A TWO MICRON ALL SKY SURVEY VIEW OF THE SAGITTARIUS DWARF GALAXY. III. CONSTRAINTS ON THE FLATTENING OF THE GALACTIC HALO

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ABSTRACT

M giants selected from the Two Micron All Sky Survey (2MASS) have been used to trace streams of tidal debris apparently associated with the Sagittarius dwarf spheroidal galaxy (Sgr) that entirely encircle the Galaxy. While the Sgr M giants are generally aligned with a single great circle on the sky, we measure a difference of 10.4 ± 2.6 between the mean orbital poles of the great circles that best fit debris leading and trailing Sgr, which can be attributed to the precession of Sgr’s orbit over the range of phases explored by the data set. Simulations of the destruction of Sgr in potentials containing bulge, disk, and halo components best reproduce this level of precession along the same range of orbital phases if the potential contours of the halo are only slightly flattened, with the ratio of the axis length perpendicular to and in the disk in the range q = 0.90–0.95 (corresponding to isodensity contours with q = 0.83–0.92). Oblate halos are strongly preferred over prolate (q > 1) halos, and flattenings in the potential of q ≤ 0.85 (q ≤ 0.75) and q ≥ 1.05 (q ≥ 1.1) are ruled out at the 3 σ level. More extreme values of q ≤ 0.80 (q ≤ 0.6) and q ≥ 1.25 (q ≥ 1.6) are ruled out at the 7 and 5 σ levels, respectively. These constraints will improve as debris with larger separation in orbital phases is found.

Subject headings: galaxies: individual (Sagittarius) — galaxies: stellar content — Galaxy: halo — Galaxy: kinematics and dynamics — Galaxy: structure — Local Group

1. INTRODUCTION

Simulations of structure formation within the standard cold dark matter cosmology predict that cluster-scale dark matter halos should typically be far from spherical, with shortest to longest axis ratios in density typically around (c/a)0 = 0.5, rarely greater than (c/a)0 = 0.8, and with no strong preference for oblate (c/a)0 < 1 or prolate (c/a)0 > 1 halos (Dubinski 1994; Jing & Suto 2002). Such studies have typically been limited to studying the shapes of halos on cluster scales because the computational expense of resolving a large enough sample of galaxy-scale halos was prohibitive. Indeed, observations leading to estimates of (c/a)0 for a handful of external galaxies proved to be roughly consistent with these findings (see Merrifield 2002, Fig. 3, for a summary). More recently, preliminary analyses of galaxy-scale dark matter halos extracted from cosmological simulations predict that they could be systematically rounder than their larger counterparts, peaking around (c/a)0 = 0.65, with examples as round as (c/a)0 = 0.95 (Bullock 2002; H. Flores et al. 2005, in preparation; Kazantzidis et al. 2004) have demonstrated that simulations that include gas cooling effects also produce rounder halos than similar simulations that neglect such dissipation. This result is especially intriguing given at least one estimate for the shape of the Milky Way’s dark matter halo that suggests that it could indeed be rather spherical [(c/a)0 > 0.95; Ibata et al. 2001], placing it at the extreme of the extragalactic (c/a)0 range [but cf. Martinez-Delgado et al. 2004, who find (c/a)0 ≈ 0.5]. However, this estimate was made using just a few dozen carbon stars thought to be associated with tidal debris from the Sagittarius (Sgr) dwarf galaxy because of their alignment with its orbit on the sky (velocity measurements and distance estimates could not conclusively support this association in most cases), and hence the accuracy of this measurement remains unclear.

Debris from the destruction of a satellite galaxy can provide a sensitive probe of the deviations of the potential of the Milky Way from spherical symmetry. Such debris occupies orbits with a range of azimuthal time periods about the satellite’s own, and this leads to the phase mixing of debris ahead and behind the satellite to form tidal tails (Johnston 1998). Helmi & White (1999) showed that in spherical potentials these tidal tails will gradually thicken within the orbital plane as a result of the range of precession rates of turning points in debris orbits. In nonspherical potentials, the range of precession rates of the orbital poles will also lead to thickening of the debris perpendicular to the (instantaneous) orbital plane of the satellite. Hence, if the Milky Way is close to spherical, debris should always remain planar and appear close to a single great circle in the sky (Johnston et al. 1996), but if the Milky Way is nonspherical, the debris should spread, over time, to cover a significant fraction of the sky. Such an alignment of a sample of faint, high-latitude carbon stars (Totten & Irwin 1998) along a single great circle in the sky previously led Ibata et al. (2001) to conclude (c/a)0 > 0.95.

More recently, Helmi (2004a) has cautioned that, since it can take a few orbits for debris to spread beyond its intrinsic thickness, stars released only a few orbits ago cannot be sensitive probes of potential flattening, and hence none of the Sgr data sets thus far detected provide any significant constraint on q. In addition to the Helmi (2004a) concern, the thickness of a debris stream will also increase with satellite mass. Hence, if either the current mass or recent mass-loss rate is poorly known, they will introduce additional uncertainties in trying to measure q from the thickness of a stream. As a final concern (and one that is much harder to correct for), thickening can also result from interactions with other massive—and possibly invisible—lumps in the halo (Moore et al. 1999; Ibata et al. 2002; Johnston et al. 2002).

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In this paper we revisit the question of what constraint tidal tail stars associated with the Sgr dwarf can place on the flattening of the Galactic potential. Our approach differs significantly from previous work in that we use the orbit alignment, rather than thickening of the debris, to measure the halo shape. For our analysis, we use M giants selected from the Two Micron All Sky Survey (2MASS; Majewski et al. 2003, hereafter Paper I). The Sgr M giants are thought to have ages of 2–3 Gyr (Paper I); hence, the thickness of the tidal streams made up of these stars cannot be expected to provide a strong constraint on q (even ignoring the additional concerns about this method we raised above). However, the approximate distances estimated from the apparent magnitude of the M giants permit a clear separation among stars leading or trailing Sgr along its orbit (because continuous streams of debris can be traced directly back to the Sgr core) and, moreover, yield a detailed view of the three-dimensional configuration of these tidal tails (e.g., Paper I). As a consequence, rather than simply looking at the thickness of debris projected on the sky, we are able to separately measure the poles of the best-fit great circles (in two dimensions) or best-fit planes (in three dimensions) of the leading and trailing debris. We use the difference in orbital poles between the two debris trails to quantify the precession of the orbital plane over this range of orbital phase. The advantage of this powerful approach is that what we are measuring is sensitive to q alone; the thickness of the debris due to parent satellite mass, debris age, or scattering off of lumps in the halo potential do not have systematic effects in this signal and merely contribute to the uncertainty in our measurement.4

To determine the expected variation in orbital poles for different values of q, we run a series of N-body simulations that mimic the Sgr system as traced by M giants. We describe our numerical simulations in §2, compare them to the M giant data set in §3, and summarize our results and discuss future prospects for this approach in §4.

2. METHODS

Our simulation technique closely follows that outlined in Johnston et al. (1996). The Milky Way is represented by a smooth, rigid potential, and Sgr is represented by a collection of $10^5$ self-gravitating particles whose mutual interactions are calculated using a self-consistent field code (Hernquist & Ostriker 1992).

As a starting point for our study, we use the results of Law et al. (2005a, hereafter Paper IV; preliminary results were presented in Law et al. 2005b), who perform simulations of satellite disruption along orbits that are consistent with Sgr’s current position, line-of-sight velocity, and direction of motion tangential to the line of sight (deduced from the orientation of the M giant plane). The mass and amplitude of tangential motion ($v_{\text{tan}}$) of Sgr and the potential of the Milky Way are systematically varied to find the closest possible fit (hereafter the default model) to the angular position, distance, and available line-of-sight velocity data for the 2MASS M giants along the leading/trailing streams. The default model is run in a three-component model for the Galactic potential, consisting of a Miyamoto & Nagai (1975) disk, Hernquist spheroid, and a logarithmic halo:

$$\Phi_{\text{disk}} = -\alpha \frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}, \quad (1)$$

$$\Phi_{\text{sphere}} = -\frac{GM_{\text{sphere}}}{r + c}, \quad (2)$$

$$\Phi_{\text{halo}} = \frac{v^2_{\text{halo}}}{2} \ln[R^2 + (z^2/q^2) + d^2], \quad (3)$$

where $\alpha = 1$, $M_{\text{disk}} = 1.0 \times 10^{11} M_\odot$, $M_{\text{sphere}} = 3.4 \times 10^{10} M_\odot$, $v_{\text{halo}} = 114$ km s$^{-1}$, $a = 6.5$ kpc, $b = 0.26$ kpc, $c = 0.7$ kpc, $d = 12.0$ kpc, and $q = 1$ (i.e., the halo component is spherical in the default model). The distance of the Sun from the Galactic center is taken to be $R_0 = 7$ kpc. Initially, the particles in the Sgr model are distributed according to a Plummer (1911) model,

$$\Phi = -\frac{GM_{\text{Sgr,0}}}{r^2 + r_0^2}, \quad (4)$$

where $M_{\text{Sgr,0}} = 7.5 \times 10^8 M_\odot$ is the initial mass of Sgr and $r_0 = 0.82$ kpc is its scale length. The satellite is allowed to evolve over five pericentric passages along an orbit with a pericenter of 14 kpc, an apocenter of 58 kpc, and a radial orbital time period of 0.9 Gyr. (The exact extent of the orbit depends on the distance scale adopted for the M giants, which is currently set by assuming a 24 kpc heliocentric distance for the Sgr core.) At the point matching Sgr’s current position and line-of-sight velocity, the satellite in the default model has a bound mass of $3 \times 10^8 M_\odot$. In Paper IV we find that the data still allow some freedom in the exact form for the Galactic potential, but that within a given potential, the final bound mass of Sgr is constrained to within a factor of 2. Once this is known, $v_{\text{tan}}$ can be found to within a few km s$^{-1}$.

Paper IV, in effect, finds the best-fitting set of parameters that describe the configuration of Sgr debris projected onto the instantaneous orbital plane, whereas the current discussion focuses on the variations in the position of the orbital plane itself. In this paper, we rerun the Paper IV default model with a variety of halo flattenings ranging from $q = 0.8$ to 1.45 (i.e., we consider both oblate and prolate potentials). Since we are interested in constraining the contours of the potential, we flatten these directly via parameter $q$ in equation (3) rather than generating them from a flattened density distribution. These oblate (prolate) potentials correspond to even greater oblateness (prolateness) (e.g., Helmi 2004a, Fig. 1) of the isodensity contours in the effective distance range that Sgr’s orbit explores. Note that even our models with spherical halos have modestly flattened potential contours as a result of the contribution of the Galactic disk.

We recalculate the values of the Galactic halo scale length $d$ and $v_{\text{tan}}$ for each value of $q$ considered to obtain the best possible fit to the M giant distance and line-of-sight velocity data within each model of the Galactic potential (see Paper IV for a description of this fitting process). The calculated values for each choice of $q$ are given in Table 1. Note that the orbital characteristics of the model dwarf will vary slightly for each of these models, and therefore the mass-loss history of the dwarf will depend on $q$. However, we do not revisit the question of the best-fit mass for Sgr in each of these potentials because we are only concerned with the differential precession of the poles of the tidal debris, which is independent of satellite mass.

4 It is conceivable that internal rotation of Sgr perpendicular to the orbital motion could lead to a systematic offset between the angular momentum distributions of the leading (trailing) debris, mimicking orbital precession, but we do not consider this since no systematic rotation in Sgr’s core has been observed.
and the velocity of the model dwarf tangential to the line of sight (for Sgr M giants; see Fig. 5). The values assumed for the halo scale length (bris orbital pole is at higher/lower model are also given.

In Paper I we find that the positions and available velocities for the Sgr M giants presented in Paper I are consistent with debris younger than about 1.9 Gyr (i.e., yellow, magenta, or cyan) in these simulations. This age estimate is consistent with the expected 2–3 Gyr lifetimes of these stars; in order for the M giants to be a significant contributor to debris older than about 1.9 Gyr, the stars would have to be stripped from the satellite less than one orbital period following their birth (see Paper I for a fuller discussion of this problem).

Throughout this paper we deliberately compare the M giant data with our simulations as viewed from the Sun, despite the fact that orbital precession is mostly naturally discussed in reference to the Galactic center. This is because transforming the data to a galactocentric viewpoint would introduce distortions due to uncertainties in the distances to both the M giants and the Galactic center that might be confused with orbital precession. In contrast, our heliocentric viewpoint of the simulations is fixed by only requiring that our simulated Sgr have the correct current position and velocity relative to the Sun. Moreover, we prefer a heliocentric system because it is the natural system for the great circle cell count (GC3) analysis we perform in § 3.2.

### 3. RESULTS

In § 3.1 we present a qualitative assessment of Aitoff projections of Sgr debris and demonstrate similar to previous discussions (e.g., Helmi 2004a) that such qualitative analyses provide little information on halo flattening. In contrast, we adopt two quantitative approaches to assess the degree of orbital plane precession of the Sgr system. The first method (§ 3.2) relies on careful measurements of the mean great circle described by the (l, b) distributions of M giants in the leading and trailing tidal tails. As applied here, this method is virtually free of observational errors or errors in derived quantities, particularly the derived distances of the M giants. In the second method (§ 3.3) we analyze the orbital plane variation using the derived three-dimensional distribution of the Sgr M giants. Both techniques advance previous discussions of the qualitative appearance of Sgr debris in Aitoff projections to show that a slightly oblate Milky Way potential is preferred.

#### 3.1. Aitoff Projections

Figure 1 shows the projection of the final positions of particles in the default simulation onto Sgr’s orbital plane and demonstrates the Λ⊙ coordinate system of Paper I; Λ⊙ is the angular distance from Sgr along the plane of its orbit, defined as zero at the core and increasing in the trailing direction. The colors represent different debris “eras,” i.e., orbits (denoted as one apogalacticon to the next apogalacticon) on which the debris was stripped from the satellite—yellow for particles lost since apogalacticon about 0.4 Gyr ago, and magenta, cyan, and green for particles stripped from the dwarf two, three, and four orbits ago, respectively (the orbital period of Sgr in all of our model Galactic potentials is about 0.75–1.0 Gyr). In Paper IV we find that the positions and available velocities for the Sgr M giants presented in Paper I are consistent with debris younger than about 1.9 Gyr (i.e., yellow, magenta, or cyan) in these simulations. This age estimate is consistent with the expected 2–3 Gyr lifetimes of these stars; in order for the M giants to be a significant contributor to debris older than about 1.9 Gyr, the stars would have to be stripped from the satellite less than one orbital period following their birth (see Paper I for a fuller discussion of this problem).

Figure 2 plots Aitoff projections of the final positions of particles in both spherical and moderately flattened halos (q = 1 and 0.85). Visual inspection of Figure 2 confirms the Helmi (2004a) conjecture that qualitative differences in the apparent thickening or precession of the most recent debris (i.e., yellow, magenta, and cyan points) are fairly small over the range of potential flattenings shown, especially for younger debris. However, it is premature to conclude that these effects do not lead to measurable variations in the disposition of the Sgr debris. We now demonstrate that orbital precession of even the most recent Sgr debris can be measured and used to discriminate between halo flattening models.

#### 3.2. Great Circle Cell Orbital Poles

In their current configuration about the Milky Way, Sgr leading-arm M giants predominate in the northern Galactic hemisphere while trailing-arm M giants dominate the southern hemisphere. Paper I demonstrated (see their Fig. 6) clear differences in the location of the Sgr M giant GC3 (Johnston et al. 1996) peaks when the M giant sample is limited to b > +30° versus b < −30° subsamples and suggested that the differences could relate to a combination of precessional and parallax differences between the leading and trailing arms. We repeat the Paper I GC3 analysis on our simulations (using the yellow, magenta, and cyan debris that best represents the Paper I M giant data) to determine the degree of precessional shift as a function of q. Figure 3 compares the shape and positions of the GC3 peaks of the models to those of the M giant data, divided into b > +30° (north/mostly leading arm) and b < −30° (south/mostly trailing arm) subsamples. Other aspects of sample selection, including limiting to stars with distances between 13 and 65 kpc and ignoring the region around the Magellanic Clouds (260° < l < 320° and −53° < b < −25°), were utilized to exactly match the selection criteria used to generate the GC3 plots in Paper I (their Fig. 6). The 13–65 kpc distance range limit serves to highlight the primary distance range for the debris corresponding to the yellow, magenta, and cyan parts of the leading and trailing arms. For the observations, this limit also removes nearby disk M giants and more distant stars at magnitudes at which 2MASS photometry becomes less reliable, whereas for both the observations and the models it limits the effects of overlapping contaminating debris on each Sgr arm from extensions of the opposite Sgr arms. The shapes of GC3 peaks reflect departures from great circle symmetry as viewed from the Sun, while the size (e.g., FWHM) of the peak is...
a function of the debris width on the sky, convolved with the cell size (here adopted as a 5° wide cell). The first thing to note is the overall consistency of the simulated and actual M giant data in both the shape and size of the GC3 peaks for both hemispheres. The detailed matches are encouraging support for the conjecture that the simulations provide rather accurate representations of the actual Sgr M giant distribution.

The second thing to note is that while there is virtually no difference in the location of the GC3 peaks for the southern (trailing arm) data as a function of $q$, the position of the GC3 peak for the northern (leading arm) data is, in contrast, highly and systematically sensitive to $q$. The effect is more pronounced in the north because (1) the leading arm extends very close...
to (virtually on top of) the Sun and a given precessional shift relative to the Galactic center will be foreshortened to a larger angular shift on the sky for closer debris, and (2) the northern sample used includes a larger fraction of older debris, torn off from Sgr one orbit earlier (i.e., the cyan debris in Fig. 1), and these very stars, which will have experienced more precession, constitute much of the Sgr debris closest to the Sun in the north. Note that the simulations were not adjusted to create a best match to the GC3 poles in Figure 3; rather, the orbit of Sgr in the simulations was set by the mean pole ($l = 273^\circ.75$, $b = 13^\circ.46$) found in the Paper I single plane fit to the Cartesian positions of both leading and trailing M giant debris. The close match to the general positions of the separated north (south) GC3 poles arises naturally from the evolution of the debris.6

The poles in Figure 3 show the simulations with $q = 0.90$ and $q = 0.95$ to be the closest match to both the absolute positions of the northern hemisphere GC3 peak and the relative difference in north (south) GC3 peak positions in the M giant data. More oblate and all prolate models yield northern GC3 peaks that are tens of degrees off from the observed positions. The GC3 analysis shows that subtle variation in the ($l$, $b$) distribution of debris (Fig. 2) can be measured and—in a way virtually free of observational bias—be used to constrain $q$.

3.3. Plane Fitting Poles

The GC3 analysis gives a phase-averaged view of the expected differential precession of Sgr leading and trailing debris. In contrast, the lines in Figure 4 show the pattern that the instantaneous pole of Sgr’s orbit traces on the sky within $\pm 1.5$ Gyr of Sgr’s current position, as viewed from the Sun. The upper (lower) panels show the pole evolution in potentials with oblate (prolate) halo components, respectively, with the solid (dotted) portions of each line corresponding to portions of the orbit trailing (leading) Sgr. The black triangle shows the best-fit pole of the 2MASS data set (Paper I), which the orbits were constrained to go through at Sgr’s current position.

The dots along each curve in Figure 4 indicate the orbital pole positions at 0.2 Gyr intervals both leading and trailing Sgr’s current location. The M giants discussed in Paper I explore orbital phases corresponding to up to (roughly) $0.6$ and $-0.4$ Gyr from Sgr’s current position, ahead and behind it in time along the orbit. (Note that the debris age—i.e., the time since stars

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6 Whereas a more precise match may be possible through trial and error adjustment of the instantaneous orbital pole of the Sgr core, this exact match is not essential to our goal of measuring differences between the leading and trailing debris.
were lost from Sgr—is much greater than this.) Hence, the poles actually measured from the M giant and simulation data can be thought of as averages of three points along the dotted curves and two points along the solid curves, weighted by the density of stars or particles along the streamers. (Note that for fixed flattening, the pole paths of orbits with \(v_{\text{tan}}\) varying from the adopted value by as much as \(\pm 10\) km s\(^{-1}\)—more than the maximum range permitted, given constraints from the M-giant distances and velocities, as shown in Paper IV—were found to be virtually indistinguishable from the orbits illustrated.) This figure demonstrates (as already seen in Fig. 3) that (1) in general, the separation of poles derived for the leading and trailing simulated data should increase with increasing deviations from \(q = 1\), (2) pole separation should be more dramatic for the oblate cases than the prolate cases, (3) the sense of precession in prolate potentials is opposite of that in oblate potentials, and (4) some (oblate-like) precession should be present even in the \(q = 1\) case because of the presence of a disk component in our Galactic potential.

We might expect the lines in Figure 4 to move monotonically in Galactic longitude. The retrograde-looping evolution of the leading (dotted) portion in the oblate cases is due to our perspective of these orbits, which have pericenters that lie just outside the solar circle. Indeed, some asymmetry between the evolution of the poles of leading and trailing debris is already apparent in the more dramatic shift of the GC3 peaks of the northern (leading) debris when compared to the southern (trailing) debris, as noted in the previous section (Fig. 3). However, the Figure 3 GC3 analysis is a somewhat blunt tool for assessing the precessional shifts because it does not take advantage of all available information—namely, the distances to the stars (particles).

To better quantify the degree of precession exhibited by Sgr debris, the poles of the best-fit orbital planes can be determined for both the M giant and the simulated data by plane-fitting to the leading and trailing arm debris in three-dimensional space.

We constrain these planes to pass through the solar position to allow us to quantify the effect precession has on Sgr tidal debris as projected on the sky (e.g., the natural observational regime as used in a GC3 analysis). This constraint means that the poles derived by this method should be interpreted only as tools for tracing the amount of precession in a given model of the Galactic potential; they are not the true galactocentric orbital poles and do not precisely represent the angular momentum vector of the debris. The best-fit planes to the M giant and simulation distributions were found by minimizing the \(\chi^2\) distribution of point distances from the plane, applying an iterative 2.5 \(\sigma\) rejection algorithm. Confidence limits on the corresponding poles were determined by statistical analysis of synthetic data sets generated using a bootstrapped Monte Carlo technique, with the confidence ellipse resulting from this analysis projected onto error bars at the 68\% confidence level in \(l\) and \(b\).

The open symbols in Figure 5 show the results of this precession analysis applied to data points in the leading tail in the range \(\Lambda_0 = 220^\circ-310^\circ\), while the filled symbols show the results for the trailing tail in the range \(\Lambda_0 = 20^\circ-145^\circ\) (see Fig. 1). The colored triangles (squares) correspond to simulated data run in prolate (oblate) potentials. (The error bars on the simulated points are comparable to the symbol sizes and are omitted for clarity.) Note that there is a systematic offset in \((l, b)\) of the order of a few degrees between the results from the observed data and the trend of the simulated data. This can be attributed to our assumption that the pole derived from the full 2MASS data corresponds to Sgr’s present orbital pole when, in fact, it merely represents an average along tidal debris with a small range of orbital phases. Nevertheless, it is clear that (1) the sense of precession in the data strongly favors oblate potentials and (2) the evolution of pole differences in the plot implies that the precession rate is most consistent with our slightly flattened halo models in which \(q \approx 0.90\).

Table 1 emphasizes this result by quoting the separation of the leading (trailing) poles for the simulations and the M giants. Flattening within the range \(0.90 < q < 0.95\) (0.83 < \(q_p\) < 0.92) lie within the 1.5 \(\sigma\) error bars on the data, while those with \(q < 0.85\) and \(q > 1\) are clearly outside these limits.

These were selected as ranges in which Sgr tail M giants may readily be identified in the 2MASS database using the selection criteria \(E(B - V) < 0.555\), \(1.0 < J - K_s < 1.1\), \(|Z_{\text{Sgr}}| < 25\) kpc, \(|b| > 30^\circ\), and distances 13 kpc < \(d_1\) < 60 kpc. See Paper I for definitions of these criteria. The Magellanic Clouds were removed from this data set using the \((l, b)\) cuts given in Paper I. For the simulations, yellow, magenta, and cyan debris was considered and subjected to the same cuts in \(\Lambda_0\), \(d_1\), and \(b\) as the M giants.
$q > 1.05$ are ruled out at the 3 $\sigma$ level. More extreme values of $q \leq 0.80$ ($q_\theta < 0.6$) and $q \geq 1.25$ ($q_\phi \geq 1.6$) are ruled out at the 7 $\sigma$ and 5 $\sigma$ levels, respectively.

The open (filled) circles in Figure 5 show the results of the same analysis performed on the older (Figs. 1 and 2, green points) simulated data at larger separations along the orbit ($\Lambda_0 = 0^\circ$–120$^\circ$ for the leading debris and 200$^\circ$–250$^\circ$ for the trailing; see Fig. 1) for the $q = 0.90$ simulation, which best reproduces the poles of the younger debris. The positions of the circles are suggestive of the evolution traced by the orbital poles in Figure 4. Note that the M giants discussed in Paper I are primarily in the yellow, magenta, and cyan portions of the tidal debris (see Paper IV), and there is no clear evidence yet for M giants in the portions of the tails corresponding to the green debris; the phase-mixing time for debris to reach these points is comparable to the stellar evolution ages of these stars (see § 3.1). The circles in Figure 5 demonstrate that an analysis such as that conducted here will provide a more powerful constraint on $q$ if tracers of this older debris can be found, so long as leading debris, which will be mainly in the southern hemisphere for “green debris,” can clearly be separated from the trailing debris using distance and/or velocity information. Indeed, at these larger phase differences from Sgr, the leading (trailing) poles differ by more than 45$^\circ$ even for flattenings of $q = 0.90$. This suggests that the accurate determination of the centroid of an older piece of the Sgr tidal stream, even at a single longitudinal point, can provide strong leverage on $q$ via comparison with test-particle integrations in different potentials.

4. CONCLUSIONS AND FUTURE PROSPECTS

We have shown that the precession of Sgr’s orbit can be accurately traced by stars in its debris streams—even the relatively recently released M giant stars—and hence used to constrain the flattening of the Galactic potential. A difference of 10.4$^\circ \pm 2.6$ is found between the best-fit orbital poles for stars in Sgr’s leading and trailing streams (in the sense that the angular momentum vector increases in $l$ and decreases in $b$ from trailing to leading debris) when those poles are measured from debris at azimuthal orbital phases within $+140^\circ$–$-145^\circ$ along its orbit as viewed from the Sun. Such a low amount of precession is most consistent (within 1.5 $\sigma$) with simulations of the destruction of Sgr run in models of the Galaxy with a slightly flattened halo, where $q$ is in the range 0.90–0.95 ($q_\theta = 0.83$–0.92). Flattenings for the halo potential of $q = 0.85$ ($q_\phi = 0.75$) or less and $q = 1.05$ ($q_\phi = 1.1$) or more are ruled out at the 3 $\sigma$ level, and oblate models are strongly preferred over prolate models. Note that these results depend on the assumed form of the potential of the Galactic disk.

Recently, Helmi (2004b) has suggested that prolate Milky Way potentials offer a means by which to solve a dilemma discussed in Paper IV, namely, that the Sgr leading-arm radial velocities are the one discrepant observable not well fitted by oblate Milky Way–Sgr models, which provide compelling overall fits to all other available observables (see Paper IV). While a prolate model solves this one problem, prolate models as shown here also introduce a serious discordance with the observed M giant precession; indeed, prolate models are found to induce precession in the opposite direction to that observed. Since orbital pole precession is almost solely sensitive to the shape of the potential, whereas a variety of other effects in addition to the halo shape—e.g., evolution in the Sgr orbit and/or the strength of the Galactic potential—can conceivably alter the dynamics of debris within the orbital plane, we are inclined to the simpler explanation of an oblate potential to match the precessional data while admitting the need for yet more sophisticated models to resolve the problem with the leading-arm velocities using these other free parameters.

Future detections of older Sgr debris at larger phase differences along its orbit will provide even stronger orbital precession constraints than those obtained here. Recently, Newberg et al. (2003) announced a new detection of Sgr debris as an overdensity of A-colored stars in the Sloan Digital Sky Survey at sufficient angular separation from Sgr ($\Lambda_0 \sim 196^\circ$) and distance from the Sun (>80 kpc) to possibly associate it with the oldest debris (Figs. 1 and 2, green points) in our simulations. Unfortunately, the debris has not yet been mapped fully enough for a determination of its mean position; when finished, however, a more accurate determination of $q$ may be possible. Thus, Sgr still has more to contribute to our understanding of the Galactic potential.

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