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A CORRELATION BETWEEN CENTRAL SUPERMASSIVE BLACK HOLES AND THE GLOBULAR CLUSTER SYSTEMS OF EARLY-TYPE GALAXIES

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ABSTRACT

Elliptical, lenticular, and early-type spiral galaxies show a remarkably tight power-law correlation between the mass $M_\bullet$ of their central supermassive black hole (SMBH) and the number $N_{\rm GC}$ of globular clusters (GCs): $M_\bullet = m_{\bullet/\star} \times N_{\rm GC}^{1.08\pm0.04}$ with $m_{\bullet/\star} = 1.7 \times 10^5\ M_\odot$. Thus, to a good approximation the SMBH mass is the same as the total mass of the GCs. Based on a limited sample of 13 galaxies, this relation appears to be a better predictor of SMBH mass (rms scatter 0.2 dex) than the $M_\bullet$–σ relation between SMBH mass and velocity dispersion σ. The small scatter reflects the fact that galaxies with high GC specific frequency S_N tend to harbor SMBHs that are more massive than expected from the $M_\bullet$–σ relation.

Key words: black hole physics – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: star clusters: general – globular clusters: general

Online-only material: color figures

1. INTRODUCTION

Supermassive black holes (SMBHs) have been detected in the centers of many nearby galaxies (Kormendy & Richstone 1995; Magorrian et al. 1998; Gültekin et al. 2009). The SMBH masses are correlated with several properties of their host galaxies (Novak et al. 2006), in particular the velocity dispersion (the $M_\bullet$–σ relation; e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Gültekin et al. 2009) and the mass and luminosity of the spheroidal component—the entire galaxy in the case of ellipticals or the bulge in the case of lenticular and spiral galaxies (Kormendy 1993; Kormendy & Richstone 1995; Marconi & Hunt 2003; Häring & Rix 2004). Spitler & Forbes (2009) find a tight correlation between SMBH and dark matter halo masses. As the dark halo properties are inferred from the number of globular clusters (GCs) in a galaxy, this also indicates a connection between GCs and SMBHs. These correlations suggest a strong link between SMBH formation and galaxy formation, although the nature of this link is poorly understood.

Numerous authors have investigated the possibility that the growth of galaxies and their SMBHs is regulated by their interactions (e.g., Haehnelt & Kauffmann 2000; Burkert & Silk 2001; Somerville et al. 2008; Cattaneo et al. 2009). SMBHs grow by several mechanisms, including accretion of gas, swallowing stars whole, or merging with other SMBHs acquired through a merger of their host galaxies. The Sołtan argument (Sołtan 1982; Yu & Tremaine 2002) suggests that gas accretion is the dominant contributor to the SMBH mass budget, and both observations (Sanders et al. 1988) and simulations (Hopkins et al. 2006) suggest that much or most of this accretion occurs during mergers. SMBH growth through gas accretion can release substantial amounts of energy that can heat the interstellar gas, quench star formation, or even drive a wind that sweeps the galaxy free of gas, thereby halting star formation completely. Simulations of gas-rich galaxy mergers, including seed black holes, can reproduce the observed $M_\bullet$–σ relation remarkably well given the simplicity of the empirical prescriptions used to model the accretion and feedback processes (Springel et al. 2005; Cox et al. 2006; Croton et al. 2006; Hopkins et al. 2008; Johansson et al. 2009a, 2009b).

The origin of the seeds of SMBHs is controversial. According to one hypothesis, the seeds were remnants of the first generation of metal-free, massive stars that formed at high redshifts. However, the existence of bright quasars at redshifts of $z \gtrsim 6$ demonstrates that SMBHs with masses exceeding $10^9\ M_\odot$ were already in place less than a billion years after the big bang. It is difficult for black-hole remnants from first-generation stars to grow fast enough to explain these observations (Mayer et al. 2009). A second hypothesis is that the seeds are much larger ("intermediate-mass") black holes of 10^2–$10^5\ M_\odot$, perhaps formed by the direct collapse of gas at the centers of protogalaxies.

GCs are among the oldest stellar systems in the universe and may have formed at the same time as the first stars. Their high stellar densities, sometimes exceeding $10^5\ M_\odot\ {\rm pc}^{-3}$, lead to a variety of complex dynamical phenomena (Spitzer 1987; Heggie & Hut 2003; Binney & Tremaine 2008). Among these is mass segregation, through which heavy, compact, stellar remnants—neutron stars and black holes—spiral into the center by dynamical friction. Once these arrive at the center it is possible, though far from certain, that they merge to form an intermediate-mass black hole (Lee 1987; Quinlan & Shapiro 1987; Portegies Zwart et al. 2004; Kawakatu & Umemura 2005). There is significant observational evidence for intermediate-mass BHs with masses 4×10^3–$4 \times 10^4\ M_\odot$ in the centers of several GCs (Gerssen et al. 2002; Gebhardt et al. 2005; Noyola et al. 2008; van der Marel & Anderson 2010), but this evidence is still controversial.[4]

The number of GCs in a galaxy, $N_{\rm GC}$, is roughly proportional to the total luminosity of the galaxy's spheroidal component. This relation was quantified by Harris & van den Bergh (1981), who introduced the specific GC frequency S_N, defined as the number of GCs per unit absolute visual magnitude $M_V = -15$,

$$S_N \equiv N_{\rm GC} \times 10^{0.4(M_V+15)} \qquad (1)$$

[4] An additional uncertainty is whether some of these systems might be tidally stripped dwarf galaxies masquerading as GCs.

where M_V is the magnitude of the spheroidal component.

Brodie & Strader (2006) have summarized the progress that has been made in the quarter-century since the work by Harris & van den Bergh (1981). It has become clear that star cluster populations are powerful tracers of galaxy evolution and that the observed correlations between GC and galaxy properties provide valuable information about their joint formation. One of the most comprehensive studies of early-type galaxies was performed by Peng et al. (2008), who measured specific frequencies for the GC systems of 100 elliptical and lenticular galaxies in the Virgo cluster. They find that early-type galaxies with intermediate luminosities ($-22 < M_V < -18$) typically have $S_N \sim 1.5$, while luminous galaxies have $S_N \sim$ 2–5. The dominant galaxy M87 has an even larger specific frequency (Racine 1968), estimated by Peng et al. to be $S_N \simeq 13$.

The formation of GCs is not well understood (see, e.g., Brodie & Strader 2006 for a review). An important clue is that gas-rich merging galaxies contain large numbers of young massive star clusters that presumably formed in the merger (Schweizer 1987; Whitmore & Schweizer 1995). As this population of cluster ages, it is likely to evolve into a population of "normal" GCs (Fall & Zhang 2001). Another scenario is the combined formation of SMBH seeds and GCs in super star-forming clumps of gas-rich galactic disks at $z \sim 2$ (Shapiro et al. 2010; McLaughlin & Pudritz 1996).

In summary, (1) both the SMBH mass $M_\bullet$ and the total number of GCs N_{GC} are roughly proportional to the total luminosity of the spheroidal component in early-type galaxies, (2) GCs may provide the black-hole seeds from which SMBHs grow, and (3) both the growth of SMBHs and the formation of GCs appear to be associated with major mergers or global gravitational instabilities in gas-rich protogalaxies. Given these observations, it is natural to ask how the properties of the GC population in early-type galaxies are correlated with the properties of their associated SMBHs.

In this paper, we show that there is a tight, power-law relation between the mass of SMBHs and the total number of GCs in elliptical, lenticular, and early-type spiral galaxies. Remarkably, this relation appears to have even less scatter than the classic relation between SMBH mass and the velocity dispersion of the host galaxy. The relation can be approximately characterized by the statement that the SMBH mass equals the total mass in GCs.

2. THE BH–GC RELATION

For this analysis, we have selected all elliptical, lenticular, and early-type spiral galaxies with good estimates of the SMBH mass $M_\bullet$ and the total number of GCs N_{GC}.

Most of the SMBH masses were taken from the recent compilation by Gültekin et al. (2009), with revised values for NGC 4486 (M87) and NGC 4649 (M60) from Gebhardt & Thomas (2009) and Shen & Gebhardt (2010), respectively. We also include two unpublished SMBH measurements, provided by Karl Gebhardt: NGC 4472 (J. Shen et al. 2010, in preparation) and NGC 4594 (Gebhardt et al. 2010, in preparation). Most of the GC numbers were taken from the ACS Virgo Cluster Survey (Peng et al. 2008, first choice) or the compilation by Spitler et al. (2008, second choice). Table 1 summarizes the data; the table contains entries for the Milky Way, the Sb spiral M31, and the dwarf elliptical M32, but these are not included in the fits below. In three cases (NGC 1399, NGC 3379, and NGC 5128) where there are two good-quality values in the literature that differ by two standard deviations or more, we have included both estimates in our fits, each at half-weight. Note that errors in GC numbers are significantly larger than Poisson, due to uncertainties in the extrapolation of the GC luminosity functions, background subtraction, and corrections of the observed area of the galaxy to the whole system; the last of these is a particular concern because the radial distribution of GCs does not always follow the radial distribution of light.

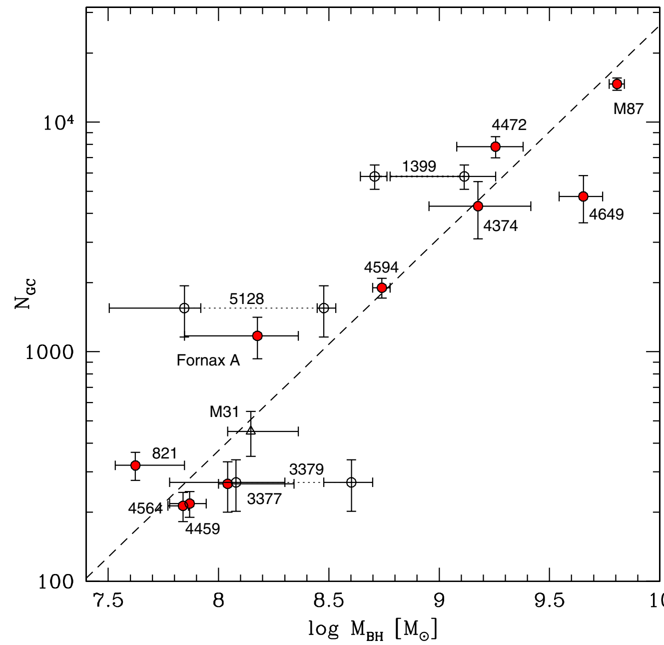

Figure 1. Number of GCs, N_{GC}, is shown as a function of SMBH mass M_{BH} for the 13 giant elliptical, lenticular, and early-type spiral galaxies in Table 1. Open circles connected by dotted lines denote the galaxies NGC 1399, NGC 3379, and NGC 5128 for which two estimates of the SMBH mass are given. The dashed curve shows the fit given by Equation (2). The location of M31 is also plotted as an open triangle, but this galaxy does not contribute to the fit.

(A color version of this figure is available in the online journal.)

The points in Figure 1 show SMBH mass $M_\bullet$ as a function of GC population N_{GC}. We fit this data to an assumed underlying relation of the form $\log M_\bullet = \alpha + \beta \log(N_{GC})$ (all logs in this paper are base 10). We determine the best-fit values of α and β by minimizing χ^2 including errors in both observational parameters, using the methods in Tremaine et al. (2002). There exists a surprisingly tight correlation (dashed line),

$$\log \frac{M_\bullet}{M_\odot} = (8.14 \pm 0.04) + (1.08 \pm 0.04) \log \frac{N_{GC}}{500}; \quad (2)$$

the χ^2 per degree of freedom is 6.6. For comparison, the $M_\bullet$–σ relation for the same sample, shown in the upper left panel of Figure 2, is

$$\log \frac{M_\bullet}{M_\odot} = (8.36 \pm 0.04) + (4.57 \pm 0.25) \log \frac{\sigma}{200 \text{ km s}^{-1}} \quad (3)$$

with χ^2 per degree of freedom of 8.5. Thus, in this admittedly small sample ($N = 13$), the correlation of SMBH mass with GC number is actually *tighter* than the classic correlation with velocity dispersion.

We have also carried out unweighted fits in which we ignore the observational errors in dispersion, luminosity, and GC number and minimize the rms residual ϵ in the log of the SMBH mass (weighted by the observational errors in mass). For the mass-dispersion relation $\epsilon = 0.30$ dex and for the mass-luminosity relation $\epsilon = 0.38$ dex, while for the mass versus GC

Table 1
Properties of Galaxies with Known SMBH Masses and GC Populations

Galaxy	Type	M_{BH} ($M_\odot$)	N_{GC}	σ km s^{-1}	M_V (total)	M_V (sph.)	S_N	f_{red}	B/T	Ref.
N821	E4	$4.2^{+2.8}_{-0.8} \times 10^7$	320 ± 45	209 ± 10	−21.0		1.3 ± 0.2	0.30	1	1,3
N1316=Fornax A	E	$1.5 \pm 0.8 \times 10^8$	1173 ± 240	226 ± 9	−22.8		0.9 ± 0.2	. . .	1	5,4
N1399[a]	E1	$1.3^{+0.5}_{-0.7} \times 10^9$	5800 ± 700	337 ± 16	−22.3		7.0 ± 0.8	0.40	1	1,3
		$5.1 \pm 0.7 \times 10^8$								
N3377	E5	$1.1^{+1.1}_{-0.1} \times 10^8$	266 ± 66	145 ± 7	−20.1		2.4 ± 0.6	. . .	1	1,9
N3379	E1	$1.2^{+0.8}_{-0.6} \times 10^8$	270 ± 68	206 ± 10	−20.9		1.2 ± 0.3	0.29	1	1,3,13
		$4 \pm 1 \times 10^8$								14
N4374	E1	$1.5^{+1.1}_{-0.6} \times 10^9$	4301 ± 1201	296 ± 14	−22.3		5.2 ± 1.4	0.11	1	1,2
N4459	E2	$7.4 \pm 1.4 \times 10^7$	218 ± 28	167 ± 8	−20.9		1.0 ± 0.1	0.48	1	1,2
N4472	E2	$1.8 \pm 0.6 \times 10^9$	7813 ± 830	310 ± 10	−22.9		5.4 ± 0.6	0.38	1	6a,2,13
N4486=M87	E1	$6.4 \pm 0.5 \times 10^9$	14660 ± 891	375 ± 18	−22.7		12.2 ± 0.7	0.27	1	7,1,2
N4564	S0	$6.9^{+0.4}_{-1.0} \times 10^7$	213 ± 31	162 ± 8	−19.9	−19.4	3.7 ± 0.5	0.38	0.63	1,2
N4594	Sa	$5.5 \pm 0.5 \times 10^8$	1900 ± 189	240 ± 12	−22.2	−22.1	2.7 ± 0.3	0.37	0.9	6b,3,13
N4649	E2	$4.5 \pm 1.0 \times 10^9$	4745 ± 1099	385 ± 19	−22.4		5.2 ± 1.2	0.37	1	8,1,2
N5128=Cen A[a]	E	$3.0^{+0.4}_{-0.2} \times 10^8$	1550 ± 390	150 ± 7	−21.5		3.9 ± 1.0	0.48	1	1,3
		$7.0^{+1.3}_{-3.8} \times 10^7$								
N224=M31	Sb	$1.4^{+0.9}_{-0.3} \times 10^8$	450 ± 100	160 ± 8	−21.2	−20.0	4.5 ± 1.0	. . .	0.34	1,3,10
N221=M32	dE2	$3.1 \pm 0.6 \times 10^6$	0	75 ± 3	−16.8		0	. . .	1	1,14
Milky Way	SBbc	$4.3 \pm 0.4 \times 10^6$	160 ± 20	105 ± 20	−21.5	note b	note b	. . .	note b	1,11,12

Notes. The columns give morphological type, SMBH mass M_{BH}, number of GCs N_{GC}, velocity dispersion σ, absolute visual magnitude M_V for the entire galaxy and for the spheroidal component alone as determined from B/T, GC specific frequency S_N relative to the spheroidal component (Equation (1)), red cluster fraction f_{red} and bulge/total luminosity ratio B/T. We list the Local Group galaxies M31, M32, and the Milky Way below the horizontal line, but these are not included in our fits.

[a] Gültekin et al. (2009) give two estimates for the SMBH masses in NGC 1399 and NGC 5128 and give half-weight to each in their fits. We adopt a similar procedure; we include both estimates but increase the error bars on each by $\sqrt{2}$ so that their combined contribution to the fit is the same as that of a single galaxy.

[b] The Milky Way contains a pseudobulge.

References. (1) Gültekin et al. 2009; (2) Peng et al. 2008; (3) Spitler et al. 2008; (4) Gómez et al. 2001; (5) Nowak et al. 2008; (6a) J. Shen et al. 2010 (in preparation); (6b) K. Gebhardt et al. 2010 (in preparation); (7) Gebhardt & Thomas 2009; (8) Shen & Gebhardt 2010; (9) Kundu & Whitmore 2001; (10) Bender et al. 2005; (11) Gillessen et al. 2009; (12) Forbes et al. 2001; (13) Rhode & Zepf 2004; (14) van den Bosch & de Zeeuw (2010). B/T ratios are taken from Kormendy et al. (2009) for NGC 4564, Gültekin et al. (2009) for NGC 4594, and J. Kormendy et al. (2010, in preparation) for M31.

number relation $\epsilon = 0.21$ dex, substantially smaller than the other two. We used the same procedure to fit to a relation of the form $\log M_\bullet = \alpha + \beta_1 \log \sigma + \beta_2 \log L + \beta_3 \log N_{GC}$ and find that $\epsilon = 0.19$, only marginally smaller than the rms residual of 0.21 to the fit involving only N_{GC} despite the presence of the two additional free parameters β_1 and β_2.

The smaller rms deviation ϵ seen in the correlation between $M_\bullet$ and N_{GC} implies that this is not a "secondary" correlation due to a tight correlation between N_{GC} and bulge properties, combined with a bulge–SMBH correlation. Additional evidence comes from the upper right panel of Figure 2, showing the correlation of N_{GC} with bulge visual luminosity L_V which is less good (χ^2 per degree of freedom of 34.8). We have also checked the correlation of N_{GC} with luminosity and dispersion using the much larger sample of 62 galaxies in the sample of Peng et al. (2008) that also have dispersions in HyperLeda and found fits of similar quality, with χ^2 per degree of freedom of 23 and 27, respectively.

Another look at the data is provided in Figure 3, which compares residuals from the best-fit $M_\bullet$–σ relation (Equation (3)) on the horizontal axis to residuals from the best-fit N_{GC}–L relation

$$\log \frac{N_{GC}}{500} = (-0.42 \pm 0.03) + (1.62 \pm 0.04) \log \frac{L_V}{10^{10}\, L_\odot} \quad (4)$$

on the vertical axis. In general, galaxies with positive (negative) residuals in one quantity have positive (negative) residuals in the other.

It is helpful to look at a few individual galaxies. Compare the galaxies M87 (NGC 4486) and Fornax A (NGC 1316), which have similar luminosities ($M_V = -22.7$ and -22.8, respectively). M87 has an SMBH mass that is larger than expected for its dispersion by 0.20 dex, while Fornax A contains an unusually small SMBH by -0.42 dex. M87 has a specific frequency $S_N = 12.2$ that is a factor of 3 larger than the average value for our sample of $S_N = 4.0$, while Fornax A is characterized by an unusually small value, $S_N = 0.9$. A second striking example is NGC 821, which has the largest residual from the $M_\bullet$–σ relation in our sample—$\log M_\bullet$ is 0.82 smaller than predicted. This galaxy also has a small specific frequency, $S_N = 1.3$, not far from the low value seen for NGC 1316.

There is growing evidence that the masses of black holes in the most luminous (core) galaxies have been underestimated in some cases; including a dark halo (Gebhardt & Thomas 2009) and allowing for triaxiality (van den Bosch & de Zeeuw 2010) both tend to increase black-hole masses by a factor of 2 or so in the few luminous core galaxies modeled so far. To test for the effect of these revisions, we have increased the black-hole masses in core galaxies, by a factor of four if the models accounted for neither a dark halo nor triaxiality and by a factor of two if the models accounted for one of these two effects. This change slightly steepens the $M_\bullet$–N_{GC} relation—the best-fit slope in Equation (2) increases from 1.08 ± 0.04 to 1.17 ± 0.04—and reduces the χ^2 per degree of freedom from 6.6 to 4.8. It also reduces the χ^2 per degree of freedom for the $M_\bullet$–σ relation, from 8.5 to 5.0. With this revised mass scale,

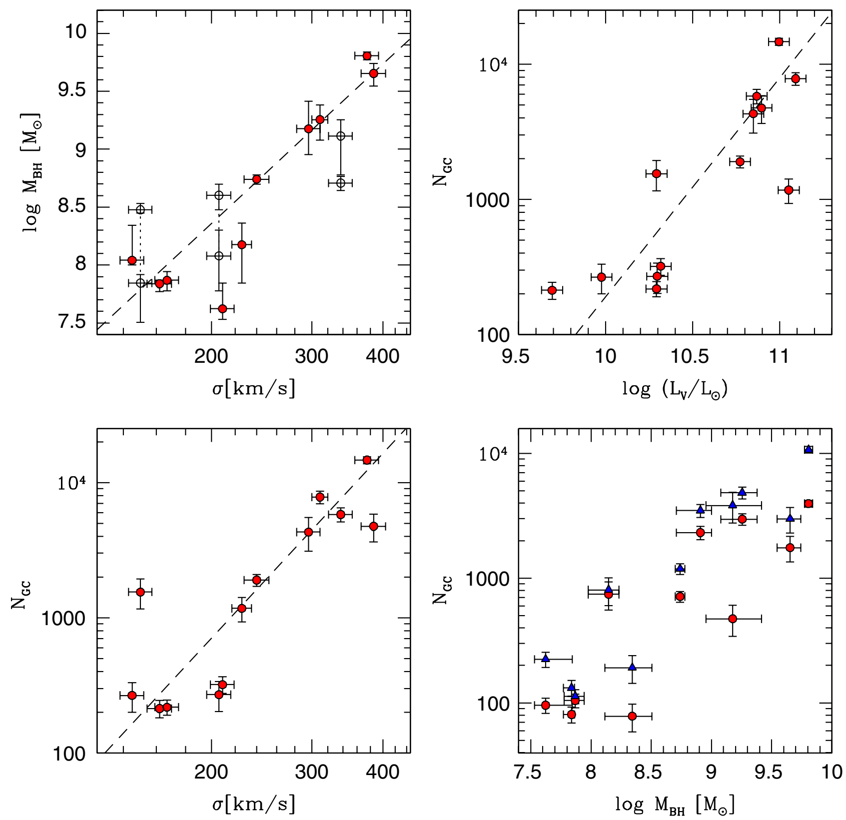

Figure 2. Upper and lower left panels show the correlation between $M_\bullet$ or N_{GC}, respectively, and the velocity dispersion. The dashed curve in the upper left panel corresponds to Equation (3), and the line in the lower left panel is $\log(N_{GC}/500) = 0.15 + 4.54 \log(\sigma/200 \text{ km s}^{-1})$. In the upper right panel, N_{GC} is plotted vs. the visual luminosity of the host galaxy; the line shows the correlation given by Equation (4). In the lower right panel, blue triangles and red points correspond to the number of blue and red GCs, respectively, vs. SMBH mass; in this panel, the galaxies NGC 1399, NGC 3379, and NGC 5128 are represented by the geometric mean of the two SMBH mass estimates.

(A color version of this figure is available in the online journal.)

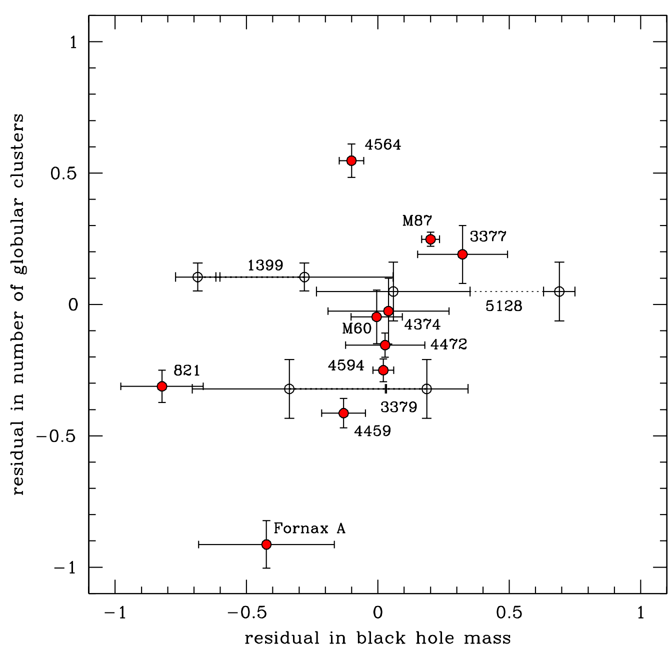

Figure 3. Residuals from the best-fit relation between SMBH mass and velocity dispersion (Equation (3)) and the best-fit relation between number of GCs and bulge luminosity (Equation (4)). Dashed lines and open circles denote the galaxies NGC 1399, NGC 3379, and NGC 1399 for which two estimates of the SMBH mass are given.

(A color version of this figure is available in the online journal.)

the unweighted best-fit $M_\bullet$–N_{GC} and $M_\bullet$–σ give rms residuals of 0.20 and 0.26, respectively.

Assuming a mean GC mass $m_{GC} = 2 \times 10^5\ M_\odot$, Equation (2) can be rewritten in terms of the total mass of the GC system $M_{GC} \equiv N_{GC}\, m_{GC}$,

$$\log \frac{M_\bullet}{10^8\ M_\odot} = (0.14 \pm 0.04) + (1.08 \pm 0.04) \log \frac{M_{GC}}{10^8\ M_\odot}. \quad (5)$$

Remarkably, to a good approximation the mass of the SMBH is the *same* as the total mass of the GCs.

3. LOCAL GROUP GALAXIES

The compact elliptical galaxy M32 has a central SMBH with mass $M_\bullet = 3 \times 10^6\ M_\odot$ (Table 1) but no known GC. This exception to the correlation between $M_\bullet$ and N_{GC} observed in more luminous galaxies probably arises because the GCs in M32 have spiraled into the center of the galaxy through dynamical friction (Tremaine 1976). The characteristic inspiral time for an object of mass m at initial radius r_i in a galaxy with dispersion σ is (Binney & Tremaine 2008, Equation (8.12))

$$\tau = \frac{1.65}{\ln\Lambda}\frac{r_i^2\sigma}{Gm} = 1.2 \times 10^{10}\ \text{yr}\frac{3}{\ln\Lambda}\left(\frac{r_i}{0.5\ \text{kpc}}\right)^2 \times \left(\frac{m}{2\times 10^5\ M_\odot}\right)^{-1}\frac{\sigma}{75\ \text{km s}^{-1}}, \quad (6)$$

where $\ln\Lambda$ is the standard Coulomb logarithm, m is normalized to the mean GC mass of $2 \times 10^5\ M_\odot$, and the dispersion is normalized to M32's (Choi et al. 2002). According to this estimate, GCs within 0.5 kpc would have spiraled into the center within a Hubble time. M32's effective radius is only 0.14–0.18 kpc (Choi et al. 2002), so it is not surprising that most or all of the GCs in this galaxy have disappeared.

The nearby Sb spiral galaxy M31 has 450 ± 100 GCs (Table 1). According to Equation (2), this leads to an SMBH mass of $(1.2 \pm 0.4) \times 10^8\, M_\odot$, in excellent agreement with the observed value of $1.4^{+0.9}_{-0.3} \times 10^8\, M_\odot$. Thus, the $M_\bullet$–N_{GC} correlation may work well for spiral galaxies as late as Hubble type Sb.

The situation is less clear for the Milky Way, which contains a small SMBH of mass $(4.3^{+0.4}_{-0.4}) \times 10^6\, M_\odot$ (Table 1). According to Equation (2), this galaxy should contain only about 20 GCs compared to the observed population of 160 ± 20. The Milky Way is quite different from the elliptical, lenticular, and early-type spiral galaxies that we have discussed so far; it has a significantly later Hubble type (Sbc) and its bulge is probably a pseudobulge (Binney 2009; Shen et al. 2010). In fact, most of the GCs in the Milky Way are associated with the Galactic halo, not the bulge, and as SMBH mass appears to correlate with bulge luminosity rather than total luminosity in spirals, it might be reasonable to expect that in late-type spirals Equation (2) applies only to the number of bulge GCs. Forbes et al. (2001) argue that metal-rich GCs at radii <5 kpc are mostly associated with the bulge and estimate that there are 35 ± 4 such clusters in the Milky Way. If we insert this number in Equation (2), we obtain an SMBH mass of $(7.8 \pm 1.2) \times 10^6\, M_\odot$; this is somewhat larger than the observed mass but in reasonable agreement since some of the metal-rich GCs in this region are likely to be disk GCs. We conclude that the Milky Way offers no strong evidence for or against the proposed correlation.

4. DISCUSSION AND CONCLUSIONS

We have found that there is a strong correlation between the number of GCs and the mass of the central SMBH in early-type galaxies. This correlation appears to be at least as tight as the well-known correlation between velocity dispersion and SMBH mass, although this conclusion is based on only 13 galaxies. To a reasonably good approximation, the BH–GC correlation simply says that the mass of the central SMBH in an early-type galaxy is equal to the mass of its GCs (Equation (5)). We suspect that the proportionality of the SMBH mass to the total GC mass offers insight into their formation processes, but the near-equality of the masses is a coincidence.

Most galaxies have GC populations with a bimodal color distribution; there are red (metal-rich) and blue (metal-poor) peaks, presumably reflecting two sub-populations of GCs (e.g., Brodie & Strader 2006). It is interesting to investigate whether the SMBH mass is correlated with one or the other of these sub-populations. Table 1 shows the red cluster fraction f_{red} for 11 galaxies, taken from Peng et al. (2008) and Rhode & Zepf (2004). Note that f_{red} is rather constant, with mean and standard deviation 0.3 ± 0.1. The lower right panel of Figure 2 shows the $M_\bullet$–N_{GC} correlation separately for the blue (triangles) and red (circles) clusters. As expected from the small rms variation in the red cluster fraction, both correlations are of similar quality.

The origin of the $M_\bullet$–N_{GC} relation is obscure. One possibility is that both the growth of SMBHs and the formation of GCs are associated with major mergers, so that galaxies that experienced a recent major merger will have anomalously large SMBH masses and GC populations. Another possibility is the correlated formation of SMBH seeds and GCs in gas-rich young galaxies.

An important next step is to expand the sample of galaxies having both reliable SMBH masses and reliable GC populations.

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