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The V_c–σ_c relation in high and low surface brightness galaxies

E.M. Corsini[1], A. Pizzella[1], E. Dalla Bontà[1], M. Sarzi[2], L. Coccato[1], and F. Bertola[1]

[1] Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio 2, I-35122 Padova, Italy
[2] Physics Department, University of Oxford, Keble Road, Oxford, OX1 3RH, UK

Abstract. We investigated the correlation between the circular velocity V_c and the central velocity dispersion of the spheroidal component σ_c. We measured V_c and σ_c for a sample of 42 high surface brightness disc galaxies (hereafter HSB), 11 low surface brightness spiral galaxies (hereafter LSB), and 24 elliptical galaxies characterized by flat rotation curves. We find that the V_c–σ_c correlation for the HSB and elliptical galaxies is consistent with a linear law out to velocity dispersions as low as $\sigma_c \approx$ 50 km s^{-1}. We analyzed the location of the elliptical galaxies with V_c based on H I data and LSB galaxies in the V_c–σ_c plane. These types of galaxies were not considered in previous studies. The data points corresponding to the elliptical galaxies with H I-based V_c follow the same relation as the HSB galaxies and the elliptical galaxies with V_c based on dynamical models. On the contrary, the LSB galaxies follow a different V_c–σ_c relation, since most of them show either higher V_c (or lower σ_c) with respect to their HSB counterparts. If the V_c–σ_c relation is equivalent to one between the mass of central supermassive black hole and that of the dark matter halo, these results suggest that the LSB galaxies host a supermassive black hole with a smaller mass compared to HSB galaxies. Moreover, the finding that at a given dark matter mass (as traced by V_c) the central σ_c of LSB galaxies is smaller than in their HSB counterparts, would argue against the relevance of baryon collapse in the radial density profile of the dark matter haloes of LSB galaxies.

Key words. galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: kinematics and dynamics – galaxies: spirals

1. Introduction

Recently, a tight correlation between the central velocity dispersion of the spheroidal component (σ_c) and the galaxy circular velocity measured in the flat region of the rotation curve (V_c) has been found for a sample of elliptical and spiral galaxies (Ferrarese 2002). The validity of this relation has been confirmed by Baes et al. (2003), who enlarged the sample of spiral galaxies.

For elliptical galaxies the existence of a relation between σ_c and V_c is not surprising, since the circular velocity curves of giant elliptical galaxies resulting from dynamical modeling by Kronawitter et al. (2000) are remarkably similar in shape and they scale only with the effective radius and total luminosity. As a conse-

Send offprint requests to: E.M. Corsini
Correspondence to: corsini@pd.astro.it

quence, the maximum circular velocity is correlated to the central velocity dispersion of the galaxy (Gerhard et al. 2001). On the contrary, both shape and amplitude of the rotation curves of a spiral galaxy depend on the galaxy luminosity and morphological type (e.g., Burstein & Rubin 1985; Persic et al. 1996). For this reason for spiral galaxies the V_c–σ_c relation is not expected a priori.

It is interesting to investigate whether the V_c–σ_c relation holds also for less dense objects characterized by a less steep potential well. This is the case of giant low surface brightness galaxies (hereafter LSB), which are disc galaxies with a central face-on surface higher than 22.6 B–mag arcsec^{-2} (e.g. Schombert et al. 1992). This class of galaxies shares the same Tully-Fisher relation as high surface brightness galaxies (hereafter HSB, see Courteau & Rix 1999, and references therein) indicating that LSB galaxies are dark matter (hereafter DM) dominated. For this reason, they have received a great deal of attention, because they represent ideal test-bed to check if the central density profile of the DM haloes is in agreement with the predictions of N-body simulations in cold DM universes (Swaters et al. 2003; de Blok et al. 2003). This issue will benefit from a study of the V_c–σ_c relation for LSB galaxies, because σ_c is related to the depth of the galactic potential well (and therefore to the central mass density) and V_c probes the potential of the DM halo.

2. Sample selection

The HSB sample consists of 50 disc galaxies with Hubble type ranging from S0 to Scd, an inclination $i \geq 30°$ and a distance $D < 80$ Mpc (Bertola et al. 1996; Corsini et al. 1999; Vega Beltrán et al. 2001; Corsini et al. 2003; Pizzella et al. 2004a). The LSB sample consists of 11 disc galaxies with Hubble type ranging from Sa to Irr, an intermediate inclination ($30° \lesssim i < 70°$), and a distance $D < 65$ Mpc (Pizzella et al. 2004b, but see also Pizzella et al. 2004c). Three LSB galaxies have been selected from the sample observed by de Blok & McGaugh (1997). The remaining eight objects are LSB galaxies with bulge. They have been selected in Lauberts & Valentijn (1989) to have a LSB disc component following the criteria described by Beijersbergen et al. (1999).

For all the HSB and LSB galaxies we obtained the ionized-gas rotation curve by folding the observed line-of-sight velocities around the galaxy center and systemic velocity after averaging the contiguous data points and applying a correction for galaxy inclination. We rejected 32 HSB galaxies because they had asymmetric rotation curves or rotation curves which were not characterized by an outer flat portion. We derived V_c by averaging the outermost values of the flat portion of the rotation curve. For the remaining 29 objects (18 HSB and 11 LSB galaxies) the ionized-gas rotation curve extends to the flat region. We are therefore confident that we are giving a reliable estimate of the asymptotic value of the circular velocity which traces the mass of the DM halo (see Ferrarese 2002, for a discussion). We derived σ_c from the stellar kinematics by extrapolating the velocity dispersion radial profile to $r = 0''$. We did not apply any aperture correction to σ_c as discussed by Baes et al. (2003) and Pizzella et al. (2004a). In order to complete our sample of disc galaxies we included all the spiral galaxies that have been previously studied by Ferrarese (2002) and Baes et al. (2003), but which are also characterized by a flat rotation curve. In summary, we have 29 galaxies (18 HSB and 11 LSB galaxies) from our preliminary sample, 17 spiral galaxies (out of 38) from Ferrarese (2002), and 7 spiral galaxies (out of 12) from Baes et al. (2003). The final sample of 42 HSB galaxies includes 14 early-type objects with Hubble type ranging from S0 to Sab. On the contrary, the sample by Baes et al. (2003) and Ferrarese (2002) was constituted only by late-type spirals with Hubble type Sb or later (except for the Sa NGC 2844).

Finally, we considered a sample of 24 elliptical galaxies with a flat rotation curve and for which both V_c and σ_c are available in literature. They include 19 objects studied by Kronawitter et al. (2000) who derived V_c by dynamical modeling and 5 objects for which V_c is directly derived from the flat portion of their H I rotation curves. The addition of these last 5 elliptical is important as it allows to test against

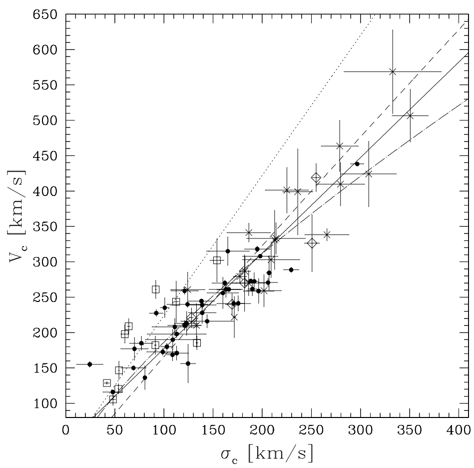

Fig. 1. The correlation between V_c and σ_c for elliptical and disc galaxies. The data points corresponding to HSB galaxies (*filled circles*), LSB galaxies (*squares*), elliptical galaxies with V_c obtained from H I data (*diamonds*), and elliptical galaxies with V_c obtained from dynamical models (*crosses*) are shown. The *dash-dotted line* and *continuous* represent the power-law (Eq. 1) and linear fit (Eq. 2) to HSB and elliptical galaxies. The *dotted line* represents the linear-law fit (Eq. 3) to LSB galaxies. For a comparison, the *dashed line* corresponds to the power-law fit to spiral galaxies with $\sigma_c > 80$ km s^{-1} by Baes et al. (2003).

model-dependent biases in the $V_c - \sigma_c$ relation. The values σ_c of all the elliptical galaxies have been corrected to the equivalent of an aperture of radius $r_e/8$ following the prescriptions of Jorgensen et al. (1995). The effective radius r_e is taken from de Vaucouleurs et al. (1991).

3. Results

The V_c and σ_c data points of the final sample of galaxies are plotted in Fig. 1. We applied a linear regression analysis to the data by adopting the method by Akritas & Bershady (1996) for bivariate correlated errors and intrinsic scatter (hereafter BCES) both in the $\log V_c - \log \sigma_c$ and V_c–σ_c plane. We did not include LSB galaxies in the analysis because they appear to follow a different V_c–σ_c relation as we will discuss later.

Following Ferrarese (2002) and Baes et al. (2003) we fit the function $\log V_c = \alpha \log \sigma_c + \beta$ to the data in $\log V_c - \log \sigma_c$ plane. We find

$$\log V_c = (0.74 \pm 0.06)\ \log \sigma_c + (0.79 \pm 0.15) \quad (1)$$

with V_c and σ_c expressed in km s^{-1}. The resulting power law ($\chi^2_\nu = 3.4$) is plotted in Fig. 1. It is in agreement with Ferrarese (2002) and Baes et al. (2003). However, they included in their fits only galaxies with $\sigma_c > 70$ km s^{-1} and $\sigma_c > 80$ km s^{-1}, respectively. In fact, they considered the few objects with $\sigma_c \leq 70$ km s^{-1} as outliers. On the contrary, we found that points characterized by $\sigma_c \lesssim 70$ km s^{-1} appear to be well represented by the fitting law as well as the ones characterized by higher values of σ_c.

Since it results $\alpha \approx 1$, we decided to fit the function $V_c = a\sigma_c + b$ to the data in the V_c–σ_c plane. We find

$$V_c = (1.35 \pm 0.08)\,\sigma_c + (42 \pm 13) \quad (2)$$

with V_c and σ_c expressed in km s^{-1}. The resulting straight line ($\chi^2_\nu = 3.3$) is plotted in Fig. 1.

4. Discussion and conclusions

In previous works a power law was adopted to describe the correlation between V_c and σ_c for galaxies with $\sigma_c > 80$ km s^{-1}. We find that data are also consistent with a linear law out to velocity dispersions as low as $\sigma_c \approx 50$ km s^{-1}. We considered the straight line given in Eq. 2 as reference fit.

It should be noticed that Ferrarese (2002) and Baes et al. (2003) considered only galaxies with a flat rotation curve extending at a distance R_{last} larger than the optical radius R_{25}. We relaxed this selection criterion to build our final sample and made sure instead that all rotation curves reached the flat outer parts. The residual plot of Fig. 2 shows that the scatter of the data points corresponding to our sample galaxies with V_c measured at $R_{last} \geq R_{25}$ is comparable to that of the galaxies with V_c measured at $R_{last} < R_{25}$. This confirms that this particular scale is not important once the asymptotic part of the rotation curve is reached by the

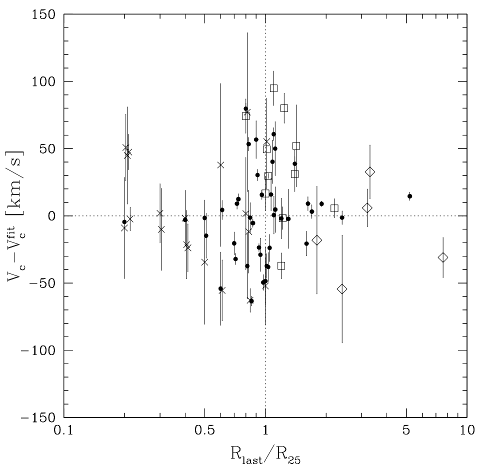

Fig. 2. Residuals from the linear-law fit to HSB and elliptical galaxies (Eq. 2) plotted as function R_{last}/R_{25}. The data points corresponding to HSB galaxies (*filled circles*), LSB galaxies (*squares*), elliptical galaxies with V_c obtained from H I data (*diamonds*), and elliptical galaxies with V_c obtained from dynamical models (*crosses*) are shown. Data with the same R_{last}/R_{25} have been shifted to allow comparison.

observations. The scatter of the complete sample is 18 km s^{-1}, which is consistent with typical measurement errors for V_c and σ_c. For this reason we conclude that the intrinsic scatter of the V_c–σ_c relation is $\approx$ 10 km s^{-1}.

We investigated the location of the elliptical galaxies with V_c based on H I data and LSB galaxies in the V_c–σ_c plane. These types of galaxies were not considered by Ferrarese (2002) and Baes et al. (2003).

The data points corresponding to the 5 elliptical galaxies with V_c based on H I data follow the same relation as the remaining disc and elliptical galaxies. They are mostly located on the upper end of the V_c–σ_c relation derived for disc galaxies, in agreement with the findings of Bertola et al. (1993). They studied these elliptical galaxies and showed that their DM content and distribution is similar to that of spiral galaxies.

The LSB and HSB galaxies do not follow the same V_c–σ_c relation. In fact, most of the LSB galaxies are characterized by a higher V_c for a given σ_c (or a lower σ_c for a given V_c) with respect to HSB galaxies (Fig. 1). By applying to the LSB data points the same regression analysis which has been adopted for the HSB and elliptical galaxies of the final sample, we find

$$V_c = (1.98 \pm 0.34)\,\sigma_c + (26 \pm 27) \qquad (3)$$

with V_c and σ_c expressed in km s^{-1}. The straight line corresponding to this fit, which is different from the one obtained for HSB and elliptical galaxies, is plotted in Fig. 1.

To address the significance of this result, which is based only on 11 data points, we compared the distribution of the normalized scatter of the LSB galaxies to that of the HSB and elliptical galaxies. We defined normalized scatter of the $i-$th data point as

$$\overline{s_i} = d_i/\Delta_i \qquad (4)$$

where d_i is the distance to the straight line of coefficient $a = 1.35$ and $b = 42$ given in Eq. 2 of the $i-$th data point, whose associated error Δ_i is

$$\Delta_i = \sqrt{\frac{4}{\pi}\Delta V_{c,i}\Delta\sigma_{c,i}}. \qquad (5)$$

We assumed $\overline{s_i} > 0$ when the data point lies above the straight line corresponding to the best fit. In Fig. 3 we plot the distributions of the normalized scatter of the LSB galaxies and of the HSB and elliptical galaxies. The two distributions appear to be different, as it is confirmed at a high confidence level (>99%) by a Kolmogorov-Smirnov test.

Both demographics of supermassive black holes (SMBH) and study of DM distribution in galactic nuclei benefit from the V_c–σ_c relation. The recent finding that the mass of SMBHs correlates with different properties of the host spheroid supports the idea that formation and accretion of SMBHs are closely linked to the formation and evolution of their host galaxy. Such a mutual influence substantiates the notion of coevolution of galaxies and SMBHs (see Ho 2004).

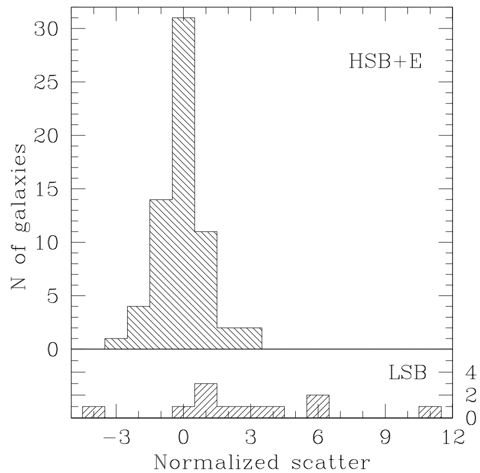

Fig. 3. The distribution of the normalized scatter of the HSB and elliptical galaxies (*upper panel*) and LSB galaxies (*lower panel*) with respect to the linear-law fit to HSB and elliptical galaxies (Eq. 2). The two distributions are different at > 99% confidence level.

An unfinished task to be pursed is to obtain a firm description of all these relationships spanning a wide range of SMBH masses and address if they hold for all Hubble types. In fact, the current demography of SMBHs suffers of important biases, related to the limited sampling over the different basic properties of their host galaxies. Pure disc galaxies, for instance, are exception in this context, which underscores that the formation of SMBHs is only linked to that of galactic bulges.

The finding that the V_c–σ_c relation holds for small values of σ_c points to the idea that SMBHs with masses smaller than about 10^6 $M_\odot$ may also exist and follow the $M_\bullet$-σ relation.

Moreover, it has been suggested that the V_c–σ_c relation is equivalent to one between the masses of SMBH and DM halo (Ferrarese 2002; Baes et al. 2003) because σ_c and V_c are related to the masses of the central SMBH and DM halo, respectively. Yet, this claim is to be considered with caution, as the demography of SMBHs is still limited and in particular as far as spiral galaxies are concerned. Neveretheless, if such relation is to hold, the deviation of LSB galaxies *with bulge* from the V_c–σ_c of HSB and elliptical galaxies suggests that for a given DM halo mass the LSB galaxies would host a SMBH with a smaller mass compared to HSB galaxies. The theoretical and numerical investigations of the processes leading to the formation of LSB galaxies should therefore account for this.

The collapse of baryonic matter can induce a further concentration in the DM distribution (Rix et al. 1997), and a deepening of the overall gravitational well in the central regions. If this is the case, the finding that at a given DM mass (as traced by V_c) the central σ_c of LSB galaxies is smaller than in their HSB counterparts, would argue against the relevance of baryon collapse in the radial density profile of DM in LSB galaxies. Confirming that LSB galaxies follow a different V_c–σ_c relation will highlight yet another aspect of their different formation history. Indeed, LSB galaxies appear to have a central potential well less steep than HSB spirals of the same DM halo mass. If the collapse of baryonic matter causes a compression of the DM halo as well, for LSB galaxies such process may have been less relevant than for HSB galaxies. Again LSB galaxies turn out to be the best tracers of the primordial density profile of DM haloes and therefore in pursuing the nature of dark matter itself.

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