

ngVLA Memo #53
**Revealing the Galactic Population of Black Holes
with the ngVLA**

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1. SCIENTIFIC MOTIVATION

In this memo, we present the case for a high angular resolution, high sensitivity, multi-epoch Galactic survey with the ngVLA to reveal the population of black holes (BHs) in close binary systems. This program has the potential to answer key questions like: How many binaries host BHs? What kinds of cosmic cataclysms produce BHs? How do BHs end up in close systems with other compact objects, in order to merge and produce gravitational waves?

Such a survey is timely, as we currently stand at the dawn of gravitational wave astrophysics. In recent years, we have seen the discoveries of stellar-mass BH-BH binaries merging, as well as one double neutron star merger (Abbott et al. 2016, 2017). While LIGO demonstrates the existence of inspiraling BH binaries (and can measure key parameters like mass and spin for these objects), understanding the origin of these systems requires information that can only come from electromagnetic studies of BH binary progenitors. Key questions remain about whether these objects form via standard binary stellar evolution (Belczynski et al. 2007), triple star evolution (Rodriguez & Antonini 2018), chemically homogeneous binary evolution (de Mink et al. 2009), or dynamically in globular clusters (Miller & Hamilton 2002). The rates of these mergers are dependent on a variety of poorly constrained parameters, including, but not limited to common envelope efficiency, BH natal kicks distributions, and the range of masses of BHs in binaries. Understanding the populations of BHs in binaries in our own Galaxy will yield crucial constraints on all of these. Furthermore, the same data that will yield the measurements needed to understand double compact object mergers will give vital insights into how the supernovae themselves explode.

1.1. The need for a BH Census. Arguments based on the metal enrichment of the Galaxy suggest that there should be $\sim 10^8 - 10^9$ stellar-mass BHs in the Galaxy (Samland et al. 1998), and this number is consistent with the upper limits from microlensing searches (Wyrzykowski et al. 2016). However, we currently know of only ~ 20 dynamically confirmed stellar-mass BHs in our Milky Way, and about 60 strong candidates (Corral-Santana et al. 2016). The known objects have mostly been discovered via bright X-ray outbursts, and then followed up spectroscopically in quiescence. Typically 1–2 new stellar-mass black holes in outburst are discovered per year, and almost all of the known stellar-mass BHs are on the near side of the Milky Way Galaxy. This selection function also creates a strong bias toward systems with long orbital periods (Arur & Maccarone 2018). Therefore, the total number of accreting BHs in our Galaxy is wildly unconstrained, potentially ranging from 100 – 10^8 (Tetarenko et al. 2016). Modelling of selection effects suggest that the total number of BH low-mass X-ray binaries is likely to be a few thousand or more (Arur & Maccarone 2018).

The number of BHs with high mass donor stars is even more uncertain, in part because wind-fed systems may evade discovery because they do not host X-ray outbursts (Tetarenko et al. 2016). There may, in fact, be a population of systems very similar to the canonical high mass X-ray binary BH system Cygnus X-1, except with wider separations so that they have lower accretion rates and X-ray luminosities. These systems are poor bets to be discovered in X-ray and optical/IR surveys because of the broad similarities between their expected appearance and the expected appearance of generic massive stars.

1.2. Lessons from the Accreting BH Population. An improved understanding of the population size of accreting BHs in the Milky Way will place strong constraints on some of the largest open questions in stellar astrophysics today. It will be a crucial constraint on the efficiency of common envelope evolution in close

binary systems (Ivanova & Chaichenets 2011). It will also constrain the strength of kicks granted to BHs in their natal supernovae.

The amplitude of BH kicks can illuminate the primary channel of stellar-mass BH formation. It has been speculated that BHs may form from a prompt collapse of the entire massive star at the end of its lifetime or, alternatively, from fallback accretion on to a neutron star. The latter case should apply a much stronger natal kick to the BH at the time of formation, both because of the temporary presence of the neutron star (Kalogera 1996) and the symmetric mass loss from a moving object in a binary (Blaauw 1961). Measurement of BH kicks is also important for determining if LIGO BH binaries are produced through normal binary evolution or dynamical interaction (i.e., in dense star clusters). The gravitational waveform reveals the misalignment of spin—of the black holes relative to one another, and relative to the orbital plane. Dynamically formed binaries should have an approximately random distribution of spin orientations, while binaries formed through binary evolution should have some preference for aligned spins—unless very large kicks take place. It is thus vital to determine whether typical BH kicks are large enough to misalign BH spins substantially from their orbital planes in order to understand how robustly misaligned spins indicate a globular cluster formation scenario. The scale heights of black holes and neutron stars in current samples seem to be quite similar (Repetto et al. 2015). However, there does seem to be at least one case, Cygnus X-1, where the applied kick appears quite small (Wong et al. 2016). An ngVLA survey for accreting BHs will constrain BH kicks in two ways—by measuring the number of BHs in close binaries in our Galaxy, and by directly measuring their proper motions.

We can also place constraints on the formation of LIGO BH mergers by comparing the BH populations in the Galactic field with those in dense stellar environments (globular clusters, Galactic center), and estimating the relative importance of binary and dynamical channels for forming close BH binaries. At the present time, there are some strong radio-selected BH candidates in globular clusters (Strader et al. 2012; Chomiuk et al. 2013). Both new detections and confirmations of existing candidates' membership can be made via astrometry.

A larger, more representative sample of black holes will enable a high-quality measurement of the BH mass distribution, and thereby constrain some of the most poorly understood aspects of supernova explosions. In particular for core-collapse supernovae, there is still no consensus about why the explosions actually take place, with the leading models being a standing accretion shock instability and the Rayleigh-Taylor instability (e.g. Belczynski et al. 2012 and references within). Because the process takes place while a thick envelope covers the stellar core, and the supernova light curves and spectra are largely sensitive only to the total energy input and the mass of the envelope, other approaches to understanding the events are vital. In principle, gravitational waves and neutrinos provide information at the time of explosion, but these are only detectable at the time of explosion and within small horizon volumes. The compact remnants of supernovae are therefore the best observational clues as to the processes driving supernovae—and specifically, the distribution of the masses of the compact stellar remnants is very information-rich. Belczynski et al. (2012) argue that models in which the explosion proceeds on a timescale of less than about 0.2 seconds after the core collapse will produce a substantial gap in masses between the heaviest neutron stars and the lightest BHs, while explosions which happen on timescales of order 0.5 seconds or more will lead to a continuous distribution of compact object masses. At the present time, there appears to be such a gap when the mass distribution is modelled as the sum of Gaussians (Özel et al. 2010; Farr et al. 2011), but other functional forms for the mass distribution allow a continuous range of masses (Farr et al. 2011).

The present size of the BH mass sample is simply not sufficient to establish firmly whether there is a mass gap. Furthermore, some biases in our estimates of the inclination angles of the binaries may be partially or fully responsible for the apparent presence of this mass gap (Kreidberg et al. 2012). Astrometric wobble measurements of even a few binaries would provide gold-standard calibration for ellipsoidal modulation measurements, and would be possible with high sensitivity, high frequency VLBI measurements. With the identification of a substantial population of accreting BHs, we will have in hand an ideal sample for follow-up observations enabled by both the ngVLA itself along with other multi-wavelength facilities available in the next decades. This larger sample will also be unbiased, sampling the full population of accreting

stellar-mass black holes to enable a measurement of the BH mass function and the amplitude of BH natal kicks.

2. SURVEY PLAN

The ngVLA can build a sample of accreting BHs with well understood selection effects, with sufficient sensitivity to detect them in quiescence over a large volume of our Galaxy. The ngVLA will also have sufficient angular resolution to measure proper motions, thereby constraining Galactic BH kinematics while filtering out background extragalactic contaminants. This proposed program would require a modest amount of time, deliver a broad range of additional science, and be easily extendable over time both by extending the field of view and making deeper observations.

Such a radio survey could be conducted in a reasonable exposure time, since objects like the radio-faintest known X-ray binaries (e.g. A0620-00 & XTE J1118+480; Gallo et al. 2006, 2014) could be detected in about 6 minutes at 6σ at a distance of 2–4 kpc with the proposed ngVLA sensitivity. BHs accreting at higher rates, like V404 Cyg in quiescence, are a factor of ~ 15 more luminous (Miller-Jones et al. 2009) and can be observed well past the distance of the Galactic Center. We thus expect to be able to detect $\sim 10\%$ of the short period BH X-ray binaries in a 10 square degree survey region near the Galactic Center. This region contains about 10% of the stellar mass of the Galaxy, meaning that we would expect to detect at least 1% of the total number of short period BH X-ray binaries in the Milky Way, and the majority of the long period, V404 Cyg-like BH X-ray binaries. We thus expect that ~ 100 new BH X-ray binaries should be discovered in this proposed survey, based on population estimates from X-ray studies (Arur & Maccarone 2018), and perhaps much larger numbers based on the surprising discovery of a single strong BH candidate with a parallax placing it in front of M15 (Tetarenko et al. 2016). By covering 10 sq. deg. of the Galactic bulge, we will survey the BH population over a substantial fraction of the Galaxy and span a range of environments, including the dense central regions and star-forming regions and the Galactic field.

We plan to observe in the band covering 4–12 GHz, as a compromise between field of view, resolution, and sensitivity (we expect the spectra of accreting BHs to be flat, $S_\nu \propto \nu^0$). We require at least three visits covering the survey area, in order to obtain high-quality proper motion measurements. We therefore estimate that each epoch will require 100 hours on source, implying that the entire survey can be carried out in 300 hours.

At a distance of 8 kpc, with 10 mas resolution (requiring significant collecting area on baselines of at least 1000 km), an uncertainty on proper motion of 20 km/s would result from a nominal two-year time baseline for 6σ detections. Thus the uncertainty will be much less than the typical stellar velocity dispersion in the Solar neighborhood, so only a small fraction of objects should be expected to have small enough proper motions to be confused with background AGN, and this fraction should decrease further if the majority of systems form with strong natal kicks.

Having long baselines (of approximately 1000 km or more) is thus crucial in order to allow sufficiently precise proper motion measurements to make the proper motions diagnostics sufficient both for ruling out background AGN sources, and allowing the measurements to yield useful information about natal kicks. While the proper motion uncertainty increases for sources behind the Galactic Center, if such sources follow the Galactic rotation curve, they will have space velocities of about 400 km/s because of the rotation relative to the Earth’s motion, so even sources at such distances, if bright enough to be detectable, should show measurable proper motions, even in the absence of natal kicks.

Besides accreting BHs, numerous other classes of Galactic sources will be present in this survey, and the combination of the radio properties with other multi-wavelength data sets will allow characterization of these other populations. We expect to detect bright flare stars, cataclysmic variables, planetary nebulae, and pulsars (most of which should be identifiable based on radio spectra, radio variability, angular extent of radio emission or obvious associations with bright foreground stars), and also neutron star X-ray binaries, transitional millisecond pulsars and colliding wind binaries (which may require more careful follow-up work). A particularly interesting class of other objects that could be found in such a survey is isolated black holes accreting from the interstellar medium (Maccarone 2005; Fender et al. 2013).

Based solely on their radio morphology and spectra, pulsars, planetary nebulae, cataclysmic variables and isolated massive stars can be identified. We should be able to distinguish BHs with high mass donor stars by their spectral index; the flat radio spectra produced by an accreting BH's jets will contrast with the optically-thick thermal spectrum expected for a massive star. Remaining will be various classes of BH and neutron star X-ray binaries, active binaries and colliding wind binaries. For these, multi-wavelength follow-ups will be necessary. The active binaries will be the most challenging class of contaminant of the X-ray binary population, but the bulk of these should be identifiable from circular polarization for relatively high signal-to-noise sources. For fainter sources radio/X-ray ratios, which will be high enough to be X-ray binaries only in flaring states, will be useful, since the source are highly unlikely to be flaring in all epochs.

We emphasize that the long baselines (~ 1000 km) and high resolution of the ngVLA are critical to this astrometric survey. In addition, relatively high frequencies (> 4 GHz) are necessary to obtain good image quality in the Galactic Plane and the Galactic Bulge, as low frequencies will be affected by scattering. A broad range of baselines is needed for these studies in order that even in the most confused regions, like those in Cygnus and those very close to the Galactic Center, good angular resolution is possible without over-resolving heavily scatter-broadened sources.

The plan outlined above shows that with just 300 hours of ngVLA time, one would be able to do some important first-order work on understanding the populations of X-ray binaries. It is important to consider, though, that this survey would discover ~ 100 BH binaries, and would only reach Galactic Center distances for the brightest ones. To build a sample of many hundreds of BH binaries, one could easily expand this survey through a combination of deeper observations on the same part of the sky, and coverage of a wider swath of the Galactic Plane. Since observations within 1 degree of the Galactic Plane will reach a height of 500 pc only at the furthest reaches of the Galaxy, we can expect that increasing the exposure time will increase the number of sources roughly linearly, since the volume included will scale as $t^{3/4}$, and until the most numerous source classes can be reached at the distance of the Galactic Center, the space density of sources should be rising with increased distance. Thus to reach a number of ~ 1000 sources, we could conduct a survey which detects objects like A0620-00 at the distance of the Galactic Center, which would require quadrupling the exposure times for one epoch.

3. CONNECTIONS WITH OTHER FACILITIES

3.1. Current VLBI: Current long baseline arrays are simply not sensitive enough to meet our science goals. It would require 23 hours per pointing to reach our per-epoch sensitivity goal with the LBO—a factor of 4000 longer than with the ngVLA, and to cover 10 square degrees at 6 GHz would require about 640 pointings, so that it would take about 7 years at 6 hours per day to conduct this survey. The European long baseline facilities are too far north to do this work effectively (e.g. e-Merlin sees the Galactic Center region as a maximum elevation of 7 degrees). The VLBA also runs into some problems with source scattering in the most scattered parts of the sky so that only a small fraction of its baselines become useful in such regions.

3.2. Gaia: While the *Gaia* mission holds some promise for identifying BHs in very wide binaries from their astrometric wobble (Barstow et al. 2014; Mashian & Loeb 2017), it will struggle to obtain results on the optically faint quiescent binaries in the crowded, dust-extinguished region of the Galactic Bulge. This dense and populous region is essential for understanding the Galactic BH population and how its characteristics depend on density. Furthermore, the orbital period range probed by *Gaia* through astrometric wobble is much longer than the orbital period range probed by detecting accreting systems – if *Gaia* does discover many stellar mass BHs as wobblers, this information is complementary to what radio observations could discover. Only about 10% of the strong candidate BH X-ray binaries known are bright enough optically for *Gaia* to detect them, despite the strong biases in existing samples toward nearby, unreddened objects..

3.3. Future O/IR Telescopes: The proposed survey should be coordinated with the WFIRST microlensing planet search fields (simultaneity is not necessary) to provide high cadence infrared data on the radio sources.

Resulting ellipsoidal modulation measurements can be used to estimate orbital periods and inclination angles for many of the objects.¹

BH mass estimates can be obtained using optical/IR spectroscopy to measure the width of emission lines, in conjunction with the Casares (2016) relation. A healthy diverse portfolio of optical/IR telescopes spanning diameters, 4–30m, would be ideal for the spectroscopic follow-up.

3.4. Future X-ray Facilities: Proposed future X-ray missions such as eROSITA and Athena (which are scheduled to proceed), and Lynx and STAR-X can be expected to deliver substantial populations of faint candidate X-ray binaries, interspersed with large numbers of members of other X-ray source classes. Because large fractions of these will be radio sources as well, particularly at the sensitivity levels we discuss here, the relatively uncrowded radio data, which will carry with them proper motion information, will help sort out the identification of these sources.

4. STELLAR-MASS BH SCIENCE ENABLED BY LONG BASELINES

We note that, in the era of the ngVLA, continental and global baselines will be of tremendous interest for follow-up of many sources discovered through astrometric surveys. Most of the known X-ray binaries are too faint optically for *Gaia* to provide parallax distances. Absolute astrometry with the *James Webb Space Telescope* is expected to be limited to about 0.5 milliarcsecond, even at arbitrarily large signal to noise, meaning that geometric parallax distances will be limited to about 1 kiloparsec. As a result, the best geometric parallax distances for accreting BHs will come from radio data, rather than from optical data. Follow-up could be done with only antennae on the outer part of the array, plus either VLBA stations, or newer longer baseline ngVLA dishes. While the follow-up would require more time per target, it could be done at higher frequencies to improve positional accuracy in a given integration time and mitigate the effects of scattering, and it could be done only for the sources of interest. It would make an excellent usage of the portion of the array that would not be needed when most of the core antennae are being used for low surface brightness extended-source projects.

In particular, μJy sensitivity, on 5000 km baselines at 40 GHz, would allow for geometric parallax distance measurements for most of the stellar-mass BHs and accreting neutron stars found by the proposed survey. Doing this requires, at bare minimum, retaining the current VLBA stations and upgrading their receivers to make them part of the ngVLA, but exposure times a factor of 5 shorter can be obtained for the same precision by putting about 10% of the collecting area on baselines longer than 1000 km.

We can anticipate that there would be about 300 baselines from the New Mexico core to the 10 VLBA antennae, so that the sensitivity would be about 5.5 times worse than the ngVLA's overall sensitivity for VLBI experiments. Putting 10% of the collecting area on longer baselines would improve the sensitivity by a factor of about 2.6, reducing the exposure time needed for such projects by a factor of about 5, and making the long baseline sensitivity only about a factor of 2 worse than the overall sensitivity.

In the case with no new collecting area beyond 1000 km, follow-up measurements to obtain parallax distances would require about 30 times the total exposure needed to detect the sources, and five epochs would be needed to make reliable parallax measurements. Since the survey observations are expected to be only 6 minutes each, this would require 15 hours per object, so that if 100 BHs were detected, this would become a 1500 hour project at most. In practice, many of the source will be significantly brighter than the detection limit, and some of the foreground objects may have detections from *Gaia* as well. If 10% of the collecting area were on long baselines, this survey could be done in about 1/5 the time, or, in approximately the same amount of time using the long baselines alone, and with somewhat better astrometric precision since a larger fraction of the collecting area would be at baselines longer than the baselines to New Mexico. With 0.2 msec resolution, and 6 σ detections, and assuming good phase calibration, one could expect parallax measurements accurate to about 15% for sources at the Galactic Center distance, and the accuracy would improve linearly with both signal to noise, and decreasing distance.

¹Because of the very large number of W UMa stars, using the WFIRST data alone is unlikely to produce good catalogs of BH and neutron star candidates.

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