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Observational evidence for a connection between supermassive black holes and dark matter haloes

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ABSTRACT

We present new velocity dispersion measurements of a sample of 12 spiral galaxies for which extended rotation curves are available. These data are used to refine a recently discovered correlation between the circular velocity and the central velocity dispersion of spiral galaxies. We find a slightly steeper slope for our larger sample, confirm the negligible intrinsic scatter on this correlation and find a striking agreement with the corresponding relation for elliptical galaxies. We combine this correlation with the well-known $M_{\rm BH}$–σ relation to obtain a tight correlation between the circular velocities of galaxies and the masses of the supermassive black holes they host. This correlation is the observational evidence for an intimate link between dark matter haloes and supermassive black holes. Apart from being an important ingredient for theoretical models of galaxy formation and evolution, the relation between $M_{\rm BH}$ and circular velocity can serve as a practical tool to estimate black hole masses in spiral galaxies.

Key words: black hole physics – galaxies: fundamental parameters – galaxies: haloes – galaxies: spiral – dark matter.

1 INTRODUCTION

Soon after the discovery of quasars in the 1960s, it was recognized that only supermassive black holes (SMBHs) in the centres of galaxies could provide the mechanism to feed active nuclei. An intriguing problem arose, however, when it became clear that quasars were much more abundant in the early Universe: what happened to these SMBHs? A natural explanation is that SMBHs still reside in the centres of present-day galaxies, but somehow the fuelling of the active nucleus stopped, for example due to the competition with star formation (Di Matteo et al. 2003). The detection of SMBHs in quiescent galaxies is a difficult task. Except for some special cases such as NGC 4258 (Miyoshi et al. 1995) and the Milky Way (Ghez et al. 1998; Genzel et al. 2000), the detection of a SMBH depends on stellar or gas kinematics. In order to be able actually to detect the SMBH, it is necessary to resolve the sphere of influence, i.e. the central region where the black hole starts to dominate the potential of the galaxy. With the limited resolution of ground-based spectrographs, this was possible for only a handful of nearby galaxies. This changed drastically with the advent of the *HST*, the excellent spatial resolution of which enabled to resolve the SMBH for a few dozen nearby galaxies (see Tremaine et al. 2002, and references therein). In nearly all of the investigated galaxies, SMBHs were discovered with masses roughly between 10^7 and 10^9 $M_\odot$. Very recently, the detections of SMBHs of much lower masses have been reported in globular clusters (Gebhardt, Rich & Ho 2002; Gerssen et al. 2002, 2003), although these detections are still controversial (Baumgardt et al. 2003a,b; Ho, Terashima & Okajima 2003).

Having detected and measured SMBHs for a sizable sample of nearby galaxies, we can proceed to tackle more fundamental questions concerning their formation and evolution. A convenient way to do so is by studying the relation between SMBHs and the galaxies that host them. It was found that black hole masses are correlated with parameters of the bulges of their host galaxies. Nearly ten years ago, Kormendy & Richstone (1995) found a correlation between the mass $M_{\rm BH}$ of the SMBH and the blue magnitude $L_{\rm B}$ of the bulge. More recently, a tighter correlation between $M_{\rm BH}$ and the velocity dispersion σ of the bulge was discovered independently by Gebhardt et al. (2000) and Ferrarese & Merritt (2000). Finally, Graham et al. (2001) presented an intriguing correlation between $M_{\rm BH}$ and the so-called concentration parameter of the bulge (or Sérsic index), in the sense that bulges with more massive black holes have steeper cusps.

This apparently tight link between bulges and SMBHs reflects an important ingredient that should be reproduced (and hopefully explained) by theoretical models of galaxy formation. Actually, the tightness of the correlations mentioned above is somewhat surprising. Indeed, in most of the state-of-the-art models (e.g. Silk & Rees

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1998; Adams, Graff & Richstone 2000; Kauffmann & Haehnelt 2000; Burkert & Silk 2001; MacMillan & Henriksen 2002; Wyithe & Loeb 2002; Volonteri, Haardt & Madau; Di Matteo et al. 2003), the total galaxy mass (or dark matter mass M_{DM}), rather than the bulge mass, plays a fundamental role in shaping the SMBHs. A close correlation could therefore be expected between M_{BH} and M_{DM}, rather than between M_{BH} and the properties of the bulge.

Unfortunately, this hypothesis is not straightforward to test observationally, because the measurement of M_{DM} and M_{BH} are difficult. An interesting approach to tackle this problem was taken by Ferrarese (2002a). She argued that a correlation between M_{BH} and M_{DM} should be reflected in a M_{BH}–v_{c} correlation, where v_{c} is the circular velocity in the flat part of the rotation curve of spiral galaxies. Unfortunately, there are only four spiral galaxies with secure SMBH masses (Genzel et al. 2000; Miyoshi et al. 1995; Bacon et al. 2001; Lodato & Bertin 2003), and only two of them have a measured rotation curve. Therefore, Ferrarese used the tight M_{BH}–σ correlation to estimate black hole masses in a larger sample of galaxies: in fact, from a literature search, she found a tight correlation between v_{c} and σ (with both v_{c} and σ measured in km s^{-1}),

$$\log v_{\mathrm{c}} = (0.84 \pm 0.09) \log \sigma + (0.55 \pm 0.19). \quad (1)$$

The tightness of this correlation (it has a negligible intrinsic scatter) suggests an intimate link between SMBHs and dark matter haloes. A possible caveat in Ferrarese's analysis is that it is based on only 16 spiral galaxies, including three spirals with $\sigma < 70$ km s^{-1} which do not satisfy the relation (1). A larger data base of galaxies with extended rotation curves and velocity dispersion measurements would be useful to check and refine this correlation. This is the goal of the present Letter. We discuss the sample selection, the observations and data reduction in Section 2. We analyse and discuss these data in Section 3.

2 THE DATA SET

We aim to increase the number of galaxies with accurate measurements of the circular velocity and the central velocity dispersion, in order to investigate a possible link between SMBHs and dark haloes. It is a well-known fact that the velocity dispersion of galaxies is a fairly difficult quantity to measure accurately: values for the velocity dispersion quoted in the literature often differ considerably depending on the authors' favorite fitting techniques, template stars, absorption line, signal-to-noise ratio, etc. In order to construct a reliable sample of galaxies, we therefore chose to select galaxies from a homogeneous sample with measured extended rotation curves, and to measure the velocity dispersions in a consistent way.

Our galaxies were drawn from the sample of Palunas & Williams (2000), who present a sample of 74 southern spiral galaxies. For each of these galaxies they constructed axisymmetric mass models based on accurate two-dimensional Hα velocity fields and I-band imaging. 32 of these galaxies have rotation curves extending to beyond the optical radius,[1] 26 of which are reasonable smooth. These formed an ideal target for our study. We were granted one night of observing time (2002 May 4) to measure the velocity dispersion of these 26 galaxies at the ESO 3.6-m telescope in La Silla. Unfortunately, owing to a very poor sky transmission, the exposure times had to be multiplied by a factor of 2.5 to obtain a sufficient signal-to-noise ratio, such that we could only observe 12 galaxies from the sample. The observed galaxies are listed in Table 1.

Table 1. The galaxies in our sample. The galaxies above the horizontal line are the galaxies from Palunas & Williams (2000) for which we have obtained a velocity dispersion. The galaxies below the horizontal line are the galaxies from Ferrarese (2002a) with a rotation curve extending beyond the optical radius. The first two columns contain the name and morphological type of the galaxies. The third and fourth columns contain the circular velocity and bulge velocity dispersion of the galaxies, with errors. The last column contains an estimate of the SMBH mass, based on the M_{BH}–σ relation (see text).

Name	Type	v_{c} (km s^{-1})	σ (km s^{-1})	$\log M_{\mathrm{BH}}$ ($\mathrm{M}_{\odot}$)
NGC 3038	Sb	256 ± 22	160 ± 16	7.74 ± 0.19
NGC 3223	Sb	281 ± 21	179 ± 10	7.94 ± 0.12
NGC 3333	SBbc	208 ± 12	111 ± 23	7.10 ± 0.38
ESO 323-G25	SBbc	228 ± 15	139 ± 14	7.50 ± 0.19
ESO 382-G58	Sbc	315 ± 20	165 ± 22	7.80 ± 0.24
ESO 383-G02	SBc	190 ± 14	109 ± 28	7.07 ± 0.46
ESO 383-G88	SBc	177 ± 16	70 ± 14	6.30 ± 0.38
ESO 445-G15	Sbc	190 ± 21	113 ± 13	7.13 ± 0.22
ESO 445-G81	SBbc	233 ± 9	134 ± 9	7.43 ± 0.14
ESO 446-G01	Sbc	213 ± 17	123 ± 12	7.28 ± 0.19
ESO 446-G17	Sbc	199 ± 14	145 ± 17	7.57 ± 0.22
ESO 501-G68	Sbc	173 ± 9	100 ± 16	6.92 ± 0.30
Milky Way	SBbc	180 ± 20	100 ± 20	6.92 ± 0.37
M31	Sb	240 ± 20	146 ± 15	7.58 ± 0.19
M33	Sc	135 ± 13	27 ± 7	4.63 ± 0.54
M63	Sbc	180 ± 5	103 ± 6	6.97 ± 0.15
NGC 801	Sc	216 ± 9	144 ± 27	7.56 ± 0.34
NGC 2841	Sb	281 ± 10	179 ± 12	7.94 ± 0.13
NGC 2844	Sa	171 ± 10	113 ± 12	7.13 ± 0.21
NGC 2903	SBbc	180 ± 4	106 ± 13	7.02 ± 0.24
NGC 2998	SBc	198 ± 5	113 ± 30	7.13 ± 0.48
NGC 3198	SBc	150 ± 3	69 ± 13	6.27 ± 0.36
NGC 4062	SBc	154 ± 13	90 ± 7	6.73 ± 0.19
NGC 4258	SBbc	210 ± 20	138 ± 18	7.48 ± 0.24
NGC 4565	Sb	264 ± 8	151 ± 13	7.64 ± 0.17
NGC 5033	Sc	195 ± 5	122 ± 9	7.27 ± 0.16
NGC 6503	Sc	116 ± 2	48 ± 10	5.64 ± 0.42
NGC 7331	Sbc	239 ± 5	139 ± 14	7.50 ± 0.19

We have taken long-slit spectra of these 12 galaxies with the EFOSC2 instrument through a 0.5 arcsec slit, giving a spectral resolution of 0.31 nm FWHM. We used the Gr#08 grating, which enabled to measure the velocity dispersions of the galaxies from the Mg I and Fe lines around 520 nm. The exposure time varied from 25 min to 150 min for the faintest galaxies. Standard data reduction and calibration of the spectra were carried out with the ESO-MIDAS package. This includes bias subtraction and trimming, cosmics removal, wavelength calibration (Legendre order 4 is used), removal of the S-distortion/tilt of the slit, sky subtraction and airmass correction. No effort was done to flux-calibrate the spectra, as we are only interested in the velocity dispersion. The reduced spectra have a wavelength domain between 430 and 630 nm, with a pixel scale of 9.8 nm pixel^{-1}.

The velocity dispersion σ of the galaxies was determined by means of a direct χ^2 fitting technique, which fits line profiles directly to the spectra after convolution with a stellar velocity template spectrum. The fitting routine calculates the full covariance matrix, from which we could determine the error bars on the dispersion. The spatial aperture over which the fit was done was chosen to maximize the signal-to-noise ratio of the spectrum, which was targeted to be

[1] The optical radius used by Palunas & Williams (2000) is $R_{23.5}$, which is the radius of the isophote corresponding to an I-band surface brightness of 23.5 mag arcsec^{-2}.

of the order of 15. In fact, our signal-to-noise values ranged between 11 and 35. We found that the value of the dispersion did not depend sensitively on the extent of the aperture. The velocity dispersions of our 12 galaxies can be found in the upper part of Table 1.

The circular velocities of galaxies were taken from table 1 of Palunas & Williams (2000). These are determined by taking a weighted average of the rotation curve points where the rotation curve becomes flat. We repeated this exercise on the original data, which were kindly provided in tabular form by P. Palunas, to obtain an estimate for the errors on the circular velocity. We find identical values as Palunas & Williams (2000), with errors of the order of 5 to 10 per cent.

3 ANALYSIS AND DISCUSSION

3.1 The correlation between v_c and σ

Combining our 12 galaxies with the 16 spiral galaxies from the compilation of Ferrarese (2002a) with a rotation curve extending beyond the optical radius (see Table 1), we obtain a total sample of 28 galaxies. In the left panel of Fig. 1 we plot the circular velocity versus the velocity dispersion for these 28 galaxies. For the 24 galaxies with a velocity dispersion greater than about 80 km s^{-1}, there is a very tight correlation between v_c and σ. We fitted a straight line to these data, taking into account the errors on both quantities (Press et al. 2002), and obtained

$$\log v_c = (0.96 \pm 0.11) \log \sigma + (0.32 \pm 0.25). \tag{2}$$

In this correlation, both v_c and σ are expressed in km s^{-1}. However, in a linear regression analysis, this is not the most meaningful unit to express these quantities. Tremaine et al. (2002) argued that the choice of appropriate units is important to avoid a strong correlation of the errors in slope and zero-point. When we repeat our fitting routine after choosing a new unit $u_0 = 200$ km s^{-1}, we obtain as a best fit

$$\log\left(\frac{v_c}{u_0}\right) = (0.96 \pm 0.11) \log\left(\frac{\sigma}{u_0}\right) + (0.21 \pm 0.02), \tag{3}$$

where indeed the uncertainty on the zero-point is much smaller.

Our newly derived v_c–σ relation has a slightly larger slope than the original correlation (1) found by Ferrarese (2002a) based on 13 galaxies. Both slope and zero-point are consistent within the 1σ error bar, though. The tightness of the correlation is still astonishing: we find a reduced $\chi_r^2 = 0.281$, corresponding to a goodness-of-fit of 99.9 per cent. The v_c–σ relation can hence be regarded as having a negligible intrinsic scatter. Important, moreover, is the fact that this correlation appears to be robust: even with the sample of galaxies nearly doubled, there are still no significant outliers. Ferrarese's v_c–σ correlation broke down for galaxies with dispersions below about 80 km s^{-1}. We confirm this result: the only galaxy we observed with $\sigma < 80$ km s^{-1} (ESO 383-G88) joins the three galaxies from Ferrarese's original sample (M33, NGC 3198 and NGC 6503) in lying significantly above this correlation.

It is interesting to compare this correlation to a corresponding one recently found for elliptical galaxies. Based on stellar dynamical models for 20 ellipticals constructed by Kronawitter et al. (2000), Gerhard et al. (2001) discovered a very tight relation between the central dispersion and the circular velocity (the circular velocity curves of ellipticals were found to be flat to within 10 per cent). Ferrarese (2002a) reports for these 20 ellipticals the correlation

$$\log v_c = (0.94 \pm 0.11) \log \sigma + (0.31 \pm 0.26), \tag{4}$$

with a reduced $\chi_r^2 = 0.66$. Both the slope and zero-point of this correlation agree amazingly well with the v_c–σ correlation (2) of our spiral galaxy sample. These expressions represents a nearly direct proportionality between the bulge velocity dispersion and the halo circular velocity, with the proportionality constant about two-thirds. To first order, elliptical galaxies form a dynamically uniform family, such that we expect a proportionality between σ and v_c (Gerhard et al. 2001). For spiral galaxies, however, this proportionality cannot be explained by simple dynamical arguments, as convincingly argued by Ferrarese (2002a). The fact that there is such a strong correlation between both velocity scales in spiral galaxies is hence not obvious, and indicates a fundamental correlation in the structure of spirals. Moreover, the fact that both spiral and elliptical galaxies obey exactly the same correlation is very striking.

3.2 The correlation between $M_{\rm BH}$ and v_c

Although derived from mainly late-type spirals (all galaxies in our sample except NGC 2844 have a Hubble type of Sb or later) with σ between 90 and 180 km s^{-1}, the v_c–σ correlation appears to

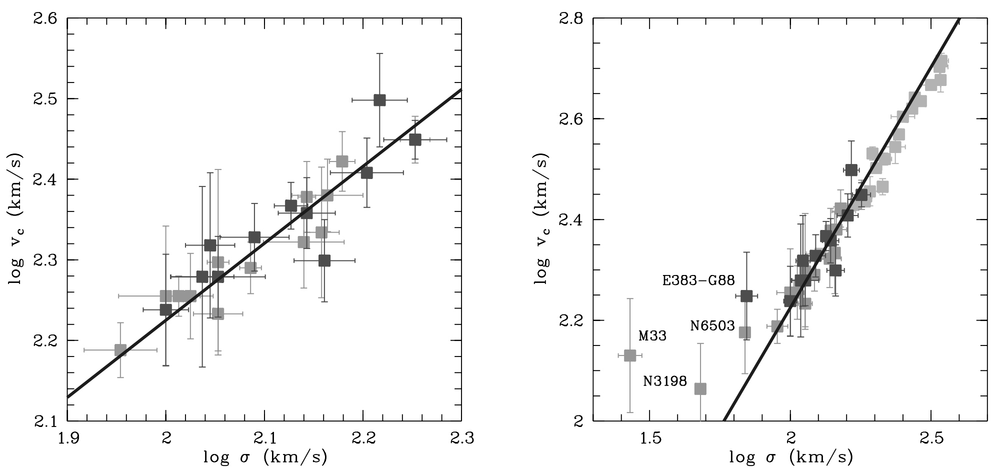

Figure 1. The correlation between the circular velocity v_c and the central velocity dispersion σ. The left-hand plot shows the v_c–σ correlation for the 24 spiral galaxies with rotation curve beyond the optical radius and a velocity dispersion $\sigma > 80$ km s^{-1}. The lighter dots are the data points from the sample of Ferrarese (2002a), the darker dots are the galaxies with new velocity dispersion from this paper. The right-hand plot zooms out and adds the elliptical galaxies from Kronawitter et al. (2000) to this plot. The straight line in both panels represents equation (3).

hold as well for a larger class of galaxies, ranging from ellipticals to late-type spirals, with a dispersion range up to 350 km s^{-1}. A similar situation appears to apply for the $M_{\rm BH}$–σ relation. From the three recently discovered empirical relations linking $M_{\rm BH}$ to the bulge properties of the host galaxies (see Introduction), the $M_{\rm BH}$–σ relation is the tightest one. The two original papers describing this correlation found significantly different slopes: 4.8 ± 0.5 (Ferrarese & Merritt 2000) versus 3.75 ± 0.3 (Gebhardt et al. 2000). There has been lively discussion regarding the exact slope of this relation, and it is argued that these differences can be ascribed to different fitting techniques, different samples and different measures of *the* central velocity dispersion (Merritt & Ferrarese 2001a; Merritt & Ferrarese 2001b; Tremaine et al. 2002). The most up-to-date version of the $M_{\rm BH}$–σ correlation, from Tremaine et al. (2002), reads

$$\log\left(\frac{M_{\rm BH}}{\rm M_{\odot}}\right) = (4.02 \pm 0.32)\log\left(\frac{\sigma}{u_0}\right) + (8.13 \pm 0.06). \quad (5)$$

This relation is derived from empirical data for some 30 nearby galaxies galaxies with secure SMBH detections. Most of these galaxies are elliptical galaxies with only a minor fraction of spiral galaxies present. Nevertheless, this correlation seems to hold for lenticular and spiral galaxies with similar scatter, contrary to the $M_{\rm BH} - L_{\rm B}$ correlation (McLure & Dunlop 2002). Moreover, the SMBHs recently claimed to be detected in the globular clusters M15 and G1, also appear to satisfy the same $M_{\rm BH}$–σ relation (Gebhardt et al. 2002).

As both the $v_{\rm c}$–σ and $M_{\rm BH}$–σ correlations seem to hold over the entire Hubble range (see e.g. de Zeeuw (2003) for a critical note), we can combine them to derive a correlation between the circular velocity and SMBH mass. For all galaxies in our sample, we have estimated $M_{\rm BH}$ via the $M_{\rm BH}$–σ correlation given by equation (5). The results can be found in Table 1. Combining our best-fitting $v_{\rm c}$–σ relation (3) with the $M_{\rm BH}$–σ relation (5), we obtain

$$\log\left(\frac{M_{\rm BH}}{\rm M_{\odot}}\right) = (4.21 \pm 0.60)\log\left(\frac{v_{\rm c}}{u_0}\right) + (7.24 \pm 0.17). \quad (6)$$

In Fig. 2 (left panel) we plot the circular velocity versus the SMBH mass for the 24 galaxies of our sample with $\sigma > 80$ km s^{-1}: we find indeed a very tight correlation between $M_{\rm BH}$ and $v_{\rm c}$. Moreover, this correlation also holds for the elliptical galaxies of Kronawitter et al. (2000), as shown in the right panel of Fig. 2. For the least massive galaxies with $\sigma < 80$ km s^{-1}, this correlation again breaks down.

The correlation between SMBH mass and circular velocity is useful for two different goals. First, if a prescription can be found to link the circular velocity of a galaxy to the total dark halo mass $M_{\rm DM}$, we can transform this $M_{\rm BH}$–vc correlation to a direct correlation between SMBH mass and total galaxy mass, which can then be compared with theoretical models of galaxy formation. A conversion between these two quantities can in principle be derived from high-resolution CDM cosmological simulations (e.g. Navarro & Steinmetz 2000; Bullock et al. 2001). Using the simulation results of Bullock et al. (2001),

$$\frac{M_{\rm DM}}{10^{12}\,{\rm M_{\odot}}} \sim 1.40\left(\frac{v_{\rm c}}{u_0}\right)^{3.32}, \quad (7)$$

Ferrarese (2002a) converts $v_{\rm c}$ to $M_{\rm DM}$ and derives a relation between SMBH and dark halo masses. If we repeat the same exercise with our larger sample of spirals and the most up-to-date $M_{\rm BH}$–σ correlation, we find

$$\frac{M_{\rm BH}}{10^{8}\,{\rm M_{\odot}}} \sim 0.11\left(\frac{M_{\rm DM}}{10^{12}\,{\rm M_{\odot}}}\right)^{1.27}. \quad (8)$$

It should be noted, however, as indicated by Ferrarese (2002a), that the uncertainties in this conversion can be quite large. For example, a major uncertainty is how the baryonic infall in dark matter haloes affects the baryonic rotation curve (e.g. Seljak 2002). Therefore, the correlation (8) should be regarded as a rough guideline only. The $M_{\rm BH}$–$v_{\rm c}$ correlation (6) on the other hand is based solely on observed quantities, and has a much smaller uncertainty. This correlation therefore serves as an important (purely observational) constraint that should be reproduced and explained by theoretical galaxy formation models. Combined with other tight relations such as the $M_{\rm BH}$–σ relation and the Tully–Fisher relation, it clearly points at an intimate interplay between the various components (dark matter, discs, bulges and SMBHs), and forms a strong test for galaxy formation and evolution models.

Apart from being an ingredient in theoretical galaxy formation models, the derived $M_{\rm BH}$–$v_{\rm c}$ relation can also serve as a practical tool to estimate the black hole content for spiral galaxies. Owing to the large scatter of the $M_{\rm BH} - L_{\rm B}$ relation, the most reliable means of estimating $M_{\rm BH}$ in galaxies is by using the $M_{\rm BH}$–σ relation. Unfortunately, the number of spiral galaxies with reliable velocity dispersion measurements is relatively small. On the contrary, extended rotation curves have been measured for large samples of spiral galaxies, mainly for use in Tully–Fisher relation studies (e.g.

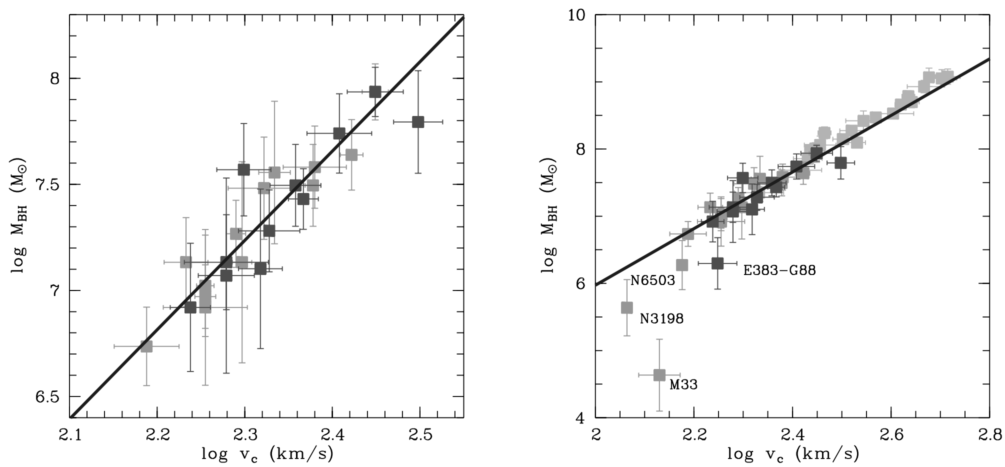

Figure 2. The correlation between the circular velocity $v_{\rm c}$ and the SMBH mass $M_{\rm BH}$. Black hole masses are estimated from the velocity dispersions through the $M_{\rm BH}$–σ relation, as given by equation (5). The layout is similar to Fig. 1. The straight line in both panels represents equation (3).

Persic & Salucci 1995; Courteau 1997; Verheijen & Sancisi 2001). This makes the tight $M_{\rm BH}$–$v_{\rm c}$ correlation a practical tool to estimate the black hole content of these galaxies. In particular, the $M_{\rm BH}$–$v_{\rm c}$ correlation can be used in a statistical way for SMBH demographics studies (e.g. Merritt & Ferrarese 2001c; Ferrarese 2002b; Aller & Richstone 2002; Yu & Tremaine 2002), by combining it with spiral galaxy velocity functions (Shimasaku 1993; Gonzalez et al. 2000). This falls beyond the scope of this Letter, and will be addressed in future work.

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