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The effect of dust on the Tremaine-Weinberg method

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Abstract. We investigate the effect of dust on the observed rotation rate of a stellar bar as measured by application of the Tremaine & Weinberg (TW) method. As the method requires that the tracer satisfies the continuity equation, it has been applied largely to early-type barred galaxies. We show using numerical simulations of barred galaxies that dust attenuation factors typically found in these systems change the observed bar pattern speed by 20–40%. We also address the effect of star formation on the TW method and find that it does not change the results significantly. This suggests that applications of the TW method can be extended to include barred galaxies covering the full range of Hubble type.

Key words. galaxies: fundamental parameters – galaxies: kinematics and dynamics – methods: N-body simulations – methods: observational

1. Introduction

The rate at which a bar rotates, its pattern speed, Ω_p, is the principle parameter controlling a barred (SB) galaxy's dynamics and morphology. Most determinations of this parameter are indirect. An often used method is to match hydrodynamical simulations of SB galaxies to observed velocity fields. The only direct and model-independent technique to measure Ω_p is the Tremaine & Weinberg (1984, hereafter TW) method. They show that for any tracer that satisfies the continuity equation, $\mathcal{V} = \mathcal{X}\,\Omega_p \sin i$. Here, $\mathcal{X} \equiv \int h(Y)\, X\, \Sigma\, dX\, dY$ and $\mathcal{V} \equiv \int h(Y)\, V_{\rm los}\, \Sigma\, dX\, dY$ are the luminosity-weighted mean positions and velocities respectively.

The number of successful applications of the TW method is rather limited and confined mostly to early type SB galaxies (e.g., Aguerri et al. 2002; Gerssen et al. 2003). Late-type barred galaxies often display prominent dust lanes along the leading edges of the bar which can invalidate the assumption of tracer-continuity. Our motivation for this study is to explore how important dust is for TW measurements of both early and especially late-type galaxies. In the latter, star formation can be a potential problem as it violates the basic assumption of the TW method. We therefore also explore the ability to measure Ω_p in a hydrodynamical simulation of a barred galaxy that includes star formation (Debattista et al. 2006).

2. Method

In a particle implementation of the TW method, the integrals over surface brightness and velocities are replaced by sums over the particles. Five out of our six N-body models

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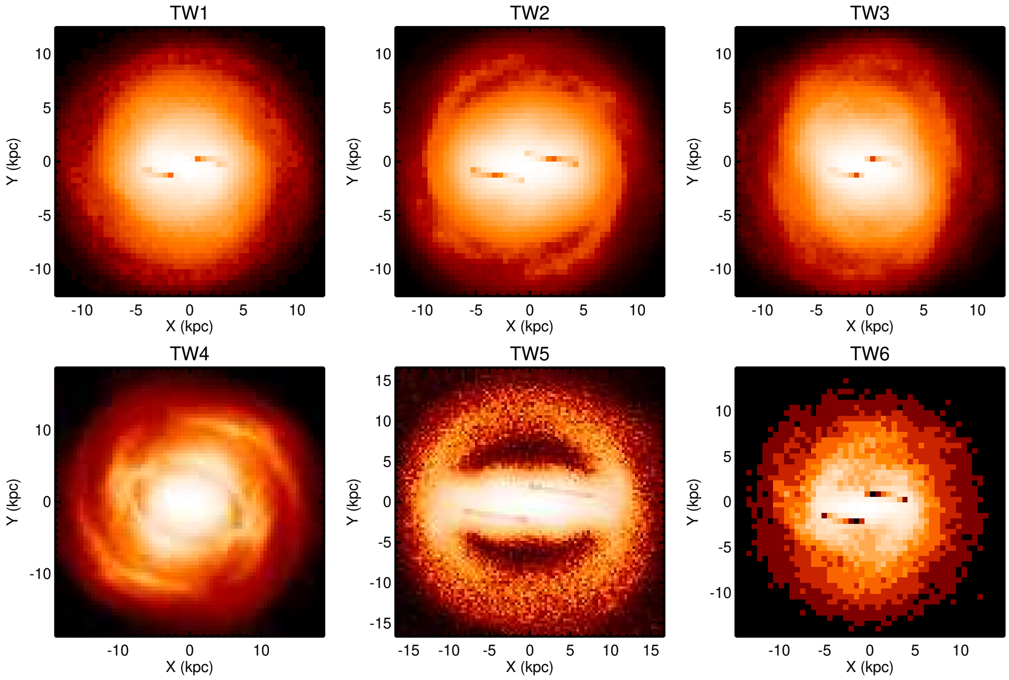

Fig. 1. Examples of the projected distribution of particle weights in our models. The models are published in Debattista (2003, TW1-TW4), Debattista & Sellwood (2000, TW5), and Debattista et al. (2006, TW6). They are shown here face-on to highlight their morphological features. Dust lanes have been included to illustrate how dust attenuation is implemented in our simulations. For clarity the dust lanes have an exaggerated extinction (A_V = 15) and width.

all have particles that are coeval and have equal mass. We therefore start by assigning the same intrinsic weights to all particles in these models. Dust lanes on the leading edges of the bars are implemented by lowering the weights of particles that reside in these areas. We assume that the dust distribution within the dust lanes is described by a double exponential model. That is, $D_{0,\mathrm{lane}} = e^{-R/h_{R,\mathrm{lane}}}\, e^{-|z|/h_{z,\mathrm{lane}}}$ when a particle resides in the dust lane and is 0 otherwise. Particles that are shadowed by dust lanes contribute to the TW integrals with lower weights. Unlike a foreground screen model, the dust extinction in our models varies with position within the disc. For each particle we need to calculate the amount of intervening dust by integrating the projected dust distribution along the line-of-sight. The weight for each particle is then given by $w_i = e^{-\tau_i}$, where the optical depth τ_i is obtained from $\tau_i = \int_{-\infty}^{s_i} D(s')\, ds'$. Examples of the weight distribution in each of our six models are shown in Fig. 1. They are shown here face-on to better illustrate their morphological features.

3. Results

3.1. Dust extinction

In these proceedings we explore the behaviour of the measured pattern speed as a function of dust extinction, expressed in A_V magnitude ($A_V = 1.086\,\tau_0$). The effects of adding a global dust disc and varying the dust lane geometry are small and are detailed in (Gerssen & Debattista 2007). Fig. 2 (left panel) shows the ratio $\Omega_\mathrm{p}/\Omega_0$ of the bar pattern speed observed with the TW method to the intrinsic bar pattern speed as a function of dust lane extinction A_V (defined face-on). The different curves show

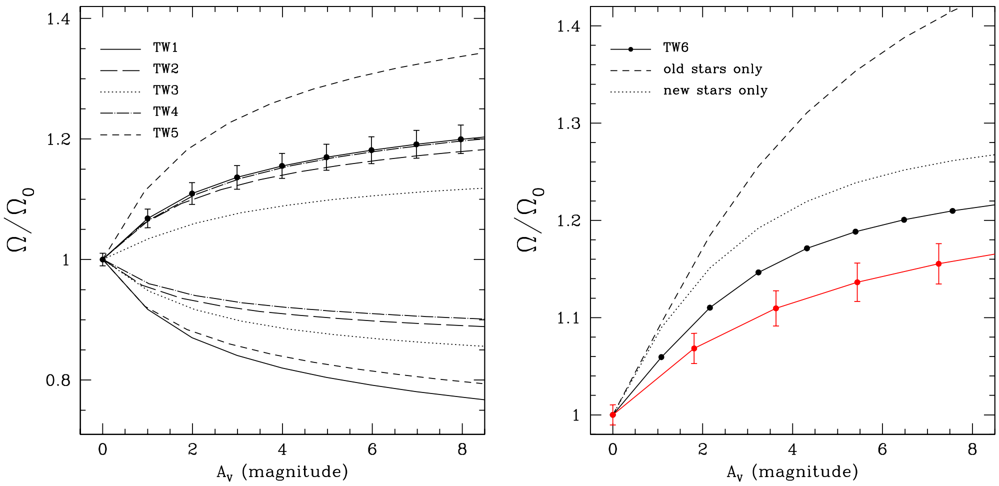

Fig. 2. Left panel: The ratio Ω/Ω_0 of the bar pattern speed observed with the TW method to the intrinsic bar pattern speed as a function of dust lane extinction A_V. The different curves show the behaviour of this ratio for the different N-body models. Two curves are shown for each model. Curves with a ratio > 1 are at $PA_{bar} = +45°$, while curves with a ratio < 1 are at $PA_{bar} = -45°$. The dust lane geometry and dust distribution are the same for every model: $w_{dl}/a_B = 0.1$, $s_{dl} = -0.3$, $x_{min}/a_B = -0.1$, $h_{R,lane} = 10$ and $h_{z,lane} = 0.1$. For clarity, the 1σ errors are shown for model TW1 only. Right panel: The bar pattern speed ratio as a function of dust extinction for the model that includes star formation (TW6). The result is not very different from the models shown in the left panel. For comparison model TW1 is overplotted as the solid line with error bars.

the behaviour of this ratio for the different N-body models (TW1 to TW5). Two curves are shown for each model. Curves with a ratio > 1 are at $PA_{bar} = +45°$, while curves with a ratio < 1 are at $PA_{bar} = -45°$. The dust lane geometry and dust distribution are the same for every model.

3.2. Star formation

In late type systems, vigorous star formation may invalidate the TW assumption that the tracer population satisfies the continuum condition. We use an N-body + SPH model (TW6) to explore these effects. The results, shown on the left, are qualitatively similar to the results derived from the N-body models TW1 to TW5. For a quantitatively comparison model TW1 is overplotted as the solid line with error bars in Fig. 2 (right panel).

4. Conclusions

With realistic amounts of absorption in the dust lanes ($A_V \sim 3$) the models predict observationally insignificant errors (20–40%) in the observed pattern speed. Our results suggest that the application of the TW method can be extended to later-type barred galaxies and facilitate direct comparisons with pattern speeds measured by hydrodynamical modeling.

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