(1–5)\tau_{obs}$ by a factor of about $(2D/h) \sim (10–50)$, where $h \sim 0.4$ kpc is the scale height of the LMC disk and $\tau_{obs} \sim 3 \times 10^{-7}$ is the observed optical depth (Alcock et al. 1997). The Einstein diameter crossing time of a typical faint stellar lens (say 0.16 $M_{\odot}$) in the LMC disk is about 50–100 days for a lens-source velocity of $\sqrt{2} \times 70$ km s^{-1} ~ 100 km s^{-1}, where 70 km s^{-1} is the typical rotational speed of stars in the LMC disk and that of the stars in the polar ring of Kunkel et al. (1997). This roughly matches the durations of the dozen or so observed microlensing events toward the LMC between 34 and 127 days (Alcock et al. 1997). Significant microlensing at a rate of about 1–5 events per year per million background stars (ideally red clump giants with a distance modulus 0.1–0.4 mag fainter than the LMC disk) is expected if there are enough bright source stars in these background tidal features.

It is worth commenting that definite tests of the model require accurate predictions of the orbital phase within 10° for the past 3 Gyr, equivalent to a proper motion accuracy of ± 10 μas yr^{-1}. The current observed proper motions of the LMC and Sgr are about 2 orders of magnitude too poor to trace back any information of the relative distance of the LMC and Sgr a few gigayears ago, except that the typical distance would be around 50 kpc. So an encounter is almost equally improbable for any values of the observed proper motions with a probability $\sim (s/R)^3 \sim 1\%$ for a closest approach $s \sim a \sim 10$ kpc, where a is the tidal radius of the LMC. However, it is still meaningful to assess whether the LMC is massive enough to scatter Sgr to a significantly low orbit with a pericentric change $|\delta| \geq 8$ kpc. The probability for various combinations of the closest approach and the change of pericenter can be read out from the contours shown in Figure 3 (see Zhao 1998b for a detailed calculation using the impulse approximation). In short, we find that the probability of a sudden change of Sgr's pericenter by between 8 and 11 kpc (the maximum) is about 0.4%. Sgr could have been circulating around the Galaxy at a "safe" distance with the pericenter about 20 kpc before such strong encounters could bring it down to the present lower orbit with the pericenter about 10–12 kpc. Not only were the Galactic pericentric shocks a factor of 3–4 weaker on the previous orbit, there was also no shocking by the Galactic disk (which ends approximately at 12 kpc from the center; Robin, Creze, & Mohan 1992). These strong encounters typically involve Sgr coming inside the tidal radius of the LMC with $s \sim a \sim 10$ kpc, which means that the disintegration of Sgr may have already started from the tidal shocks of the LMC, which was then followed by several more shocks by the Galaxy. These strong encounters should be contrasted with milder encounters with a change of the pericenter by between 3 and 6 kpc, which has a probability of about 9% with a typical impact parameter $s \sim 25$ kpc; these can change the tidal forces by a factor of 2. Flybys with $s >$ 30 kpc are common but play no role in explaining the orbit and the survival of the Sgr. The fact that there is an upper limit of $|\delta| < 11$ kpc means that a drastic change of pericenter by much more than 10 kpc would not be possible unless the potential well of the LMC was in fact much deeper earlier on, with a circular rotation speed $V_{c,\,LMC} \geq 80$ km s^{-1}. The same argument also implies that any deflection by the less massive SMC would be much milder than one by the LMC.

Future astrometric experiments, such as the *Space Interferometry Mission*, *Global Astrometric Interferometer for Astrophysics*, and the *Deutsches Interferometer für Vielkanalphotometrie und Astrometrie* missions as planned by American and European space agencies, which promise accurate proper motions of horizontal-branch stars to a few kilometers per second at 20–100 kpc with space interferometry, will certainly either refine the model given here or rule it out. In the nearer future, the model is also observationally testable by mapping out tidal debris along the great circle of Sgr. If the disruption of Sgr started from the collision with the LMC, there should be plenty of time for material to spread out to a very long tidal tail: the trailing arm of the debris should be visible at 45° below the Galactic plane and the leading arm should be visible 15° above the Galactic plane if the *N*-body simulation of Velázquez & White (1995) is simply rescaled from 1 to 2–3 Gyr.

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