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Proper Motions to Test Radio Source Membership in Galactic Globular Clusters

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ABSTRACT

Theory suggests that stellar-mass black holes (BHs) may influence the structural evolution of globular star clusters (GCs), and linger in the cores of some present-day GCs. If the BHs are in accreting binaries, they may be detectable as radio continuum sources. Shishkovsky et al. (2020) reported the discovery of 54 radio sources with flux densities $S_{5\,\mathrm{GHz}} \sim 10 - 100\,\mu$Jy *toward* the cores of 14 Galactic GCs. Some of these faint sources will be background active galactic nuclei *behind* the GCs. But if the faint radio sources are *in* the GCs, their proper motions should match the known proper motions of the GCs. Here, we sketch out a campaign to measure the proper motions of the faint radio sources using the NSF VLBA and ngVLA Long.

Keywords: Globular star clusters (656); Low-mass x-ray binary stars (939); Black holes (1596)

1. MOTIVATION

Globular star clusters (GCs) in the Galaxy are theorized to favor the dynamical creation of accreting binaries with stellar-mass black holes (BHs; e.g., Kulkarni et al. 1993; Pooley et al. 2003; Mackey et al. 2008; Morscher et al. 2015a,b; Kremer et al. 2018b). Moreover, such accreting binaries are expected to reside preferentially within the GC cores because their BHs, being more massive than the stars in GCs, will have mass-segregated to that location over time (e.g., Spitzer 1969; Baumgardt & Hilker 2018; Weatherford et al. 2018).

Mass-sorting driven by stellar-mass BHs can influence the structural evolution of GCs by supporting them against gravothermal contraction (e.g., Merritt et al. 2004; Mackey et al. 2008; Breen & Heggie 2013). More recent theoretical studies estimate that some present-day GCs should harbor few or no stellar-mass BHs, while other GCs should possess at most a few thousand solar masses of stellar-mass BHs (e.g., Askar et al. 2018; Weatherford et al. 2020; Dickson et al. 2024). Among any lingering stellar-mass BHs, some could be in binaries. Still, it has been suggested that the presence of accreting binaries with BHs has little correlation with the total BH count in a GC (Askar et al. 2018; Kremer et al. 2018b).

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Finding accreting binaries with BHs in present-day GCs would be direct evidence that they host stellar-mass BHs, and thus test this overall theoretical framework. Hence the wide-spread interest in reports of candidate binaries with BHs based on their accretion signatures (Maccarone et al. 2007; Strader et al. 2012; Chomiuk et al. 2013; Miller-Jones et al. 2015) and reports of detached binaries with dynamical constraints on their BH masses (Giesers et al. 2018, 2019).

The overall theoretical framework also underpins predictions for gravitational wave detections of Galactic GCs by the *LISA* mission (Kremer et al. 2018a). Testing and perhaps adjusting the overall framework are best done before *LISA* launches in a decade (Amaro-Seoane et al. 2023).

2. RADIO SOURCES *TOWARD* GCS

Continuum emission at X-ray and/or radio wavelengths are well-established signposts of accreting binaries with stellar-mass BHs (e.g., Fender & Muñoz-Darias 2016). Here we focus on the radio tracers, because observations in that regime can offer superior, mas-level localizations of targets well into the Galaxy's halo.

Shishkovsky et al. (2020) recently used the NSF Jansky Very Large Array (JVLA) to image 25 Galactic GCs with a typical synthesized beam width at full-width-half-maximum (FWHM) of about 500 mas. They detected 54 individual radio sources toward 14 GC cores, with each source having a projected radius from a GC center of $r < r_c$, where r_c is the core radius of the GC. No radio

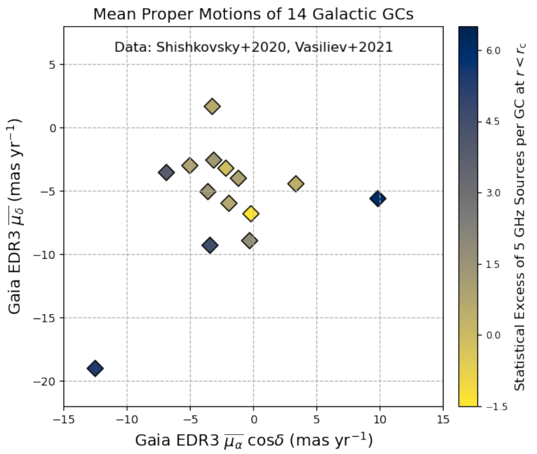

Figure 1. Mean proper motions of Galactic GCs (Vasiliev & Baumgardt 2021) with individual radio sources *toward* their cores. Colors encode the *statistical* evidence for excess radio sources in the GC cores, compared to the local sky density of background sources (Shishkovsky et al. 2020).

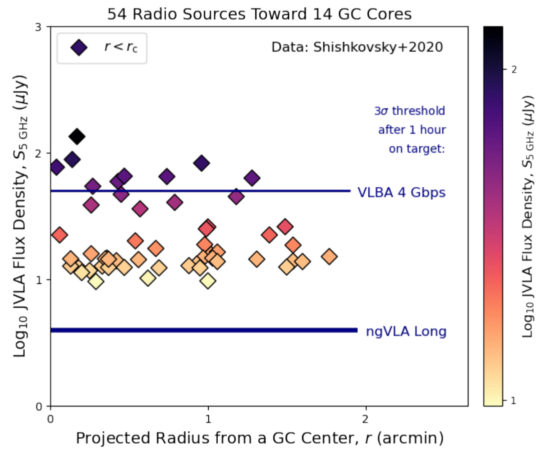

Figure 2. Flux densities $S_{5\,\mathrm{GHz}}$ and projected radii r of individual sources *toward* the cores of Galactic GCs (Shishkovsky et al. 2020). Each radio source has a projected radius from a GC center of $r < r_c$, where r_c is the core radius of the GC. These radio sources are candidates for being accreting binaries with BHs.

sources were detected toward the cores of the 11 other GCs. Overall, about a third of the 25 GC cores showed *statistical* evidence for excess radio sources compared to the local sky density of background sources.

Importantly, if the 54 individual radio sources are members of the GCs, they should share the known, mean proper motions of the 14 GCs (Vasiliev & Baumgardt 2021). Figure 1 conveys those mean proper motions and the *statistical* evidence from Shishkovsky et al. (2020) for excess radio sources in their cores.

Obtaining *direct* evidence of GC membership via proper motions will be challenging due to the faintness of the JVLA sources. As Figure 2 shows, their flux densities range over $S_{5\,\mathrm{GHz}} \sim 10 - 100\,\mu$Jy and most have flux densities near $S_{5\,\mathrm{GHz}} \sim 10\,\mu$Jy.

3. RADIO SOURCES *IN* GCS

So far, only two of the 54 radio sources toward GC cores have been targeted in a proper motion study, and that study required the expensive resources of the High Sensitivity Array (HSA) (J. C. A. Miller-Jones et al., in preparation).

A proper motion campaign on the remaining 52 sources could take a tiered approach at 5 GHz. Figure 2 shows indicative 3σ detection thresholds after 1 hour on target with the NSF Very Long Baseline Array (VLBA) and with its planned replacement, the Long subarray of the next generation Very Large Array (ngVLA). Here σ is the root-mean-square noise level in a naturally weighted Stokes I image according to available exposure calculators[3]. Each facility can offer a synthesized beam width at FWHM of about 1 mas, well suited for studying the expected proper motions displayed in Figure 1.

Figure 2 suggests that 7 additional core radio sources could be targeted now with the VLBA. These involve 5 GCs. Two of those GCs each have 2 sources in their cores, and VLBA observations toward those GCs could capitalize on that facility's ability to correlate a GC observation at more than one phase center[4].

Figure 2 also suggests that the remainder of the core radio sources, 45, could easily be targeted with ngVLA Long. Seven of the relevant GCs each have 2 or more sources in their cores, and ngVLA Long observations toward those GCs could take advantage of that facility's ability to form up to 10 synthesized beams (Selina et al. 2018).

Constraints on the proper motion of a core radio source can be had after $N = 2$ observations, and separating those observations by a year reduces contamination from the effects of trigonometric parallax. ($N > 2$ observations might be desirable as proper motion precision scales as $N^{-3/2}$ (Reid 2022).) Constraints on the proper motions of the 2 HSA targets and the 7 VLBA targets could potentially be in hand within a few years, thus before *LISA* launches. Constraints on the proper motions of the 45 ngVLA Long targets might not emerge

[3] https://planobs.jive.eu/ and https://ngect.nrao.edu/
[4] https://vlba.nrao.edu

until after ngVLA construction ends, nominally late in the 2030s[5].

Radio sources that are shown to reside in the GC cores will be high-priority targets for follow-up studies. For example, optical spectroscopy can test if their minimum dynamical masses are consistent with the high values expected for stellar-mass BHs (Giesers et al. 2018, 2019). As another example, radio-based trigonometric parallaxes could be sought to map out the depths of the radio sources in the GC cores.

More broadly, gaining experience with this kind of proper motion study will be especially valuable when applied to candidate intermediate-mass BHs that might emerge from ever-deeper radio surveys of GCs (e.g., Paduano et al. 2024).

4. RADIO SOURCES *BEHIND* GCS

Radio sources that are shown to be behind the GC cores also have value. They are likely to be active galactic nuclei (AGNs; Shishkovsky et al. 2020). As such, they may be useful as phase calibrators or amplitude-check sources, which could help with the calibration fidelity of observations of the radio sources in the GC cores. They may also be useful for aligning the radio/optical/X-ray frames, which could improve the cross-matching of the radio sources in the GC cores at multiple wavelengths.

Figure 3 shows the radio sources away from the GC cores and also likely to be background AGNs (Shishkovsky et al. 2020). As such, these may also help with calibration fidelity and multi-wavelength cross-matching. For VLBA or ngVLA Long observations pointed at the GC centers, some of the sources in Figure 3 will be noticeably attenuated by the primary beam.

5. CONCLUSIONS

We have sketched out a VLBA and ngVLA Long campaign to measure the proper motions of 54 faint sources, with $S_{5\,\mathrm{GHz}} \sim 10 - 100\,\mu$Jy, discovered *toward* the cores of 14 Galactic GCs (Shishkovsky et al. 2020). If the 54 radio sources are members of the 14 GCs, they should share the known, mean proper motions of the GCs (Vasiliev & Baumgardt 2021). Radio sources that are shown to reside *in* the GC cores will be high-priority targets for expensive follow-up studies, such as optical spectroscopy to dynamically constrain their BH masses (Giesers et al. 2018, 2019).

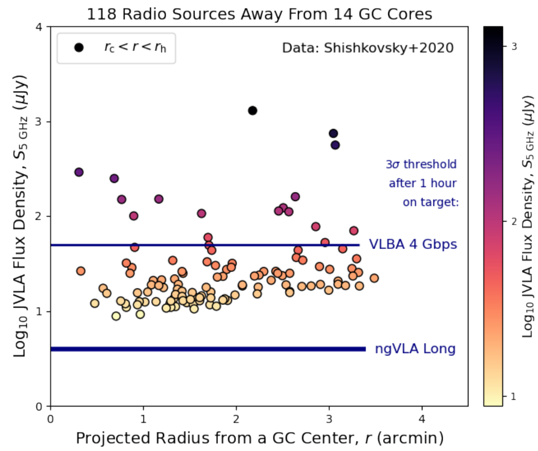

Figure 3. Flux densities $S_{5\,\mathrm{GHz}}$ and projected radii r of individual sources away from the cores of Galactic GCs (Shishkovsky et al. 2020). For each radio source, its projected radius from a GC center is between the GC's core radius r_c and half-light radius r_h. These radio sources are likely to be background AGNs.

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Facilities: VLA - Very Large Array, VLBA - Very Long Baseline Array

Software: matplotlib (Hunter 2007)

[5] https://ngvla.nrao.edu

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