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Shining Radio Light on Supermassive Black Hole Binaries: A Targeted, Deep VLBI Search in Post-Merger Galaxies

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Identifying and studying supermassive black hole binaries is critical to our understanding of SMBH growth, massive binary evolution, and feedback processes.

Supermassive black holes (SMBHs) are thought to reside in the core of all massive galaxies. Major galaxy mergers will inevitably introduce multiple SMBHs into the galactic environment. As the SMBHs evolve in their environment, dynamical friction from the stellar population and gas content of the galaxy will remove energy and momentum from the SMBHs, dragging them towards the gravitational center. Eventually, the SMBHs will form a gravitationally bound binary at parsec-scale separation. Through yet unknown means, the orbital separation of the binary will shrink, and the binary, at sub-parsec separation, will emit low-frequency gravitational waves, which are soon to be detected by current pulsar timing array experiments. Gravitational wave emission will efficiently bring the binary system to coalescence. For SMBH binaries, anisotropic emission of gravitational waves due to e.g., unequal mass ratio or misaligned black hole spins, may impart a recoil velocity of up to 5000 km s^{-1} onto the newly merged SMBH. In the most extreme cases, these SMBHs will escape from their host galaxy entirely. In most cases, however, the recoiling SMBH will oscillate in the host galaxy's gravitational potential, during which time we may observe spatial and/or kinematic signatures of its recoiling nature.

Detections of these systems are difficult. In particular, SMBH binaries can only be conclusively identified via ultra high-resolution imaging available through Very Long Baseline Interferometry (VLBI), often requiring long integration times. Yet, radio emission associated with an SMBH is rare (~10%). These make blind searches for binaries unfeasible, and require *a-priori* knowledge of the best candidates to host a binary. To date, only one binary has been identified, though hundreds of candidates exist via a multitude of search techniques. No confirmed recoiling SMBHs have been discovered, though a few candidates present compelling evidence. With forthcoming detections of low-frequency gravitational waves by pulsar timing arrays and space-based gravitational wave antennas, electromagnetic identification of SMBH binaries and recoiling SMBHs is essential to unlocking the potential of multi-messenger astronomy, which will open the window to understanding binary evolution and its astrophysical implications.

We present here the initial results for a targeted search for SMBH binaries in a sample of six late-stage galaxy merger systems. As late-stage mergers, those which exhibit characteristics of a recent merger event, e.g., tidal tails, but only contain a single stellar core, these galaxies are optimal candidates to search for SMBH binary or recoiling systems, the latest stages of massive binary evolution. Archival radio data, available through the FIRST and NVSS campaigns, has shown each of these galaxies a strong, central, compact radio source. Our observational campaign uses hundreds of hours of multi-frequency Very Long Baseline Array (VLBA) observations to reach deep sensitivities ($\lesssim 10$ uJy) at all frequencies on all sources. Our deep sensitivities will be able to detect radio components down to a luminosity ~10^{19} W Hz^{-1}, probing the faintest emission. With the superior angular resolution of VLBI and the vicinity of all our targets, we are able to resolve binary components with sub-pc spatial separations. Our initial results include the discovery of a compact symmetric object (CSO), which are believed to be the youngest stage of the evolution of radio galaxies, and multi-epoch observations on a changing-look Active Galactic Nucleus (AGN), a potential recoiling SMBH.