Star clusters and black holes in galaxies across cosmic time
Proceedings IAU Symposium No. 312, 2014
Y. Meiron, S. Li, F.-K. Liu & R. Spurzem, eds.

doi:10.1017/S1743921315008017

Black hole and nuclear cluster scaling relations: $M_{\rm bh} \propto M_{\rm nc}^{2.7\pm0.7}$

Alister W. Graham

Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia.
email: AGraham@swin.edu.au

Abstract. There is a growing array of supermassive black hole and nuclear star cluster scaling relations with their host spheroid, including a bent (black hole mass)–(host spheroid mass) $M_{\rm bh}$–$M_{\rm sph}$ relation and a different (massive compact object mass)–(host spheroid velocity dispersion) $M_{\rm mco}$–σ relations for black holes and nuclear star clusters. By combining the observed $M_{\rm bh} \propto \sigma^{5.5}$ relation with the observed $M_{\rm nc} \propto \sigma^{1.6-2.7}$ relation, we derive the expression $M_{\rm bh} \propto M_{\rm nc}^{2-3.4}$, which should hold until the nuclear star clusters are eventually destroyed in the larger core-Sérsic spheroids. This *new* mass scaling relation helps better quantify the rapid evolutionary growth of massive black holes in dense star clusters, and the relation is consistently recovered when coupling the observed $M_{\rm nc} \propto M_{\rm sph}^{0.6-1.0}$ relation with the recently observed quadratic relation $M_{\rm bh} \propto M_{\rm sph}^2$ for Sérsic spheroids.

Keywords. galaxies, black holes, nuclear star clusters.

1. Introduction

Over the past two decades there has been wide-spread interest in the scaling relations connecting supermassive black holes (SMBHs) with their host galaxy, and in particular with their host bulge. This has been, in part, due to observations which suggested that they grow in tandem, with feedback from the black hole (previously) thought to establish a near constant 0.1–0.2% mass ratio with the host spheroid. Over the last decade there has been a quieter realisation that the nuclear star clusters (NSCs)† at the centres of most Sérsic galaxies also correlate with the properties of their host spheroid. This connection continues until the disappearance / destruction of the clusters in the (massive) core-Sérsic galaxies with partially depleted cores (Bekki & Graham 2010, and references therein). Given the coexistence of SMBHs within dense star clusters (e.g. Seth *et al.* 2008; González Delgado *et al.* 2008; Graham & Spitler 2009; Graham 2012b; Leigh *et al.* 2012; Neumayer & Walcher 2012; Scott & Graham 2013) one may wonder if massive black holes might also be intimately connected with their host star cluster, in addition to their host spheroid, or perhaps SMBHs and dense NSCs merely inevitable co-inhabitants at the bottom of each galaxy's gravitational potential well.

In this review talk I briefly present the latest scaling relations between both SMBHs and NSCs with their host spheroid's (*i*) velocity dispersion (Section 2) and (*ii*) stellar mass (Section 3). After then reminding ourselves what Sérsic and core-Sérsic galaxies are (Section 4), these relations are consistently brought together in a way that eliminates the spheroid and yields, for the first time, the mass relation between SMBHs and their host NSCs (Section 5).

† Nuclear star clusters are so-named because of their location at the nuclei of galaxies.

2. The $M_{\rm mco}$-σ relations

Massive black holes and dense nuclear star clusters† are collectively referred to here as massive compact objects (mco). In the (massive compact object mass)–(host spheroid velocity dispersion) $M_{\rm mco}$-σ diagram, SMBHs and NSCs follow different tracks.

The $M_{\rm bh} \propto \sigma^X$ relation has a logarithmic slope X of around 5.5±0.3 (Graham & Scott 2013; McConnell & Ma 2013). Galaxies with bars have also been observed to display an apparent offset to lower black hole masses in the $M_{\rm bh}$–σ diagram (Graham 2008; Hu 2008; Graham & Li 2009; Graham *et al.* 2011). As was noted by Hu (2008) and Graham (2008), this may be due to under-massive black holes in what might be pseudobulges (an idea preferred by Greene *et al.* 2010 and Kormendy & Bender 2011), or instead it may be due to the occurrence of higher velocity dispersions. Hartmann *et al.* (2013) have recently shown that the dynamics associated with bars are indeed fully capable of explaining the observed offset in the $M_{\rm bh}$–σ diagram in terms of elevated velocity dispersions (see also Brown *et al.* 2013 and Debattista *et al.* 2013), and Graham & Scott (2013) have found no offset between barred and unbarred galaxies in the $M_{\rm bh}$–$L_{\rm sph}$ diagram, disfavouring the pseudobulge idea suggested 7 years ago.

The $M_{\rm nc}$–σ^Y relation has a much shallower slope than the $M_{\rm bh}$–σ^X relation. Excluding nuclear disks, Graham (2012b) reported a logarithmic slope Y of 1.57 ± 0.24, while Scott & Graham (2013) reported a value of 2.11 ± 0.31 having over-lapping error bars. Leigh *et al.* (2012) have however reported a steeper value of 2.73 ± 0.29, attributed to their inclusion of nuclear disks which can be an order of magnitude more massive than the biggest nuclear star clusters.

3. Sérsic versus core-Sérsic galaxies

Sérsic galaxies contain spheroids, either bulges or the main elliptical galaxy itself, whose projected light is well described by Sérsic's $R^{1/n}$ (1963) model. These Sérsic spheroids may additionally contain NSCs. In contrast, core-Sérsic galaxies display a partially depleted core, not due to dimming by dust and typically less than a few hundred parsec in radius, relative to the inward extrapolation of their outer Sérsic profile (Graham *et al.* 2003; Trujillo *et al.* 2004). The Sérsic versus core-Sérsic divide built on but differs from the “core” versus “power-law” galaxy divide (Lauer *et al.* 1995) in that “core” galaxies do not always have a partially depleted core relative to their outer profile (see Dullo & Graham 2014, and references therein). The core-Sérsic galaxies are thought to have formed from the dry merger of Sérsic (and/or core-Sérsic) galaxies, wherein the SMBHs sink to the centre via the gravitational ejection of stars from the core of the newly formed galaxy.

With Sérsic indices from less than 1 to $\sim$4, Sérsic spheroids follow a log-linear luminosity-(central surface brightness) relation ($L - \mu_0$) and a log-linear $L - n$ relation (e.g. Graham & Guzmán 2003). Due to the non-homology in their light profiles, i.e. the fact that they do not all have the same ($R^{1/4}$, for example) light profiles, this systematic change in n with luminosity produces a non-linear luminosity-dependent difference between μ_0 and $\langle\mu\rangle_{\rm e}$ (the mean surface brightness within the effective half light radius, $R_{\rm e}$). This results in a strongly curved $L - \langle\mu\rangle_{\rm e}$ relation. Given that $L = 2\pi\langle I\rangle_{\rm e} R_{\rm e}^2$, where $\langle I\rangle_{\rm e}$ is the average intensity associated with the average surface brightness, the $L - R_{\rm e}$ relation is also strongly curved. These relations are in fact so curved that the faint ($n \lesssim 2$) and bright ($n \gtrsim 2$) arms of the relations have, before the consequences of structural non-homology

† By this term we mean to exclude (obvious) nuclear discs, which can be much more extended than compact nuclear star clusters (see Balcells *et al.* 2007).

https://doi.org/10.1017/S1743921315008017 Published online by Cambridge University Press

were known, been mistakenly heralded as evidence for a dichotomy between faint and bright early-type galaxies (see Graham *et al.* 2013 for an extended review).

Due to the depleted cores in the core-Sérsic spheroids (typically $M_B < -20.5 \pm 0.75$ mag), they branch off from the $L - \mu_0$ relation toward lower central surface brightnesses. Core-Sérsic and Sérsic spheroids/galaxies do however follow the same steep $M_{\rm bh}$–σ relation (e.g. Graham & Scott 2013).

4. The $M_{\rm mco}$-$M_{\rm sph}$ relations

Before getting to observations of the $M_{\rm mco}$-$M_{\rm sph}$ relations, one can already predict the general behavior in the case of the $M_{\rm bh}$-$M_{\rm sph}$ relation. This is done by noting a transition or bend in the $L - \sigma$ relation found by Davies *et al.* (1983) such that low-luminosity early-type galaxies (not pseudobulges) follow the relation L–σ^2 while the high-luminosity galaxies ($M_B < -20.5$ mag) follow a steeper relation. Matković & Guzmán (2005) explained the bend in terms of Sérsic versus core-Sérsic galaxies. This bend was recently shown again as a bend in the $M_{\rm sph}$–σ relation by Davies and his collaborators in Cappellari *et al.* (2013).

Coupled with the log-linear $M_{\rm bh}$–σ relation noted in Section 2, the bent $M_{\rm sph}$–σ relation necessitates a bent $M_{\rm bh}$–$M_{\rm sph}$ relation. As was pointed out in Graham (2012a), for things to be consistent there *must* be a bent relation rather than the log-linear relation which had been assumed and claimed for well over a decade. This of course introduces a huge change to our understanding of the physical relation between SMBHs and their host spheroid.

While the bent $M_{\rm bh}$–$M_{\rm sph}$ relation was first presented in Graham (2012a) with actual data, the black hole masses did not probe very far down the mass function, making the discovery somewhat hard to see (although still statistically significant). However in Graham & Scott (2013), see also Scott, Graham & Schombert (2013), they were able to include data down to $M_{\rm bh} \approx 10^6 M_\odot$, and in Graham & Scott (2014, in prep.) it reaches down to $10^5 M_\odot$ through the inclusion of over 100 active galactic nuclei with indirectly measured black hole masses. What the two papers in 2013 confirmed is that Sérsic galaxies follow a near-quadratic $M_{\rm bh}$–$M_{\rm sph}$ relation, i.e. a power-law with a slope close to 2, as predicted in Graham (2012b). It is only the core-Sérsic galaxies, built from simple additive mergers, which branch off and follow a near-linear $M_{\rm bh}$–$M_{\rm sph}$ relation. As a result, fitting a single log-linear relation to samples of Sérsic and core-Sérsic galaxies produces a slope greater than 1 and a relation which is not optimal for either population.

The $M_{\rm bh}/M_{\rm sph}$ mass ratio for core-Sérsic galaxies was found by Graham (2012a) to be 0.36%, double the previously assumed constant value for all galaxy types, and it was increased to 0.49% in Graham & Scott (2013). However, due to the quadratic relation for the Sérsic galaxies, their $M_{\rm bh}/M_{\rm sph}$ mass ratio can be far lower.

The $M_{\rm nc}$–$M_{\rm sph}$ relation was found by Balcells *et al.* (2003) among the bulges of disk galaxies, and later by Graham & Guzmán (2003) using a sample of predominantly elliptical galaxies. The slope of this relation has since been measured many times, most recently by den Brok *et al.* (2014) who reports $L_{\rm nc} \propto L_{\rm sph}^{0.57\pm0.05}$ ($F814W$), in fair agreement with the value of 0.60 ± 0.10 from Scott & Graham (2013) for the $M_{\rm nc}$–$L_{\rm sph}$ (K-band) relation for early-type galaxies. Previous works have claimed slopes around 0.75 but as high as 1 when including nuclear disks (e.g. Grant *et al.* 2005; Wehner & Harris 2006; Côté *et al.* 2006; Balcells *et al.* 2007).

https://doi.org/10.1017/S1743921315008017 Published online by Cambridge University Press

5. The (new) $M_{\rm bh}$-$M_{\rm nc}$ relation

Coupling $M_{\rm nc} \propto M_{\rm sph}^{0.6-1.0}$ with $M_{\rm bh} \propto M_{\rm sph}^{2}$ for the Sérsic spheroids gives $M_{\rm bh} \propto M_{\rm nc}^{2-3.3}$.

Coupling $M_{\rm bh} \propto \sigma^{5.5}$ with $M_{\rm nc} \propto \sigma^{1.6-2.7}$ from Section 2 gives $M_{\rm bh} \propto M_{\rm nc}^{2.0-3.4}$.

Depending on which precise slopes one adopts from the wedded pair of relations above, one ends up with a different slope for the new relation between black hole mass and host nuclear star cluster mass. While the author's past work would favour a steeper exponent (3.4), encompassing the wider literature suggests something like $M_{\rm bh} \propto M_{\rm nc}^{2.7\pm0.7}$ given the range of slopes for the initial relations. It is hoped that further observations and analysis, combined with theory, will be able to refine and explain this steep (non-linear) relation which may not simply be a consequence of the relations from which it was derived here.

As noted in the Introduction, not all galaxies with SMBHs have NSCs, and as such a certain degree of common sense is required in application of this new relation. For instance, core-Sérsic galaxies do not have a NSC, which was likely eroded away prior to the formation of their partially-depleted cores. Given this, as one approaches the high-mass end of the Sérsic galaxy sequence (from lower masses), it is expected that the NSCs will flay and some Sérsic galaxies would no longer house any significant NSC (e.g., NGC 5831, Graham *et al.* 2003). At the low-mass end, and as with the $M_{\rm bh}$–σ relation and the $M_{\rm bh}$–$M_{\rm sph}$ relation, the frequency of massive black holes below $10^5 M_\odot$ is not yet known. The occurrence of NSCs is however known to tailor off, or at least become harder to identify, in early-type galaxies fainter than $M_{F814W} = -15$ mag (den Brok *et al.* 2014), which may then reflect some kind of lower bound to the relation. Finally, it is remarked that massive BHs in globular clusters may be better matched to the new $M_{\rm bh}$-$M_{\rm nc}$ relation than the $M_{\rm bh}$-$M_{\rm sph}$ relation.

6. Conclusions

SMBHs grow rapidly relative to their stellar nurseries, i.e. the nuclear cluster of stars which still enshroud many. This is not to say that we know if the SMBHs were born in these nurseries; although once they become one hundred million solar mass grown-ups their nursery is gone. The growth of the BH relative to the NSC is extremely rapid: $M_{\rm bh} \propto M_{\rm nc}^{2.7\pm0.7}$, with the author favouring higher values for the exponent, especially if new data steepens the $M_{\rm bh}$–σ relation, and if the $M_{\rm bh}$-$M_{\rm sph}$ relation *is* super-quadratic for the Sérsic galaxies.

Acknowledgements

The author thanks the conference organizers for bringing together researchers of massive black holes and star clusters, and for the opportunity to present this invited review/update which resulted in the formulation of the steep (black hole mass)–(nuclear star cluster mass) relation given here.

References

Balcells, M., Graham, A. W., Domínguez-Palmero, L., & Peletier, R. F. 2003, *ApJ Lett.*, 582, L79

Balcells, M., Graham, A. W., & Peletier, R. F. 2007a, *ApJ*, 665, 1084

Bekki, K. & Graham, A. W. 2010, *ApJ Lett.*, 714, L313

Brown, J. S., Valluri, M., Shen, J., & Debattista, V. P. 2013, *ApJ*, 778, 151

Cappellari, M., McDermid, R. M., Alatalo, K. *et al.* 2013, *MNRAS*, 432, 1862

Côté, P., Piatek, S., Ferrarese, L., *et al.* 2006, *ApJS*, 165, 57
Davies, R. L., Efstathiou, G., Fall, S. M., Illingworth, G., & Schechter, P. L. 1983, *ApJ*, 266, 41
Debattista, V. P., Kazantzidis, S., & van den Bosch, F. C. 2013, *ApJ*, 765, 23
den Brok, M., Peletier, R. F., Seth, A., *et al.* 2014, *MNRAS*, accepted (arXiv:1409.4766)
Dullo, B. T. & Graham, A. W. 2014, *MNRAS*, 444, 2700
González Delgado, R. M., Pérez, E., Cid Fernandes, R., & Schmitt, H. 2008, *AJ*, 135, 747
Graham, A. W. 2008, *ApJ*, 680, 143
Graham, A. W. 2012a, *ApJ*, 746, 113
Graham, A. W. 2012b, *MNRAS*, 422, 1586
Graham, A. W. 2013, in "Planets, Stars and Stellar Systems", Vol. 6, p.91-140, T.D.Oswalt & W.C Keel (eds.), Springer Publishing (arXiv:1108.0997)
Graham, A. W., Erwin, P., Trujillo, I., & Asensio Ramos, A. 2003, *AJ*, 125, 2951
Graham, A. W. & Guzmán, R. 2003, *AJ*, 125, 2936
Graham, A. W., Onken, C. A., Athanassoula, E., & Combes, F. 2011, *MNRAS*, 412, 2211
Graham, A. W. & Li, I-H. 2009, *ApJ*, 698, 812
Graham, A. W. & Scott, N. 2013, *ApJ*, 764, 151
Graham, A. W. & Spitler, L. R. 2009, *MNRAS*, 397, 2148
Grant, N. I., Kuipers, J. A., & Phillipps, S. 2005, *MNRAS*, 363, 1019
Greene, J. E., Peng, C. Y., Kim, M., *et al.* 2010, *ApJ*, 721, 26
Hartmann, M., Debattista, V. P., Cole, D. R., *et al.* 2013, *MNRAS*, 441, 1243
Hu, J. 2008, *MNRAS*, 386, 2242
Kormendy, J. & Bender, R. 2011, *Nature*, 469, 377
Lauer, T. R., Ajhar, E. A., Byun, Y.-I., *et al.* 1995, *AJ*, 110, 2622
Leigh, N., Böker, T., & Knigge, C. 2012, *MNRAS*, 424, 2130
Matković, A., & Guzmán, R. 2005, *MNRAS*, 362, 289
McConnell, N. J. & Ma, C.-P. 2013, *ApJ*, 764, 184
Neumayer, N. & Walcher, C. J. 2012, *Advances in Astronomy*, 2012, (arXiv:1201.4950)
Scott, N. & Graham, A. W. 2013, *ApJ*, 763, 76
Scott, N., Graham, A. W., & Schombert, J. 2013, *ApJ*, 768, 76
Sérsic, J.-L. 1963, *Boletin de la Asociacion Argentina de Astronomia*, vol.6, p.41
Seth, A., Agüeros, M., Lee, D., & Basu-Zych, A. 2008, *ApJ*, 678, 116
Trujillo, I., Erwin, P., Asensio Ramos, A., & Graham, A. W. 2004, *AJ*, 127, 1917
Wehner, E. H. & Harris, W. E. 2006, *ApJ Lett.*, 644, L17