The $v_c$-$\sigma_c$ relation in low mass and low surface brightness galaxies

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ABSTRACT

We present an updated investigation of the relation between large scale disk circular velocity, $v_c$, and bulge velocity dispersion, $\sigma_c$. New bulge velocity dispersions are measured for a sample of 11 low surface brightness (LSB) and 7 high surface brightness (HSB) spiral galaxies for which $v_c$ is known from published optical or HI rotation curves. We find that, while LSB galaxies appear to define the upper envelope of the region occupied by HSB galaxies (having relatively larger $v_c$ for any given $\sigma_c$), the distinction between LSB and HSB galaxies in the $v_c$-$\sigma_c$ plane becomes less pronounced for $\sigma_c \lesssim 80$ km s$^{-1}$. We conclude that either the scatter of the $v_c$-$\sigma_c$ relation is a function of $v_c$ (and hence galaxy mass) or that the character of the $v_c$-$\sigma_c$ relation changes at $v_c \sim 80$ km s$^{-1}$. Some implications of our findings are discussed.

Key words: black hole physics — dark matter — galaxies: haloes — galaxies: nuclei

1 INTRODUCTION

The existence of supermassive black holes (SBHs) in galactic nuclei has been accepted since the detections in the nearby spiral NGC 4258 (Miyoshi et al. 1995) and in our own galaxy (Schödel et al. 2003; Ghez et al. 2003). Compelling cases now exist in three dozen additional galaxies (see Ferrarese & Ford 2005 for a review), making our own galaxy (Schödel et al. 2003; Ghez et al. 2003). Further exploring the $v_c$-$\sigma_c$ relation is of interest because, by linking galactic components on vastly different scales, the relation is a reflection of the interplay between disks and spheroids during galaxy formation/evolution. Furthermore, if $v_c$ and $\sigma_c$ are used as surrogates for $M_{DM}$ and $M_{BH}$ respectively, equation (1) implies a strong causal relation between SBHs and DM haloes.

Pizzella et al. (2005) report evidence of a separation in the $v_c$-$\sigma_c$ plane between High and Low Surface Brightness spiral galaxies (HSB and LSB respectively), the latter having distinctly larger $v_c$ at a given $\sigma_c$ compared to the former. Based on this, the authors argue against the importance of baryonic collapse in shaping the density profiles of DM haloes in LSBs, and suggest that for a given DM halo mass, LSBs might host less massive SBHs than HSBs. The behaviour of HSBs themselves is somewhat controversial: while Pizzella et al. (2005) find that HSB in the range

2000: Monaco, Salucci & Danese
1999: Haehnelt, Natarajan & Rees
1998: Cattaneo, Haehnelt & Rees
1995: Haehnelt & Kauffmann
1994: Silk & Rees
1993: Kormendy & Richstone
1992: Marconi & Hunt
1991: Graham et al.
1989: Gebhardt et al.
1988: Ferrarese & Merritt
1987: Di Matteo et al.
1986: Kawakatu et al.
1983: Wyithe & Loeb
2003: Adams, Graff & Richstone

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2 OBSERVATIONS AND DATA REDUCTION

To compare the behaviour of LSBs and HSBs in the $v_c \lesssim 220$ km s$^{-1}$ range of the $v_c - \sigma_c$ relation, we crafted a sample of galaxies with $v_c$ known from published rotation curves, and proceeded to obtain new optical spectra from which to measure $\sigma_c$. We targeted 11 LSB galaxies with optical rotation curves from the Palunas & Williams (2000) compilation, and seven HSB galaxies with HI rotation curves from the Ursa Major sample of Verheijen (2001). Besides the need of selecting galaxies visible in the given observing season, and bright enough to produce spectra with the required signal-to-noise ratio (S/N), the one essential criterion in our sample selection is that the published rotation curves must be symmetric relative to the galaxy’s centre, and reach an asymptotic value at large radii.

Details of the sample and observations are given in Table 1. The LSB galaxies were observed with the VLT/UT4 telescope of the European Southern Observatory on the nights of 2004 April 20, 29 and May 6. The holographic grism GRIS $\lambda$120x+29 on FORS2 was centred on the Calcium absorption triplet around 8500Å, producing an instrumental broadening $\sigma_{instr} \approx 35$ km s$^{-1}$ with the I'7 slit. The seven HSB galaxies were observed with the TWIN spectrograph at the 3.5m Calar Alto telescope, on 2005, June 6-19. The T06 grating was used in 1st order, again centred at the Ca triplet. The instrumental broadening was $\sigma_{instr} \approx 20$ km s$^{-1}$ for the I'2 wide slit. All spectra were divided into several exposures to ease cosmic ray identification and removal.

Standard data reduction was performed with MIDAS, IRAF and additional software developed specifically for this project. After basic data processing (dark and bias subtraction, flat fielding and trimming), atmospheric emission lines were identified and removed through an interpolation scheme, after which the spectra were rectified and wavelength calibrated. Cosmic rays were removed by applying a median filter along the spatial axis.

3 DATA ANALYSIS

Deriving accurate kinematical quantities of galaxies is a non-trivial task. The result of the extraction can vary depending on the applied fitting techniques, the S/N, the template stars, the absorption lines used, etc. (e.g., De Bruyne et al. 2003). To lower this degree of subjectivity, we derived velocity dispersions using two independent techniques: a direct $\chi^2$ fit to the spectrum (De Bruyne et al. 2004), and the PPXF algorithm (Cappellari & Emsellem 2004) (see Fig. 2, which is based on a Penalized Likelihood approach. Velocity dispersions derived using these two methods agree to within 10%; the final values quoted in Table 1 were obtained using the $\chi^2$ fit to the spectrum (De Bruyne et al. 2004).
Figure 3. Left panel: The relation between the large scale disk circular velocity \( v_c \) and the central bulge velocity dispersion \( \sigma_c \) for HSBs (black circles) and LSBs (red triangles). Data from Ferrarese (2002), Baes et al. (2003), Pizzella et al. (2005) (full symbols) and this paper (open symbols) are plotted. Right panel: as in the left panel, with fits superimposed. The solid and dashed black lines are least square fits to HSB galaxies with \( \sigma_c \geq 80 \text{ km s}^{-1} \) and \( \sigma_c \leq 80 \text{ km s}^{-1} \) respectively. The red solid line is the fit to LSB galaxies with \( \sigma_c \leq 80 \text{ km s}^{-1} \). Dotted lines represent the 1σ uncertainties in the fits.

routine. In analyzing the spectra, sky residuals that deviated by more than 3 times the average sigma in the nearby continuum were rejected; furthermore, to minimize the effects of template mismatch, six different template stars were used, each with weight calculated by a quadratic fit to the central row of the spectrum. In keeping with previous works, velocity dispersions were extracted from spectra binned, in the spatial direction, out to 1/8th of the bulge effective radius, estimated from the literature in the case of the HSB galaxies [Baggett et al. 1998, Courteau 1996, Heraudeau et al. 1996, Möllenhoff & Heidt 2001], and from published surface brightness profiles for the Palunas & Williams (2000) galaxies. Within this radius, the effect of a possible contamination by the disk rotational velocity should be negligible. This was verified by measuring the dispersion profiles along the major axis (without binning spatially); the velocity dispersion of most galaxies (see Fig. 2) indeed remained nearly constant in the bulge dominated region.

The circular rotational velocities and errors are published by Verheijen (2001) for the HSB galaxies. These were derived from HI observations and extend beyond the optical radius \( R_{25} \), well into the flat part of the curve. For the LSB galaxies, we measured \( v_c \) as the weighted average of the flat part of the optical rotation curve published in Palunas & Williams (2000); the error on \( v_c \) was derived by means of a bootstrap method and reflects any slight asymmetries in the rotation curves. The optical rotation curves are not as extended as the HI observations of the HSB galaxies, however all rotation curves reach an asymptotic value at large radii. As shown in Pizzella et al. (2005), when this condition is satisfied, \( v_c \) can be extracted reliably; therefore we do not expect any systematic biases in the \( v_c \) measurements between our samples of HSBs and LSBs. The results of the dynamical analysis are given in Table 1.

4 DISCUSSION AND CONCLUSIONS

The \( v_c - \sigma_c \) relation for HSB galaxies is plotted in the left panel of Fig. 3. The 11 LSB galaxies studied in this paper populate the region between 40 \( \leq \sigma_c \leq 80 \text{ km s}^{-1} \), where previously only three galaxies could be found. Furthermore, in the same region, we more than double the number of HSB galaxies, from three to eight. Pizzella et al. (2005) conclude that, relative to the \( v_c - \sigma_c \) relation defined by HSB galaxies, LSB galaxies appear to have larger circular velocities, \( v_c \), at any given value of \( \sigma_c \). This conclusion is reaffirmed by our data. However, with the addition of the present sample, it has now become more evident that there is some overlap in the locations occupied by LSB and HSB galaxies in the \( v_c - \sigma_c \) plane. In other words, LSB galaxies appear to occupy the upper envelope of the strip defined by HSB galaxies. Furthermore, at low velocity dispersions \( 30 \leq \sigma_c \leq 80 \text{ km s}^{-1} \), the \( v_c - \sigma_c \) relation for both LSB and HSB galaxies appears to be shifted towards larger circular velocities relative to the relation defined by the (HSB) galaxies with larger velocity dispersion.

A least-square fit, taking into account the errors on both quantities [FITEXY; Press et al. 2002], to the sample of HSBs with \( \sigma_c \geq 80 \text{ km s}^{-1} \) gives:

\[
\log v_c = (0.68 \pm 0.04) \log \left( \frac{\sigma_c}{129 \text{ km s}^{-1}} \right) + (2.33 \pm 0.01),
\]

with \( \chi^2 = 2.58 \). For \( 30 \leq \sigma_c \leq 80 \text{ km s}^{-1} \), on the other hand,
log \(v_c\) = \((1.33 \pm 0.86) \log \left(\frac{\sigma_c}{63 \text{ km s}^{-1}}\right) + (2.21 \pm 0.03)\), (3)

with \(\chi^2 = 0.23\) for HSB galaxies, and

log \(v_c\) = \((1.91 \pm 0.68) \log \left(\frac{\sigma_c}{58 \text{ km s}^{-1}}\right) + (2.20 \pm 0.02)\), (4)

with \(\chi^2 = 1.55\) for LSB galaxies.

Although the uncertainties are large, equations (3) and (4) are consistent with each other well within 1\(\sigma\), but inconsistent with equation (2) (see also right panel of Figure 3).

Two interpretations are open at this point. The samples studied to date are far from complete or homogeneous, and it is conceivable that, as more data are collected, more galaxies will fill the gap between the LSB galaxies, which are mainly found in the low-velocity dispersion region, and the extrapolation to low \(\sigma_c\) of equation (2), defined mainly by HSB galaxies. This interpretation allows for the possibility that the log-log \(v_c - \sigma_c\) relation, including both HSB and LSB galaxies, is linear, but that its scatter increases going from large to small velocity dispersions. Alternatively, it is possible that the log-log \(v_c - \sigma_c\) relation is not linear, and that indeed its character changes dramatically below \(v_c \sim 200 \text{ km s}^{-1}\), as originally suggested by Ferrarese (2002) and Baes et al. (2003). In either case, it seems unavoidable to conclude that the efficiency of bulge (and, perhaps, SBH) formation, is regulated by intrinsic parameters in addition to the depth of the global potential well.

The implications of these findings for the central SBHs cannot be easily quantified. The \(M_{BH} - \sigma_c\) relation is not characterised for LSBs, for which no SBH detection has been attempted. It is also not defined below \(\sigma_c \leq 80 \text{ km s}^{-1}\), which corresponds to SBHs too small to be detected given current space or ground-based instrumentation. We reiterate the conclusion of Ferrarese et al. (2002) and Baes et al. (2003) that the behaviour of the \(v_c - \sigma_c\) relation at \(\sigma_c \lesssim 80 \text{ km s}^{-1}\) might reflect the inability of these galaxies to form a central SBH, as argued on theoretical grounds by, for instance, Shankar et al. (2006), Haehnelt, Natarajan & Rees (1998), Silk & Rees (1998), Loeb & Rasio (1994). Numerical simulations [Di Matteo et al. (2003), Robertson et al. (2006)] predict that the \(M_{BH} - \sigma_c\) relation originates from the feedback between the central SBH and the progenitor of the hot stellar component at the early stages of the formation of both; therefore, in low-mass, late-type HSB and LSB galaxies internal factors might lead to the suppression of such feedback, creating a dynamical relation between disk, bulge and SBH which is starkly different from that displayed by more massive systems.

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Table 1. Column 1 gives the galaxy’s name, while columns 2 & 3 give the J2000 coordinates. The asymptotic circular velocity \( v_c \) is tabulated in column 4, it is taken directly from Verheijen (2001) for the HSB galaxies, and measured from the published rotation curves for the LSB galaxies. Central velocity dispersion (\( \sigma_c \)) at \( r_e/8 \) and the effective radius of the galaxy can be found in columns 5 and 6. The heliocentric radial velocity, Hubble classification, total I band magnitude, inclination can be found in columns 7 to 10 and are taken from Verheijen (2001) for the HSB galaxies and Palunas & Williams (2000) for the LSB galaxies and the online NED database. Finally, the total exposure time and S/N/pixel at 8500 Å are given in columns 11 and 12.

| Name            | R.A.   | Dec.   | \( v_c \) | \( \sigma_c \) | \( r_e/8 \) | Morph | \( m_I \) | Incl. | Exp.Time | S/N |
|-----------------|--------|--------|------------|---------------|-------------|-------|-----------|-------|----------|-----|
|                 | (J2000)| (J2000)| (km s\(^{-1}\))| (km s\(^{-1}\))| (arcsec)    |       | (mag)     | (degrees) | (seconds) | (@ 8500 Å) |
| LSB galaxies    |        |        |            |               |             |       |           |        |          |     |
| ESO0215-G39     | 11h17m04s | −49°12’05’’ | 162±3 | 71±11 | 4.5 | 4335 | SABc | 12.01 | 50 | 500 | 20.03 |
| ESO0268-G44     | 12h48m42s | −45°06’29’’ | 190±9 | 70±9  | 3.5 | 3477 | Sb   | 12.22 | 62 | 450 | 25.08 |
| ESO0222-G19     | 12h20m07s | −40°40’24’’ | 141±9 | 49±10 | 0   | 3190 | Sbc  | 12.64 | 79 | 900 | 22.19 |
| ESO0234-G24     | 12h55m01s | −40°58’20’’ | 158±4 | 54±9  | 4   | 4203 | Sc   | 11.53 | 69 | 450 | 30.32 |
| ESO0235-G73     | 13h04m02s | −38°11’57’’ | 163±7 | 70±7  | 2   | 4929 | Sbc  | 12.44 | 48 | 450 | 35.29 |
| ESO0374-G03     | 09h51m57s | −33°04’25’’ | 146±3 | 40±6  | 6   | 2931 | SAbc | 11.51 | 71 | 600 | 21.80 |
| ESO0382-G06     | 13h05m32s | −32°57’38’’ | 171±4 | 54±8  | 2   | 4809 | Sab  | 13.20 | 54 | 600 | 21.01 |
| ESO0444-G21     | 13h23m31s | −30°06’52’’ | 116±21 | 53±9 | 4.5 | 4265 | Sc   | 12.86 | 84 | 1900 | 20.46 |
| ESO0444-G47     | 13h28m25s | −31°51’28’’ | 154±6 | 61±14 | 0   | 4389 | Sbc  | 12.82 | 71 | 900 | 22.01 |
| ESO0509-G91     | 13h40m03s | −25°28’26’’ | 203±9 | 62±11 | 6.5 | 5113 | Sbc  | 12.70 | 79 | 900 | 20.91 |
| ESO0376-G10     | 12h42m09s | −36°56’07’’ | 220±11 | 54±12 | 7   | 3184 | Sbd  | 11.00 | 76 | 600 | 20.27 |
| HSB galaxies    |        |        |            |               |             |       |           |        |          |     |
| NGC 3953        | 11h53m40s | +52°19’36’’ | 223±5 | 115±9 | 66  | 1052 | Sbc  | 9.03  | 63 | 2500 | 60.01 |
| NGC 3877        | 11h46m08s | +47°29’40’’ | 167±11 | 84±8  | 53.5 | 895  | Sc   | 9.91  | 83 | 3600 | 66.08 |
| NGC 4088        | 12h05m34s | +50°32’21’’ | 173±14 | 62±7  | 76  | 757  | SAbc | 9.51  | 71 | 3600 | 58.13 |
| NGC 3949        | 11h53m41s | +47°51’32’’ | 164±7 | 63±5  | 36  | 800  | Sbc  | 10.23 | 56 | 4000 | 57.15 |
| NGC 4157        | 12h11m04s | +50°29’05’’ | 185±10 | 71±6  | 35  | 774  | SAbc | 9.93  | 90 | 4000 | 63.30 |
| NGC 3769        | 11h37m44s | +47°53’35’’ | 122±8 | 80±7  | 29  | 737  | Sb   | 11.08 | 78 | 8000 | 66.25 |
| NGC 3726        | 11h33m21s | +47°01’45’’ | 162±9 | 63±10 | 84  | 866  | Sc   | 9.50  | 49 | 6600 | 38.44 |

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