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Intermediate-Mass Black Holes in Globular Cluster Systems

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Abstract. Using the Next Generation Very Large Array (ngVLA), we will make a breakthrough inventory of intermediate-mass black holes (IMBHs) in hundreds of globular cluster systems out to a distance of 25 Mpc. IMBHs have masses $M_{IMBH} \sim 100 - 100,000\ M_\odot$. Finding them in globular clusters would validate a formation channel for seed black holes in the early universe and inform event predictions for gravitational wave facilities. Our IMBH inventory is well suited for ngVLA Early Science.

1. Scientific Motivation

Theory suggests that globular clusters (GCs) of stars can host intermediate-mass black holes (IMBHs) with masses $M_{IMBH} \sim 100 - 100,000\ M_\odot$ (Miller & Hamilton 2002; Gurkan et al. 2004; Portegies Zwart et al. 2004; Giersz et al. 2015; Mezcua 2017). Finding IMBHs in GCs would validate a formation channel for seed black holes (BHs) in the early universe (e.g., Volonteri 2010; Sakurai et al. 2017); populate the mass gap between the well-understood stellar-mass BHs and the well-studied supermassive BHs (e.g., Kormendy & Ho 2013; Tetarenko et al. 2016); and test if scaling relations between stellar systems and their central BHs extend into poorly-explored mass regimes (e.g., Graham & Scott 2015). Also, the GC system of a typical galaxy contains several hundred GCs (Harris 2016). Thus studying such a system could constrain the mass spectrum of IMBHs in its GCs and, related, the ability of its GCs to retain their IMBHs and foster gravitational wave (GW) events (Fragione et al. 2017). These properties could vary from galaxy to galaxy, so many GC systems should be studied.

To search for IMBHs in GCs, one looks for evidence that the IMBHs are affecting the properties of their GC hosts. For GCs in the Local Group, a common approach is to use optical or infrared data to look for the dynamical signatures of IMBHs on the orbits of stars in the GCs. Such sphere-of-influence studies are contentious (Mezcua 2017, and references therein), even leading to differing IMBH masses when using the orbits of stars or of radio pulsars in the same GC (e.g., Gieles et al. 2017; Perera et al. 2017).

Having 3-dimensional velocity fields should improve the dynamical searches (Drukier & Bailyn 2003) but, even so, they remain susceptible to measuring high concentrations of stellar remnants rather than an IMBH (e.g., den Brok et al. 2014).

An independent approach that bypasses these issues is to look for the accretion signatures of IMBHs in GCs (Maccarone 2016, and references therein). This approach leverages on decades of studies of the signatures of accretion onto both stellar-mass and supermassive BHs (Fender & Munoz-Darias 2016, and references therein). Here, we apply a synchrotron radio model to search for the signatures of accretion onto IMBHs in entire GC systems. The model was developed for GCs in the Local Group (Maccarone 2004; Maccarone & Servillat 2008, 2010; Strader et al. 2012) and is summarized in Section 2. We have used the US National Science Foundation's Karl G. Jansky Very Large Array (VLA; Perley et al. 2011) to demonstrate the feasibility of a radio search for IMBHs in one nearby GC system (Wrobel et al. 2016) and summarize that effort in Section 3. In Section 4 we demonstrate the breakthrough role that the Next Generation VLA (ngVLA; Selina & Murphy 2017) will have in searching for IMBHs in hundreds of GC systems hosted in nearby galaxies. We close, in Section 5, by linking these searches to related studies using facilities contemporary with the ngVLA.

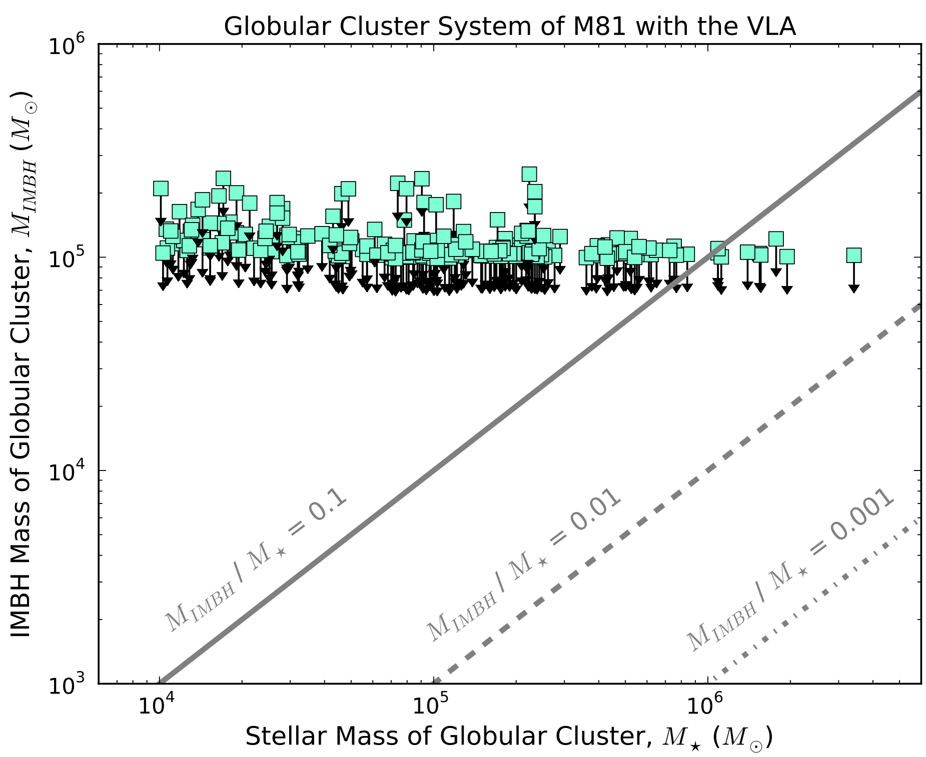

Figure 1. 3σ upper limits to the mass of the IMBH, M_{IMBH}, according to the Strader et al. (2012) model, as a function of the stellar mass, $M_\star$, for probable GCs in M81 (Wrobel et al. 2016). The grey diagonal lines of constant $M_{IMBH}/M_\star$ convey fiducial ratios of IMBH mass to stellar mass.

2. Synchrotron Radio Model

We invoke a semi-empirical model to predict the mass of an IMBH that, if accreting slowly from tenuous GC gas, is consistent with the synchrotron radio luminosity of a GC (Strader et al. 2012, and references therein). Following Strader et al. (2012), we assume gas-capture at 3% of the Bondi rate (Pellegrini 2005) for gas at a density of 0.2 particles cm^{-3} as measured by Freire et al. (2001), and at a constant temperature of 10,000 K as justified by Scott & Rose (1975). We also assume that accretion proceeds at less than 2% of the Eddington rate, thus involving an advection-dominated accretion flow with a predictable, persistent X-ray luminosity. (An IMBH accreting at higher than 2% of the Eddington rate would enter an X-ray-luminous state (Maccarone 2003) and be easily detectable in existing surveys. But no such X-ray sources exist in Galactic GCs.) We then use the empirical fundamental-plane of BH activity (Merloni et al. 2003; Falcke et al. 2004; Plotkin et al. 2012) to predict the synchrotron radio luminosity. The radio emission is expected to be persistent, flat-spectrum, jet-like but spatially unresolved, and located near the dynamical center of the GC.

From parameter uncertainties, Strader et al. (2012) estimate that the IMBH mass associated with a given radio luminosity could be in error by 0.39 dex, thus a factor of 2.5. To improve the robustness of such masses, one could fold in more recent data, especially regarding the highly uncertain gas-capture parameter. It could also be profitable to examine the model's underlying framework. For example, guided by Scott & Rose (1975), the model assumes that the classic Bondi flow toward a point mass, the IMBH, is isothermal. Yet the classic Bondi accretion rate would be lower if the flow could be argued to be adiabatic (Pellegrini 2005; Perera et al. 2017). On the other hand, models for an isothermal flow toward an IMBH embedded in a realistic GC potential appear to achieve higher accretion rates than classic Bondi flows that are isothermal (Pepe & Pellizza 2013).

3. Globular Cluster System of M81 with the VLA

We searched for the radiative signatures of IMBH accretion from 206 probable GCs in M81 (Wrobel et al. 2016), a spiral galaxy at a distance of 3.63 Mpc (Freedman et al. 1994). Forty percent of the probable GCs are spectroscopically confirmed, with the balance deemed to be good GC candidates (Nantais et al. 2011). Our search used a four-pointing VLA mosaic at a wavelength of 5.5 cm and a spatial resolution of 1.5 arcsec (26.4 pc). It achieved 3σ upper limits of $3\times(4.3-51)$ μJy for point sources in individual GCs, depending on their location in the mosaic. Weighted-mean image stacks yielded 3σ upper limits of 3×0.43 μJy for all GCs and 3×0.74 μJy for the 49 GCs with stellar masses $M_\star \gtrsim 200,000 M_\odot$ based on the Nantais et al. (2011) photometry. We applied the Strader et al. (2012) synchrotron model to predict the IMBH mass, M_{IMBH}, consistent with a given luminosity at 5.5 cm. Figure 1 shows upper limits on M_{IMBH} and $M_\star$ for the individual GCs.

For 7 GCs in M81 the ratios of their IMBH masses to stellar masses, $M_{IMBH}/M_\star$, appear to be less than 0.03-0.09. These upper limits are competitive with the value of 0.02 for the five-times-closer G1, the only extragalactic GC with an IMBH inferred by spatially resolving its sphere of influence on cluster stars (Gebhardt et al. 2005). (Note, though, that G1's X-ray and radio properties suggest a ratio of less than 0.01 (Miller-Jones et al. 2012).) Also, the M81 stacks correspond to mean IMBH masses of less than 42,000 $M_\odot$ for all GCs and less than 51,000 $M_\odot$ for the 49 GCs with high stellar masses. The VLA is thus making inroads into the difficult-to-observe regime of IMBHs in extragalactic GCs. Further significant progress demands deeper radio observations of individual GCs in M81 and in other nearby GC systems.

4. Globular Cluster Systems with the ngVLA

We consider using Band 3 of the ngVLA (Selina & Murphy 2017) to examine globular cluster systems in the local universe. Band 3 has a central frequency of 17 GHz and a bandwidth of 8.4 GHz. We approximate its central wavelength as 2 cm. The Harris et al. (2013) compilation of GC systems involves 422 galaxies. The distribution of the galaxies' distances shows two peaks. A minor peak contains tens of galaxies with distances out to 10 Mpc. A major peak contains hundreds of galaxies with distances between 10 and 25 Mpc. A typical galaxy's GC system holds several hundred GCs spread over an effective diameter of a few tens of kpcs (Harris 2016; Kartha et al. 2016). Notably, the major peak in distance contains tens of thousands of GCs in total.

We applied the Strader et al. (2012) synchrotron model to predict the luminosity at 2 cm as a function of the mass, M_{IMBH}, of a putative IMBH in a GC. The associated point-source flux densities, S_{2cm}, were then derived for GCs at distances of 10 and 25 Mpc. In Figure 2, the sloping lines show how to convert from S_{2cm} to M_{IMBH} for the two distances, while the vertical lines show 3σ detections with the ngVLA, assuming tapered and robust weighting, with integrations of 1, 10 and 100 hours (Selina & Murphy 2017). At higher signal-to-noise ratios, the wide frequency coverage could test the flat-spectrum prediction, as well as raise flags about steep-spectrum contaminants such as background galaxies.

At 10 Mpc the synchrotron model predicts a flux density of $S_{2cm} = 0.35\ \mu$Jy from an IMBH of 83,000 $M_\odot$. The ngVLA can make a 3σ detection with a 10-hour integration and a tapered, robustly-weighted resolution of 100 mas (5 pc). This resolution matches the half-starlight diameter of a GC (Brodie & Strader 2006). From Selina & Murphy (2017), the field of view (FOV) of the ngVLA is a circle of diameter 3.4 arcmin (10 kpc) at full width half maximum. Most of a GC system can therefore be encompassed in a few FOVs. Each FOV can simultaneously capture many GCs. Undetected GCs can also be stacked. A stacking performance as for M81 (Section 3) can improve the IMBH mass sensitivity by a factor of two. At 25 Mpc the synchrotron model predicts a flux density of $S_{2cm} = 0.35\ \mu$Jy from an IMBH of 163,000 $M_\odot$. The ngVLA can make a 3σ detection with a 10-hour integration, localize the source to the GC, and encompass most of the GC system in a few FOVs. Each FOV can simultaneously capture many GCs. Stacking can also be done, and is expected to reach the mass sensitivity mentioned above for an individual GC at 10 Mpc. *In summary, with its sensitivity, bandwidth, spatial resolution, and FOV, the ngVLA at 2 cm will efficiently probe IMBH masses in hundreds of GC systems out to a distance of 25 Mpc.*

5. The ngVLA and Its Contemporary Facilities in the 2030s

Gravitational Wave Facilities. Fragione et al. (2017) explored the fate of primoridal GCs, each born with a central IMBH. They modelled the evolution of the GCs in their host galaxy, and of the IMBHs undergoing successive, GW-producing mergers with

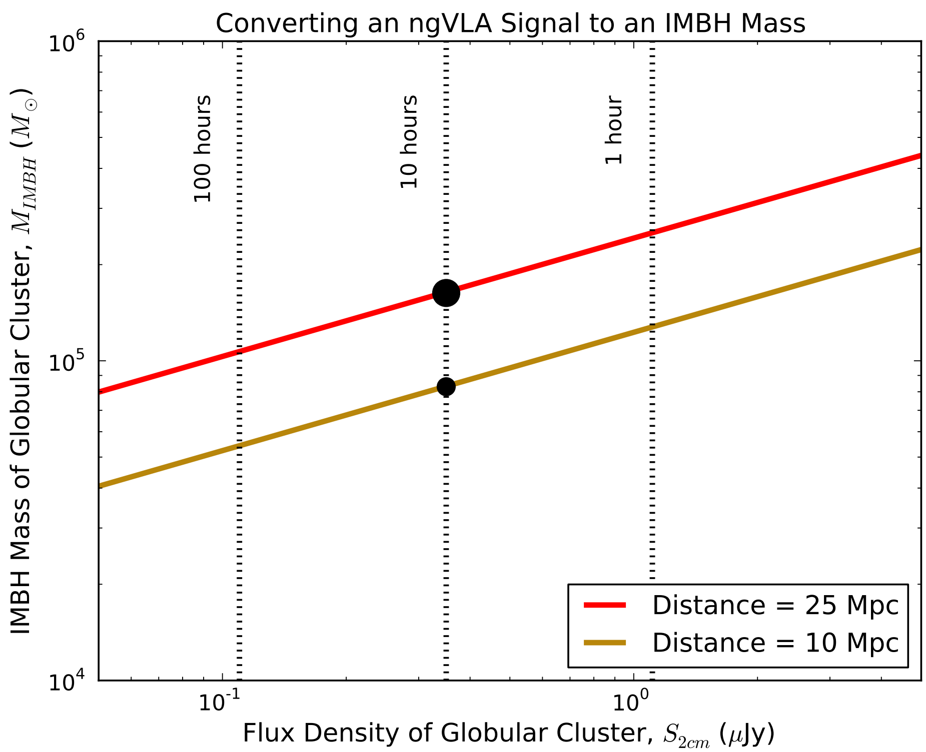

Figure 2. ngVLA signals, S_{2cm}, from IMBH masses, M_{IMBH}, in GCs at distances of 10 and 25 Mpc, according to the Strader et al. (2012) model. The small and big black dots highlight 3σ mass sensitivities at 10 and 25 Mpc, respectively, for a 10-hour integration. Hundreds of GC systems have distances between 10 and 25 Mpc, and hold tens of thousands of GCs in total.

stellar-mass BHs in the GCs. For primordial GCs that survived to the present day, they found that a few percent retained their IMBHs and the balance lost their IMBH when a GW recoil ejected it from the GC host. They used these results to predict GW event rates for the *Laser Interferometer Space Antenna* (*LISA*; Amaro-Seoane et al. 2017) and Europe's Einstein Telescope (Hild et al. 2011). The rates for the latter facility also apply to the US's similarly-scoped Cosmic Explorer (Abbott et al. 2016). IMBHs with masses between 1000 and 10,000 $M_\odot$ yielded mergers at higher rates that could be detected by all three GW facilities. IMBHs with masses $\gtrsim 10,000\ M_\odot$ yielded mergers at lower rates that could be detected only by *LISA*. If the ngVLA searches do not find the expected mix of IMBHs in GC systems, it could challenge the framework underlying the GW predictions. ngVLA searches for point-like emission from IMBHs would be easy to conduct during Early Science starting in 2028. Guided by such early ngVLA results, Fragione et al. (2017) could revisit their GW predictions.

Electromagnetic Wave Facilities. A key science driver for extremely large telescopes (ELTs) in the 30-m class is to measure, at a distance of 10 Mpc, a BH mass as low as 100,000 $M_\odot$ by spatially resolving its sphere of influence in its GC host (Do et al. 2014). For example, if the Infrared Imaging Spectrometer (IRIS) [1] on the Thirty Meter Telescope (TMT) can achieve the diffraction limit of 18 mas at 2 μm, then this approach will yield a sample of IMBHs in GCs out to a distance of 10 Mpc. A sphere-of-influence study with IRIS must be done one GC at a time, a shortcoming that makes it expensive to inventory the range of IMBH masses in a galaxy's GC system. The TMT's Infrared Multi-object Spectrometer (IRMS) [2] in spectroscopy mode will have a FOV of 2.0 arcmin $\times$ 0.6 arcmin. This being a tenth of the ngVLA FOV, a sphere-of-influence study with IRMS would require ten pointings to cover one ngVLA pointing. Regardless of the situation at 10 Mpc, the ELT approach cannot reach the hundreds of GC systems with distances between 10 and 25 Mpc.

The *Chandra* X-ray mission and its proposed successors, *Lynx* [3] and the *Advanced X-ray Imaging Satellite* [4], feature spatial resolutions of 300 to 500 mas. These will suffice to roughly localize X-ray sources to GCs out to a distance of 25 Mpc. But an X-ray–only search for the accretion signatures of IMBHs in GCs will be hindered by confusion from X-ray binaries in GCs (e.g., Joseph et al. 2017). Specifically, X-ray–only detections of GCs cannot discriminate between X-ray binaries and IMBHs. Fortunately, the empirical fundamental-plane of BH activity (Merloni et al. 2003; Falcke et al. 2004; Plotkin et al. 2012) implies that the persistent radio emission from IMBHs is expected to be several hundred times greater than that from X-ray binaries. Thus ngVLA imaging can be used to separate X-ray detections into bins for X-ray binaries and for IMBHs. X-ray binaries are known to be time-variable in both the radio and X-ray bands, so this radio–X-ray synergy would be strengthened by simultaneous observations with the ngVLA and the X-ray mission.

The deployment baseline of SKA1-Mid (Dewdney et al. 2015; Borjesson 2017) will offer a spatial resolution of 57 mas at 3.3 cm with uniform weighting. This resolution suffices to search for the accretion signatures of IMBHs in GCs with declinations south of 10 degrees. But as only 67 SKA1-Mid antennas will be available at 3.3 cm, the effective collecting area of that telescope will only be about that of the current VLA, which is insufficient for our purposes.

Many of the GC systems in Harris et al. (2013) will need further optical imaging before finding charts are available for all of their GCs. Such images can mostly be acquired with current ground-based telescopes in the 4-m class (e.g., Hargis & Rhode 2014) or 8-m class (e.g., Brodie et al. 2014). But for some particularly confused regions, it may be necessary to obtain images from space-based telescopes. For example, the Near Infrared Camera on the *James Webb Space Telescope* will offer spatial resolutions of 80 and 160 mas in its short- and long-wavelength channels, respectively [5].

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[1] `https://www.tmt.org/page/science-instruments`

[2] `https://www.tmt.org/page/science-instruments`

[3] `http://cxc.harvard.edu/cdo/cxo2lynx2017/index.html`

[4] `http://axis.astro.umd.edu`

[5] `https://jwst.stsci.edu/files/live/sites/jwst/files/home/instrumentation/technical\documents/jwst-pocket-guide.pdf`

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