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The dark matter content of early-type barred galaxies

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The dynamics of a barred galaxy depends on the pattern speed of its bar. The only direct method for measuring the pattern speed of a bar is the Tremaine-Weinberg technique. This method relies on the analysis of the distribution and dynamics of the stellar component. It is best suited to gas-poor galaxies and therefore it has been restricted to early-type barred galaxies. On the other hand, a variety of indirect methods, which are based on the analysis of the distribution and dynamics of the gaseous component, has been used to measure the bar pattern speed in late-type barred galaxies. The complete sample of galaxies for which the bar pattern speed has been directly measured with the Tremaine-Weinberg method is given. Nearly all the measured bars are as rapidly rotating as they can be. By comparing this result with recent high-resolution N-body simulations of bars in cosmologically-motivated dark matter halos, it is possible to conclude that these bars are not located inside centrally-concentrated halos.

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1. Introduction

Barred galaxies account for roughly half of all disk galaxies in the local universe [1]. This is also true at higher redshift, because the rest-frame optical bar fraction is constant out $z \sim 1$ [2]. This makes bars ideal probes of the mass distribution in the central regions of disk galaxies. Therefore the study of the dynamics of bars offers an alternative way to constrain the distribution of dark matter (DM hereafter) in galaxy disks.

The morphology and dynamics of a barred galaxy depend on the pattern speed of its bar, Ω_p. Usually, it is parametrized with the bar rotation rate $\mathcal{R} \equiv D_L/a_B$. This is the distance-independent ratio between the corotation radius, $D_L = V_{\rm c}/\Omega_p$, and the length of bar semi-major axis, a_B. At D_L the gravitation and centrifugal forces cancel out in the rest frame of the bar. $V_{\rm c}$ is the disk circular velocity. As far as the value of $\mathcal{R}$ concerns, if $\mathcal{R} < 1.0$ the stellar orbits are elongated perpendicular to the bar and the bar dissolves. For this reason, self-consistent bars cannot exist in this regime. Bars with $\mathcal{R} \gtrsim 1.0$ are close to rotate as fast they can, and there is not a priori reason for $\mathcal{R}$ to be significantly larger than 1.0. Therefore the knowledge of $\mathcal{R}$ allows to distinguish between fast bars ($1.0 \leq \mathcal{R} \leq 1.4$) and slow bars ($\mathcal{R} > 1.4$). Although there is general consent in setting at $\mathcal{R} = 1.4$ the division between fast and slow bars, this choice does not imply anything about the actual rotation velocity of bar.

2. Measuring the bar pattern speed

The only direct method for measuring pattern speeds is the Tremaine-Weinberg technique [3] (hereafter TW). It gives Ω_p for a tracer population satisfying the continuity equation. This is the case of old stellar populations in the absence of significant and patchy obscuration due to the dust distribution. The TW equation is $\mathcal{X}\,\Omega_p \sin i = \mathcal{V}$. where $\mathcal{X} = \int X\,\Sigma\,dX / \int \Sigma\,dX$, and $\mathcal{V} = \int V_{\rm los}\,\Sigma\,dX / \int \Sigma\,dX$ are the luminosity-weighted average of the position X and line-of-sight velocity $V_{\rm los}$ measured parallel to the major axis of the galaxy disk, respectively. Σ and i are the surface brightness and disk inclination, respectively. Slit observations parallel to the major axis of the disk measure all the quantities needed by the TW equation. In fact, for each slit $\mathcal{X}$ is derived from the surface-brightness profile, which is obtained by collapsing the galaxy spectrum along the wavelength direction. On the other hand, $\mathcal{V}$ is derived from the one-dimensional spectrum, which is obtained by collapsing the galaxy spectrum along the spatial direction. Plotting $\mathcal{V}$ versus $\mathcal{X}$ for the different slits produces a straight line with slope $\Omega_p \sin i$.

To date the TW method has been successfully applied to measure the bar pattern speed of the galaxies listed in Table 1. All the galaxies, except for NGC 3992, are SB0's or early-type spirals. NGC 2950 is the only double-barred galaxy of the sample. For all the galaxies, $\mathcal{R}$ is consistent with being in the range between 1.0 and 1.4.

This is not a property of early-type barred galaxies only, but it seems to constitute a generic property of barred galaxies. In fact, a variety of indirect methods has been used to measure Ω_p and corresponding $\mathcal{R}$ in late-type barred galaxies. They rely on the identification of morphological features with the location of Lindblad's resonances, the comparison of the observed gas velocity and density fields with numerical models of gas flows, and the analysis of the offset and shape of dust lanes which traces the location shocks in the gas flows. All these methods are model

Table 1: Barred galaxies with bar pattern measured by TW method

Galaxy (1)	Morp. Type (2)	D (Mpc) (3)	a_B (arcsec) (4)	Ω_B (km s^{-1} arcsec^{-1}) (5)	D_L (arcsec) (6)	$\mathcal{R}$ (7)	Ref. (8)
ESO 139-G09	(R)SAB0^0(rs)	71.9	17^{+6}_{-3}	21.4 ± 5.8	14^{+5}_{-3}	$0.8^{+0.3}_{-0.2}$	[4]
ESO 281-G31	SB0^+(rs)	45.2	11 ± 1	10.5 ± 4.1	20^{+12}_{-4}	$1.8^{+1.1}_{-0.4}$	[5]
IC 874	SB0^0(rs)	34.7	20 ± 5	7.0 ± 2.4	27^{+13}_{-7}	$1.4^{+0.7}_{-0.4}$	[4]
NGC 271	(R')SBab(rs)	50.3	29 ± 1	7.8 ± 4.3	44^{+30}_{-16}	$1.5^{+1.0}_{-0.5}$	[5]
NGC 936	SB0^+(rs)	14.9	50 ± 5	4.7 ± 1.1	69 ± 15	$1.4^{+0.5}_{-0.4}$	[6]
NGC 1023	SB0^-(rs)	5.8	69 ± 5	5.1 ± 1.8	53^{+29}_{-14}	$0.8^{+0.4}_{-0.2}$	[7]
NGC 1308	SB0/a(r)	82.4	12^{+2}_{-3}	39.7 ± 13.9	9^{+5}_{-2}	$0.8^{+0.4}_{-0.2}$	[4]
NGC 1358	SAB0/a(r)	51.6	19 ± 3	9.3 ± 4.5	23^{+19}_{-7}	$1.2^{+1.0}_{-0.4}$	[5]
NGC 1440	(R')SB0^0(rs):	18.4	24^{+6}_{-5}	7.4 ± 1.7	38^{+11}_{-7}	$1.6^{+0.5}_{-0.3}$	[4]
NGC 2950	(R)SB0^0(r)	19.7	34 ± 3	11.2 ± 2.4	34^{+9}_{-6}	$1.0^{+0.3}_{-0.2}$	[8]
NGC 3412	SB0^0(s)	16.0	31 ± 3	4.4 ± 1.2	47^{+17}_{-10}	$1.5^{+0.6}_{-0.3}$	[4]
NGC 3992	SBbc(rs)	16.4	57 ± 12	5.7 ± 0.4	45 ± 3	0.8 ± 0.2	[5]
NGC 4596	SB0^+(r)	29.3	66 ± 7	3.9 ± 1.0	60^{+20}_{-12}	$0.9^{+0.5}_{-0.2}$	[9]
NGC 7079	SB0^0(s)	34.0	25 ± 4	8.4 ± 0.2	31 ± 1	$1.2^{+0.3}_{-0.2}$	[10]

NOTE – Col.(2): Morphological classification from RC3, except for ESO 281-G31 (NED). NGC 2950 is a double-barred galaxy and the listed values refer to its primary bar. Col.(3): Distance obtained as $V_{\rm CBR}/H_0$ with $V_{\rm CBR}$ from RC3 and $H_0 = 75$ km s^{-1} Mpc^{-1}. Col.(4): Bar length. It is from reference papers, except for NGC 936 [11] and NGC 4596 [12]. Col.(5): Bar pattern speed. Col.(6): Bar corotation radius. Col.(7): Bar rotation rate. Col.(8): Reference papers.

dependent. Nevertheless, nearly all the measured bars are found to be fast (see [13] for a review). If this result will be confirmed by a successful application of the TW method to late-type barred galaxies, an important selection bias present in the current sample of directly measured pattern speeds would be remedied. This problem could be addressed by using near-infrared spectroscopy in order to deal with dust obscuration. [14] applied this technique to NGC 1068, finding $\mathcal{R} < 1.0$. However, they obtained the observables required by the TW method along two slit positions only, which makes it hard to constrain Ω_p.

3. Dark matter distribution in barred galaxies

Theory and N-body simulations favor the birth of fast bars, while the time evolution of $\mathcal{R}$ depends on the DM distribution of the galaxy. Direct measurement of bar pattern speeds are consistent with bars being fast rotators. This conclusion places important constraints on the relative fraction of luminous to dark matter at least inside the optical region of early-type barred galaxies.

The dynamical friction with a dense DM halo brakes the bar on a short time scale compared with the ages of galaxies [15]. As a bar slows down, $\mathcal{R}$ increases to values larger than 1.4. Fast bars require that the disk, in which they formed, contributes most of the rotational support in the inner parts of the galaxy [16]. This means that barred galaxies have a maximal disk, instead of a centrally-concentrated DM halo. This conclusion holds also for bright unbarred galaxies. They have comparable fractions of DM at a given radius as do their barred counterparts, as it results from both the comparison of their Tully-Fisher relations [16,17] and the analysis of their mass distribution [e.g., 18].

At present there is a lively debate about this suggestion for barred galaxies. For example, some high-resolution N-body simulations with centrally-concentrated DM halos produce bars with $\mathcal{R} = 1.7$ [19]. It has been argued that these slow bars are still consistent with data given in Table 1. However, it should be noticed that this limit is reached only in those galaxies with the largest uncertainties and ignores other source of scatter [20]. Nevertheless, it is clear that there is still the need of an accurate measurement of $\mathcal{R}$ in a statistically significant number of barred galaxies. Direct measurements of Ω_p with the TW method using near-infrared spectroscopy will open the possibility of a systematical investigation of $\mathcal{R}$ not only in early-type but also in late-type barred galaxies.

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References

[1] P. Eskridge et al., *The frequency of barred spiral galaxies in the near-infrared*, *ApJ* **00** (119) 563

[2] S. Jogee et al., *Bar evolution over the last 8 billion years: a constant fraction of strong bars in the GEMS survey*, *ApJ* **04** (615) L19

[3] S. Tremaine, D. Weinberg, *A kinematic method for measuring the pattern speed of barred galaxies*, *ApJ* **84** (282) L5

[4] J.A.L. Aguerri, V.P. Debattista, & E.M. Corsini, *Measurement of fast bars in a sample of early-type barred galaxies*, *MNRAS* **03** (338) 465

[5] J. Gerssen, K. Kuijken, & M.R. Merrifield, *Model-independent measurements of bar pattern speeds*, *MNRAS* **03** (345) 261

[6] K. Kuijken, M.R. Merrifield, *The pattern speed of the bar in NGC 936*, *MNRAS* **95** (274) 933

[7] V.P. Debattista, E.M. Corsini, & J.A.L. Aguerri, *A fast bar in the post-interaction galaxy NGC 1023*, *MNRAS* **02** (332) 65

[8] E.M. Corsini, V.P. Debattista, & J.A.L. Aguerri, *Direct confirmation of two pattern speeds in the double-barred galaxy NGC 2950*, *ApJ* **03** (599) L29

[9] J. Gerssen, K. Kuijken, & M.R. Merrifield, *The pattern speed of the bar in NGC 4596*, *MNRAS* **99** (306) 962

[10] V.P. Debattista, T.B. Williams, *Fabry-Perot absorption-line spectroscopy of NGC 7079: kinematics and bar pattern speed*, *ApJ* **04** (605) 714

[11] S.M. Kent, G. Glaudell, *The bar in NGC 936*, *AJ* **89** (98) 1598

[12] S.M. Kent, *The bar in NGC 4596*, *AJ* **90** (100) 377

[13] B. Elmegreen, *Pattern speeds in galaxies*, *ASP Conf. Ser.* **96** (91) 197

[14] A.J. Baker et al. *Pattern speed measurements in two barred galaxies*, *ASP Conf. Ser.* **01** (249) 78

[15] M.D. Weinberg *Evolution of barred galaxies by dynamical friction*, *MNRAS* **85** (213) 451

[16] V.P. Debattista, J.A. Sellwood, *Constraints from dynamical friction on the dark matter content of barred galaxies*, *ApJ* **00** (503) 704

[17] S. Courteau, D. R. Andersen, M. A. Bershady, L. MacArthur, H.-W. Rix, *The Tully-Fisher relation of barred galaxies*, *ApJ* **03** (594) 208

[18] G. Gentile, P. Salucci, U. Klein, D. Vergani, P. Kalberla, *The cored distribution of dark matter in spiral galaxies*, *MNRAS* **04** (351) 903

[19] O. Valenzuela, A. Klypin, *Secular bar formation in galaxies with a significant amount of dark matter*, *MNRAS* **03** (305) 406

[20] V.P. Debattista, *On position angle errors in the Tremaine-Weinberg method*, *MNRAS* **03** (342) 1194