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Astrometric Constraints on a Massive Black Hole Binary in NGC 4472

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ABSTRACT

In an EHT study of a Jy-level target, Safarzadeh et al. (2019) show how astrometric monitoring could constrain massive black hole binaries with the wide separations that make them long-lived against gravitational wave losses, and with the small mass ratios expected from merged satellite galaxies. With this ngVLA study, we show how such frontier topics could be explored for the more numerous mJy-level targets, such as NGC 4472. We also discuss how ngVLA astrometric monitoring could test the upper limits from pulsar timing arrays on gravitational waves from NGC 4472.

Keywords: Accretion (14); Active galactic nuclei (16); Supermassive Black Holes (1663); Interferometry (808)

1. MOTIVATION

The merger of two galaxies, each hosting a massive black hole (MBH), could yield a bound MBH binary. Eventually the orbit of the MBH binary will shink due to gravitational wave (GW) emission (Begelman et al. 1980). Such GW signatures are sought with pulsar timing arrays like the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and are projected to be detected with the future Laser Interferometer Space Array. Searches are also underway for the electromagnetic (EM) signatures of bound MBH binaries. Decades of data seeking indirect EM signatures, such as periodicities in emission line velocities or photometric variability, have been used to identify candidate MBH binaries. See Burke-Spolaor et al. (2019) and De Rosa et al. (2019) for recent reviews of the aforementioned topics.

One direct EM signature would be to resolve and monitor the orbit of one or both members of a bound MBH binary. EM strategies for achieving this are only now being devised (D'Orazio & Loeb 2018; Safarzadeh et al. 2019; Dexter et al. 2020). These strategies invoke recent or projected advances in interferometry at millimeter or near-infrared wavelengths. Here, we consider a strategy proposed by Safarzadeh et al. (2019) for continuum targets at Jansky (Jy) levels observable at 230 GHz (1.3 mm) with the Event Horizon Telescope (EHT; EHT Collaboration et al. 2019), and adapt it for the more numerous targets at milliJansky (mJy) levels observable at 80 GHz (3.7 mm) with a next-generation Very Large Array (ngVLA; Murphy et al. 2018; Selina et al. 2018).

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2. TARGET SELECTION

We focus on NGC 4472, Virgo Subcluster B's dominant galaxy which shows evidence for size and mass growth via the accretion of satellite galaxies (e.g., Capaccioli et al. 2015). VLBI imaging of the low-luminosity active galactic nucleus (LLAGN) in NGC 4472 is available only at 5 GHz and 8.4 GHz (Nagar et al. 2005; Anderson & Ulvestad 2005). The most constraining size information comes from the VLBA image at 8.4 GHz showing a 4-mJy source (Anderson & Ulvestad 2005). At the assumed distance of 16.7 Mpc ($1'' = 81.0$ pc; Blakeslee et al. 2009), the upper limit on the radio source's major axis, 730 μas, corresponds to 0.059 pc. Attempts to probe smaller size scales via VLA time variability at 8.4 GHz and 15 GHz were inconclusive (Nagar et al. 2005; Anderson & Ulvestad 2005). Hydrodynamical simulations with radiative processes and MBH feedback suggest that the LLAGN can be understood as jet-like emission launched from a radiatively inefficient accretion flow (Inayoshi et al. 2020).

3. NGVLA ASTROMETRIC OBSERVATIONS

We adopt the ngVLA's Long Baseline Array (LBA) at 80 GHz, the frequency assigned to notional continuum studies in the highest frequency band (Wrobel et al. 2020). The resolution associated with the maximum baseline has a point spread function $PSF = 90\,\mu$as (0.0073 pc) at FWHM (Rosero 2019). To accrue a reasonable time on the target, one antenna at each LBA station would observe the phase calibrator while the rest continuously observed NGC 4472 (e.g., Thompson et al. 2001). After 10 hours on target the RMS noise is projected to be about $3\,\mu\mathrm{Jy\,beam}^{-1}$ (Rosero 2019).

The astrometric accuracy of the ngVLA observation will have contributions from a term due to the signal-to-noise ratio S/N on the target, $\sigma_{\rm s/n}$, and a term due the relative accuracy achieved via phase referencing, $\sigma_{\rm pr}$. We discuss both in turn.

Regarding $\sigma_{\rm s/n}$, an ALMA archival image at 98 GHz (3.1 mm) with a $PSF = 0.61''$ (49 pc) shows a 2-mJy source that is slightly resolved, possibly due to residual phase calibration errors. If only its peak signal of $1.3\,\mathrm{mJy\,beam}^{-1}$ is available to the LBA at 80 GHz, it would have an $S/N \sim 430$ and be localized with an associated accuracy of $\sigma_{\rm s/n} = PSF/(1.665 \times S/N) \sim 0.1\,\mu$as. Regarding $\sigma_{\rm pr}$, a sub-degree separation between NGC 4472 and its phase calibrator would be required to reach $\sigma_{\rm pr} \sim 1\,\mu$as (Reid et al. 2018). One such a calibrator is already known.

We are preparing a VLBA proposal on NGC 4472 to help improve our estimate of $\sigma_{\rm s/n} \sim 0.1\,\mu$as. For now, we assume that the astrometric accuracy of the ngVLA observation will be dominated by the $\sigma_{\rm pr} \sim 1\,\mu$as term.

4. INTERPRETATION

4.1. *ngVLA Astrometric Monitoring*

Following Safarzadeh et al. (2019), we examine how astrometric monitoring of NGC 4472 could contrain the reflex motion of the LLAGN's primary black hole of mass M_{pri}, as it is tugged on by a putative secondary black hole of mass M_{sec}. These masses define a binary mass $M_{bin} = M_{pri} + M_{sec}$ and mass ratio $q = M_{sec}/M_{pri} \leq 1$. We allow q to vary but adopt $M_{bin} = 2.5^{+0.7}_{-0.5} \times 10^9\,\mathrm{M}_\odot$ from the total black-hole mass estimated by Rusli et al. (2013).

We assume a circular orbit for the MBH binary and use Kepler's third law to tie the binary's semimajor axis a_{bin} to its mass M_{bin} and orbital period P (equation (1) of Dexter et al. 2020). The reflex motion of M_{pri} as it orbits, with semimajor axis a_{pri}, about the binary's center of mass is $a_{pri} = a_{bin} \times q/(1+q)$ (equation (1) of Safarzadeh et al. 2019). We recast this as

$$a_{bin} = a_{pri} \times (1+q)/q. \tag{1}$$

If astrometric monitoring of the LLAGN position could achieve a 95% accuracy of $2\,\mu$as, the reflex constraint would become $a_{pri} = 2\,\mu\mathrm{as} \times 81.0\,\mathrm{pc}/10^6\,\mu\mathrm{as} = 0.00016\,\mathrm{pc}$. Inserting this value for a_{pri} into equation (1) then defines how a_{bin} varies with q. This behavior is shown as the navy diagonal line in Figure 1. The parameter space to the right (left) of this line is acessible (inaccessible) via astrometric monitoring of NGC 4472 with the adopted accuracy. The PSF of the ngVLA at 80 GHz is marked for reference in Figure 1.

Figure 1 also indicates the values of a_{bin} associated with two fiducial MBH binary periods, $P = 4$ yr and $P = 40$ yr. Astrometric monitoring through a quarter of a period would be sufficient to constrain the range of q values allowed for the period (Safarzadeh et al. 2019). Therefore, if no reflex motion is detected for M_{pri} after 1 year of monitoring, then an MBH binary with $P = 4$ yr and $q > 0.01$ could be excluded. The darker blue shading in Figure 1 indicates where MBH binaries with shorter periods and higher mass ratios might also be excluded.

If reflex motion remains undetected after a decade of astrometric monitoring of NGC 4472, then an MBH binary with $P = 40$ yr and $q > 0.003$ could be excluded. Shorter periods with higher mass ratios could also be excluded, as shown by the lighter blue shading in Figure 1.

As Safarzadeh et al. (2019) highlight in their EHT study of a Jy-level target, using astrometry to open a broad parameter space in a_{bin} and q enables probes of MBH binaries with the wider separations that make them longer-lived against GW losses, and with the smaller mass ratios expected from merged satellite galaxies. With this ngVLA study, we have suggested how such frontier topics might be explored for the more numerous mJy-level targets, such as NGC 4472. Indeed, small q values are expected for NGC 4472, given independent evidence that it has built up its size and mass by accreting satellite galaxies (e.g., Capaccioli et al. 2015).

In contrast to many previous efforts that aim to detect the radio emission from a pair of MBHs in a merger remnant, this strategy requires that only one of them have associated radio emission. And importantly, the combination of the frequency coverage, angular resolution, and sensitivity of the ngVLA LBA would enable searches well into the regime at which an MBH binary is emitting GWs, unlike previous efforts (e.g., Bansal et al. 2017). We elaborate further on this topic in the next subsection.

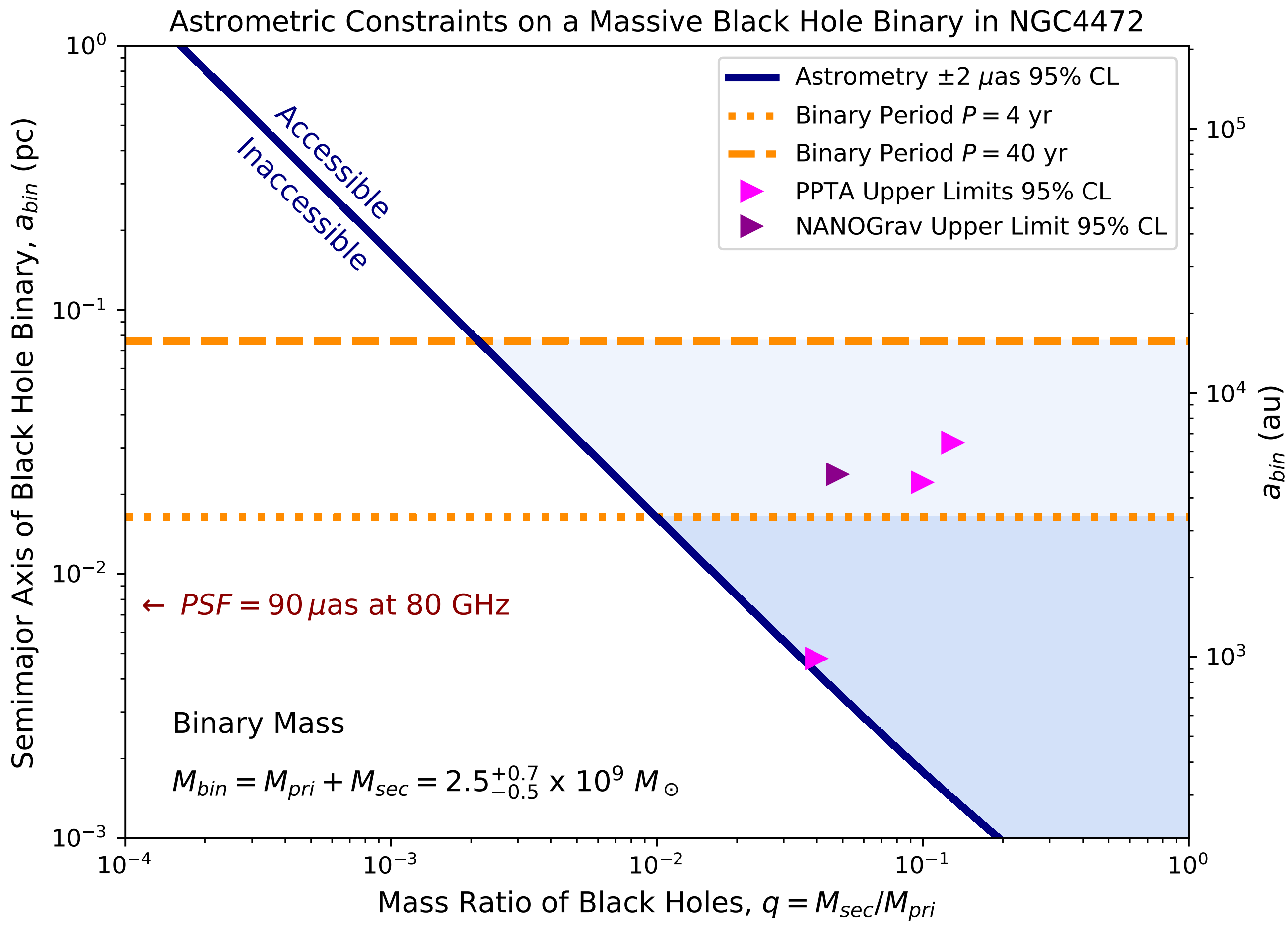

Figure 1. Parameter space for a_{bin} and q for a hypothetical MBH binary in NGC 4472, the dominant galaxy in Virgo Subcluster B. M_{bin} is from Rusli et al. (2013). GW constraints from the PPTA are tabulated in Schutz & Ma (2016), while that from NANOGrav is derived from Aggarwal et al. (2019).

4.2. *ngVLA Tie-Ins to GW Findings*

ngVLA astrometric monitoring could serve to independently test the GW upper limits on q plotted in Figure 1 for NGC 4472 from the Parkes Pulsar Timing Array (PPTA; Schutz & Ma 2016) and from NANOGrav at its highest sensitivity, occuring at a GW frequency of 9 nHz (Aggarwal et al. 2019). Values for q are calculated using equation (5) of Schutz & Ma (2016) with the GW-inferred chirp masses and the binary mass from Rusli et al. (2013).

The NANOGrav search involves a GW frequency range of 2.8 nHz to 317.8 nHz. This range corresponds to orbital periods of a putative MBH binary from $P = 22.6$ yr to $P = 0.2$ yr, equivalent to $a_{\rm bin} = 11000$ au to $a_{\rm bin} = 460$ au for $M_{bin} = 2.5 \times 10^9\,{\rm M}_\odot$ (Rusli et al. 2013). GW-derived axes are so small that they are often expressed not in pc, but in au. (An au axis is provided in Figure 1.) The *PSF* adopted for the ngVLA astrometry of NGC 4472 corresponds to 1500 au, making it complementary to and midway within the range of axes constrained by Aggarwal et al. (2019). Those GW constraints degrade significantly below about 5 nHz, due to the 11 yr data span. Future observations, potentially including ngVLA pulsar timing observations (Chatterjee et al. 2018), will improve the NANOGrav constraints, and extend them to lower GW frequencies or longer orbital periods.

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