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Research Statement

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1. BLACK HOLE MASS SCALING RELATIONS

1.1. *The $M_\bullet$–ϕ Relation*

Seigar et al. (2008) first presented evidence of a relationship between the mass of a black hole, ($M_\bullet$) and the pitch angle (ϕ) of its host galaxy. This relation introduced a powerful tool to estimate the masses of black holes in distant galaxies using only simple imaging data, without the need for telescope-expensive spectral data (or even photometric calibration). In Berrier et al. (2013), we increased the number of spiral galaxies with directly-measured supermassive black holes (SMBHs) from five (as it was in Seigar et al. 2008), to 22. In Davis et al. (2014), we generated a black hole mass function (BHMF) for local spiral galaxies by applying the updated $M_\bullet$–ϕ relation to a volume-limited sample of 144 galaxies from the Carnegie-Irvine Galaxy Survey (Ho et al. 2011). In a follow-up study (Mutlu-Pakdil et al. 2016), we also derived the BHMF for the complementary sample of 68 early-type galaxies. An ongoing work is focusing on the low-mass end of the BHMF (Fusco et al. 2022). In Davis et al. (2017), we redoubled the number (up to 44) of directly measured black holes used to generate the $M_\bullet$–ϕ relation. This work received favorable coverage in the media, and I was invited to write an article for *Australasian Science* (Davis 2017).[1]

1.2. *The $M_\bullet$–$M_{\star,\rm sph}$ Relation*

My main attraction to moving to Australia was the opportunity to work with Alister Graham. I consider him the world's foremost expert when it comes to the multi-component decomposition of galactic light profiles and the modeling of their spheroids with Sérsic profiles. I learned much from him during my four years at Swinburne, becoming adept at the aforementioned skills and cutting-edge software (Ciambur 2015, 2016) that our research group utilizes. The majority of studies, particularly large surveys and pipelines, perform simple, automated, two-component (i.e., bulge/disk) decompositions to galaxies. Our research shows that this näiveté and oversimplification can be harmfully misleading, and is often wrong.

I performed meticulous multi-component decompositions of the spiral galaxy sample from Davis et al. (2017). In Davis et al. (2019a), we presented these detailed decompositions and our unprecedentedly accurate stellar bulge masses ($M_{\star,\rm sph}$). From our resulting sample, we performed a custom, sophisticated Bayesian linear regression to define the $M_\bullet$–$M_{\star,\rm sph}$ relation for spiral galaxies, finding that $M_\bullet \propto M_{\star,\rm sph}^{2.44\pm0.33}$. This slope is significant due to its marked difference from the slope we later found for early-type galaxies, $M_\bullet \propto M_{\star,\rm sph}^{1.27\pm0.07}$ (Sahu et al. 2019a). Since the latter relation is almost ubiquitously reproduced in large N-body galaxy simulations for *all* types of galaxies, our research has important implications for such simulations; simulations that tune their results to a universal linear rate of growth between bulges and black holes need revision.

Furthermore, in Sahu et al. (2019a, see figure 8) we showed that the seemingly sufficient single relation for early-type galaxies is misleading by revealing that early-type galaxies with and without a disk define two separate (parallel) $M_\bullet \propto M_{\star,\rm sph}^{1.9\pm0.2}$ relations, which are offset by more than an order of magnitude (1.12 dex) in the $M_\bullet$-direction.

1.3. *The $M_\bullet$–$M_{\star,\rm tot}$ and $M_\bullet$–$M_{\star,\rm disk}$ Relations*

We released our study of bulge stellar masses in tandem with our study of total ($M_{\star,\rm tot}$) and disk ($M_{\star,\rm disk}$) stellar masses Davis et al. (2018), where we presented evidence that the $M_\bullet$–$M_{\star,\rm tot}$ relation is steeper, but not significantly less accurate than the $M_\bullet$–$M_{\star,\rm sph}$ relation for spiral galaxies. This flexibility is advantageous because it implies that black holes can be reliably predicted by measuring $M_{\star,\rm tot}$, a task that is significantly easier than isolating the stellar mass of its bulge. Saving time is appealing for extensive surveys and pipelines, for whom, producing thousands of time-consuming decompositions would be prohibitively time-intensive. We also presented evidence that $M_\bullet$ does weakly correlate with $M_{\star,\rm disk}$, a correlation which was previously thought not to exist (e.g., Kormendy & Gebhardt 2001).

[1] https://www.australasianscience.com.au/article/issue-sepoct-2017/how-you-can-weigh-black-holes.html

1.4. *The $M_\bullet$–σ and L–σ Relations*

In Sahu et al. (2019b), we followed-up on the paradigm-shifting discovery in Sahu et al. (2019a) and searched for similar hidden substructures in the $M_\bullet$–(σ) central stellar velocity dispersion diagram. We investigated divisions based on the presence of a depleted stellar core (major dry-merger), a disk (minor wet/dry-merger, gas accretion), or a bar (evolved unstable disk), in a sample of 145 galaxies. Ultimately, we showed that Sérsic and core-Sérsic galaxies define two distinct relations: $M_\bullet \propto \sigma^{5.75\pm0.34}$ and $M_\bullet \propto \sigma^{8.64\pm1.10}$, with $\Delta_{rms|\bullet} = 0.55$ and 0.46 dex, respectively (see Sahu et al. 2019b, figure 4). We also report on the consistency with the slopes and bends in the galaxy luminosity (L)–σ relations. Our new, type-dependent, $M_\bullet$–σ relations more precisely estimate $M_\bullet$ in other galaxies, and hold implications for galaxy/BH coevolution theories, simulations, feedback, and can improve predictions for the detection of long-wavelength gravitational waves using pulsar timing arrays and space-based interferometers.

1.5. *The $M_\bullet$–$\mathrm{n_{sph}}$ and $M_\bullet$–$\mathrm{R_{e,sph}}$ Diagrams*

In the work of Sahu et al. (2020), we further unearth the morphological dependencies of galaxies and the relationships observed amongst their black holes and parameterizations of their spheroids: both their Sérsic indices ($\mathrm{n_{sph}}$) and half-light radii ($\mathrm{R_{e,sph}}$). We show strong type-dependences when segregating the samples by early vs. late types, as well as disk, bar, or bulge morphologies. These new morphology-aware relations offer useful predictive capabilities that do not require photometric calibration. Furthermore, our findings pose pivotal checks for simulations trying to reproduce realistic galaxies, and for theoretical studies investigating the dependence of black hole mass on basic spheroid properties. Our Sahu et al. (2022a) report presents a concise summary of our morphology-dependent black hole–host galaxy correlations. A subsequent paper (Sahu et al. 2022b) investigates spheroid spatial stellar mass density and its correlation with the black hole mass.

1.6. *The $M_\bullet$–$v_{\max}$ and $M_\bullet$–M_{DM} Relations*

Some of my research involves investigating the connection between spiral galaxy structure, black hole mass, and dark matter halo mass (M_{DM}). I have previous experience working with dark matter halo masses from my work on Seigar et al. (2014). Kennicutt (1981) first presented evidence that ϕ correlates with the maximum rotational velocity ($v_{\max}$) of disk galaxies. Ferrarese (2002) initially showed that black hole mass correlates with M_{DM}. In Davis et al. (2019b), we updated both of these relations and demonstrated that these relations are consistent with our $M_\bullet$–$M_{\star,\mathrm{tot}}$ relation (Davis et al. 2018) and the Tully-Fisher relation (Tully & Fisher 1977).

2. INTERMEDIATE-MASS BLACK HOLES

Astronomers have discovered two sizes of black holes in the universe: SMBHs ($\geq 10^5\,\mathrm{M}_\odot$) and solar mass black holes ($<10^2\,\mathrm{M}_\odot$). However, the so-called intermediate-mass black holes (IMBHs) theorized to fill in the evolutionary gap ($10^2\,\mathrm{M}_\odot \leq M_\bullet < 10^5\,\mathrm{M}_\odot$), remain elusive. The further discovery of IMBHs would be a great boon to research/theory and provide potential multi-messenger targets for future generations of gravitational wave detectors.

Recently, I was involved with an international collaboration to use multiple scaling relations, including X-ray and radio luminosity relations, to search for possible IMBHs (Koliopanos et al. 2017). Subsequent research has included a *Chandra X-ray Observatory* Large Program (Soria 2016), which has imaged 52 galaxies with the ACIS-S detector. In Graham et al. (2019), we predicted the central black hole masses in these galaxies using the latest black hole scaling relations involving ϕ, σ, and $M_{\star,\mathrm{tot}}$; focused study of promising candidates is currently underway. We have bolstered this sample by using suitably deep archival *Chandra* images for an additional 22 spiral galaxies in the Virgo cluster, providing a complete sample of 74 spiral galaxies with star-formation rates $>0.3\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

So far, this project has demonstrated the potential for half-a-dozen, high-impact papers. In Graham et al. (2021b), we focused on 11 IMBH candidates. Moreover, we made a serendipitous discovery of a potential shredded offset nuclear star cluster with an IMBH, identified by an X-ray source and optical/infrared counterpart (Graham et al. 2021a). In Davis & Graham (2021), we have combined ten different black hole mass estimates for a single galaxy (NGC 3319) in order to produce a probability density function of black hole mass for the galaxy, and thus a refined mass estimate with a better precision than that of individual estimates. Recent research (Davis et al. 2024) repeats this procedure and measure pitch angles for all (85) of the later type spiral galaxies (i.e., Hubble type Sd) in the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991), in a further search for IMBH candidates.

3. LOGARITHMIC SPIRAL ARM PITCH ANGLE

Logarithmic spiral arm pitch angle was the focus of my Ph.D. thesis (Davis 2015) and continues to be a fundamental part of my research and a subject for which I possess a high level of expertise. Logarithmic spirals are ubiquitous throughout nature, manifesting themselves as optimum rates of radial growth for azimuthal winding in numerous structures such as mollusk shells, tropical cyclones, and the arms of spiral galaxies. I have been personally involved in the development of independent software packages to analyze images of galaxies and quantify their pitch angles (Davis et al. 2012, 2016; Davis & Hayes 2014; Seigar et al. 2018; Shields et al. 2015, 2022).

Spiral density wave theory has existed and been the most popular theory governing spiral structure in disk galaxies, for more than a half-century now. Lin & Shu (1966) made a specific prediction that ϕ should be dictated by both the bulge mass and density of gas in the disk of a spiral galaxy. In Davis et al. (2015), we observationally confirmed this prediction. Thus, the spiral density wave depends on the density of the disk, rather than the total mass of the disk, and it is the mass of the bulge that effectively anchors the spiral arm, a bit like setting the tension in a vibrating string of a violin by adjusting its tuning peg.

Spiral density wave theory predicts that when measured in different wavelengths of light, spiral arms will display slightly different pitch angles. In Pour-Imani et al. (2016) and Miller et al. (2019), we measured the pitch angles for spiral galaxies in multiple passbands from the far-ultraviolet to $8.0\,\mu$m. We found that ϕ was statistically tightest in $3.6\,\mu$m, and loosest in $8.0\,\mu$m images. In Abdeen et al. (2020), we expanded upon this method of measuring the pitch angle in multiple wavelengths in order to determine the co-rotation radii of spiral galaxies. Furthermore, we were able to observe an age gradient across spiral arms (with phase crossings at the co-rotation radii) via analysis of star formation history maps and spatially resolved stellar clusters in spiral galaxies (Abdeen et al. 2022).

4. FUTURE PROJECTS AND PLANS

My research is ideally suited for graduate and undergraduate students. During my time as a graduate student, I mentored an REU student each summer, whom I taught my pitch angle software and how to measure spiral galaxies. Many of these summer projects led to these students co-authoring papers with me, including Matt Hartley, Luke Johns, and Russell Flatman. As a postdoc, I was an associate supervisor for Ph.D. students: Nandini Sahu and Suei-Hei (Dexter) Hon (Hon et al. 2022), and mentored an undergraduate honors student, James Sanders, who quantified the (X/peanut)-shaped structure in face-on disk galaxies (Sanders 2019). I have trained these students to use our decomposition software and am actively reviewing their projects and editing their manuscripts. Many of the students I have worked with have had limited experience with astronomy and possessed more general scientific backgrounds. With a little effort, I find it has been straightforward to train them in the methodologies necessary for my research and develop their knowledge as astronomers.

I aim to continue my impactful research and maintain my international collaborations, which extend to four continents now. I desire to establish a vibrant and productive extragalactic research group with passionate and motivated colleagues. I have learned from experience that students are very interested in what is new and disruptive in science. Perhaps the most exciting new field in science today is the study of gravitational waves. I am an affiliate of OzGrav and a member of the LISA Consortium (co-author of Amaro-Seoane et al. 2023). Thus, I have many connections in the field of gravitational radiation, including the LIGO collaboration.

As ground-based detectors become more sensitive to longer wavelength gravitational radiation, they will be able to detect the coalescence of IMBHs from the mergers of late-type galaxies. My ongoing research into black hole mass scaling relations and BHMFs for spiral galaxies will help to establish estimates for the frequency of detections for the next generation of gravitational-wave observatories and future space-based detectors like LISA. For example, Mapelli et al. (2012) discuss the detection of gravitational waves generated by the merging of a nuclear star cluster and an SMBH. More immediately, we can further improve the prediction of the amplitude and frequency for ground-based detections of long-wavelength gravitational waves produced by merging SMBHs using pulsar timing arrays (Shannon et al. 2015).

At New York University Abu Dhabi, I am currently working on several projects that are based on machine-learning and N-body simulations (e.g., Waterval et al. 2024). Zehao Jin and I have a work (Davis & Jin 2023, 2024) describing the first interesting higher-dimensional black hole mass scaling relation we have found using symbolic regression (Cranmer 2023); further, more comprehensive results are described in Jin & Davis (2023) and ongoing machine learning causality studies (e.g., Pasquato et al. 2023, and work in preparation). We also plan to test the physics behind these new scaling relations in cosmological zoom-in hydrodynamical simulations (Wang et al. 2015) and work to improve the black hole feedback modeling. From gravitational waves to IMBHs, and my recent foray in machine learning, there should be numerous possible funding opportunities and student-oriented projects on the horizon.

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