Interactions between massive dark halos and warped disks

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Abstract. The normal mode theory for warping of galaxy disks, in which disks are assumed to be tilted with respect to the equator of a massive, flattened dark halo, assumes a rigid, fixed halo. However, consideration of the back-reaction by a misaligned disk on a massive particle halo shows there to be strong coupling leading to efficient damping (or in some circumstances excitation) of the misalignment, and hence the warp. We therefore discuss possible alternative explanations of the warp phenomenon, with emphasis on the effect of a responsive, gravitationally live massive galactic halo.

1. Introduction

The majority of large HI disks studied to date are warped: the plane of the gas tilts as a function of galactocentric radius (Bosma 1991). Furthermore, there are regularities to this warping: the inner parts of the disk (typically within \(R_{25}\)) are coplanar, then between this radius and the Holmberg radius the disk often warps with a common line of nodes, and then at yet larger radii the line of nodes tends to form a leading spiral (Briggs 1990). The HI layer of the Milky Way is known to be warped as well: while its amplitude is small (ca. \(5^\circ\) maximum tilt, Burton 1988), it follows the same pattern out to a radius of \(1.5R_0\). At larger radii, however, the plane is no longer simply tilted, but distorted: the outermost HI in the Milky Way disk is displaced towards the NGP by about 1 kpc. Several other examples of regular and irregular warps exist.

As with spiral structure, warps present a winding problem: because of differential precession of bending wave packets at different radii, large-scale bending waves in a galaxy disk will soon wind up, in conflict with the observed straight line of nodes for the inner regions of the disk. In this case, also, self-gravity of the disk has been invoked as a mechanism for halting the differential winding. Sparke & Casertano (1988), building on the work of Hunter & Toomre (1969), showed that a disk in the equator of a flattened halo could support standing bending waves provided the disk was not too extended, or the halo too flattened. [Isolated cold disks are not able to support such waves: unless the disk surface density \(\Sigma\) is truncated at the outer edge of the disk such that \(\Sigma(R) \propto (R_{\text{out}} - R)^\alpha\) with \(\alpha < 1\), bending waves will slow down and dissipate before reaching the edge and being able to reflect off it.]

The Sparke & Casertano modes are large-scale, global modes of the disk, which makes it instructive to step away from the local WKB approximation and to consider the dynamics of the entire system. This can be done most easily
by considering a galactic disk as consisting of a collection of concentric spinning rings, able to tilt with respect to each other, and moving in the combined gravity field of the other rings and a surrounding massive halo. It can be shown that a set of stars on initially circular orbits behaves in the same way as such a ring under the action of torques. Such a system is clearly in equilibrium when all the rings are co-planar, and moreover, if the halo is spherical, a new equilibrium is obtained when all rings are tilted through the same angle. Sparke & Casertano recognised the normal modes they calculated as a continuation of this trivial mode to non-spherical halos. The halo exerts a net torque on the disk once it is tilted, causing an overall precession of the spin axis of the disk; and by allowing the disk to warp, the precession speeds of the rings can all be adjusted to that same common value. [Rings which would naturally precess more slowly than the overall pattern need to be further from the halo equator, so that the torque on them can be augmented by the gravity of the remaining, less-inclined parts of the disk.] The precession speed \( \Omega_p \) of the pattern is also simply obtained as the ratio of the torque exerted by the halo (with circular \& vertical frequencies \( \Omega_H(R) \) and \( \nu_H(R) \)) to the spin of the disk (given by the total angular velocity of the disk matter \( \Omega(R) \)):

\[
\Omega_p = \frac{\int dRR^3 \Sigma(R) (\Omega_H^2 - \nu_H^2)}{\int 2dR\Omega(R)R^3 \Sigma(R)}
\]  

(1)

The numerator in this expression is the overall torque from the halo experienced by the disk if it is inclined by unit angle, and the denominator the torque exerted by the coriolis force in the frame rotating with the precession frequency of the mode \( \Omega_p \). The balance as a function of radius of the coriolis and halo torques determines the shape of the warped equilibrium. If the coriolis torque dominates over most of the disk, the warp will be away from the halo equatorial plane (type I in SC’s notation), otherwise the outer parts of the disk will warp down towards the halo equator (type II).

The linear analysis of Sparke & Casertano can be extended to non-linear tilt amplitudes (Kuijken 1991): such calculations reveal that realistic amplitudes can indeed be attained with models of this kind, though the maximum amplitude of the type I warps is rather small.

2. Back-reaction on the halo

A possible worry (Toomre 1983; Binney 1992) is that the halo has been assumed to be a fixed ‘potential bath’ for the disk to precess in. At least, this assumption violates conservation of angular momentum of the system as a whole, unless the halo is considered to have an infinite moment of inertia. More crucially, if real dark halos are stellar dynamical entities, they will respond to gravitational fields on dynamical time scales, and in particular the central regions of a halo may be expected to respond to the disk precessing through it.

Typical precession speeds for a SC normal mode are \( \Omega_p \sim -\epsilon V_c/R_d \), where \( V_c \) and \( R_d \) are the circular speed and half-mass radius of the disk and \( \epsilon \) is the flattening of the halo potential; for typical halo flattenings of 0.1 (much smaller amplitudes will not generate warps of the observed amplitudes) the precession
of the disk might be expected to provoke a significant response of the dark halo at radii inside $10R_d$.

The importance of this back-reaction may be assessed in two ways: either by considering the effect of the precessing disk on halo orbits, from which a first-order halo over-density (and hence the gravitational effect of this over-density, or wake, on the disk precession) can be derived; or from numerical simulations, which give fully self-consistent, but less general, results. The first approach has been taken by Nelson & Tremaine (1995), and the second approach by Dubinski & Kuijken (1995). Results agree: the effects of halo response to the disk precession are strong, operating on the dynamical time-scale of the halo. As a consequence, halos cannot be viewed as rigid background sources for a torque, but it is essential to view the disk-halo system as one, coupled, whole.

A representative numerical simulation of the evolution of a tilted, precessing disk in a flattened halo is illustrated in Figure 1. Even though initially the precession is set to agree with the SC formula, the halo responds quickly to the misaligned disk, and the inclination of the disk with respect to the halo decays before the disk has been able to complete a single precession. Since dynamical times are longest in the outer parts of the system, the disk-halo alignment spreads outwards, completing on ca. 3 local orbital times. Responsive dark halos appear unable to support the warp modes envisaged by SC. Inaccuracies in the N-body simulations are not the cause of this finding: when the disk particles are replaced by a solid, spinning disk whose dynamics are followed with the Euler equations the same result is found, whereas keeping the halo particles fixed in space and only allowing the disk particles to evolve in the passive halo yields the long-lived normal mode predicted by SC.

Nelson & Tremaine (1995) derive slightly longer time-scales from their analytic work, presumably because the self-gravity of the halo response is not included in their calculations. Their calculations also show that radially anisotropic velocity dispersion in the halo (a plausible consequence of a collapse formation for the halo) lead to faster damping than isotropic velocity ellipsoids. Interestingly, they find that under certain circumstances bending can be excited rather than damped by the halo, on similarly short time-scales: this can occur when the halo is prolate (i.e. the disk lies perpendicular to the longest halo axis), or the halo rotates retrograde to the disk. The prediction for excitation in counter-rotating halos has since been verified by Dubinski & Nelson (in preparation) with N-body simulations. In any case, only under very special circumstances can a misaligned, precessing disk survive for a large number of dynamical times in a dark halo.

3. **Alternative explanations**

Given the problems for the normal mode theory, we are still left lacking an explanation for this common phenomenon of disk warping. Promising avenues to possible explanations include:

3.1. **Accretion (Ostriker & Binney 1989; Binney 1992)**

If isolated galaxies are unlikely to be able to sustain warps for very long, interaction with the environment perhaps offers a solution. In closed or critical-density
Figure 1. N-body simulation of a stellar-dynamical disk in a live, non-rotating particle halo (Dubinski & Kuijken 1995). Only disk particles are shown. The precession of the disk is rapidly halted as a result of the halo aligning with the disk, showing that the warp modes derived assuming rigid background halos in fact are damped on dynamical time-scales.
universes, galaxies continue to accrete matter from ever-larger distances as time goes on. Tidal torquing between different collapsing galaxies will give this infalling material some non-zero angular momentum, and as this material merges into the dark halo, the changing angular momentum will probably result in some realignment of the halo axes. The time-scale for this realignment is set by cosmology, and is probably close to the Hubble time.

How will a disk respond to such realignment? If the disk were rigid, it would certainly change its orientation under the influence of the changing tidal halo field it was experiencing. In reality, disks are floppy, with different natural precession frequencies at different radii, so this overall disk slewing will be accompanied generically by warping.

3.2. Equipartition with a lumpy halo (Nelson & Tremaine 1996)

The energy associated with a warp mode excited to realistic amplitude is found to be comparable to the orbital energy of a massive globular cluster in the halo. If there is sufficient time for equipartition to be established, and if the halo is dominated by object in this mass range, then statistical physics dictates that warps will have to be excited stochastically to observed amplitudes. The main argument against this possibility are the standard ones against halo objects of such high mass: they would also strongly heat the stellar disk. Furthermore, if the microlensing results reported by Freeman at this conference are to be believed, halo objects have much smaller masses.

3.3. Forcing by satellites (Weinberg 1995)

M. Weinberg recently showed that the resonant response of the Milky Way halo to the orbiting Magellanic Clouds raises sufficient tides in the halo to have a noticeable effect on the stellar disk; moreover, it does not take excessively high estimates for the mass of the LMC to obtain the observed amplitude for the Milky Way’s warp. This result highlights the importance of self-consistent treatment of the halo response to perturbations, and the strength of coupling of a wake raised at large radius to the inner regions of the halo. (Weinberg’s model for the halo is a scalefree isothermal halo, but the same gravitational propagation of the response to smaller radii would be expected in other halo models too). As a ubiquitous explanation for warps, this work may be criticized on the grounds that not all warped galaxies have satellites as important as the LMC, and that while the warp of the Milky Way is rather low-amplitude compared to other examples, the mass of the LMC is quite possibly lower than assumed by Weinberg’s calculations. Nevertheless, this striking result is a vivid reminder of the importance of collective and resonant effects in galaxy interactions.

3.4. Halo-enhanced tides

If not all warped galaxies have companions which may have distorted them, perhaps infrequent passages by other galaxies may raise sufficient tides in the halos to warp the disks noticeably. A very naive model (see Fig. 2) shows that such an effect might be important: consider a galaxy as made up of a massive, spinning inner disk, and a surrounding dark halo which we here model as a rigid, possibly spinning, concentric ring surrounding it. If we now tidally perturb such a galaxy with a distant passage, what will happen to the system? Assuming all
Figure 2. A simple two-component galaxy, consisting of a spinning, rigid central disk, and a flattened halo, here represented by a massive outer ring.

Tilt angles are small, it is possible to show that the dynamics of symmetry axes of the disk and surrounding ‘halo’ are governed by the equations

\[
\begin{align*}
\ddot{x}_d &= -S_d y_d + C m_h (x_h - x_d) \\
\ddot{y}_d &= S_d x_d + C m_h (y_h - x_d) + T(t) I_d \\
\ddot{x}_h &= -S_h y_h + C m_d (x_d - x_h) \\
\ddot{y}_h &= S_h x_h + C m_d (y_d - x_h) + T(t) I_h.
\end{align*}
\]

Here \((x_d, y_d)\) and \((x_h, y_h)\) are the orientations of the polar axis of the disk and halo, where \(x_d = \theta_d \cos \phi_d\), etc. for spherical polar coordinates \((\theta_d, \phi_d)\).

The coefficient \(C\) expresses the gravitational coupling between the halo and the disk, \(T(t)\) is the strength of the tidal torque (the perturber is assumed to move uniformly along the \(z\)-axis), and \(I_d\) and \(I_h\) are the moments of inertia of disk and ‘halo’.

In the absence of the halo \((C = 0)\), the disk will respond to the tidal field, and execute a small precessing motion. After the passage is over, overall energy and angular momentum conservation of the disk return it in its original state. [A real disk would warp during the reaction to the tidal field, but eventually the bending waves would dissipate and the disk would return to its original orientation.] However, if we include the coupling between the disk and the halo, the result becomes very different. The halo, having a larger radius and a smaller spin than the disk, responds more strongly to the tidal field than the disk. As it tilts, however, it exerts its own tidal field on the disk, and, because of the halo’s proximity to the disk, this field is stronger than the external one. The net result is that the halo mediates the external field, and transmits it onto the disk more strongly than the original one. Depending on the rotation of the halo, this
response is stronger or weaker: simple numerical experiments with equations (5) show that a factor of five enhancement is not difficult to attain (Fig. 3).

Less drastically simplified models of the halo give comparable results (Lynden-Bell 1985; see also Nelson & Tremaine 1996).

4. Summary and Conclusions

The phenomenon of warps, affecting many disk galaxies, continues to puzzle. The promising Sparke-Casertano model that warps reflect a long-lived misalignment between a disk and a flattened massive halo appears to fail once the response of the halo to the precession of the disk is taken into account (Nelson & Tremaine 1995; Dubinski & Kuijken 1995), leaving us to search for other possibilities. Perhaps the answer lies in magnetic generation of warps (Battaner et al., 1990; see Binney 1991 for a critical discussion of this possibility), but other gravitational possibilities remain. In this article, I have tried to stress the point that the dark halo should be considered an integral, dynamical part of the galaxy, rather than just a potential energy bath. With the discovery by Weinberg (1994) that spherical models can undergo very weakly damped modes, goes the implication that once disturbed, halos can ring for a large number of dynamical times, forcing oscillations and warps in embedded galaxy disks. Combined with the enhanced excitation of tides on the disk by the halo, perhaps most galaxy warps are such weakly-damped, tidally induced ringing?

How can these ideas be tested further?
We still lack a clear observational study of the statistics of warps. In particular, it would be good to know how regular warps are, if there is any relation between warps and bars, warps and lopsidedness, kinematic peculiarities and warps, links with environment, etc. On the theoretical side, simulations of some of the suggested scenarios would be very useful: in particular, the details of the response of the halo, and hence the disk, to secondary infall are difficult to predict and would benefit from such a study.

It is clearly not yet time for warps to stop challenging people’s minds!

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