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Intermediate-Mass Black Holes in Extragalactic Globular Clusters

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☒ Multi-Messenger Astronomy and Astrophysics

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Abstract (optional): Intermediate-mass black holes (IMBHs) have masses of about 100 to 100,000 solar masses. They remain elusive. Observing IMBHs in present-day globular clusters (GCs) would validate a formation channel for seed black holes in the early universe and inform event predictions for gravitational wave facilities. Reaching a large number of GCs per galaxy is key, as models predict that only a few percent will have retained their gravitational-wave fostering IMBHs. Related, many galaxies will need to be examined to establish a robust sample of IMBHs in GCs. These needs can be meet by using a next-generation Very Large Array (ngVLA) to search for IMBHs in the GCs of hundreds of galaxies out to a distance of 25 Mpc. These galaxies hold tens of thousands of GCs in total. We describe how to convert an ngVLA signal from a GC to an IMBH mass according to a semi-empirical accretion model. Simulations of gas flows in GCs would help to improve the robustness of the conversion. Also, self-consistent dynamical models of GCs, with stellar and binary evolution in the presence of IMBHs, would help to improve IMBH retention predictions for present-day GCs.

1. Globular Star Clusters as Hosts of Intermediate-Mass Black Holes

Both theory and computational modeling suggest that globular clusters (GCs) can host intermediate-mass black holes (IMBHs) with masses $M_{IMBH} \sim 100 - 100,000\ M_{\odot}$, but they have yet to be convincingly found in such settings [reviewed in 27]. Detecting IMBHs in GCs would validate one formation channel for seed black holes (BHs) in the early universe [reviewed in 22] and have broad implications for the GCs' dynamical evolution [19]. GCs reside in galaxy halos, with each galaxy hosting a system of a hundred to a thousand GCs [17]. Studying these so-called GC systems could constrain the ability of GCs to retain IMBHs and provide key input into event predictions for gravitational wave (GW) facilities. For example, a GC system with a low fraction of IMBHs at present could be linked to a high rate of GW events in the past [13,14,19]. Observing a large number of GCs is critical, as [13,14,19] predict that only a few percent will have retained their IMBHs. This implies that to gain a robust picture of IMBHs in GCs, many galaxies must be examined and each galaxy's GC system must be well sampled. Figure 1 shows the distances of galaxies whose GC systems have been studied [17], with an inset displaying an example GC system [8]. The effective diameter of a GC system is a few tens of kpcs [12] and the half-starlight diameter of a typical GC itself is 5 pc [7].

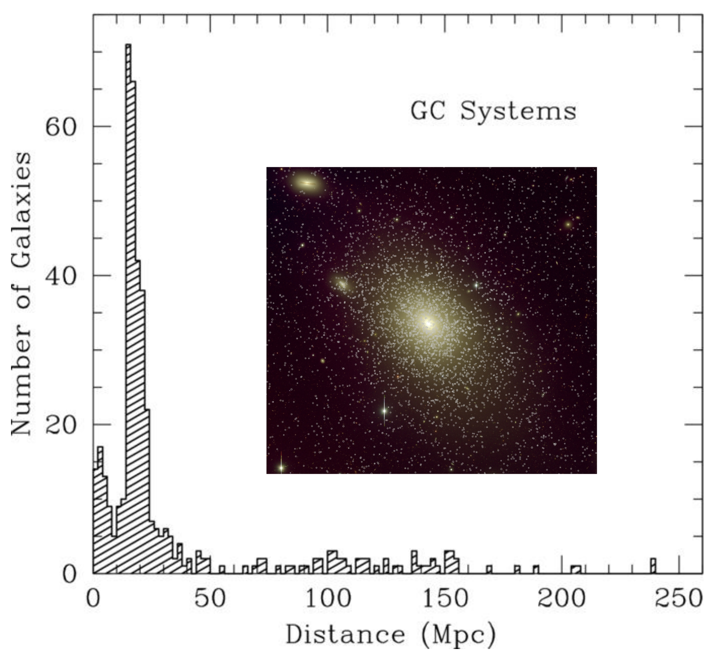

Figure 1: *Distances of galaxies whose systems of GCs have been studied [17]. The inset shows an example GC system, of the early-type galaxy NGC 4365 at 23 Mpc [8]. The sprinkling of symbols mark GC candidates in the inner 18′ (120 kpc) of a* gri *Suprime-Cam image.*

To search for IMBHs in GCs, one looks for evidence that the IMBHs are affecting the properties of their GC hosts [reviewed in 27, 35]. 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 have a contentious history [5], even leading to differing IMBH masses when using the orbits of stars or of radio pulsars in the same GC [16,30]. A basic limitation of dynamical searches is that they are susceptible to measuring high concentrations of stellar remnants rather than an IMBH [26,35]. To make progress, it is important to develop independent approaches that bypass these issues.

One promising approach is to search for radio signatures of accretion from IMBHs in GCs [reviewed in 25]. This approach leverages on decades of studies of the signatures of accretion onto stellar-mass and supermassive BHs [reviewed in 11]. Section 2 gives a synopsis of the synchrotron radio model. Section 3 describes applying the model to two galaxies and underscores the sensitivity shortfalls of radio facilities into the 2020s. Section 4 examines the prospects for applying the model to many galaxies in the 2030s. Section 5 describes ways to improve the model's theoretical underpinnings and interpretive framework.

2. Synchrotron Radio Model

Following [25,34], we invoke a semi-empirical model to predict the mass of an IMBH that, if accreting slowly from the tenuous gas supplied by evolving stars, is consistent with the synchrotron radio luminosity of a GC. We assume gas-capture at 3% of the Bondi rate [29] for gas at a density of 0.2 particles cm^{-3} [1] and at a constant temperature of 10,000 K. We also assume that accretion proceeds at less than 2% of the Eddington rate, thus involving an inner 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 [24] and be easily detectable in existing surveys. But no such X-ray sources exist in Milky Way GCs.) We then use the empirical fundamental-plane of BH activity as refined by [32] to predict the synchrotron radio luminosity. The radio emission is expected to be persistent, flat-spectrum, jet-like but spatially unresolved, and located at or near the dynamical center of the GC.

3. Observational Shortfalls into the 2020s

We have used the NSF's Karl G. Jansky Very Large Array (VLA) [31] at a 6-cm wavelength and 20-pc resolution to search for the signatures of accretion from IMBHs in 337 candidate GCs in NGC 1023 [36] and 206 probable GCs in M81 [37]. None of the individual GCs were detected. From the radio synchrotron model, the lowest mass limits inferred were $M_{IMBH} < 390,000\ M_\odot$ for NGC 1023 at 11 Mpc and $M_{IMBH} < 100,000\ M_\odot$ for M81 at 3.6 Mpc. Our stacking analysis of each GC system achieved about a factor of two improvement in the IMBH mass limits. The stacks assumed that each GC system had a high IMBH retention fraction and a uniform IMBH mass distribution. So far, modelling suggests that neither assumption is likely to be valid [13,14,19], which weakens any inferences from the VLA stacks.

For a dozen GCs in M81, the upper limits on their IMBH-to-stellar mass ratios were less than 0.15 [37]. Mass ratios in that regime are observed in some ultracompact dwarf galaxies [2] and predicted for some present-day GCs [14]. Thus, our VLA study of M81 provides a first glimpse of the potential for deeper radio searches to constrain IMBHs in GCs out to tens of Mpcs.

In the 2020s the deployment baseline of SKA1-Mid plans to offer a spatial resolution of 57 mas at wavelength of 3 cm [6,9]. Declinations south of +10 degrees will be viewable. At a distance of 25 Mpc the spatial resolution corresponds to 7 pc, close to a GC's half-starlight diameter of 5 pc [7]. Only 67 SKA1-Mid antennas will be available at 3 cm. This means that the effective collecting area of SKA1-Mid will be about that of the current VLA, which is insufficient to reach many galaxies.

4. Observational Imperatives in the 2030s

4.1. Applying the Synchrotron Radio Model in the 2030s

In [38], we considered using Band 3 of the next-generation Very Large Array (ngVLA) [33] to examine GC systems out to distances of tens of Mpcs. Band 3 has a central frequency of 17 GHz and a bandwidth of 8.4 GHz. Its central wavelength is 2 cm. The field of view (FOV) is a circle of diameter $3.6'$ at full width half maximum. Declinations north of -40 degrees will be viewable.

The compilation of GC systems presented in Figure 1 involves 422 galaxies [17]. The distribution of the galaxies' distances shows two peaks. A minor peak contains tens of galaxies, either isolated or group members, with distances out to 10 Mpc. A major peak contains hundreds of galaxies with distances between 10 and 25 Mpc, including members of the Virgo and Fornax clusters of galaxies. The major peak in distance contains tens of thousands of GCs in total. These GC counts can be further boosted by the recently-recognized population of intracluster GCs in the Virgo Cluster [23].

In [38], we applied the synchrotron model to predict the luminosity at 2 cm as a function of the mass, M_{IMBH}, of a putative IMBH in a GC. We then derived the associated point-source flux densities, S_{2cm}, 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 [33]. 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. (Potential radio contaminants in extragalactic GCs were considered and ruled out by [38].)

From Figure 2, the synchrotron model predicts a flux density of $S_{2cm} = 0.27$ μJy from an IMBH of mass 76,000 $M_\odot$ at 10 Mpc or of mass 150,000 $M_\odot$ at 25 Mpc. The main subarray of the ngVLA can make 3σ detections with 10 hours on target and a tapered, robustly-weighted resolution of 100 mas [33]. This spatial resolution matches the half-starlight diameter of 5 pc [7] for a GC at 10 Mpc and suffices to localize the source to a GC at 25 Mpc. A GC system has an effective diameter of a few tens of kpcs [12], so at these distances most of it can be encompassed in a few FOVs. An important consequence is that each $3.6'$ FOV can simultaneously capture many GCs. To summarize, with its sensitivity, bandwidth, spatial resolution, and FOV, the ngVLA at a wavelength of 2 cm could efficiently probe IMBH masses in hundreds of GC systems out to a distance of 25 Mpc. ***To search for these IMBHs, we recommend constructing the next-generation Very Large Array (ngVLA).***

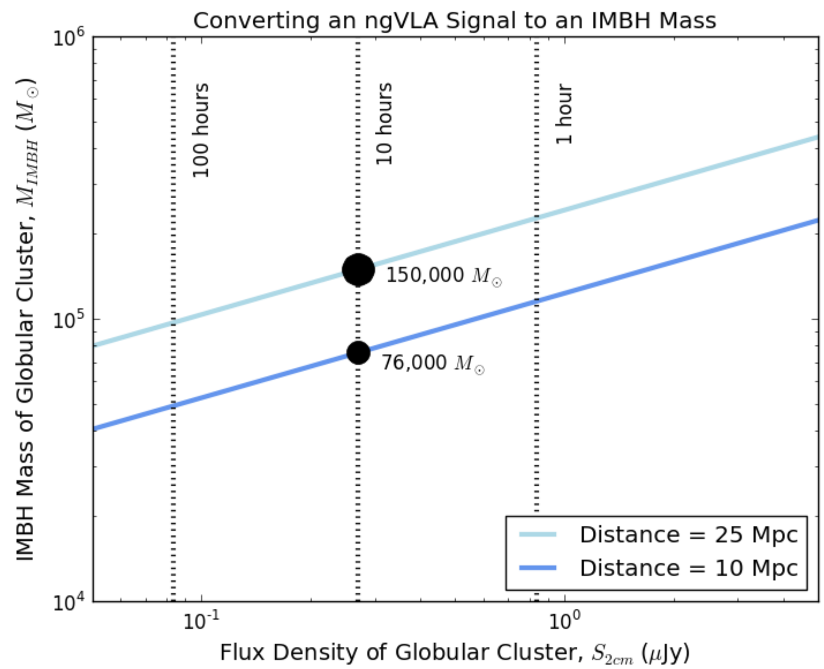

Figure 2: *ngVLA signals, S_{2cm}, from IMBH masses, M_{IMBH}, in GCs at distances of 10 and 25 Mpc. The small and big black dots highlight 3σ mass sensitivities at 10 and 25 Mpc, respectively, after 10 hours on target. Adapted from [38].*

4.2 Radio Synergies with Gravitational Wave Facilities in the 2030s

The fate of primordial GCs, each born with a central IMBH, was explored by [13,14,19]. They modelled the evolution of the GCs in a variety of host galaxies, and of the IMBHs undergoing successive, GW-producing mergers with stellar-mass BHs in the GCs. For primordial GCs that survived to the present day, only a few percent retained their IMBHs and the balance lost their IMBH when a GW recoil ejected it from the GC host. Once ejected, the IMBHs are no longer able to foster GW events. Retained IMBHs gained mass via tidal disruption events and captures of stellar-mass BHs, while host GCs lost mass due to stellar winds and tidal stripping [14]. Illustrative present-day GCs achieved high values for IMBH masses ($M_{IMBH} \sim 160,000\ M_\odot$) and IMBH-to-stellar mass ratios (6-12%).

These results were used to predict volumetric event rates for planned GW facilities (*LISA* [4], Einstein Telescope [18], Cosmic Explorer [3]). IMBHs with masses between 1000 and 10,000 $M_\odot$ yielded mergers at rates that could be detected by all three GW facilities. IMBHs with masses $\gtrsim 10,000\ M_\odot$ yielded mergers at rates that could be detected only by *LISA*, slated to begin observing in 2036 or earlier [4]. *LISA* would also be able to detect stellar-mass BHs and stellar remnants as they interact with the IMBH [4], which could provide important constraints on the stellar population and dynamical state of the host GC. In the interim, ngVLA searches for IMBHs in present-day GCs could occur, via Early Science notionally starting in 2028 or via Full Science notionally starting in 2034. If the ngVLA searches do not match the present-day predictions, it would challenge the framework underlying the merger-rate predictions for all three planned GW facilities.

4.3 Radio Synergies with Other Electromagnetic-Wave Facilities in the 2030s

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 $M_{IMBH} \sim 100,000\ M_{\odot}$ by spatially resolving its sphere of influence in its GC host [10]. For example, if the Infrared Imaging Spectrometer (IRIS) on the Thirty Meter Telescope (TMT) can achieve the diffraction limit of 18 mas at 2 μm, then this approach could yield a sample of IMBHs in GCs out to a distance of 10 Mpc. An IRIS study must be done one GC at a time, a shortcoming that makes it expensive to inventory many GCs per galaxy. The TMT's Infrared Multi-object Spectrometer (IRMS) in spectroscopy mode will have a FOV of $2.0' \times 0.6'$. 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 out to 10 Mpc, the ELT approach cannot reach the hundreds of GC systems with distances between 10 and 25 Mpc. A white paper by Greene et al. covers further aspects of IMBH searches using ELTs.

The *Chandra* X-ray mission and its proposed successors, *Lynx* [15] and the *Advanced X-ray Imaging Satellite* [28], 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 [21]. Specifically, X-ray–only detections of GCs cannot discriminate between X-ray binaries and IMBHs. Fortunately, the empirical fundamental-plane of BH activity as refined by [32] 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. White papers by Gallo et al. and Haiman et al. cover further aspects of IMBH searches using X-ray facilities.

5. Theoretical Imperatives in the 2030s

Self-consistent dynamical models of GCs, with stellar and binary evolution in the presence of IMBHs, would help to improve IMBH retention predictions for present-day GCs, and should be pursued with priority. If these models yield higher IMBH retention fractions, one could stack the ngVLA data for a galaxy's GC system and improve IMBH mass sensitivities by about a factor of two. Also, from parameter uncertainties, [34] estimate that the IMBH mass associated with a given radio luminosity could be in error by a factor of 2.5. To improve the robustness of such masses, the assumed gas-capture rate from a Bondi flow should be replaced by realistic simulations [e.g., 20] of gas flows in GCs.

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