Nuclear Star Clusters & Black Holes

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Abstract. We summarize the recent results of our survey of the nearest nuclear star clusters. The purpose of the survey is to understand nuclear star cluster formation mechanisms and constrain the presence of black holes using adaptive optics assisted integral field spectroscopy, optical spectroscopy, and HST imaging in 13 galaxies within 5 Mpc. We discuss the formation history of the nuclear star cluster and possible detection of an intermediate mass BH in NGC 404, the nearest S0 galaxy.

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INTRODUCTION

Nuclear star clusters (NSCs) are found at the centers of a majority of galaxies with Milky Way mass and below [1, 2, 3]. These NSCs have similar sizes to globular clusters (~5 pc), but are much more luminous and massive [4]. Their morphology is often complicated and their star formation history is typically extended [e.g. 5]. The relationship of NSCs to supermassive black holes (BHs) typically found at the centers of more luminous galaxies is not clear. NSCs and supermassive BHs co-exist in some galaxies [6], and both have masses that scale with the mass and dispersion of the galaxy they live in [e.g. 7]. Unlike BHs, the histories of NSCs are recorded in their morphology, kinematics, and stellar populations, making them excellent tools to study how mass accumulates at the centers of galaxies.

NEARBY NUCLEAR STAR CLUSTER SURVEY

We are conducting an ongoing survey of the nearest NSCs, observing a sample of 13 galaxies within 5 Mpc. By resolving the kinematics and stellar populations in these NSCs, we can understand how they formed and constrain the masses of any BHs within them. Their proximity makes them among the most promising objects for detecting intermediate mass BHs, constraining the low mass end of the BH-galaxy scaling relations and the occupation fraction of low mass galaxies. Because the BHs in these galaxies are likely to not have undergone much subsequent evolution, measuring their properties is
FIGURE 1. MMT 6.5m optical spectrum of the NGC 404 nuclear cluster (black line) with the best fit spectral synthesis model (overplotted gray line). The spectral templates used to fit the spectra (shown in light gray) are drawn from 11 possible age bins ranging from 1 Myr to 13 Gyr in age. More than 50% of the light is in stars with ages 1-3 Gyr, while ∼10% is at ages \leq 10 Myr. Residuals are about 1%. Vertical gray lines indicate areas excluded from the fit due to emission lines.

one of the only ways of constraining the initial formation mechanism of supermassive BHs [e.g. 8].

We are obtaining adaptive optics assisted integral field spectroscopy on the entire sample using Gemini/NIFS (PI: Seth) and VLT/SINFONI (PI: Neumayer). In addition, we are obtaining low resolution optical spectroscopy to examine the stellar populations in the nucleus and HST imaging to constrain their morphology. Our first published results [9], show a flattened multi-component NSC with strong rotation in the edge-on spiral galaxy NGC 4244. This NSC must have formed from repeated accretion of material from the disk of the host galaxy, a scenario tested in simulations by Markus Hartmann (this volume).

THE NUCLEUS OF NGC 404

We now focus on the NSC formation and possible intermediate mass BH in NGC 404, the nearest S0 galaxy (D=3.1 Mpc). The galaxy is nearly face-on and has a total mass of about $10^9 \, M_\odot$ and $M_V = -17.35$. NGC 404 also hosts the nearest LINER nucleus, although whether this observed activity is actually the result of an accreting BH is a matter of some contention. The results shown here are presented in much greater detail in a paper submitted to the ApJ.

Nuclear Star Cluster
The surface brightness profile of the inner part of NGC 404 (see left panel of Fig. 2) can be decomposed into three distinct components each with distinct kinematics and stellar
FIGURE 2. Left – The surface brightness profile of NGC 404 in F814W/I band made from HST imaging. The lines show the best bulge+NSC fit, where both components are assumed fit as Sérsic profiles. The central 0.2” show a clear excess above these profiles. Right – Results from the gas dynamical model of a disk of molecular H$_2$ gas emission. Shown are $\chi^2$ contours as a function of BH mass and disk inclination. The best fitting BH mass is $4.5^{+3.5}_{-2.0} \times 10^5$ M$_\odot$, however the stellar dynamical models suggest a BH mass upper limit of $1 \times 10^5$ M$_\odot$.

populations. The bulge of the galaxy has a mass of $9 \times 10^8$ M$_\odot$ and dominates the light profile outside the central arcsecond (15 pc). Optical spectra of the stellar populations of this component show that it is dominated by old stars with ages $>5$ Gyr. The nuclear star cluster dominates the light in the central arcsecond and has a half-light radius of 10 pc and a dynamical mass of $10^7$ M$_\odot$, larger than expected from NSC scaling relations. Its optical spectrum is dominated by the light of stars with age of 1-3 Gyr, with stellar population synthesis fits suggesting that over half the mass of the cluster was formed during this period. The cluster shows mild rotation in the same direction as HI gas at larger radii in the galaxy [10], which has been suggested to have a merger origin. Finally, within the central 0.2”, the central excess of emission seen in the surface-brightness profile, is also found to be counter-rotating relative to the NSC. The emission of this component probably results from a combination of young ($<100$ Myr) stars, hot dust emission and perhaps AGN continuum.

The nuclear star cluster in NGC 404 appears to have a quite different formation from the episodic disk accretion seen in NGC 4244. The burst of star formation $\sim 1$ Gyr ago is suggestive of a merger origin, a scenario that is also consistent with the difference in rotation between the central excess and nuclear star cluster.

Possible Intermediate Mass BH
Signs of BH accretion in NGC 404 are conflicting, with the strongest evidence coming from the presence of variable UV emission [11]. We also find compact and possibly variable hot dust emission indicative of BH accretion at the center of the NSC.

From the Gemini/NIFS data we have obtained kinematic measurements of both the stars (as measured by the CO-bandhead absorption at 2.3$\mu$m) and for a gas disk seen in emission of excited H$_2$ at 2.12$\mu$m. The NIFS adaptive optics observations have a
PSF core with a FWHM=0.09” containing 50% of the light. We have created dynamical models to fit to the kinematics of both tracers. The starting point of both models is a mass model for the galaxy generated from HST imaging data using the multi-gaussian expansion method [12]. The mass model assumes a constant mass-to-light ($M/L$) ratio.

The stellar dynamical model uses axisymmetric Jeans modeling with the JAM package [13, see also contribution in this volume] to fit the CO bandhead velocity and dispersion in the central 1.5” (22 pc) of the galaxy. The model fits the NSC $M/L$, the anisotropy ($\beta_z$), and the BH mass ($M_{BH}$). Assuming a constant $M/L$, we find a $M/L = 0.70$ in the $I$ band and a 3-$\sigma$ upper limit of $M_{BH} < 1 \times 10^5 \, M_\odot$. The $M/L$ determined from the dynamical model matches the best-fit stellar population synthesis $M/L$ to within 10%.

The gas dynamical model is similar to that presented in Neumayer et al. [14], and assumes a thin disk geometry. It uses the $M/L$ from the stellar dynamical model and finds the disk inclination and BH mass that best match the $H_2$ kinematics. The results of this fit are shown in the right panel of Fig. 2. The best-fit $M_{BH} = 4.5^{+3.5}_{-2.0} \times 10^5 \, M_\odot$ (3$\sigma$ errors), somewhat inconsistent with the BH mass upper limit from the stellar kinematics. However both BH mass estimates are comparable to the uncertainty in the central stellar mass of $< 3 \times 10^5 \, M_\odot$ due to possible $M/L$ variations within the cluster. Despite this uncertainty, the dynamical models constrain the mass of the possible BH to be smaller than any previously dynamically measured BH and below several bulge mass scaling relations. We hope to obtain HST spectroscopy and imaging of the stellar populations across the nucleus to better refine the mass model and robustly measure the BH mass in NGC 404.

REFERENCES

1. T. Böker, S. Laine, R. P. van der Marel, M. Sarzi, H.-W. Rix, L. C. Ho, and J. C. Shields, *AJ* **123**, 1389–1410 (2002).
2. C. M. Carollo, M. Stiavelli, M. Seigar, P. T. de Zeeuw, and H. Dejonghe, *AJ* **123**, 159–183 (2002).
3. P. Côté, S. Piatek, L. Ferrarese, A. Jordán, D. Merritt, E. W. Peng, M. Haşegan, J. P. Blakeslee, S. Mei, M. J. West, M. Milosavljević, and J. L. Tonry, *ApJS* **165**, 57–94 (2006).
4. C. J. Walcher, R. P. van der Marel, D. McLaughlin, H.-W. Rix, T. Böker, N. Häring, L. C. Ho, M. Sarzi, and J. C. Shields, *ApJ* **618**, 237–246 (2005).
5. A. C. Seth, J. J. Dalcanton, P. W. Hodge, and V. P. Debattista, *AJ* **132**, 2539–2555 (2006).
6. A. C. Seth, M. Aguéros, D. Lee, and A. Basu-Zych, *ApJ* **678**, 116–130 (2008).
7. L. Ferrarese, P. Côté, E. Dalla Bontà, E. W. Peng, D. Merritt, A. Jordán, J. P. Blakeslee, M. Haşegan, S. Mei, S. Piatek, J. L. Tonry, and M. J. West, *ApJL* **644**, L21–L24 (2006).
8. M. Volonteri, G. Lodato, and P. Natarajan, *MNRAS* **383**, 1079–1088 (2008).
9. A. C. Seth, R. D. Blum, N. Bastian, N. Caldwell, V. P. Debattista, and T. H. Puzia, *ApJ* **687**, 997–1003 (2008).
10. M. S. del Río, E. Brinks, and J. Cepa, *AJ* **128**, 89–102 (2004).
11. D. Maoz, N. M. Nagar, H. Falcke, and A. S. Wilson, *ApJ* **625**, 699–715 (2005).
12. E. Emsellem, G. Monnet, and R. Bacon, *A&A* **285**, 723–738 (1994).
13. M. Cappellari, *MNRAS* **390**, 71–86 (2008).
14. N. Neumayer, M. Cappellari, J. Reunanen, H.-W. Rix, P. P. van der Werf, P. T. de Zeeuw, and R. I. Davies, *ApJ* **671**, 1329–1344 (2007).