Tidal Torques and Galactic Warps

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Abstract

We investigate the tilting and warping of galactic disks in response to tidal torquing. The strength of the torque is determined from cosmological N-body simulations. We find the tidal torques to be dominated by substructure in the galactic halo, such as dwarf satellites, and by a misalignment between the disk angular momentum and the figure axes of the dark matter halo. The radial dependence of the torque can approximated by a power law of index -2.5. A massless disk subjected to such a torque develops a trailing warp similar to those seen in a large number of disk galaxies, i.e. the inner regions of the disk tilt faster than the outer disk. In the case of massive disks, self gravity causes the inner disk to stay locally flat and only the outer regions show the signatures of warps. The radius outside of which a massive disk is warped depends on the local surface density of the disk and on the product of the strength of the torque and the exposure time to this torque.

1 Introduction

Many edge-on disk galaxies show integral-sign warps, where the majority of the disk is planar but where the outer region of the disk lies above the plane on one side of the galaxy and below the plane on the other (e.g. Binney 1992). Most extended H I disks appear warped (e.g. Briggs 1990) and half of all disk galaxies have optical warps (Reshetnikov & Combes 1998).

Various methods have been proposed for creating and maintaining warps, such as normal bending modes (e.g. Sparke & Casertano 1988) and disks askew in flattened dark matter halos (Toomre 1983; Dekel & Shlosman 1983). Motivated by the idea that infalling material will alter the direction of the angular momentum of a galaxy (Quinn & Binney 1992), Ostriker & Binney (1989) studied the reaction of massive rings to a slewing disk potential. They found that warps occurred in regions of low surface density. Also motivated by the cosmic infall of angular momentum, Debattista & Sellwood (1999) found that when the angular momenta of a halo and disk are misaligned, dynamical friction between them can produce a warp.

In a cosmological setting, a galactic disk is expected to continuously experience tidal torques from a variety of sources, the three more important being the distribution of mass in the local environment of a galaxy, substructure in the dark matter halo such as dwarf satellites and high velocity clouds (HVCs), and a misalignment between the disk angular momentum and the figure axes of the dark matter halo. In this paper, we use cosmological N-body simulations to deduce what gravitational tidal torques a typical galaxy experiences from these three sources, and study whether these torques provide a possible origin for warped disks.

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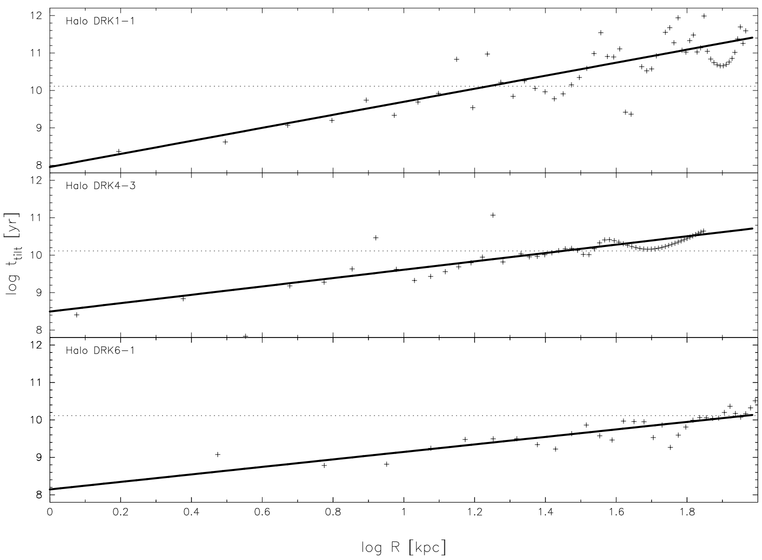

Figure 1: Gravitational torques, expressed in terms of $t_{\rm tilt}$, at 60 evenly-spaced radii for three typical halos. The solid lines are power law fits for the data points at $R \geq 1.5$ kpc. Dotted lines correspond to the Hubble time (13 Gyr).

2 Torques in a Cosmological Context

We determine the strength and radial dependence of the torque by analyzing a sample of 19 halos formed in an N-body simulation of structure formation in the standard cold dark matter scenario ($\Omega_0 = 1$; for details, see Navarro & Steinmetz 1997). Each halo consists of at least 1000 particles and has been selected not to be significantly disturbed by recent merger events. We assume a disk to form in the plane perpendicular to the angular momentum of the dark matter halo.

The magnitude and radial dependence of the torque from all sources is determined by calculating the gravitational force component that is exerted by all particles in the simulation and that is acting perpendicular to the disk. The torques are expressed in terms of the tilting timescale $t_{\rm tilt}(r)$ defined as the time required for a solid massless ring of radius r to react to the torque by tilting by one radian.

We separate the mass in the simulation into that inside the halo (defined by the virial radius r_{200}) and that outside the halo and compare the torques due to each. We find the torque due to the mass outside the halo to be negligible, indicating that galaxies in the local universe and cosmic tidal shear do not contribute to the torque a (field) disk galaxy experiences.

The torques inside three sample halos are shown in Figure 1. The solid line is a power-law fit for each halo. The fits reproduce the broad behavior of the torquing forces, but there is significant deviation at specific radii. This power-law type radial dependence is characteristic of misalignments typical for dark matter halos that form by hierarchical clustering (Cole & Lacey 1996; Warren et al. 1992), with mild misalignments of typically 20° for a moderately flattened ($b/a \approx 0.8$) dark matter halo. The deviations in the radial behavior from the power-law type dependence are due to substructure within the halo, such as satellite dwarfs, and, to some extent, due to numerical noise.

The inner regions of the halo exhibit stronger torques (or equivalently shorter tilting timescales) than the outer parts, i.e., the inner disk should tilt faster. This is because the torquing force, which scales roughly as the density, increases more rapidly toward the centre than the disk's ability to resist the torque due to its angular momentum. Also note that the timescales are less than a Hubble time (indicated by the dotted lines) over much of the disk, so we should see the effects of these

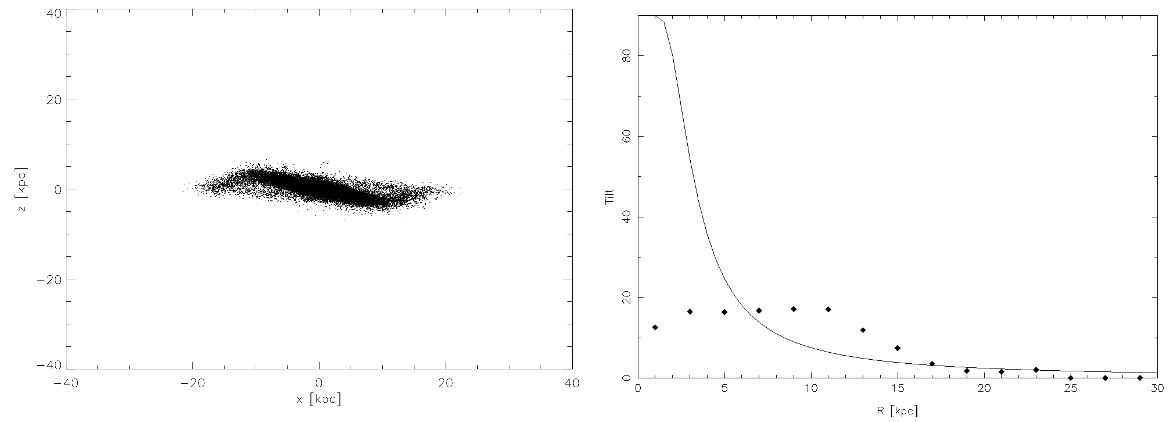

Figure 2: a) *(left)* Simulation of a disk galaxy with mass 3×10^{10} $M_\odot$ subjected to a typical cosmological torque for 1 Gyr. b) *(right)* Tilt of the disk from its original plane, computed in spherical shells of width 2 kpc. The solid line is the expected behaviour of a massless disk.

torques in a large number of observed galaxies, consistent with observational findings (Briggs 1990, Reshetnikov & Combes 1998).

3 Reaction of the Disk

We study the reaction of a disk to these torques by performing numerical N-body simulations of a massive Milky Way type galactic disk (maximum circular velocity $v_{\max} = 233\,\mathrm{km\,s^{-1}}$, scale length $r_d = 3.5\,\mathrm{kpc}$, vertical scale height $h_z = 325\,\mathrm{pc}$) subject to the torques found in section 2. Equilibrium disk models of disk mass 1×10^{10} $M_\odot$, 3×10^{10} $M_\odot$, and 5.6×10^{10} $M_\odot$ in a static spherically-symmetric NFW halo potential (Navarro, Frenk & White 1997) with concentration parameter $c = 15$ and a virial velocity of $v_{200} = 175\,\mathrm{km\,s^{-1}}$ are constructed using the method of Hernquist (1993). Each disk contains 16384 particles. The models were evolved using GRAPESPH (Steinmetz 1996) for 2 Gyr, which took 5000–7000 timesteps depending on the model. A plummer softening of 0.3 kpc has been used.

Figure 2a shows the simulation of a 3×10^{10} $M_\odot$ disk subjected to a torque for 1 Gyr. The disk was aligned with the xy-plane at $t = 0$. The inner part of the disk is flat and clearly tilted toward the positive x-axis. Beyond 11 kpc, the disk warps back toward the original plane. It distinctly resembles observed warped galaxies. The particles of the simulated galaxy were binned into spherical shells 2 kpc wide, and the minor axis of each bin was found from the moment of inertia tensor. Figure 2b plots the tilt angle of each ring from the initial plane of the disk. The flat region shows up clearly as the inner rings which are all tilted a uniform 17° from the initial plane, while beyond 11 kpc (the *warp radius*) the disk warps back toward the initial plane. A massless disk, in contrast, does not exhibit an inner flat region and is warped at all radii, as shown by the solid line in Figure 2b. The self-gravity of the massive disk maintains its flatness in its inner regions.

The warp radius r_w at which the warp starts, 11 kpc in the disk shown in Figure 2, is well-defined and can be followed over time. It coincides with the radius at which the difference between the tilt of the massive disk and the tilt of an equivalent massless disk is maximized, i.e. the data point that lies highest above the solid line in Figure 2b. As the disk evolves under the influence of the torque, this warp radius moves out through the disk at a rate that depends on the mass of the

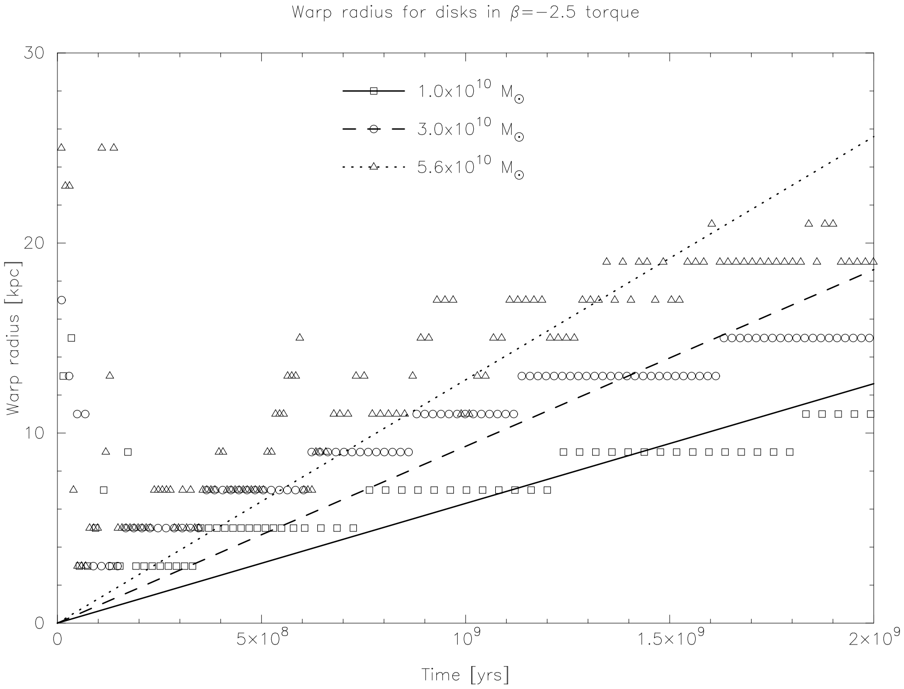

Figure 3: The symbols indicate the warp radius as a function of time for three disks of mass $1 \times 10^{10}\,\mathrm{M}_\odot$, $3 \times 10^{10}\,\mathrm{M}_\odot$ and $5.6 \times 10^{10}\,\mathrm{M}_\odot$ respectively. Because the particles were binned into spherical shells of width 2 kpc, the warp radii appear quantized. Lines are linear least square fits.

disk, as seen in Figure 3. The three sets of symbols represent simulations with disks of different mass. Warps move faster through higher mass disks than through lower mass disks.

The effect of the disk mass on the rate of warp growth implies that the self-gravity of the disk is important to the formation of the warp. In a massive disk, particles at different radii are coupled to each other gravitationally and act to keep the disk locally flat. This suggests that the crucial factor that determines where the warp develops is the local surface density of the disk. In fact, Ostriker & Binney (1989) examined the effect of a slewing disk potential on a set of self-gravitating rings and found that regions of high surface density react like a solid body, but that warps can occur where the surface density is lower. Hofner & Sparke (1994) noted that in most cases the group speed of bending waves in a disk of surface density $\Sigma(r)$ and angular rotation velocity $\Omega(r)$ is $c_g = \frac{\pi G \Sigma(r)}{\Omega(r)}$, and therefore the time for a warp to settle at a given radius is inversely proportional to the surface density at that radius.

To test this hypothesis, we translate the warp radii r_w of Figure 3 into local surface densities using $\Sigma(r_w) = \frac{M_d}{4\pi r_e^2} e^{-r_w/r_e}$ for a disk of mass M_d and exponential scale length r_e, and plot the surface density at the warp radius as a function of time for the three disks of different mass in Figure 4. The surface density at the warp radius falls as the warp moves out through the disk. Note that the local surface densities at the warp *at a given time* are quite similar for all models. It appears that the local surface density is the important parameter for determining the warp radius at a given time.

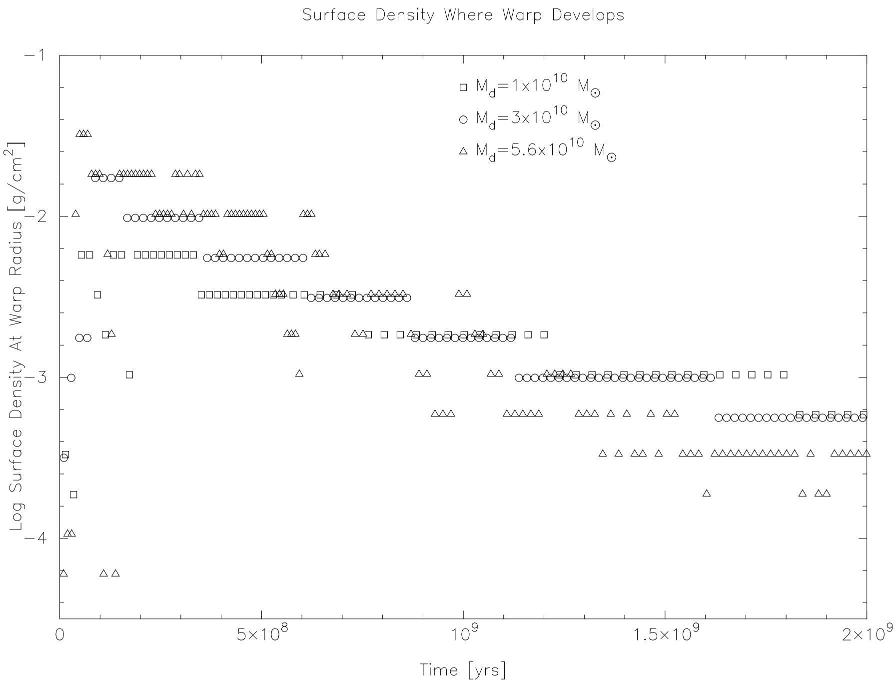

Figure 4: For the same simulations as in Fig. 3, we show the local surface density at the warp radius. As the warp moves out through the disk, the local surface density at that radius falls. The local surface density at the warp radius is similar for all models at each epoch.

4 Summary

Our conclusions are the following:

- Cosmological N-body simulations show that galactic disks are usually misaligned with the mass distribution of the dark matter halo in which they are embedded. Tidal torques are dominated by this misalignment and by asymmetries in the halo mass distribution, such as satellite dwarfs. The resulting radial dependence of the torque follows a power law of index -2.5. The gravitational torque is typically strong enough to tilt the disk by 1 radian in 1 to 10 Gyr. Torques from mass outside the halo appear unimportant.

- The tilting of the inner portions of the disk owing to the torque proceeds faster than that of the outer regions, resulting in a warped disk. The self-gravity keeps the inner regions of a massive disk locally flat.

- The radius inside which the disk is flat grows with time. More massive disks have faster-growing warps, mostly because only at large radius is the surface density sufficiently low that its self-gravity cannot maintain the flat disk.

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