A NEW SCENARIO FOR THE ORIGIN OF GALACTIC WARPS

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Abstract
Galactic warps represent an old unresolved problem, since the discovery, at the end of the fifties, of the HI warp of the Milky Way. In this paper, we propose a new scenario explaining a large fraction of the observed optical warps. Based on N-body simulations, we show that realistic galactic disks, where the dark matter is essentially distributed in a disk, are subject to bending instabilities. S-, U-, and asymmetric warps are spontaneously generated and in some cases are long-lived. While this scenario presents the advantage of explaining the three observed types of warps, it also brings new constraints on the dark matter distribution in spiral galaxies. Finally, it gives us a unified picture of galaxies where galactic asymmetries, like bars, spirals and warps result from gravitational instabilities.

Keywords: galactic dynamics, warps, dark matter

1. Why do disk galaxies have often spirals and warps?

Here we propose that the fundamental reason why spiral galaxies present frequently warps is identical to the one why spirals have frequently spiral arms and bars: the dissipational component, gas-dust, brings these systems toward a critical state with respect to gravitational instabilities, producing spiral arms and bars in the radial direction, and warps in the vertical direction. As long as gas dissipates the dynamical reheating induced by the instabilities compensates the cooling due to radiative losses in the gas. The critical state is maintained and disk galaxies remain very responsive to perturbations.

In such conditions any perturbations, be it gas infall or interactions, trigger large and long-lived responses of the disks in the form of grand design spirals
or large warps. Thus while external perturbations help galaxies to produce spirals and warps the fundamental cause why the disk response is large and slow lies in the marginally stable state of such systems reached by the secular energy losses.

Consistent with this scenario is that gas poor disk galaxies, such as S0’s possess typically only small, tightly wound spiral arms, and warps are rare. When too little gas is left it is unable to regenerate gravitational instabilities.

The interesting by-product of such a scenario is that the matter content of galaxy disks is then constraint. Several observational results, like spiral structures in HI disks (Masset & Bureau, 2003), dark matter and HI correlation (Bosma, 1978; Hoekstra et al., 2001; Pfenniger & Revaz, 2005), star formation in low gas density regions (Cuillandre et al., 2001) and more recently, diffuse gamma-rays in the Galaxy (Grenier et al., 2001) suggest that dark baryons are in galactic disks associated to HI and classical molecular clouds. A substantial amount of matter in the disks would therefore explain many aspects of disks galaxies, and in passing warps.

Bending instabilities are Jeans like gravitational instabilities that occur in flat systems and cause them to warp. Toomre (1966) and Araki (1985) have shown that an infinite slab of finite thickness may be unstable when the ratio of the vertical velocity dispersion $\sigma_z$ to the velocity dispersion in the plane $\sigma_u$ is less than 0.293 (This value is called the Araki limit). In this work we use N-body simulations to quantify the effects produced by bending instabilities in self-gravitating disks of different thicknesses, and to quantify the amount of matter that bending instabilities require in the disk in order to be unstable, and the amount of matter that is left in the halo up to the disk radius.

2. The heavy disk model

We have studied the spontaneous formation of warp resulting from bending instabilities in 9 different galactic models. All mass model are composed of a bulge, an exponential stellar disk ($H_R = 2.5$, $H_z = 0.25 \text{ kpc}$) and a heavy disk made of HI gas and dark matter proportional to it. With a respective mass fraction for the 3 components of 0.068, 0.206, 0.726 the rotation curve is approximately flat up to $R = 35 \text{ kpc}$. The 9 models differ only by the thickness $h_z$ and flaring $R_f$ of the dark matter component.

The initial vertical velocity dispersion $\sigma_z$ is found by satisfying the equilibrium solution of the stellar hydrodynamic equation in cylindrical coordinates, separately for each components. To set the azimuthal and radial dispersions, we have used the epicycle approximation and the ratio between the radial and vertical epicyclic frequency $\kappa$ and $\nu$. See Revaz & Pfenniger (2005) for more details on the models.
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All models (from 01 to 09) are displayed on Fig. 1, where the ratio $\sigma_z/\sigma_R$ (stability index) is plotted as a function of the vertical dispersion. This latter value gives an idea of the disk thickness. Thin disks are found at lower left end while thick disks are found at the upper right end. The dotted line corresponds to Araki’s stability criterion $\sigma_z/\sigma_R = 0.293$. We thus expect that thinner disk will be less stable.

![Figure 1](image-url)

Figure 1. Ratio $\sigma_z/\sigma_R$ as a function of the vertical dispersion $\sigma_z$ at $R = 15$ kpc. The values are taken at the radius where $\sigma_z/\sigma_R$ is minimum. The dotted line corresponds to Araki’s limit.

3. Stability as a function of the disk thickness

As expected from Fig. 2., the evolution of the models depends strongly on the thickness of the heavy disk. According to their evolution, the models can be divided in four groups:

1) Model 01 has a ratio $\sigma_z/\sigma_R$ of 0.18. It is very unstable. The bending instability occurs quickly and generates a transient asymmetric warp that extends up to $z = 4$ kpc at $R = 35$ kpc (see Fig. 2(a)). After the perturbation the disk is thickened and the galaxy is stabilized.

2) Models 02, 07 and 03 have still a ratio $\sigma_z/\sigma_R$ well below the Araki limit. The bending instability occurs during the first 2 Gyr. An axisymmetric bowl mode $m = 0$ (U-shaped warp) grows during about 1 Gyr (Fig. 2(b)), before that $\sigma_z$ increases and stabilizes the disk.

3) The four models 08, 04, 09 and 05 develop S-shaped warped modes ($m = 1$). Except model 05 which has a ratio $\sigma_z/\sigma_R = 0.3$ just above Araki’s limit, all are unstable with respect to a bending. In the case of model 08, the warp is long-lived and lasts more than 5.5 Gyr, corresponding to about 5 rotation times at $R = 30$ kpc (Fig. 2(c)).

4) Model 06 has a ratio $\sigma_z/\sigma_R$ well above 0.3. The model is stable.

These simulations show that the bending instability in heavy disk model may be at the origin of the 3 observed type of warp: S-shaped, U-shaped and
asymmetric. The high frequency of observed S-shaped warps (Reshetnikov, 1998) is naturally explained because S-shaped warps develop near the Araki limit (marginally unstable regime) and then are long lived.

4. Dark matter constraint

The previous results have been obtained in the absence of a dark halo. We have checked up to which point the disk self-gravity leads to bending instabilities when the disk is embedded in a conventional hot halo.

For a realistic model, where a fraction \((1 - f)\) of the dark matter has been transferred into a halo, the vertical instabilities are damped if more than half of the dark matter is in the halo \((f < 0.5)\). On the contrary, the disk may be unstable.

When taking into account the dissipational behavior of the gas, as this is the case in the plane for spirals, the disk is expected to reach a marginally unstable regime at the Araki limit corresponding to \(f = 0.5\) in our model. We can then deduce, that half of the dark matter is situated in the disk and the other half in the halo. The flattening of our model is then in agreement with the flattening of the Milky Way, recently determined by Johnston et al. (2005) based on the study of the Sagittarius orbit.

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