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Non-Keplerian rotation curves derived from simulations of warped galaxies

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Abstract. In this work we present Monte-Carlo simulations of warped galaxies using the tilted-ring model in order to investigate the effects these spatial distortions cause on the velocity fields of discoidal galaxies. Based on this we evaluated the rotation curves extracted by an observer who ignores the effects of the warps to interpret the observed velocity fields. We defined three different parameters to quantify the effect of the warps on the observed rotation curves. The distribution of these parameters in our simulations reflects two main components from which we are able to separate the conditions when warps effects dominated on the velocity fields, causing, consequently rising, constant and decreasing rotation curves, including sub-keplerian rotation curves.

Resumo. Neste trabalho nos apresentamos simulações Monte-Carlo de galáxias com warp utilizando o modelo de anéis deslocados com o objetivo de investigar os efeitos que estas distorções provocam nos campos de velocidades de galáxias discoidais. Baseado nisto nós determinamos curvas de rotação extraídas por um observador que ignora os efeitos dos warps para interpretar os campos de velocidade observados. Nós definimos três parâmetros diferentes para quantificar o efeito dos warps nas curvas de rotação derivadas. A distribuição destes parâmetros em nossas simulações refletem duas componentes principais, a partir das quais nós podemos separar as condições quando os efeitos dos warps dominam no campo de velocidades, gerando consequentemente curvas de rotação crescentes, constantes e decrescentes, incluindo curvas de rotação sub-keplerianas.

Keywords. Galaxies: kinematics and dynamics – Galaxies: structure – Method: numerical

1. Introduction

Warps are systematic deviations from the mid-plane of a discoidal galaxy that becomes more accentuated in their outermost regions. Although warps are difficult structures to be detected, they are present in our own galaxy (Chen et al 2019) and in over 35% of discoidal galaxies (Reshetnikov et al. 2016). In spite of these distortions the disk component is still dominant and the rotation curves are the main resources to evaluate the masses of discoidal galaxies. However it is hard to observe warps in no edge-on galaxies, and their presence is only marginally inferred from their velocity fields (Briggs 1990).

2. Objective and Methods

The objective of this work is to build tilted-ring models of warped galaxies based on the observations of edge-on galaxies and evaluate the effects that these distortions would cause on the observed rotation curves using Monte-Carlo simulations.

Using the tilted ring model we need to define the following parameters (Fig. 1 (a), (b)): the number of rings (n), the angular displacement of each ring relative to the mean plane (wa), the azimutal angle relative to the line of nodes of warp (θ_w) and the radial profile of the warp ($wa(r)$).

1. Warp angle: First we studied in the literature the frequency, the magnitude of the warp angle and the distribution of such angles. The main reference to this subject was the work by Reshetnikov et al. (2016)).
2. Warp Profile: It measures the warp angle as a function of the radius. Since warps present a smooth variation along the radius we describe it as a low order polynomial. Using the number of rings and the maximum warp angle it can be written as:

$$wa_n = \arctan\left((n/n_{max})^2 \cdot \tan(wa_{max})\right) \quad (1)$$

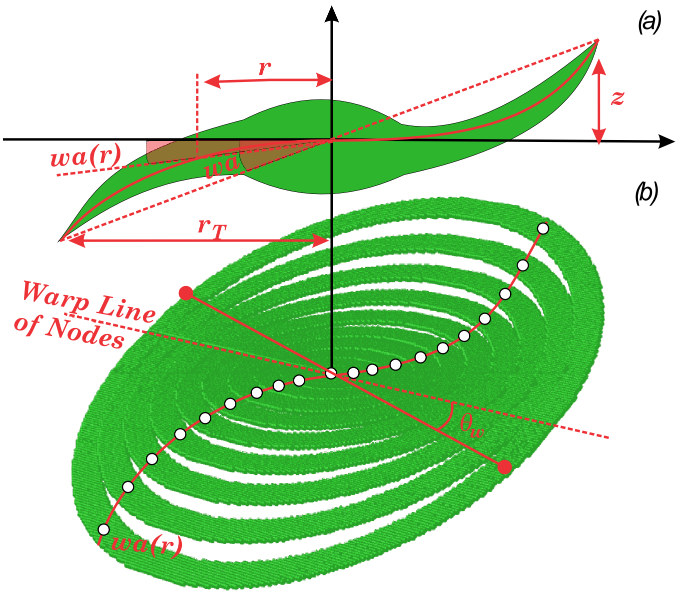

Figure 1. Geometrical representation of the model parameters based in Rogstad (1975). (a) Profile. (b) Perspective.

3. Projections: In the tilted-ring model, the rotation velocities follows the plane of each ring. For this reason, each point of the rings has a distinct projection in the sky plane and the velocities (related by differentiation) are projected in the line of sight depending of the warp parameters following:

$$\begin{pmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{pmatrix} = \begin{pmatrix}-\dot{x}_w \sin\phi - \dot{y}_w \cos\phi\cos i - \dot{z}_w \cos\phi \sin i\\ \dot{x}_w \cos\phi - \dot{y}_w \sin\phi\cos i - \dot{z}_w \sin\phi\sin i\\ \dot{y}_w \sin i + \dot{z}_w \cos i\end{pmatrix} \quad (2)$$

where, i and ϕ are respectively the overall galaxy inclination and position angle, the therms $\dot{x}$, $\dot{y}$ and $\dot{z}$ are the velocities projected in coordinate system fixed in the main plane of the galaxy, while the same therms with a "w" index are relative to the same components measured in each ring. So the therm $\dot{z}$ is the line-of-sight velocity.

3. Results, Discussion and Conclusions

In order to evaluate the effects of the warps on the rotation curves we simulated the observation of galaxies with keplerian rotation curves, respecting the warp parameters in Figure 1, a constant line of nodes of warp and random inclinations (i), position angles (ϕ) and line of nodes of warp angles.

Since in the simulations we are able to separate the components of the warps we can rebuild the contribution of the warps in the velocity fields to interpret the observed rotation curves (Fig. 2).

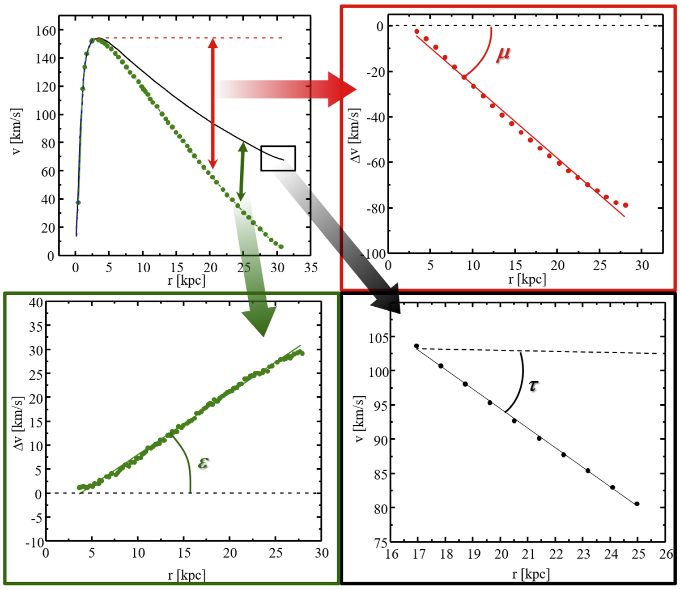

FIGURE 2. Definition of the parameters τ, ε and μ.

Based on comparisons between the observed and the inserted rotation curves we defined three parameters: τ, which is the angular coefficient of the linear fit over the last 10 points of the rotation curve. It allow us to verify if the observed rotation curve is subkeplerian, constant or superkeplerian; ε that represents the angular coefficient of the linear fit on the differences between observed and inserted rotation curves. It provides us a way to analyze the effect of the warps relative to the inserted rotation curve; and μ, that provides the angular coefficient obtained from the linear fit on the differences between the observed and a constant rotation curve based in the maximum of the inserted rotation curve. With this it is possible to compare the effects of the warps relative to the constant rotation curve (see Fig. 2).

Using Monte-Carlo procedures and the criteria presented in section 2 we compiled 5000 set of observations simulating an observer who extracts the rotation curves following the traditional procedures by Begeman (1987), but ignores the effect of the warps on the rotation curves. We measured then the parameters τ, ε and μ and we obtained the histograms in Figure 3.

The area are under these histograms provides the amount of rotation curves that deviate from the real one. Our main conclusions is that the effect of warps is symmetrical to produce

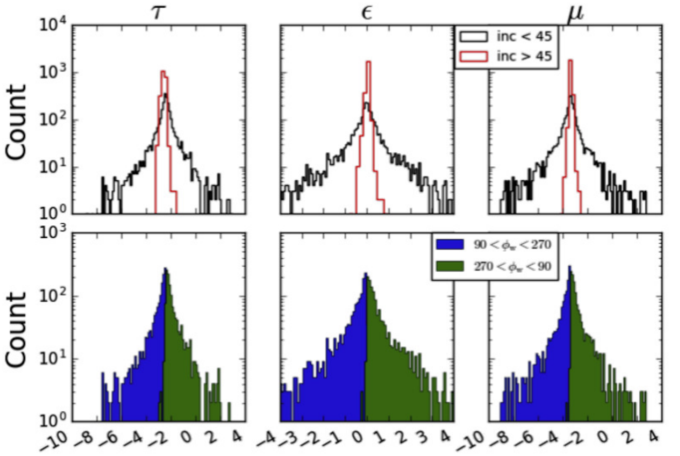

FIGURE 3. Histograms of the parameters τ, ε and μ that measure the deviance of the rotation curves in reason of the warps.

rising or decreasing velocity components to the rotation curves. There are two main components associated to the inclinations. For lower inclinations galaxies the effects of warps dominate the velocities, otherwise the rotation curve dominates. With these data we obtained parameter maps that summarize the possible effects of the warps and allow us to explain fluctuations of the rotation curves, specially the subkeplerian rotation curves as the one observed for M51 (Fig. 4). The parameter maps obtained may be useful to identify potential galaxies that may be affected by warps.

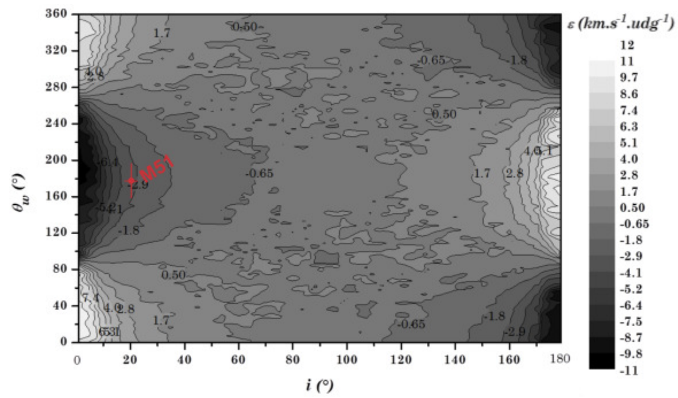

FIGURE 4. Example of map showing the parameter ε as a function of the parameters inclination and the line of nodes of the warp angle (Scarano & Lépine 2007). The darker regions are associated to subkeplerian rotation curves while the lighter ones to superkeplerian rotation curves. The spiral galaxy M51 is a remarkable case of subkeplerian rotation curve (Sofue 2017).

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