EVIDENCE FOR COUPLING BETWEEN THE SAGITTARIUS DWARF GALAXY AND THE MILKY WAY WARP

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ABSTRACT

Using recent determinations of the mass and orbit of Sagittarius, I calculate its orbital angular momentum. From the latest observational data, I also calculate the angular momentum of the Milky Way’s warp. I find that both angular momenta are directed toward \( l = 270^\circ, b = 0^\circ \) and have magnitude \( (2–8) \times 10^{12} M_\odot \) kpc km s\(^{-1}\), where the range in both cases reflects uncertainty in the mass. The coincidence of the angular momenta is suggestive of a coupling between these systems. Direct gravitational torque of Sgr on the disk is ruled out as the coupling mechanism. Gravitational torque due to a wake in the halo and the impulsive deposition of momentum by a passage of Sgr through the disk are still both viable mechanisms pending better simulations to test their predictions on the observed Sagittarius–Milky Way system.

Subject headings: galaxies: individual (Sagittarius dSph) — galaxies: interactions — Galaxy: disk — Galaxy: halo — Galaxy: kinematics and dynamics

1. INTRODUCTION

The disk of the Milky Way is warped like an integral sign, rising above the plane on one side and falling below the plane on the other. This warp is seen both in maps of neutral hydrogen (e.g., Diplas & Savage 1991) and in the stellar distribution (Reed 1996; Drimmel, Smart, & Lattanzi 2000; López-Corredoira et al. 2002b). The Sun lies along the line of nodes of the warp, where tilted outer rings cross the inner plane (see Fig. 1).

Despite their tendency to disperse when isolated (Hunter & Toomre 1969), warps are common in external galaxies (Bosma 1981; Briggs 1990; Christodoulou, Tohline, & Steiman-Cameron 1993; Reshetnikov & Combes 1998). This has driven many authors to search for universal mechanisms to excite or maintain warps (see Binney 1992 for a review). Many of these proposed mechanisms rely on the dark halo to either stabilize warps as discrete bending modes within the halo (Sparkes & Casertano 1988; but see also Binney, Jiang, & Dutta 1998) or provide the torque necessary to create the warp (Ostriker & Binney 1989; Debattista & Sellwood 1999; Ida et al. 2000). Other proposed mechanisms include the infall of intergalactic gas (López-Corredoira, Betancourt-Rijo, & Beckman 2002a), magnetic fields (Battaner, Florido, & Sanchez-Saudora 1990), and interactions with satellite galaxies (e.g., Huang & Carlberg 1997).

Each of these mechanisms can, in particular circumstances, produce realistic-looking galactic warps. Although no single mechanism appears universal enough to account for all warps, the evolution toward a bending mode (even when no discrete mode exists) appears enough like an observed warp (Hofner & Sparkes 1994) that warping may be a generic response of disks to the individual perturbations they experience. In this case, we should look at individual warped galaxies for specific evidence of particular perturbations that explain their warps rather than search for a universal mechanism that may not exist.

The Magellanic Clouds have been proposed as the perturbation responsible for the Milky Way’s warp. While Hunter & Toomre (1969) found that the tidal distortion from the clouds alone is not sufficient to cause the observed warp, Weinberg (1998) proposed that orbiting satellites could set up wakes in the Milky Way’s halo that could provide the necessary torque. Tsuchiya (2002) performed self-consistent simulations of such a system and confirmed that for a sufficiently massive halo \( (2.1 \times 10^{12} M_\odot) \), the magnitude of the torque can be increased enough to cause a warp of the same magnitude as the Milky Way’s.

The Magellanic Clouds orbit about the center of the Galaxy in a direction orthogonal to the line of nodes, i.e., near the line of maximum warp (see Fig. 1). García-Ruiz, Kuijken, & Dubinski (2000) demonstrated that the warp caused by a satellite will have its line of nodes oriented \( \ell \) along the satellite’s orbit. A simple way of understanding this result is to recognize that a torque is a transfer of angular momentum, and therefore the disk will acquire angular momentum along the same axis as the orbital angular momentum of the satellite that is providing the torque and tilt toward that axis. Therefore, the Magellanic Clouds are a bad candidate for producing the Milky Way warp.

The orbital plane of the Sagittarius dwarf galaxy (Ibata, Gilmore, & Irwin 1994) does intersect the line of nodes, suggesting that it may be a good candidate for producing the Milky Way warp (Lin 1996). It is located behind the Galactic bulge and is on a nearly polar orbit (Ibata et al. 1997). Ibata & Lewis (1998) argued that in order for the component of the Milky Way disk’s angular momentum that does not lie in the common plane. I show that they have the same direction and the same magnitude. As there is no a priori reason to expect them to be within orders of magnitude of each other, this is evidence that Sgr is coupled to the warp and therefore responsible for it.

2. THE ANGULAR MOMENTUM OF SATELLITE GALAXIES

The position, distance, and motion of Sagittarius are given in Table 1, along with estimates of its mass and orbital angular momentum. The angular momentum can range between \( 1.7 \) and \( 8.6 \times 10^{12} M_\odot \) kpc km s\(^{-1}\) and is directed toward \( l = 276^\circ, b = 0^\circ \).

The major uncertainty in this calculation is the determination of the mass. Ibata & Lewis (1998) argued that in order for the satellite to have survived to the present day, it must have a
massive extended dark matter halo and a total $M/L \sim 100$ in solar units (Ibata et al. 1997). However, Helmi & White (2001) found viable models with more moderate masses ranging from $4.66 \times 10^5 \, M_\odot$ for a purely stellar model to $1.7 \times 10^8 \, M_\odot$ for their model with an extended dark matter envelope [see also Jiang & Binney 2000, who find that if the original mass of Sgr was large enough for dynamical friction to be important, the majority of the mass would have been stripped off after a Hubble time, leaving a current mass of $(1-3) \times 10^6 \, M_\odot$.] The properties of the models of Helmi & White (2001) seem most in agreement with the expected properties of dwarf spheroidal galaxies, and therefore I adopt $(0.4-2.0) \times 10^7 \, M_\odot$ as the range of possible masses of the Sagittarius dwarf.

Table 2 shows the magnitude and direction of the angular momenta of the Galactic satellites with measured proper motions, along with that of the Milky Way warp, which is calculated in § 3. The orbital angular momentum of the Large Magellanic Cloud (LMC) was calculated using data from Kroupa & Bastian (1997). For the remaining satellites, the mass was taken from Mateo (1998) and the velocity vector from the tabulated reference.

3. THE ANGULAR MOMENTUM ASSOCIATED WITH THE MILKY WAY WARP

I calculate the component of the disk angular momentum that is due to the warp in the Milky Way’s disk, i.e., that which is not directed toward the north Galactic pole (NGP). If the disk rises a height $h(R)$ above the plane at cylindrical radius $R$, then the total angular momentum in the disk that is due to the warp is

$$L_\omega = \int_{R_m}^{\infty} 2\pi R^2 v_\Sigma(R) \frac{h(R)}{\sqrt{h(R)^2 + R^2}} \, dR. \tag{1}$$

The mass distribution of the disk is taken from Dehnen & Binney (1998). The disk surface density for a given component in these models is given by

$$\Sigma(R) = \Sigma_0 \exp \left( -\frac{R_m}{R} - \frac{R}{R_0} \right), \tag{2}$$

where $\Sigma_0$ is the normalization, $R_0$ is the scale length of the component, and $R_m$ is introduced to allow the interstellar medium (ISM) to have a central depression; $R_m = 4$ kpc for the gas disk and $R_m = 0$ for the stellar disk. The relative contributions to the surface density at the solar circle $\Sigma_0$ are 0.25 for the ISM and 0.75 for the stars. Dehnen & Binney (1998) distinguish between thin and thick disk components of the stellar disk, but because these only differ in vertical scale height, which does not affect the angular momentum, I treat them as

Note that eq. (1) of Dehnen & Binney (1998) has a typo, which is fixed above (W. Dehnen 2002, private communication).

### Table 1

**Properties of the Sagittarius Dwarf**

| Parameter | Value |
|-----------|-------|
| Galactic coordinates | $l = 57^\circ, b = -14^\circ$ |
| Galactocentric distance | $16 \pm 2$ kpc |
| Space motion $(U, V, W)$ | $(232, 0, 194) \pm 60$ km s$^{-1}$ |
| Galactocentric radial velocity | $150 \pm 60$ km s$^{-1}$ |
| Galactocentric tangential velocity | $270 \pm 100$ km s$^{-1}$ |

### Table 2

**Angular Momenta of the Milky Way Warp and Some Milky Way Satellites**

| Object | Angular Momentum $(M_\odot \, kpc \, km \, s^{-1})$ | Direction (deg) | Reference |
|--------|----------------------------------|----------------|----------|
| Milky Way warp  | $(1.6-7.3) \times 10^{12}$ | $l = 270, b = 0$ | ... |
| Sgr dSph  | $(1.7-8.6) \times 10^{12}$ | $l = 276, b = 0$ | 1, 2 |
| LMC  | $2 \times 10^{11}$ | $l = 184, b = 9$ | 3 |
| Fornax dSph  | $3 \times 10^{11}$ | $l = 106, b = -16$ | 4, 5 |
| Ursa Minor dSph  | $3 \times 10^{11}$ | $l = 213, b = 9$ | 4, 6 |
| Sculptor dSph  | $1 \times 10^{11}$ | $l = 226, b = 7$ | 4, 7 |

References.—(1) Ibata et al. 1997. (2) Helmi & White 2001. (3) Kroupa & Bastian 1997. (4) Mateo 1998. (5) Piatek et al. 2002. (6) Schweitzer, Cudworth, & Majewski 1997. (7) Schweitzer et al. 1995.
a single component. Their models 1–4, which differ primarily in disk scale length, $R_d$, are all acceptable fits to the observations and therefore provide a reasonable range of mass distributions with which to estimate the angular momentum. Table 3 gives the essential parameters for the four models. The circular velocity, $v_c$, of the disk from 3 kpc to the solar circle is $\approx 200$ km s$^{-1}$ (e.g., Merrifield 1992). While most measurements at $R > R_d$ show a rising rotation curve, Binney & Dehnen (1997) argue that a constant rotation curve is consistent with the data when the correlations between errors are taken into account. I adopt $v_c = 200$ km s$^{-1}$ at all radii. The uncertainty in the angular momentum due to uncertainties in the mass models dominates over any error in the circular velocity.

The height of the warp above the plane as a function of radius, $h(R)$, appears to differ for the stars and for the gas. Drimmel et al. (2000) fit Hipparcos measurements of OB stars and find

$$h(R) = \begin{cases} (R - R_w)^{1/2} & R > R_w, \\ 0 & R \leq R_w \end{cases}$$

with the warp starting at $R_w = 6.5$ kpc and scaled by $R_s = 15$ kpc. Binney & Merrifield (1998) approximate the $m = 1$ mode of the ISM warp as

$$h(R) = \begin{cases} (R - R_w)/(aR) & R > R_w, \\ 0 & R \leq R_w \end{cases}$$

where $R_w = 10.4$ kpc and $a = 5.6$ when converted to $R_s = 8$ kpc as assumed in the Dehnen & Binney (1998) models (Tsuchiya 2002). Binney & Merrifield (1998) also fit an $m = 2$ mode, but the net angular momentum of any even $m$ mode is aligned with the angular momentum of the flat disk, so it will not contribute.

I use equation (3) for the stellar disk and equation (4) for the gas disk. The results are shown in Table 3. The majority of the angular momentum is contained in the range 10 kpc $\leq R \leq 25$ kpc in all models. The Sun lies within 10° of the line of nodes, so $L_\nu$ is directed toward $260^\circ \leq l \leq 280^\circ$, $b = 0^\circ$.

4. DISCUSSION

Table 2 shows the magnitude and direction of the angular momentum of the Milky Way warp and of the Galactic satellites with measured proper motions. Both the magnitude and direction of the angular momentum of Sagittarius are strikingly similar to that of the Milky Way warp. There is no a priori reason to expect this; the angular momenta of the other satellites with known orbits span 3 orders of magnitude and almost $180^\circ$ of Galactic longitude (although there is a strong tendency for the satellites to have polar orbits with low values of $|b|$, as suggested by Lynden-Bell 1976 and noted in the anisotropic distribution about the Milky Way by Hartwick 2000). The coincidence of the two angular momentum vectors is probably evidence that they are dynamically coupled, i.e., that Sagittarius is the perturber responsible for the Galactic warp.

There are three possibilities for the nature of the coupling. The first is a direct gravitational tidal torque by the satellite itself (Hunter & Toomre 1969), the second is the gravitational torque of a wake in the Galactic dark matter halo (Weinberg 1998; Tsuchiya 2002), and the third is an impulsive deposition of momentum to the gas disk by passage through it (Ibata & Razoumov 1998). The direct tidal torque for a satellite of mass $m$ and distance $r$ scales as $m/r^3$. Therefore, the direct tidal effect of Sgr is no stronger than that of the LMC, whose direct tidal torque is not sufficient to induce the warp (Hunter & Toomre 1969). This means that the gravitational torque of Sgr itself cannot be the coupling mechanism.

If the primary perturber is instead a wake in the halo, the strength of the torque scales as $m_{\text{wake}}/r_{\text{wake}}^3$. The mass of the wake scales as the mass of the satellite and as the density of the halo at the wake radius (Weinberg 1998). The wake develops at half the satellite’s orbital radius (Tsuchiya 2002). Therefore, for an isothermal halo, the strength of the torque scales as $m/r^3$. In this case, the effect of Sagittarius is 10–50 times stronger than that of the LMC. It is plausible that in the lower mass simulation of Tsuchiya (2002), in which the LMC did not excite a warp, a satellite with Sagittarius’s parameters would have. Further simulations that better reproduce the observed Sagittarius–Milky Way system could confirm or falsify this suggestion.

Ibata & Razoumov (1998) suggest that the impulsive deposition of momentum to the gas disk could excite the warp. The mass they use for Sgr, $5 \times 10^7 M_\odot$, is quite large, and they find very little warping in their $1 \times 10^7 M_\odot$ simulation. However, they model only a single interaction. In order for the angular momenta to reach an equilibrium, as they appear to have done, there must be repeated or continual encounters. Helmi & White (2001) find orbital periods of $\sim 1$ Gyr for Sagittarius, indicating that it has passed through the disk several times. Further simulations that follow the evolution of the system over many encounters are necessary to better understand the predictions of this model; meanwhile, it cannot be ruled out.

### Table 3

| Parameter                        | Model |
|----------------------------------|-------|
|                                 | 1    | 2    | 3    | 4    |
|----------------------------------|------|------|------|------|
| Surface density at solar circle | $\Sigma_0 (M_\odot \text{pc}^{-2})$ | 43.3 | 52.1 | 52.7 | 50.7 |
|                                 |       |      |      |      |
| Derived Warp Angular Momenta ($10^{15} M_\odot \text{ kpc km s}^{-1}$) |       |      |      |      |
| Stellar disk                     | 1.10 | 2.16 | 3.36 | 4.73 |
| ISM disk                         | 0.52 | 1.10 | 1.78 | 2.57 |
| Total                            | 1.62 | 3.26 | 5.14 | 7.30 |

* Direction is $l = 270^\circ \pm 10^\circ$, $b = 0^\circ$. 

### Notes

1. Surface density at solar circle
2. Stellar disk scale length $R_d$ (kpc) $\approx 10.4$ kpc km s$^{-1}$
3. ISM disk scale length $R_{d,\text{ISM}}$ (kpc) $\approx 15$ kpc
4. Surface density at solar circle $\Sigma_0 (M_\odot \text{pc}^{-2})$ $\approx 50$ $M_\odot$ pc$^{-2}$
5. Derived Warp Angular Momenta ($10^{15} M_\odot \text{ kpc km s}^{-1}$) $\approx 5.6$ $10^{15} M_\odot$ kpc km s$^{-1}$
5. SUMMARY

The orbital angular momentum of the Sagittarius dwarf galaxy and the component of the Milky Way disk angular momentum due to the Galactic warp are both directed toward \( l \approx 270^\circ \), with magnitude \( b = 0^\circ \) with magnitude \((2-8) \times 10^{12} M_\odot \) kpc km s\(^{-1}\). Such a coincidence suggests that they are a coupled system, i.e., that Sgr is responsible for the warp. The direct gravitational tidal torque of Sgr cannot cause the warp. Interaction via a gravitational wake in the Milky Way’s dark matter halo and impulsive deposition of momentum into the disk by passing through it are still both possible coupling mechanisms. More simulations of each of these models are necessary to discriminate between their effects.

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