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$M_{\rm BH}$–σ relation between supermassive black holes and the velocity dispersion of globular cluster systems

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ABSTRACT

We find evidence that the mass $M_{\rm BH}$ of central supermassive black holes (SMBHs) correlates with the velocity dispersion $\sigma_{\rm GC}$ of globular cluster systems of their host galaxies. This extends the well-known $M_{\rm BH}$–$\sigma_{\rm sph}$ relation between black hole mass and velocity dispersion of the host spheroidal component. We compile published measurements of both $M_{\rm BH}$ and $\sigma_{\rm GC}$ for a sample of 13 systems and find the relation $\log{(M_{\rm BH})} = \alpha + \beta \log{(\sigma_{\rm GC}/200)}$, with $\alpha = 8.63 \pm 0.09$ and $\beta = 3.76 \pm 0.52$. We also consider blue (metal-poor) and red (metal-rich) globular cluster subpopulations separately and obtain a surprisingly tight correlation using only the velocity dispersion $\sigma_{\rm GC}^{\rm red}$ of the red clusters with $\alpha = 8.73 \pm 0.09$ and $\beta = 3.84 \pm 0.52$ and an intrinsic scatter $\varepsilon_0 = 0.22$ dex compared to $\varepsilon_0 = 0.27$ dex for the $M_{\rm BH}$–$\sigma_{\rm sph}$ relation of our sample. We use this $M_{\rm BH}$–$\sigma_{\rm GC}^{\rm red}$ relation to estimate the central black hole mass in five galaxies for which $\sigma_{\rm GC}^{\rm red}$ is measured.

Key words: black hole physics – galaxies: evolution – galaxies: fundamental parameters – globular clusters: general – galaxies: nuclei – galaxies: star clusters: general.

1 INTRODUCTION

It has been known for more than a decade that supermassive black holes (SMBHs) reside at the centre of many galaxies (Kormendy & Richstone 1995) and that their mass correlates with various properties of their host galaxies, for example with the spheroid luminosity (Magorrian et al. 1998), the spheroid velocity dispersion $\sigma_{\rm sph}$ (Ferrarese & Merritt 2000; Gebhardt et al. 2000; see also Gültekin et al. 2009, hereafter G09), the spheroid mass (Magorrian et al. 1998; Marconi & Hunt 2003) and the kinetic energy of random motions (Feoli & Mancini 2009). Recently, extension of these correlations to barred galaxies and pseudo-bulges (Graham 2008a,b; Hu 2008; Graham et al. 2011) as well as galaxies hosting nuclear star clusters (Ferrarese et al. 2006; Graham 2012) has also been proposed. In addition, a new correlation between the mass of SMBHs and the observed total number of globular clusters (GCs) of their host galaxies has been discovered (Burkert & Tremaine 2010, hereafter BT10; Harris & Harris 2011; see also Snyder, Hopkins & Hernquist 2011). The physics underlying these observations is not fully understood, but it is widely believed that feedback processes are responsible for such correlations (Silk & Rees 1998). It is not known whether these relations evolve with time or are primordial and have been set at the time of formation of the SMBHs and galaxies (Di Matteo, Springel & Hernquist 2005; Cox et al. 2006; Hopkins et al. 2007; Hopkins, Murray & Thompson 2009; Volonteri & Natarajan 2009). Furthermore, the physical scale at which the feedback is effective is still not clear. Studies emphasizing that black hole mass is coupled to the dark matter (DM) potential rather than the spheroid (Ferrarese 2002; Booth & Schaye 2010; Volonteri, Natarajan & Gültekin 2011) seem to indicate that feedback processes operate on large scales even though Kormendy & Bender (2011) argue that there is no direct relation between DM haloes and central black holes. Better and more data, extending to higher redshifts, shall shed more light on these questions.

In this Letter we provide evidence that the classical $M_{\rm BH}$–$\sigma_{\rm sph}$ relation between black hole mass and spheroid velocity dispersion is also working with the velocity dispersion of GC systems. We use the published data for the velocity dispersion $\sigma_{\rm GC}$ of the GC systems and the estimated black hole mass in 13 galaxies. We then study separately the two subpopulations: blue, metal-poor GCs and red, metal-rich and younger GCs which are generally closer to the centre of the galaxy. We show that the correlation degrades from the red to the blue GCs subpopulation.

This Letter is organized as follows. In Section 2, we present the data. The correlation between the mass of SMBHs and the velocity dispersions of the GC systems of their host galaxies is presented in Section 3. The red and blue subpopulations are studied separately in Section 4. In Section 5, we estimate the black hole mass for five galaxies and conclude in Section 6.

2 THE DATA

We have found 19 galaxies for which measurements of the line-of-sight velocity dispersion of the GC system are known. 13 of these are accompanied by the estimate of the mass of their central black

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Table 1. Sample of galaxies with measured line-of-sight velocities of GCs and mass of the central black hole.

Galaxy		Type	$M_{\rm BH}$ ($\rm M_{\odot}$)	Ref.	$\sigma_{\rm GC}$ ($\rm km\,s^{-1}$)	$\sigma_{\rm GC}^{\rm blue}$ ($\rm km\,s^{-1}$)	$\sigma_{\rm GC}^{\rm red}$ ($\rm km\,s^{-1}$)	Ref.
NGC 224	M31	Sb	$1.5^{+0.9}_{-0.3} \times 10^8$	1	134^{+5}_{-5}	129^{+8}_{-6}	121^{+9}_{-10}	6
NGC 524		S0	$8.3^{+2.7}_{-1.3} \times 10^8$	9	186^{+29}_{-29}	197^{+39}_{-39}	169^{+43}_{-43}	5
NGC 1316	Fornax A	SAB	$1.5^{+0.75}_{-0.8} \times 10^8$	2	202^{+33}_{-33}			7
NGC 1399		E1	$1.3^{+0.5}_{-0.66} \times 10^9$	1	274^{+9}_{-9}	291^{+14}_{-14}	255^{+13}_{-13}	8
			$5.1^{+0.7}_{-0.7} \times 10^8$					
NGC 3031	M81	Sb	$8.0^{+2.0}_{-1.1} \times 10^7$	1	128^{+9}_{-9}	141^{+15}_{-15}	125^{+11}_{-11}	10
NGC 3379		E0	$1.2^{+0.8}_{-0.58} \times 10^8$	1	175^{+24}_{-22}			11
NGC 4472	M49	E4	$1.5^{+0.2}_{-0.2} \times 10^9$	4	312^{+27}_{-8}	342^{+33}_{-18}	265^{+34}_{-13}	12
NGC 4486	M87	E1	$3.6^{+1.0}_{-1.0} \times 10^9$	1	320^{+11}_{-11}	335^{+15}_{-15}	295^{+23}_{-23}	13
NGC 4594	M104	Sa	$5.7^{+4.4}_{-4.0} \times 10^8$	1	204^{+16}_{-16}	203	207	14
NGC 4649	M60	E2	$2.1^{+0.5}_{-0.6} \times 10^9$	1	217^{+14}_{-16}	207^{+15}_{-19}	240^{+20}_{-34}	16
NGC 5128	Cen A	S0/E	$3.0^{+0.4}_{-0.2} \times 10^8$	1	150^{+2}_{-2}	149^{+4}_{-4}	156^{+4}_{-4}	17
			$7.0^{+1.3}_{-3.8} \times 10^7$					
NGC 7457		S0	$4.1^{+1.2}_{-1.7} \times 10^6$	1	69^{+12}_{-12}			3
MW		Sbc	$4.3^{+0.4}_{-0.4} \times 10^6$	18		120^{+14}_{-14}	61^{+10}_{-10}	15

References: (1) G09; (2) Nowak et al. (2008); (3) Chomiuk, Strader & Brodie 2008; (4) Shen & Gebhardt (private communication); (5) Beasley et al. (2004); (6) Lee et al. (2008); (7) Goudfrooij et al. (2001); (8) Richtler et al. (2004); (9) Krajnović et al. (2009); (10) Nantais & Huchra (2010); (11) Bergond et al. (2006); (12) Côté et al. (2003); (13) Strader et al. (2011); (14) Bridges et al. (2007); (15) Zinn (1996); (16) Hwang et al. (2008); (17) Woodley et al. (2010); (18) Gillessen et al. (2009).

hole. These galaxies are presented in Table 1. To our knowledge, the mass of the central black holes has not yet been determined for the six other galaxies for which we have the velocity dispersion of the GC system: NGC 1407 (Romanowsky et al. 2009), NGC 3923 (Norris et al. 2012), NGC 4494 (Foster et al. 2011), NGC 4636 (Lee et al. 2010), Large Magellanic Cloud (LMC; Freeman, Illingworth & Oemler 1983) and M33 (Schommer et al. 1991; Chandar et al. 2002).

2.1 Velocity dispersion of globular cluster systems

Galaxies for which we found measurements of $\sigma_{\rm GC}$ as well as $\sigma_{\rm GC}^{\rm red}$ and $\sigma_{\rm GC}^{\rm blue}$ are listed in Table 1 along with the corresponding references. Whenever available, we use the value of $\sigma_{\rm GC}$ corrected for the global rotation of the GC system. Comments on individual systems are given below.

(i) *NGC 1399*. We use the results of Richtler et al. (2004) which give $\sigma_{\rm GC}$ for all GCs and for both red and blue subpopulations. Schuberth et al. (2010) give detailed results for different subsamples and different distances which are in general not too different from Richtler et al. (2004).

(ii) *NGC 3031 (M81)*. Results have been obtained separately by Perelmuter, Brodie & Huchra (1995), Schroder et al. (2002) and Nantais & Huchra (2010). We use the values given by Nantais & Huchra (2010) which are consistent with the other groups. Measurement uncertainties in $\sigma_{\rm GC}$, $\sigma_{\rm GC}^{\rm red}$ and $\sigma_{\rm GC}^{\rm blue}$ were provided by Nantais (private communication).

(iii) *NGC 4594 (M104)*. The value of $\sigma_{\rm GC}$ is taken from Bridges et al. (2007). They also measured $\sigma_{\rm GC}^{\rm red}$ and $\sigma_{\rm GC}^{\rm blue}$ but do not give the corresponding error bars. Consequently, we do not include M104 in our best-fitting estimate when treating red and blue GCs separately.

(iv) *Milky Way*. Zinn (1996) gives $\sigma_{\rm GC}$ for three groups of GCs lying approximately around the direction of the galactic centre. The corresponding line of sights are therefore nearly parallels and we can treat the measured radial velocities as projection on a single line of sight similarly to what is done for external galaxies. The three groups are metal-poor (blue), red clusters lying between 2.7 and 6 kpc from the galactic centre, and very metal rich disc clusters. We choose the dispersion of the red clusters ($\sigma_{\rm GC}^{\rm red} = 61 \pm 10\,{\rm km\,s^{-1}}$) to compare with the dispersion of red GCs in others galaxies. We note that a similar value was found by Harris (1999) for metal-rich clusters lying in the range 4–9 kpc. Concerning the metal-poor clusters, we retain the value $\sigma_{\rm GC}^{\rm blue} = 120 \pm 14\,{\rm km\,s^{-1}}$ given by Harris (1999). However, we point out that comparison with external galaxies is not straightforward in this case since we can no longer consider the projection of cluster velocities on a single line of sight.

2.2 Mass of central black holes

The mass of central black holes in nine out of the 13 galaxies in our sample, namely NGC 224, NGC 1399, NGC 3031, NGC 3379, NGC 4486, NGC 4594, NGC 4649, NGC 5128, NGC 7457 and Milky Way (MW) has been studied and analysed by G09. To avoid systematic errors and for general consistency, we have decided to use these results although we are aware that other values also exist in the literature. For NGC 1399 and NGC 5128, G09 give two possible values for the mass. We follow their procedure and include both values with a weight of 1/2 when performing the linear fit, a method also used by BT10. For the MW, we use $M_{\rm BH} = 4.3 \times 10^6\,{\rm M_{\odot}}$ from Gillessen et al. (2009) (G09 give $M_{\rm BH} = 4.1 \times 10^6\,{\rm M_{\odot}}$).

For NGC 4636 only two upper limits for $M_{\rm BH}$ are given in Beifiori et al. (2009). We do not incorporate these values in the determination of the parameters of the relation. However, we still include a posteriori NGC 4636 in all of the presented figures by taking the mean of the values found in Beifiori et al. (2009) as an upper limit for $M_{\rm BH}$.

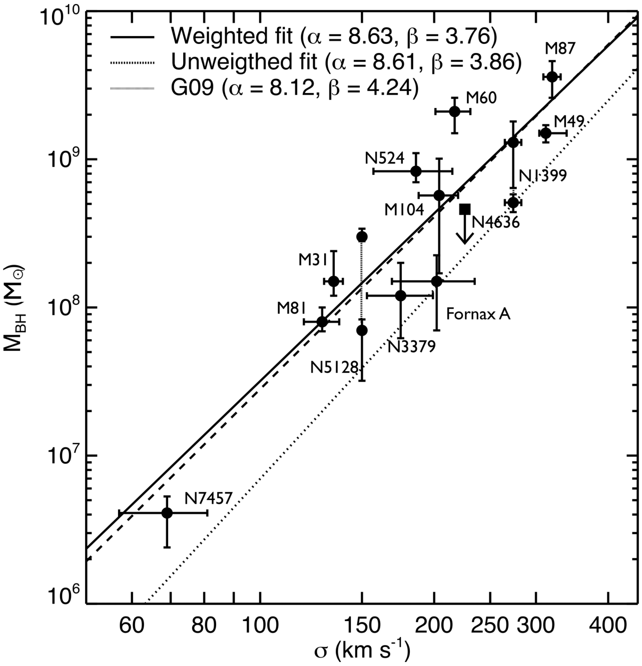

Figure 1. Mass $M_{\rm BH}$ as a function of $\sigma_{\rm GC}$ for the 12 galaxies in our sample. Circles indicate galaxies included in the fitting procedure. NGC 4636, for which only an upper limit of $M_{\rm BH}$ is available, is shown as a square. The solid black line is the best-fitting relation obtained using the weighted χ^2 minimization procedure of Tremaine et al. (2002). The dashed line is the best-fitting relation found using an unweighted least-squares method without taking into account error bars. The dotted line is the M–σ relation of G09.

3 THE $M_{\rm BH}$–$\sigma_{\rm GC}$ RELATION

In Fig. 1 we plot the central black hole mass $M_{\rm BH}$ versus the velocity dispersion $\sigma_{\rm GC}$ of the GC system with the error bars (see Table 1). To facilitate comparison with the previous works of G09, we use the same presentation. We assume a relation of the form $\log\left(\mathrm{M_{BH}/M_{\odot}}\right) = \alpha + \beta\,\log\left(\sigma_{\rm GC}/200\,\mathrm{km\,s^{-1}}\right)$. The parameters of the relation are calculated by the χ^2 minimization technique of Tremaine et al. (2002) using the IDL MPFITEXY routine (Williams, Bureau & Cappellari 2010) which includes error bars in both $M_{\rm BH}$ and $\sigma_{\rm GC}$ (weighted fit) and allows the determination of the intrinsic scatter ε_0 in $M_{\rm BH}$ at fixed $\sigma_{\rm GC}$. The MPFITEXY routine depends on the MPFIT package (Markwardt 2009). We also carry out a standard linear least-squares fit without taking into account error bars (unweighted fit) for comparison. We obtain $\alpha = 8.63 \pm 0.09$ and $\beta = 3.76 \pm 0.52$ for the weighted fit (Table 2). For the full sample used by G09, these values are $\alpha = 8.12 \pm 0.08$ and $\beta = 4.24 \pm 0.41$. The slope of the relation between $M_{\rm BH}$ and $\sigma_{\rm GC}$ is consistent with the one obtained by G09. However, for the same $M_{\rm BH}$ the velocity dispersion of the GC system is systematically smaller than that obtained for the spheroid. The intrinsic scatter we found is $\varepsilon_0 = 0.27$. As a comparison, we have examined the usual $M_{\rm BH}$–$\sigma_{\rm sph}$ relation using the galaxies in our sample with values of $\sigma_{\rm sph}$ taken from G09 and obtained a similar value of $\varepsilon_0 = 0.27$ with the same fitting procedure. Thus, it seems that, for the limited number of galaxies in our sample, $M_{\rm BH}$ correlates equally well with either $\sigma_{\rm sph}$ or $\sigma_{\rm GC}$.

Table 2. Values of the parameter of the relation $\log\left(\mathrm{M_{BH}/M_{\odot}}\right) = \alpha + \beta\log\left(\sigma/200\,\mathrm{km\,s^{-1}}\right)$ for the full GC system as well as for the red and blue subpopulations.

	α	β	ε_0
Full sample	8.63 ± 0.09	3.76 ± 0.52	0.27
Red GCs	8.73 ± 0.09	3.84 ± 0.52	0.22
Blue GCs	8.66 ± 0.12	3.00 ± 0.72	0.33

4 RELATION FOR BLUE AND RED GLOBULAR CLUSTER SYSTEMS

GCs are usually divided into two subpopulations with different features: the metal-poor GCs which are generally older and have a shallower number density profile than the metal-rich GCs which consist mostly of younger objects associated with the spheroid and lying closer to the centre. The two subpopulations are often referred to as the blue and red GC subpopulations, respectively. Here, we examine separately the $M_{\rm BH}$–$\sigma_{\rm GC}$ relation of these two categories.

Concerning the red GCs, measurements of $\sigma_{\rm GC}^{\rm red}$ were available for nine systems in our sample (including the red subpopulation for the MW). The data points as well as the best-fitting relations are shown in Fig. 2 (the same fitting techniques detailed in Section 3 were used here for the red and blue GCs). The relation we find has $\alpha = 8.73 \pm 0.09$ and $\beta = 3.84 \pm 0.52$ with an intrinsic scatter $\varepsilon_0 = 0.22$, making it a *tighter* relation than the $M_{\rm BH}$–$\sigma_{\rm sph}$ relation for the same sample. However, since the MW probes a rather different region of parameter space and because its black hole mass is known to be of high accuracy compared to other systems, it could potentially introduce a bias in the estimation of the parameters. None the less, we found little difference in the resulting parameters even if we removed the MW. We also point out that both fitting methods gave almost the same results, indicating that the parameters are well

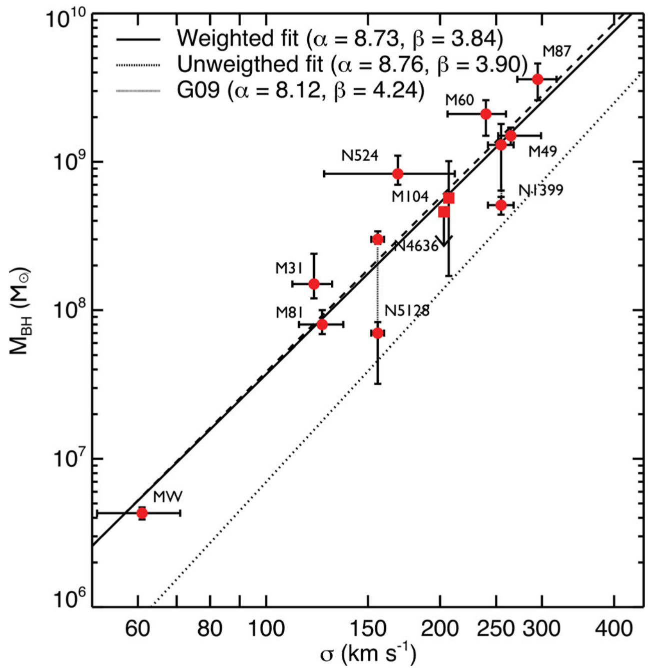

Figure 2. Mass $M_{\rm BH}$ versus velocity dispersion $\sigma_{\rm GC}^{\rm red}$ of the red, metal-rich GC system for galaxies in our sample. As in Fig. 1, circles are data points included in the fitting procedure, whereas squares are systems which do not contribute to the best-fitting relation, namely NGC 4594 and NGC 4636. The lines have the same meaning as in Fig. 1.

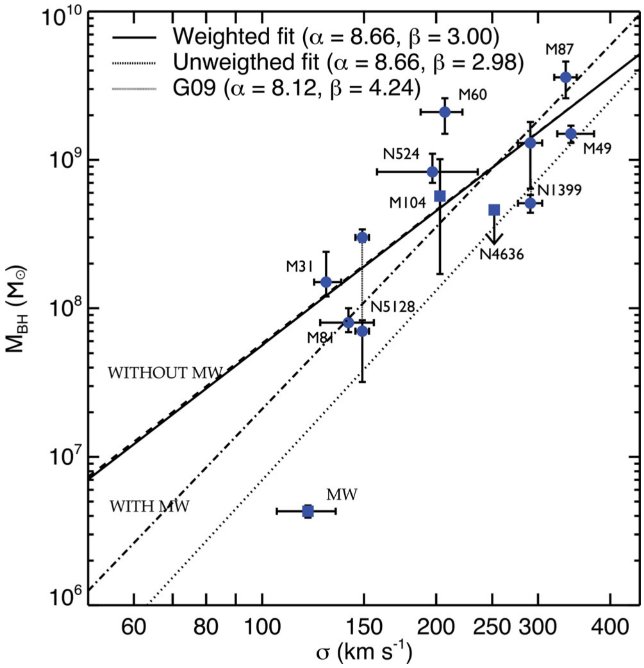

Figure 3. Same as Fig. 2, but considering the velocity dispersion $\sigma_{\rm GC}^{\rm blue}$ of the blue, metal-poor GC system. The dot–dashed line is the best fit obtained by including the MW in the fitting procedure.

constrained. We note that our value of β is close to the value given by G09 for early-type galaxies ($\beta = 3.86$) and ellipticals ($\beta = 3.96$).

For blue GCs (Fig. 3), we obtain $\alpha = 8.66 \pm 0.12$ and $\beta = 3.00 \pm 0.72$ without including the MW. The intrinsic scatter $\varepsilon_0 = 0.33$ is larger than the previous one obtained for either the full GC system or the red GCs and the slope is also only marginally consistent with both estimates. Thus, it seems that SMBHs and metal-poor GCs are only weakly connected. Note that if we include the MW, we obtain a higher value for the slope $\beta = 4.07 \pm 0.89$, which is more consistent with G09 and with the metal-rich GCs, but the scatter is even larger in this case.

Finally, we point out that, according to our best-fitting relations for red and blue GCs, there are preferred values of $M_{\rm BH}$ for NGC 1399 and NGC 5128 (Figs 2 and 3) which are $M_{\rm BH} = 3.0 \times 10^8$ and $1.3 \times 10^9\,{\rm M}_\odot$, respectively.

5 PREDICTION OF $M_{\rm BH}$ FOR FIVE GALAXIES

As we have shown, $\sigma_{\rm GC}^{\rm red}$ seems to be the best proxy for black hole mass for the sample we considered. Thus, we use the $M_{\rm BH}$–$\sigma_{\rm GC}^{\rm red}$ relation to estimate the black hole mass of galaxies for which $\sigma_{\rm GC}^{\rm red}$ is known, namely for NGC 1407, NGC 3923, NGC 4494, M33 and the LMC (Table 3).

(i) *M33*. We obtain $M_{\rm BH} = 1.32 \pm 1.93 \times 10^6\,{\rm M}_\odot$, which is consistent with M33 having no central black hole. We remark that Gebhardt et al. (2001) have used the $M_{\rm BH}$–$\sigma_{\rm sph}$ relation ($\alpha = 8.11$ and $\beta = 3.65$) to estimate the black hole mass in M33. They found $5.6 \times 10^4\,{\rm M}_\odot$. Merritt, Ferrarese & Joseph (2001) find $M_{\rm BH} = 3 \times 10^3\,{\rm M}_\odot$ as an upper limit. They conclude that either M33 does not contain a BH or has an intermediate-mass black hole or that the M–σ relation cannot be extrapolated to such low masses. Using the observed relation between circular velocity at large radii and black hole mass, Gebhardt et al. (2001) have calculated a mass of $M_{\rm BH} \sim 6 \times 10^6\,{\rm M}_\odot$. X-ray observations (Foschini et al. 2004; Weng et al. 2009; Zhang et al. 2009) give $M_{\rm BH} \sim 10\,{\rm M}_\odot$. Using also X-ray data and a different method, Dubus, Charles & Long (2004) find a black hole mass in the range 10^5–$10^6\,{\rm M}_\odot$. Further data are needed before a final conclusion can be drawn.

Table 3. Estimated black hole mass using the measured velocity dispersion of the red GC subpopulation.

Galaxy	$\sigma_{\rm GC}^{\rm red}$ (km s^{-1})	Ref.	$M_{\rm BH}$ (M$_\odot$)
NGC 1407	243^{+21}_{-16}	1	$1.12 \pm 0.42 \times 10^9$
NGC 3923	200^{+22}_{-22}	2	$5.31 \pm 2.50 \times 10^8$
NGC 4494	92^{+8}_{-21}	3	$2.69 \pm 2.04 \times 10^7$
M33	42^{+18}_{-8}	4	$1.32 \pm 1.93 \times 10^6$
LMC	17	5	$4.11 \pm 5.36 \times 10^4$

References: (1) Romanowsky et al. (2009); (2) Norris et al. (2012); (3) Foster et al. (2011); (4) Schommer et al. (1991); (5) Freeman (1993).

(ii) *Large Magellanic Cloud*. The LMC, being a satellite galaxy, is clearly different from the other systems in the sample used to derive the $M_{\rm BH}$–$\sigma_{\rm GC}$ relation. The centre is not well defined and its GCs are not old. However, since the kinematics of the GC system is available (Freeman 1993), we simply mention that assuming the $M_{\rm BH}$–$\sigma_{\rm GC}$ relation can be applied it predicts $M_{\rm BH} = 4.1 \pm 5.4 \times 10^4\,{\rm M}_\odot$, which hints towards an intermediate-mass black hole but is also consistent with the LMC having no central black hole.

The black hole mass estimates are summarized in Table 3.

6 CONCLUSION

In this Letter, we have shown that the velocity dispersion of GC systems projected on the line of sight (i.e. the observed radial velocities) is well correlated with the mass of central black holes, particularly for red (metal-rich) GCs. The slope of the correlation is similar to the one obtained by G09, but the normalization is different, meaning that at fixed black hole mass, the velocity dispersion of the GC system is smaller than the dispersion of the spheroid. We also show that the relation for red clusters has the same slope as that of G09 for early-type galaxies. Thus, it seems that the relation with red GCs is an extension of what happens with $\sigma_{\rm sph}$. For blue GCs, the relation is clearly weaker and the slope is also lower than the classical $M_{\rm BH}$–σ relation. Therefore, it is not clear whether a direct connection between DM haloes, as probed by blue GCs, and central black holes really exists or not. We have also used the tight relation with red GCs to estimate the black hole mass in NGC 1407, NGC 4494, NGC 3923, M33 and the LMC.

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