Did massive black holes in globular clusters initially satisfy galactic scaling relations?

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ABSTRACT
The masses of supermassive black holes (SMBHs, $M_{\text{BH}} = 10^6$–$10^{11} M_\odot$) in the centres of galaxies are related to the host stellar spheroid mass and velocity dispersion. A key question is how these relations originate, and over which range of black hole masses they hold. It has been speculated that intermediate-mass black holes (IMBHs, $M_{\text{BH}} = 10^2$–$10^5 M_\odot$) could play a fundamental role in the growth of SMBHs. A handful of IMBHs have recently been detected in Galactic globular clusters (GCs), but their masses are inconsistent with the galactic scaling relations of SMBHs. In this Letter, we derive the initial properties of the GCs using a standard analytical evolutionary model, of which the free parameters are fixed by independent constraints. We find that the observed IMBH masses initially followed the galactic SMBH scaling relations and subsequently moved off these relations due to the dynamical evolution of their host GCs. This work is concluded with a brief discussion of the uncertainties and the implications of our results for the possible universality of massive black hole growth.

Key words: black hole physics – globular clusters: general – galaxies: bulges – galaxies: evolution – galaxies: kinematics and dynamics – galaxies: nuclei.

1 INTRODUCTION
The supermassive black holes (SMBHs) that reside in the centres of galaxies have masses $M_{\text{BH}}$ that are tightly correlated with the properties of their host stellar spheroid, such as its velocity dispersion $\sigma$ (i.e. the $M_{\text{BH}}-\sigma$ relation; see e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Gültekin et al. 2009) and its luminosity or stellar mass $M_{\text{sph}}$ (i.e. the $M_{\text{BH}}-M_{\text{sph}}$ relation; see e.g. Kormendy & Richstone 1995; Magorrian et al. 1998; Häring & Rix 2004; Gültekin et al. 2009). The origin of these scaling relations is still an open question, and the answer presumably requires an understanding of the formation and growth mechanisms for SMBHs, which is thought to be driven by gas accretion and/or black hole mergers (e.g. Silk & Rees 1998; Di Matteo, Springel & Hernquist 2005; Hopkins et al. 2006; Fanidakis et al. 2011). While a complete understanding of the growth rate has not yet been achieved, the presence of $\sim 10^5$–$10^6 M_\odot$ SMBHs at $z \sim 7$ (e.g. Mortlock et al. 2011) suggests that some substantial part of the SMBH growth must have already taken place in the early Universe.

In an effort to extend the $M_{\text{BH}}$ scaling relations to lower masses, and to find possible building blocks of SMBHs, there has been a surge of observational work looking for intermediate-mass black holes (IMBHs) in globular clusters (GCs; e.g. Baumgardt et al. 2003; Gebhardt, Rich & Ho 2005; van den Bosch et al. 2006; Noyola, Gebhardt & Bergmann 2008; van der Marel & Anderson 2010; Strader et al. 2012; Lützgendorf et al. 2013a). The existence of IMBHs (Silk & Arons 1975) has been predicted as the result of runaway merging in dense stellar systems (Portegies Zwart & McMillan 2002; Gürkan, Freitag & Rasio 2004; Portegies Zwart et al. 2004) or as the possible end products of Population III stars (Madau & Rees 2001; Trenti & Stiavelli 2007). The search for IMBHs has been guided by the existing SMBH scaling relations, which predict $M_{\text{BH}} = 10^3$–$10^5 M_\odot$ for the (initial) mass range of massive GCs ($10^6$–$10^7 M_\odot$). At present, a handful of IMBHs have been identified through integral-field spectroscopy of GCs (see Lützgendorf et al. 2013b for a compilation), typically at the $3\sigma$ level. Other methods are generally less successful (although see e.g. Miller et al. 2003) or even present evidence against the existence of IMBHs. Strader et al. (2012) do not find any radio emission in the GCs M15, M19 and M22. This could be due to the well-known paucity of gas in GCs or the possibly episodic nature of the accretion on to an IMBH – these and other factors obstruct the straightforward detection of IMBHs in GCs (Miller & Hamilton 2002).

Under the assumption that the kinematic detections of IMBHs are real, the sample of detected IMBHs has grown sufficiently to enable a statistical comparison of their masses and host GC properties to the SMBH scaling relations. The key result of this comparison is that the IMBHs have masses that lie above the SMBH scaling relations, and follow their own, shallower relations that intersect the SMBH scaling relations at $M_{\text{BH}} = 10^7$–$10^8 M_\odot$ (Lützgendorf et al. 2013b). However, it is known (1) that GCs must have lost a substantial fraction of their initial mass by dynamical evolution and (2) that...
they must have expanded since their birth (Elmegreen & Efremov 1997; Vesperini 1997; Fall & Zhang 2001; Elmegreen et al. 2010; Gieles, Heggie & Zhao 2011; Kruĳssen et al. 2012). Both effects imply that their position relative to the SMBH scaling relations is continuously evolving in a way that is different from galaxies.

In this Letter, we account for the evolution of GCs using a simple, standard evolutionary model that has been used in the past to explain several other characteristics of GCs. We find that the observed IMBH masses initially followed the galactic SMBH scaling relations and subsequently moved off these relations due to the dynamical evolution of their host GCs – provided that most of the IMBH growth occurred early on.

2 MASSIVE BLACK HOLE SCALING RELATIONS

2.1 Data sample

We use two different samples of dynamical black hole mass measurements: SMBHs in galaxies and IMBHs in GCs. For the galaxies, we adopt the sample summarized in McConnell et al. (2011) and McConnell & Ma (2013), including their tabulated host galaxy properties and best-fitting scaling relations. The data set comprises 72 black hole mass and velocity dispersion measurements in massive galaxies, including new measurements as well as literature values. A subset of 35 galaxies has known bulge masses. The SMBH masses are dynamical, i.e. they are derived by measuring the velocity dispersion profile of gas, stars and/or masers, and by modelling the mass distribution of the galaxy. A strong rise of the velocity dispersion in the centre of the galaxy requires a high black hole mass in order to explain the kinematic data.

The second data set incorporates 14 measurements and upper limits of IMBH masses in GCs (Noyola et al. 2010; Lützgendorf et al. 2011, 2012b, 2013a). In Lützgendorf et al. (2013b), we collected the kinematic measurements of IMBH masses in GCs in order to compare their scaling relations with those of SMBHs in galaxies. The measurements were mainly taken with integral-field units (IFU) and the IMBH masses have been obtained with a similar method as is common practice for estimating galactic SMBH masses. From the IFU data, a velocity dispersion profile was obtained that was fitted with dynamical models, varying the central IMBH mass and the mass-to-light ratio. Furthermore, Monte Carlo and N-body simulations were used in order to exclude other possible explanations for the central rise of the velocity dispersion (e.g. radial anisotropy) and to handle the largest uncertainties such as shot noise. While the analysis has been performed using the best available data and methods, we note that the IMBH mass measurements are still under debate due to the indirect nature of their detection and contradictory results from different groups (e.g. Hurley 2007; Strader et al. 2012).

2.2 Globular cluster evolution model

We account for the dynamical evolution of GCs by comparing the observational data to cluster evolution models. We produce cluster isochrones in the $M_{\text{BH}}-M_{\text{gph}}$ plane using the semi-analytic cluster model SPACE (Kruĳssen & Lamers 2008; Kruĳssen et al. 2009), which for a given static tidal field provides a description for the mass-loss history of clusters that resembles the results of N-body simulations within a few per cent (Lamers et al. 2005; Lamers, Baumgardt & Gieles 2010). It includes stellar evolution (adopting a metallicity of $Z = 0.001$; Marigo et al. 2008), the production and retention of stellar remnants (with retention fractions as in Kruĳssen 2009) and the escape of stars due to two-body relaxation. Note that the details of the stellar evolution and remnant retention model do not affect the results of this work. The mass-loss rate due to dynamical evolution is parametrized in the models as

$$\frac{dM}{dt} = -\frac{M}{t_{\text{dis}}} = -\frac{M^{1-\gamma}}{t_0},$$

where $t_{\text{dis}} = t_0 M^{\gamma}$ is the disruption time-scale, with $M$ the cluster mass in solar masses, $\gamma$ a constant in the range 0.6–1 (Spitzer 1987; Lamers et al. 2005) and $t_0$ a normalization constant that represents the lifetime of a hypothetical 1 $M_\odot$ cluster and is set by the tidal field (or angular velocity $\Omega$) as $t_0 \propto \Omega^{-1}$. We note that the results presented in this work do not strongly depend on the adopted value of $\gamma$. We use $\gamma = 0.7$, which implies $t_0 = 10.7$ Myr for the Galactic tidal field at the galactocentric radius of the solar neighbourhood (Kruĳssen & Mieske 2009), and is consistent with theory (Baumgardt 2001) and N-body simulations (Lamers et al. 2010). As shown by Lamers et al. (2005), $\gamma \sim 0.7$ leads to a near-linear decrease of the cluster mass with time. They also present an analytical fit to the resulting mass evolution, which agrees with the numerical integration of equation (1) to within a few per cent.

The comparison of the GCs and their IMBHs to the galactic SMBH scaling relations only depends on the typical total mass-loss of the GCs, which is set by $t_0$. Previous studies have shown that $t_0 \sim 1$ Myr (implying $t_{\text{dis}} = 16$ Gyr for a cluster with an initial mass of $M_{\text{dis}} = 10^5 M_\odot$). These results are consistent with the scaling relations of IMBH masses in GCs (Noyola et al. 2010; Kruijssen et al. 2012). Such a disruption time-scale is a factor of $5$–$10$ shorter than that expected for the current orbital characteristics of the Galactic GC system. This substantial difference should be expected, because basing the disruption time-scale on the current orbits assumes a steady state and does not account for the total amount of disruption over cosmic time. The high-redshift, natal environment of GCs was rich in dense gas clouds, and hence much more disruptive than the smooth Galactic halo (Gieles et al. 2006; Kruĳssen et al. 2011), causing much of the GC disruption to have occurred at early times (Elmegreen 2010; Kruĳssen et al. 2012). We adopt the standard value of $t_0 = 1$ Myr and discuss the effect of different disruption time-scales below. As shown in Kruĳssen & Portegies Zwart (2009), the GC mass distribution is modelled with a similar accuracy when adopting the median disruption time-scale compared to modelling a full spectrum of disruption time-scales. The present age of the GC population is taken to be $\tau = 12$ Gyr.

2.3 A single scaling relation spanning seven decades in mass

We can test whether IMBHs in GCs initially followed the galactic $M_{\text{BH}}-M_{\text{gph}}$ relation by first assuming that they did, modelling the GC mass evolution due to disruption and then comparing the resulting relation to the observed one. As detailed in Section 2.2, we adopt a cluster evolution model in which the only important free parameter ($t_0 = 1$ Myr) is set by independent observations of the GC mass function and their stellar content. This model accounts for the dynamical mass-loss of the GCs, while the IMBH mass remains constant after being set by the galactic SMBH scaling relation. Note that dynamically, it is desirable to compare the present galaxies to young GCs – because the dynamical time-scale of GCs is much shorter, an $\sim 10^7$-yr-old GC and a present-day massive galaxy have similar dynamical ages of $\sim 10^8$ dynamical times. Hence, the evolutionary state of the GCs should be ‘rewinded’ before comparing them to the galactic scaling relations.
The modelled GC isochrones in the $M_{\text{BH}}-M_{\text{sph}}$ plane are shown in the left-hand panel of Fig. 1, together with the observed black hole masses. The IMBH masses are situated above the SMBH scaling relation (red line) and follow their own, shallower relation (blue line). However, the evolved form of the galactic $M_{\text{BH}}-M_{\text{sph}}$ relation (black, solid line) agrees remarkably well with the observed GC and IMBH masses. The dotted lines indicate how the isochrones change for the expected variation of $t_0$, which is roughly consistent with the observed scatter.

The above approach can also be reversed, to show the black hole mass as a function of the initial GC mass (right-hand panel of Fig. 1). We use the black, solid line from the left-hand panel to estimate the initial masses of the observed GCs, and leave the galactic bulge masses unchanged. The figure shows that the initial GC masses are consistent with their IMBHs following the galactic $M_{\text{BH}}-M_{\text{sph}}$ relation. The respective distributions of the initial GC masses and bulge masses around the relation, i.e. $\Delta M = \log (M_{\text{bh,in}}/M_{\text{sph,in}})$, where $M_{\text{sph,in}}$ is the host spheroid mass implied by the $M_{\text{BH}}-M_{\text{sph}}$ relation for a given observed black hole mass, are statistically consistent at the $p=0.88$ level, as opposed to $p=0.04$ when using the present-day GC masses. We conclude that when accounting for the dynamical evolution of GCs, the $M_{\text{BH}}-M_{\text{sph}}$ relation extends to the GC regime.

### 2.4 The black hole mass–velocity dispersion relation

Analogous to the $M_{\text{BH}}-M_{\text{sph}}$ relation in Section 2.3, we can test whether the deviation of IMBHs in GCs from the galactic $M_{\text{BH}}-\sigma$ relation is consistent with the dynamical evolution of GCs. This requires the conversion of the present-day GC velocity dispersion to its value at the time of IMBH formation. The GC sample of Lützgendorf et al. (2013b) follows a Faber & Jackson (1976) type of relation with $M \propto \sigma^{3.0}$, which we adopt to map the present-day model GC masses to velocity dispersions. If we make the reasonable assumption that the GCs retain virial equilibrium throughout their disruption history, the velocity dispersions at two different times $t_1$ and $t_2$ can be related:

$$f_\sigma(t_1, t_2) = \frac{\sigma(t_2)}{\sigma(t_1)} = \left( \frac{M(t_2)}{M(t_1)} \right)^{1/2} \left( \frac{R(t_2)}{R(t_1)} \right)^{-1/2},$$

where the new variable $R$ is the cluster radius. While the ratio $M(t_2)/M(t_1)$ is given by the cluster evolution models from Section 2.2, accounting for the radius evolution requires additional, highly uncertain physics. The radius evolution is very sensitive to the cluster’s detailed tidal history (Gieles et al. 2011). Considering the many unknowns in the accretion history of Galactic GCs and the smaller galaxies they may have orbited in the past, this cannot be accurately constrained. We therefore focus on the cluster mass evolution model of Section 2.2, but using the model of Gieles et al. (2011), we also illustrate the possible effect of the cluster radius evolution, with an expansion factor of $R(t_2)/R(t_1) \sim 1.3$ (see Appendix A). As in Section 2.3, any free parameters are set by independent constraints.

The modelled GC isochrones in the $M_{\text{BH}}-\sigma$ plane are shown in the left-hand panel of Fig. 2, together with the observed black hole masses. As in Fig. 1, the IMBH masses are situated above the SMBH scaling relation (red line) and follow their own, shallower relation (blue line). However, the evolved form of the galactic $M_{\text{BH}}-\sigma$ relation including cluster mass-loss only (black line) agrees remarkably well with the observed GC and IMBH masses. The green line shows the relation when a rough estimate of the typical GC expansion since their accretion into the Galactic halo is also included, and gives somewhat better agreement (see below).

The black hole mass is shown as a function of the initial GC velocity dispersion $\sigma_{\text{init}}$ in the right-hand panel of Fig. 2, using the...
black and green lines from the left-hand panel to derive \( \sigma_{\text{init}} \) (black and green symbols, respectively). As before, the galactic velocity dispersions are left unchanged. The figure shows that the initial GC velocity dispersions are consistent with their IMBHs following the galactic \( M_{\text{BH}} - \sigma \) relation, depending only weakly on whether or not their expansion is included. We again run KS tests of the differences between the power-law relation and the respective distributions of the initial GC and galactic velocity dispersions, i.e. \( \Delta \sigma \equiv \log(\sigma_{\text{init}}/\sigma_{\text{vol}}) \), excluding the GCs which only have upper limits on \( M_{\text{BH}} \). These clearly show that the GCs are statistically consistent with the galactic relation – accounting for the mass evolution only gives \( p = 0.09 \), whereas also including some GC expansion yields \( p = 0.98 \). When the present-day GC velocity dispersions are used, the observed IMBH masses are undeniably inconsistent with the galactic scaling relation, at \( p = 1.0 \times 10^{-6} \). Like the \( M_{\text{BH}} - M_{\text{sph}} \) relation, the \( M_{\text{BH}} - \sigma \) relation extends to the GC regime when accounting for the dynamical evolution of GCs.

3 DISCUSSION

3.1 Observational and model uncertainties

We use a simple, semi-analytic model for the dynamical evolution of GCs, which has been used previously to explain several other features of GC populations, to relate observed IMBH masses to the initial masses and velocity dispersions of their host GCs. We find that these systems were initially consistent with the two main galactic scaling relations for SMBH masses (\( M_{\text{BH}} - M_{\text{sph}} \) and \( M_{\text{BH}} - \sigma \)), and moved off these relations due to dynamical evolution.

Despite an increasing number of 2–3\( \sigma \) detections, the existence of IMBHs is still debated (e.g. Strader et al. 2012). Hence, we cannot rule out the possibility that the IMBH detections are spurious, in which case it is remarkable that accounting for GC evolution makes them align with the scaling relations without fitting any free parameters. Given the uncertainties of the IMBH mass measurements, the probability that the IMBH detections are statistical noise and still exhibit the observed scatter around the relations is \( p \leq 3 \times 10^{-6} \), indicating that only systematic errors in the detection method could affect our findings. A potential issue is that the required disruption parameter \( t_0 \) is lower by a factor of 5–10 than expected for the current, Galactic environment of GCs. However, several earlier, independent observations have required the same shorter-than-current disruption time-scale, and Figs 1 and 2 add two more independent tests. Above all, a short disruption time-scale need not be a fundamental problem – it is likely that GCs underwent most of their mass-loss before entering their present-day environment (Elmegreen 2010; Kruisjes et al. 2012).

3.2 A universal mechanism for black hole growth

While we refrain from deriving any definitive conclusions regarding massive black hole growth from our results, the agreement between IMBH and SMBH scaling relations is both intriguing and suggestive. It requires (or predicts) that while galactic SMBHs are still growing, most of the IMBH growth occurred during a rapid initial phase, when their host GCs were much denser and potentially still gas rich. If the SMBH scaling relations reflect some imprint of the black hole formation process (and even if they simply arise from the central limit theorem; e.g. Peng 2007), then our results also imply that this growth process may very well be universal over seven decades in black hole mass. Universality is not necessarily contradicted by current deviations from the SMBH scaling relations – it is important to realize that the black hole scaling relations are evolving, and tidal effects should also lead to differences between the scaling relations of brightest cluster galaxies and satellites (as is indeed observed; see McGee 2013).

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The Galactic halo forces us to use the median half-mass radius (especially at old ages (Gaburov & Gieles 2008)). We therefore adopt a median initial radius, i.e. the current median mass over the present-day GC radius. We use the current median mass over the present-day GC radius, which is a natural proxy for the initial radius by the radius at the time of accretion. Rocha, Peter & Bullock (2012) show that the median accretion time of the current Galactic satellite dwarf galaxies is $t_{\text{acc}} \sim 6.5\,\text{Gyr}$ ago (the hat indicates a median value), but this number is naturally biased to dwarfs that have not yet merged with the Milky Way. The galaxy formation simulations of Sales et al. (2007) suggest that the median accretion time of all dwarf galaxies precedes that of the survivors by $\sim 1.5\,\text{Gyr}$, and hence $t_{\text{acc,all}} \sim 8\,\text{Gyr}$. Based on the current orbital parameters of our GC sample (Dinescu, Girard & van Altena 1999), we find that during these 8 Gyr, the median disruption parameter of the sample is $t_0 \sim 7.3\,\text{Myr}$ (using equation 7 of Kruijssen & Mieske 2009).

The model of Gieles et al. (2011) allows us to derive the radius at the time of GC accretion as a function of the mass-loss since that time and the present-day GC radius. We use the current median mass of the sample, i.e. $M = 7.1 \times 10^5\,M_\odot$, which for $t_0 = 7.3\,\text{Myr}$ implies $M_{\text{acc}} = 8.3 \times 10^5\,M_\odot$ at the time of accretion into the Galactic halo. The projected half-light radii $R_{\text{hl,2D}}$ are taken from Harris (1996, 2010 edition). The difference between projected and deprojected, 3D half-light radii in the simulations of Hurley (2007) is about a factor of 2, and the possible effect of mass segregation on the conversion from a half-light to a half-mass radius is minor, especially at old ages (Gaburov & Gieles 2008). We therefore adopt a median half-mass radius $R = 2R_{\text{hl,2D}} = 5.5\,\text{pc}$. With the formalism of Gieles et al. (2011), we derive $R(t_{\text{acc}}) = 4.4\,\text{pc}$, implying a median expansion factor since accretion of $R(t_{\text{acc}})/R(t_{\text{acc}}) = 1.3$. As stated before, the unknown evolution of the GCs prior to the accretion into the Galactic halo forces us to use $R(t_{\text{acc}})$ as a proxy for the initial systems. We combine $R(t_{\text{acc}})$ with the total mass-loss $M/M_{\text{init}}$ in equation (2) to show the effect of expansion on the initial velocity dispersions.

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