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WHAT IS THE WARP'S FAVORITE HALO ?

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Abstract. Since the first HI observations of the Milky Way warp 50 years ago, numerous hypotheses have been proposed to explain this galactic common phenomenon. While actually most of the works on warps are based on the assumption of a disk embedded in a dark matter halo, the possibility of a heavy self-gravitating disk is often neglected. The aim of this paper is to better understand the constraints imposed by the shape of the dark component on the dynamic of the warp. Two set of simulations have been performed. The first one is based on a traditional dark matter halo, while the second one uses a heavy flaring self-gravitating disk.

1 The Models

1.1 The components

In order to highlight the influence of the shape of the dark matter, we have tried to construct two N-body models, differing from each other only by the dark matter component. Both models are composed of a stellar exponential disk and an oblate nucleus-spheroid. The third component represents the dark matter.

In the first model, the dark matter is distributed in an exponential halo where the dark matter mass is 5 times the optical disk and thus the self-gravitation of the latter is not completely negligible.

In the second model the dark matter lies in a heavy disk (Pfenniger et al. 1994). As it has been observed by Bosma (1981), Carignan et al. (1990) or Broeils (1992), in samples of galaxies, the ratio between the dark matter and HI surface density is roughly constant well after the optical disk. These observations suggest that the dark matter follows the HI distribution along the disk. The heavy disk has been modeled by the following density distribution:

$$\rho_{\rm dm}(R,z) \sim \frac{e^{-\frac{R_{\rm dm}}{R}}}{R}\,\frac{e^{-\frac{|z|}{h_z(R)}}}{h_z(R)}\,\arccos\left(\frac{R}{R_{\rm dm}^{\rm max}}\right)\,, h_z(R) = h_{z0}\,e^{\frac{R}{R_{\rm f}}} \qquad (1.1)$$

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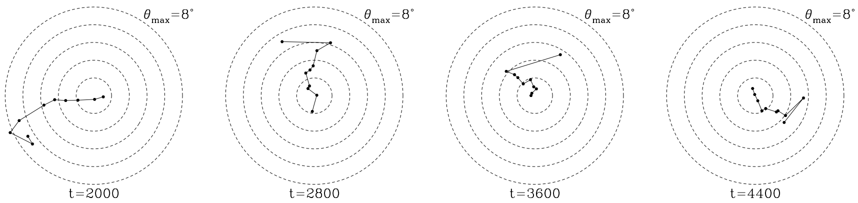

Fig. 1. Evolution of the warp in the halo, from $t = 2000$ to $t = 4400$ Myr.

with $R_{\rm dm} = 5$ the horizontal scale length, $R_{\rm dm}^{\rm max} = 50$ the cutoff radius and $h_z(R)$, the variable vertical scale length ($h_{z0} = 0.025$ and $R_{\rm f} = 15$). This latter is used to reproduce the flaring observed in the HI (Burton 1992). The mass of the dark matter component is about 3 times the optical disk.

In order to get a warp, each N-body model is embedded in a non-rotating warped potential. The potential, calculated with a grid code, is a deformation of the potential of the initially flat galaxy. The warp is obtained by adding a term in the vertical coordinate : $z \rightarrow z - wR^2 \cos\phi$, where ϕ is the azimuthal angle and w, the warp parameter. To warp adiabatically the galaxy, the outer potential is flat at $t = 0$ and warps slowly as function of time, rising the maximum deformation at $t = 1200$ Myr. Particles are driven by the potential and the warp is comparable to the Milky Way's one. The outer potential is then removed and the galaxies evolve freely.

2 Evolution of the warp

In order to determine the characteristics of the warp, we have decomposed each galactic disk in a family of concentric rings. The evolution of the warp is then followed by the evolution of these rings in *tip-LON* plots (Briggs 1990), which are polar projections of the normal vector defining each ring.

2.1 Evolution of the disk in the halo

At the end of the perturbation, the halo has rotated by an angle of about 15° from it's initial direction and the warped disk is tilted by 8° compared to the halo. The misalignment between the halo and the disk angular momentum will cause the disk to precess around the halo angular momentum. Because of dynamical friction, the amplitude and the period of the precession decreases slowly. After $t = 5$ Gyr the disk is still misaligned by about 2°. Fig. 1 shows the evolution of the warp during the precession. The pronounced warp at $t = 2000$ decreases very slowly. 4 Gyr after the perturbation, the warp is still observable ($z_w \cong 0.5$ kpc at 20 kpc). Moreover, the line of nodes (LON) is kept straight at every time and it seems that the disk precesses as a rigid body.

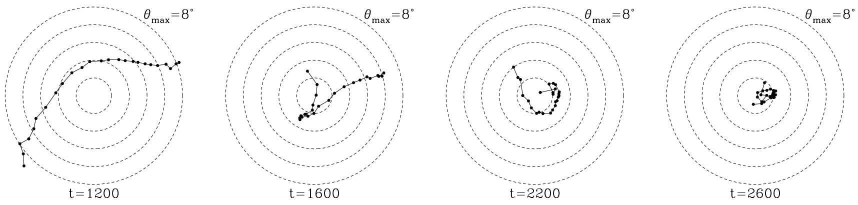

Fig. 2. Evolution of the heavy warped disk, from $t = 2000$ to $t = 4400$ Myr.

2.2 *Evolution of the heavy disk*

In order to better understand the dynamic of the disk, the *tip-LON* plots are calculated from the privileged reference frame defined by the total angular momentum ($\vec{L}_t$) of the galaxy. At $t = 1200$ the warp is well pronounced and its LON is straight until about 30 kpc where it turns anti-clockwise. At $t = 1600$ the LON forms a hairpin around $\vec{L}_t$ meaning that the rings between 20 and 40 kpc are quasi aligned around $\vec{L}_t$. This flat region grows inward and feeds the central parts with a winding LON. At this stage, seen from the central part, the galaxy is flat until 30 kpc and warps steeply outward. The remnant LON is straight. At $t = 2600$ the disk has extended until the edge of the galaxy and the warp has disappeared.

3 Discussion

In the halo-disk model, the misalignment of the disk and the halo angular momentum causes the disk to precess and allows the warp to be long lived ($\cong 4$ Gyr), keeping a straight LON. But such a halo imposes a uniform dynamic over a large scale. The warp is regular along the galaxy. This is not any more the case with a heavy disk which allows fluctuations like wiggles or elbow often observed in warped galaxies (Briggs 1990; Jones et al. 1999). But the relative short life time of its warp ($\cong 800$ Myr) imposes that it should be continuously generated. This can be the case if, for example, the galaxy is fed through accretion events. Finally we will mention that in both models it appears that the total angular momentum is a dominant value which will strongly influence the evolution of the warp.

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