Warps in disk galaxies
García Ruiz, Iñigo

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The Warp of the Galaxy and the LMC

Based on a paper by I. García-Ruiz, K. Kuijken & J. Dubinski

We study the possibility that the Galactic warp is caused by the tides of the Magellanic clouds. Using a specialized N-body particle+ring code we investigate the role of extra torques on the disk induced by gravitational wakes in the dark halo created by the LMC. We find that even when the wake in the halo is taken into account, the influence of the LMC is too weak to generate the observed warp amplitude in the Galaxy.

2.1 Introduction

We know since 1957 that the outer parts of the Galaxy are warped (Burke, 1957; Kerr, 1957). Studies of external galaxies have extensively shown that this phenomenon is not uncommon at all: at least three out of four galaxies exhibit warps in their outer HI disks (Sancisi, 1976; Sánchez-Saavedra et al., 1990; Bosma, 1991). In this era of astrophysics where most of the matter of the universe is believed to be dark, the main hypotheses for the excitation and/or maintenance of warps make use of this dark matter in the shape of a halo surrounding the galaxies. Warping modes of disks embedded in somewhat flattened (dark) halos (Sparke & Casertano, 1988) seemed to provide a good descriptions of warps, but they assumed that the halo didn’t respond to the gravitational influence of the disk. When later this effect was taken into account (Dubinski & Kuijken, 1995; Nelson & Tremaine, 1995), warp modes damped too quickly and dynamicists began looking for an alternative explanation.

Galaxy-galaxy encounters are known to produce tidal features that may bend the outer parts of the disk in the observed fashion (see, for example, (Schwarzkopf & Dettmar, 2001)). The problem with this scenario is that
there are several galaxies where no companion is seen close to the warped galaxy, or the companion doesn't have enough mass to generate the observed warp amplitudes. In our own galaxy, for example, the LMC's direct tidal forcing at its present distance is too weak to produce the observed warp (Hunter & Toomre, 1969).

Recent work by Weinberg (1998) describes a calculation in which a disk galaxy surrounded by a dark halo is perturbed by a massive satellite, similar to the LMC. By means of a linear perturbation analysis, he follows the perturbation (wake) created by the satellite in the halo, including its self-gravity. He finds that the torque exerted by this wake on the disk is several times larger than that due directly to the satellite. The latter is amplified because (i) the satellite-induced wake in the halo itself exerts a torque, roughly in phase with that from the satellite; and (ii) the wake itself further perturbs the halo, resulting in a torque that is larger again. As Weinberg shows, the details of the disk model (and hence its vertical oscillation mode spectrum) sensitively determine the degree of warping in response to the satellite and halo wake perturbations. The amplification of the satellite tidal effect on the disk by a wake was originally addressed in a calculation by Lynden-Bell (1985) of a similar scenario, as well as in a simple model described by Kuijken (1997).

Weinberg’s calculation, while impressive, relies on a number of simplifying assumptions:

1. The halo model is taken to be a King model, i.e., spherical and radially scalefree over a substantial radial range. The symmetry reduces the dimensionality of phase-space, making calculation of the response of the halo more tractable. However, real galaxies will have halos that are somewhat flattened by their disks, and which are not scalefree.

2. The response of the disk is calculated after that of the halo is established, i.e., the disk’s back reaction on the halo is ignored. But, as shown by Dubinski & Kuijken (1995) and Nelson & Tremaine (1995) disk damping against the halo is an important effect.
3. The satellite orbit is taken to be quasi-periodic, as is appropriate for a non-decaying orbit. However, a satellite massive enough to warp the disk will be affected by dynamical friction, and hence will have a decaying orbit.

4. Only the steady-state forced response is calculated, not the transient responses. Since satellite orbital frequencies are rather low (the orbital period of the LMC is about 1.5 Gyr) the transients may be important.

In this chapter we investigate these questions by means of N-body simulations. §2.2 contains a description of the N-body code used, and §2.3 the results of our simulations: there we show that the amplification by the halo wake in our model is modest. In §2.4 we give our conclusions.

2.2 Simulation details

2.2.1 N-body Ring Code

The N-body code used to evolve the system uses a hybrid approach. The halo is modeled using particles while the disk is modeled using a system of concentric, spinning rings. The gravitational potential of the halo is computed using a self-consistent field (SCF) code (Hernquist & Ostriker, 1992), expanding the potential in terms of radial (quantum number \( n \)) and spherical harmonic (numbers \( l, m \)) basis functions. Basis functions up to \( n = 6, l = 4 \) were used in this paper. We have made several checks to make sure that we have used high enough harmonics in our expansion. We have compared the particle density directly determined from the particle halo (Fig. 2.4) with the truncated expansion used by the SCF code for the same halo (Fig. 2.5). The match shows us that an expansion up to \( n = 6, l = 4 \) is able to resolve the wakes generated by the satellites in the halo with sufficient accuracy (the imaging of the wake is explained in detail in §2.3.4). As a double check, we also run some simulations with higher harmonics \( (n = 6, l = 8) \), and no significant variation in either the warp nor in the wake was detected.

The disk is treated as a system of spinning rings centered on the halo. The rings are spaced uniformly but have varying mass to represent the disk density profile. Each ring is realized as 36 equal mass particles that are azimuthally equally spaced. The gravitational potential generated by the ring-particles are calculated using a tree code (Barnes & Hut, 1986) since the SCF method cannot accurately determine the potential for highly flattened systems. The gravitational forces on these individual “ring-particles” are then used to calculate the torque on each ring which were used in the solution of Euler’s equations.

Finally, we treated satellites as single particles with a Plummer-law potential. The force exerted by a satellite on the simulation particles was eval-
Table 2.1— Summary of all the simulations used in this article. (1) See §2.2.2, (2) Mass of the satellite in units of $1.5 \times 10^{10} M_{\odot}$ (M$_{\text{LMC}}$), (3) Number of halo particles, (4) Sense of rotation of the orbit, (5) Is satellite orbit allowed to decay under dynamical friction? (6) Is halo allowed to respond to satellite (form a wake)? (7) Is halo allowed to respond to disk?

<table>
<thead>
<tr>
<th>$N_r$</th>
<th>Halo Model</th>
<th>$M_{\text{act}}$</th>
<th>$N_{\text{halo}}$</th>
<th>$L_{x,\text{act}}$</th>
<th>Dyn. Fr.</th>
<th>Sat $\rightarrow$ Halo</th>
<th>Disk $\rightarrow$ Halo</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>King</td>
<td>0</td>
<td>500,000</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>no</td>
</tr>
<tr>
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<td>500,000</td>
<td>–</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>King</td>
<td>1</td>
<td>500,000</td>
<td>–</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>4</td>
<td>King</td>
<td>1</td>
<td>5,000,000</td>
<td>–</td>
<td>no</td>
<td>yes</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>King</td>
<td>10</td>
<td>500,000</td>
<td>–</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>6</td>
<td>King</td>
<td>10</td>
<td>500,000</td>
<td>–</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>7</td>
<td>King</td>
<td>10</td>
<td>500,000</td>
<td>–</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>8</td>
<td>King Relaxed</td>
<td>0</td>
<td>500,000</td>
<td>–</td>
<td>–</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>9</td>
<td>King Relaxed</td>
<td>10</td>
<td>500,000</td>
<td>–</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

We simultaneously integrate the equations of motion for the halo particles and the system of Euler’s equations for the rigid-ring system describing the disk. Total energy and angular momentum of the combined particle and ring system were found to be well-conserved with typical errors less than 1% in these quantities by the end of a typical simulation.

### 2.2.2 Initial conditions

To simulate the tidal amplification of a satellite by a halo we have chosen a set of initial conditions following Weinberg (1998). We have adopted as a halo the one that generated the greatest warp in his calculations, as well as an exponential disk with a scale-length of 4.5 kpc. The disk is exponential in the first 5 scale-lengths, and then it is tapered smoothly to zero in the last scale-length as described in Kuijken & Dubinski (1995).

The units of the model translate to the Galaxy (disk scale-length 4.5 kpc, and the rotation velocity at 8.5 kpc of 220 km s$^{-1}$) as follows: length unit = 4.5 kpc, velocity unit = 315 km s$^{-1}$, time unit = $1.40 \times 10^7$ years, mass unit = $1.0 \times 10^{11} M_{\odot}$. With these numbers, the disk mass of our model is $5.24 \times 10^{10} M_{\odot}$, and the satellite (LMC) has a mass of $1.5 \times 10^{10} M_{\odot}$, the biggest current mass estimate for the Clouds (Schommer et al., 1992). In the coordinate system of the simulations, $z = 0$ is the disk plane, and the orbit of the satellite lies in the $x = 0$ plane.

We have used two different types of simulations: semi-live and live. In the ‘semi-live’ simulations, the effect of the disk on the halo is suppressed. The halo model used for these simulations is a King model of $\Psi_0/\sigma_0^2 = -6$, a tidal radius of 44, and mass of 10 disk masses (see Fig. 2.1 for the mass...
profile and rotation curve). We use this halo for the simulations in which the effect of the disk on the halo is suppressed.

In the ‘live’ simulations the halo is allowed to feel the effects of the disk. Here the initial conditions need to be different, as our King model halo and the exponential disk are obviously not in equilibrium. Hence for these runs we have allowed our halo to relax before. For this purpose we evolved the King halo with a disk, forcing the disk to remain flat in the initial configuration until the system does not evolve any more. Once the halo and disk have relaxed, we introduce the satellite and allow the disk to depart from the disk plane. Letting the halo relax in the presence of the disk causes the density to increase in the internal parts of the halo, which makes the contribution of the halo to the rotation curve higher in the inner parts. It peaks higher (by \( \approx 20\% \)) and at a smaller radius (25\%) than before.

For each model we used \( N_h = 500,000 \) particles for the halo and 600 rings for the disk. Each ring contained 36 particles. Various runs where made with more rings and more particles per ring, without significant changes in the results described below. We also made a simulation with 5,000,000 particles for the halo (simulation nr. 4, described in §2.3.3) and obtained the same results.

We use two Plummer-law satellites, symmetrically placed with respect to the center of the halo-disk system to null out the dipole term of the tidal field. In this way, we avoid relative movements of the galaxy with respect to the satellites and focus on the quadrupole \((l = 2)\) terms which dominate in generating the warp.

The simulations begin with the satellite at its apocenter where the density of the halo is lowest, to minimize disturbance to the equilibrium halo-disk model and give enough time for the halo to develop a gravitational wake due to the satellite, before it gets to its pericenter.

The satellites are placed in a polar orbit with pericenter at 50 kpc and apocenter at 100 kpc, consistent with recent determination of the orbit of the Clouds (Lin et al., 1995). In the first simulations dynamical friction is suppressed but incorporated later when the response of the halo to the disk is computed (§2.3.6). The orbit of the satellite in the case where dynamical friction is neglected is shown in Figure 2.2.

Our standard model consists of the exponential disk, the King model halo, and the satellite orbiting in the 50 kpc - 100 kpc non-decaying orbit recently described. All simulations were run for 320 time units (which corresponds to 4.5 Gyr).

2.3 Results

We have performed a number of simulations to look for the effect described in Weinberg (1998). We first simulate a system resembling the Galaxy and
Chapter 2: The Warp of the Galaxy and the LMC

2.3.1 Control simulation

We first simulated our standard model parameters for the disk and the halo but without satellites (simulation no. 1) to determine any disk warping from particle noise. We find that the particle noise due to the halo had excited a warp in the disk with an amplitude of 3.5 degrees at \( r = 6 \).

2.3.2 Semi-live halo

In this section, we calculate the bending of the disk caused by orbiting satellites by switching off the effect of the disk on the halo (and hence its backreaction on the disk), in an effort to reproduce Weinberg’s calculations.

First, we switch off the effect of the satellite on the halo as well (simulation no. 2), to quantify the warp amplitude in the case of only direct tidal forcing by the satellite. This simulation shows warp amplitudes indistinguishable from the control simulation, indicating that the raw tidal field of the satellite is much too weak to affect the disk.

The standard model (resembling the LMC - Galaxy, simulation no. 3), including the effect of the satellite on the halo develops a warp no bigger than 0.5 degrees above the control simulation.

LMC and later increase the mass of the satellite to observe the warp above our particle noise level. For a summary of all the simulations performed, see Table 2.1.
Figure 2.3— Torques on a flat disk caused by the satellite (dashed line), the halo (dotted line), and the total torque (solid line). The left plot shows torques calculated from the high resolution simulation (simulation nr. 4), while the plot at the right shows the SCF simulation results (simulation nr. 6, with a satellite 10 times more massive and a factor of 10 less halo particles than simulation nr. 4).

The wake that is created in our halo as a result of the perturbed satellite peaks inside the orbit of the satellite, but not as deeply as half the distance (2:1 resonance mentioned in Weinberg (1998)). Since tides depend strongly on distance, this more distant wake results in insufficient amplification of the tidal effect on the disk.

2.3.3 High resolution halo simulation and massive satellites

We tried to detect the wake in the halo by comparing simulations 2 and 3 but particle noise is too high to detect the small wake in our halo. We address this problem of resolution using two approaches. We first did one higher resolution simulation with 5M particles in the halo (an order of magnitude higher than our standard simulations) of a satellite orbiting a halo (simulation nr. 4) using a parallel treecode (Dubinski, 1996). We do not include a disk in this simulation, which had otherwise the same initial conditions as simulation nr. 3.

We have also run simulations with the same initial conditions as in simulations 2 and 3 but with a satellite an order of magnitude more massive ($1.5 \times 10^{11} M_\odot$). We again performed a simulation including only the direct tidal forcing of the satellite on the disk (simulation nr. 5) and another one including the influence of the satellite on the halo (simulation nr. 6).

We keep the satellite in the same orbit as in simulations 2 and 3 but allow the halo to respond to the more massive satellite to induce a stronger wake in the halo. We don't let the satellite orbit evolve self-consistently or otherwise the satellite would spiral into the galaxy in a timescale shorter than a Hubble time.

If the wake in the halo is still in the linear perturbation regime, we would expect the wake (and therefore the torque on the disk) of the high resolution simulation to be an order of magnitude smaller than that of simulation nr. 6 (because the wake scales linearly with the mass of the satellite).
We compared simulations 4 and 6 by computing the torque that the halo (with the wake created by the satellite) would create on a flat disk. We then compared it with the direct torque that the disk feels from the satellite. Figure 2.3 shows these torques for both simulations. The first conclusion we derive from this figure is that both simulations agree at an excellent level in the contribution of the wake to the total torque, which is not larger than 25%. The fact that the wakes in the 5M particle halo are producing the same amount torque on a disk suggests that we are converging to the correct dynamical behavior.

Thus, even though the halo does contribute to the torque that a disk experiences from a satellite, this extra contribution is quite modest. Note as well that the torque generated by the wake on the halo is not exactly in phase with the torque arising directly from the satellite. The wake is slightly behind the satellite, which causes the torque from the wake to peak some time after the torque from the satellite has. This will make the combined torque from both wake and satellite smaller than the sum of both, so we expect the warp amplitudes not to be increased by more than 25% when the wake is taken into account.

The comparison between the high resolution simulation and simulation nr. 6 also indicates that the SCF simulations accurately represent the satellite-halo interaction, and that we can use them to explore the properties of warps in halo-satellite-disk systems.

2.3.4 The wake and the satellite

We have compared simulations 5 (no wake) and 6 (wake) to estimate the contribution of the wake to the warping of the disk.

The difference in the warping of the disk between simulations nr. 5 and nr. 6 is the warping induced by the wake in the halo on the disk. If this effect is very important we would expect larger warps in simulation nr. 6. In agreement with the lower-mass satellite simulations (nr. 2,3) and torque calculations of Figure 2.3, the disk warp obtained is less than 20% larger in simulation nr. 6 than in nr. 5, indicating that the wake in the halo contributes only a fraction of the torque exerted by the satellite itself.

We then attempted to image the wake in the halo by subtracting the estimated halo density from the particle distribution simulation nr. 5 (no wake) from that of simulation nr. 6 (wake included). Contour plots of the halo density in the orbital plane are shown in Figure 2.4. We have also calculated the wake in density comparing the SCF expansions for both simulations (Figure 2.5). The wake follows the satellite from behind clearly along the simulation, having its maxima at a smaller radius than where the satellite is. Although we lack resolution to tell exactly where the maxima of the wake are (these maps are smoothed), it is further out than half the orbital radius of the satellite. This smoothing has to be taken into account when
Figure 2.4— Wake in the halo, calculated directly from the particle density in the halo at different timesteps. For this plot only the particles in a slice of 1 disk scale-length centered in the satellite plane were considered. The contours are overdensities and underdensities with respect to the unperturbed halo model. To suppress particle noise, we smoothed these maps to a resolution of 6 scale-lengths. The positions of the satellites are given by the crosses. See §2.3.4 for details on the imaging of the wake.
Figure 2.5 — Wake in the halo, as calculated from the SCF code with terms up to $n = 6$, $l = 4$. The contours are overdensities and underdensities with respect to the unperturbed halo model, and have been calculated in the orbital plane of the satellite. See §2.3.4 for details on the imaging of the wake.
comparing the figures 2.4 and 2.5. If we smoothed the density plots of figure 2.5, the peak of the wake would shift outwards in radius.

2.3.5 Halo particle noise

As a check on the influence of particle noise on our results, we performed another simulation (simulations nr. 7) with the same parameters as nr. 6 but with the orbit of the satellites having opposite angular momentum ($z_{\text{sat}} = -z_{\text{sin7}}$). In absence of halo particle noise, we would obtain the same warp amplitude in both simulations, with a difference in the position angle of the line of nodes of 180°. On the other hand, if we see that the line of nodes of simulation nr. 7 is close to that of nr. 6, this means that the noise from halo discreteness is dominating the warp.

The warps of both simulations are shown in Figures 2.6 and 2.7, where we have plotted tip-LON diagrams (Briggs, 1990) at different timesteps for these two simulations. We have computed the line of nodes averaging the disk every 50 rings (0.5 scale-lengths). In these plots we can see that up to $t = 160$ the effect from the wake and the satellite is dominant, but after this the halo particle noise grows, dominating the shape (and orientation) of the warp.

At the end of the simulation ($t = 320$), the maximum amplitude of the warp at 6 scale-lengths is smaller than 6 degrees. This poses an upper limit to the warp generated by the satellite and the halo wake, since the noise excited warp is the main driver of the warp we see. If the warp excited by the satellite-halo system were as important as the noise excited one we would detect differences in the final warp of simulations nr. 5 and nr. 6, which we don’t. If we get a maximum warp of 6° with a satellite of $1.5 \times 10^{11} M_\odot$, the amplitude of the warp that a LMC-like satellite ($1.5 \times 10^{10} M_\odot$) is going to generate on the Galaxy is not going to be bigger than 0.6 degrees. This is a conservative upper limit, taken into account that we know that the halo noise generates a considerable percentage of this quantity.

2.3.6 Full simulation

In this section we take into account the effect that the gravity of the disk has on the halo, and the backreaction of the halo on the disk. We also consider the effect of the halo on the satellite, causing its orbit to spiral inwards by dynamical friction. The satellite we use in this simulation is as massive as the one in simulation nr. 5, but its decaying orbit has been calculated with a satellite with the mass of the LMC, to avoid rapid decay of the orbit in an unrealistically short period of time. For the halo, we have used the relaxed King model halo described in §2.2.2.

We have made two simulations with these settings. The first of them (simulation nr. 8) is a control simulation with no satellite to determine the
Figure 2.6— tip-LON diagrams at different timesteps for the simulation nr. 6. We have binned the disk every 0.5 scale-lengths in radius. There is a dotted circle every degree.

Figure 2.7— tip-LON diagrams at different timesteps for the simulation that has the same parameters as the one in Figure 2.6 except that the satellite is orbiting in the opposite sense (simulation nr. 7). We have binned the disk every 0.5 scale-lengths in radius. There is a dotted circle every degree.
effect of halo particle noise in our disk. The disk in this simulation doesn't develop a more or less coherent warp as in simulation 1 (control simulation without backreaction). Instead, the inclination of the rings fluctuates fast and the line of nodes changes drastically with radius. At the end of the simulation (t=320) the outer rings are inclined by 2.5° (with a completely wound up line of nodes).

Now we introduce the satellites (simulation nr. 9) to see how the influence of the disk on the halo will influence the warp. The first difference we observe in the evolution of the disk is that in this simulation the inclination of the inner parts is smaller than in previous simulations. This is caused by the fact that the halo is now flattened in the vicinity of the disk due to the potential of the disk, and this creates a preferred plane (Dubinski & Kuijken, 1995). In previous simulations a slight asymmetry in the initial halo can cause the inner disk to tilt with respect to the $z = 0$ plane. The flattening of the halo now exerts a torque on the disk in the direction of the line of nodes of the warp, besides the torque due to the wake created by the satellite. A flattened halo would have the same consequences in the previous simulations.

We also note that the warp has lost most of its coherence. The line of nodes is tightly wound up, smearing out the growing warp pattern, consistent with the simulations in Binney, Jiang & Dutta (1998). A warp like this would be much more difficult to detect observationally than the warps we were getting without considering the backreaction of the halo on the disk. The amplitude of the warp are somewhat higher than in simulations nr. 6 and 7, due to the fact that the satellites now are affected by dynamical friction and this carries them closer to the disk, increasing their tidal force on it.

### 2.4 Conclusions

We have been unable to reproduce Weinberg’s prediction (1998) of strong tidal amplification of a disk warp by a satellite’s gravitational wake. In the case of the Milky Way - LMC system an amplification of the order of 500% is required, while we get amplifications no higher than 25% in the total torques and smaller than 20% in warp amplitudes. This amplification is achieved for the halo profile and satellite parameters that had a maximum amplification in the calculations by Weinberg (1998). It is possible that some halo profiles, together with specific satellite orbits may increase this amplifications somewhat, but we have found no evidence that the tidal field from a satellite can be amplified as much as 500% by means of the halo. We have tried several different simulation techniques, with large and varying number of particles, and consistently find evidence for only weak tidal field amplifications.

We conclude that the amplitude of the warps generated with LMC-like
satellites is much lower than what is observed in the Galaxy. Assuming a high mass for the LMC, the typical inclination angles from the plane defined by the inner part of the disk are of the order of 0.6 degrees (or less), which is a factor of 5 less than in the Galaxy. Furthermore, the line of nodes of the resulting warp is tightly wound. If smaller mass estimates for the Clouds are used (Meatheringham et al., 1988), the results are even more discouraging. So, although periodic forcing of disk warps by tidal fields of orbiting satellites would appear to circumvent many of the persistence problems of other tidal field models for warps, we conclude that in the case of the Galaxy this does not appear to be a feasible model.

Even if a halo is able to amplify the satellite tidal field (though the extent to which this happens may depend quite subtly on the halo structure), it will also strongly perturb the disk precession that accompanies the warping. Dubinski & Kuijken (1995) and Nelson & Tremaine (1995) showed that most realistic halo mass distributions damp the precession strongly, while Binney, Jiang & Dutta (1998) showed that in the process the line of nodes of the warp winds up very fast, effectively destroying the forming integral-sign warp. Obtaining the amplification of the tidal field without the accompanying damping of the disk precession would seem to require halos which are present at large radii, but not near the disk’s gyration radius, otherwise the disk would be too tightly coupled to the inner halo.

Our results thus suggest that the explanation for warps should be sought elsewhere. Either there is a frequently occurring, and presumably quite gentle, dynamical instability of disk/halo systems that has been overlooked so far, or an entirely different mechanism needs to be considered. Possibilities include late cosmic infall which continuously realigns the angular momentum vector of galaxies (Ostriker & Binney, 1989), or a generic misalignment between disk and halo angular momentum vectors which may excite warps (Debattista & Sellwood, 1999).