GALACTIC WARPS IN TILTED HALOS

Avishai Dekel
Caltech and Yale University

Izhak Shlosman
Tel-Aviv University

The current suggestions for the origin of warps in disk galaxies (see Toomre, this volume) find difficulties in explaining their frequent occurrence and an external driving mechanism seems to be required in order to maintain long-lived warps. Such a mechanism can be provided by an extended dark halo if a) it dominates the gravity at large radii while the inner disk is self-gravitating, b) it is slightly flattened and becomes flatter at larger radii, and c) it is tilted relative to the inner disk. Such a configuration may be formed as a result of tidal encounters, or of clouds infalling into halos.

Assume that the halo is oblate with its minor axis tilted relative to the disk, and consider test circular orbits. They precess about the local Laplace plane, where the external torque vanishes, which determines the mean shape of the system. It coincides with the disk plane at small radii while merging into the equitorial plane of the halo at large radii. An analogous problem is well known in celestial mechanics: the orbits of moons and rings deviate from the equitorial planes of their planets towards the ecliptic because of the torque exerted by the sun.

Toomre has considered the simple, but illustrative, case of a tilted massive ring. A detailed study that considers realistic halos is in progress from which results are briefly described here. The shape of edge-on warps in two disk-halo systems is shown in figure 1. The disk is thin and has an exponential surface density profile with a length scale r_d = 5, 3 kpc in a and b respectively, and a mass M_d = 15, 6 x 10^{10} $M_\odot$. The halo has a $1/r^2$ density profile with a core length scale r_h = 15, 18 kpc, and a mass of 10, 8 x 10^{11} $M_\odot$ inside 60 kpc. The eccentricity of the halo must grow with radius. Otherwise, there is no torque exerted by external shells on the inside. In figure 1 the eccentricity $e = [1 - (\text{axial ratio})^2]^{\frac{1}{2}}$ grows with the radius as a power law with a power 0.8, starting from e = 0.2 at 5 kpc. The relative tilt is 15°, which is comparable to the extreme observed cases (e.g. NGC 5907).

The gravitational potential is calculated analytically for discrete shells. Equipotential contours are plotted (dashed line). The warped

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 187–188.

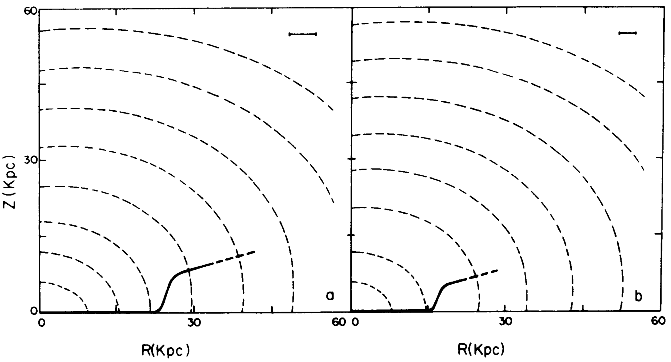

Figure 1. Edge on warps in tilted disk-halo configurations.

Laplace plane (thick line) is determined by the minima of the potential at given radii. The deviation from the disk plane occurs quite abruptly, and the Laplace plane coincides quickly with the halo equitorial plane, in agreement with the geometry of observed warps (see Bosma and Sancisi in this volume). The general shape of the warp is insensitive to the detailed structure of the disk or the halo. The radius at which the warp occurs is mostly determined by r_h/r_d.

The crucial point is that the survival time of the tilted disk-halo configuration can be comparable to the Hubble time. Assume a simple case in which the halo potential has only a monopole component and a smaller quadropole component of the form $\phi_2(r)P_2(\cos\theta)$. A circular orbit (r, v) initially in the disk plane (inclination i between halo and disk) will precess about the halo equitorial plane with an angular frequency $\omega_p = -3\phi_2(r)\cos i/2vr$. Except for the special case $\phi_2(r) \propto v(r)r$ the precession tends to be differential, but in fact the disk would precess as a rigid body out to a few length scales because of its self-gravity: the torque exerted by the disk on a particle slightly out of its plane is dominant over the torque exerted by the halo out to > 5 r_d in the realistic cases studied. The disk precession rate can be estimated at the giration radius r_g ($=\sqrt{6}r_d$ for an exponential disk), and is slower than the rotation rate there by a factor of $\sim \epsilon_\phi(r_g)$, where $\epsilon_\phi = 3\phi_2(r)/2v(r)^2$ is the ellipticity of the equipotential surface at r. If $\epsilon_\phi \lesssim 0.05$ at $\sim$10 kpc the precession rate is of the order of the Hubble time. In the case shown above $\epsilon_\phi \cong 0.04$ at 10 kpc.

As a result of the precession of the disk inside the halo they exchange angular momentum and suppress their mutual tilt. In a Hubble time, the disk may affect the tilt of the inner halo only out to $\sim$10 kpc. The disk tends to settle down in the halo equitorial plane as a result of dynamical friction. Our analytical study of the interaction between a rigid precessing disk and a family of simple halo orbits shows that the time scale for the tilt dampening is longer than the precession time scale. Preliminary results from an N-body experiment confirm the analytical estimate, demonstrating the fact that the life time for a disk-halo tilt is indeed very long (Shlosman, Gerhard and Dekel 1983, in preparation).