1. Introduction

Given that most galaxies harbor supermassive black holes at their centers, and that galaxy mergers are common, binary black holes should likewise be common. Despite this, very few systems have been found, perhaps because they proceed rapidly to parsec-scale separations which cannot be resolved by current X-ray or optical telescopes. Fortunately, in the case where both black holes are radio loud, they can be imaged using VLBI techniques. An understanding of these systems is important for an understanding of the evolution and formation of galaxies in general.

Source properties including X-shaped radio galaxies, double-double radio galaxies, helical radio-jets, double-horned emission line profiles, and semi-periodic variations in lightcurves have all been taken as indirect evidence for compact binary black holes (Komossa 2003) though other explanations are possible. Some wider systems have, however, been found more directly. The ultraluminous galaxy NGC 6240, discovered by the Chandra X-ray observatory, has a pair of active supermassive black holes at its center (Komossa et al. 2003), separated by 1.4 kpc. Most recently, a potential triple black hole system was discovered in J1502+1115 by Deane et al. (2014), though sensitive VLBA images have resulted in some concern that the closer components may instead be the hotspots of a Compact Symmetric Object (Wrobel, Walker & Fu 2014). Analysis of VLBI survey data shows that resolved systems are very rare (Burke-Spolaor 2011).

Our ability to resolve both supermassive black holes in any given binary system depends on the projected separation between them, on their distance from Earth, and on the resolving power of the telescope used. It is believed that the longest timescales in the evolution of a supermassive binary black hole system leading up to coalescence is the stage in which the system is closely bound (∼0.1 - 10 pc) (Begelman, Blandford & Rees 1980). The radio galaxy 0402+379 is the best candidate of a binary supermassive black hole system with a very small projected separation. This source has been found to contain two central, compact, flat spectrum, variable components (designated C1 and C2, see Fig. 1), a feature which has not been observed in any other compact source. The two nuclei appear nearly stationary (within the measurement uncertainties), while the jets emanating from the weaker of the two nuclei appear to move out in a predictable manner and terminate in bright hot spots (see Fig. 2). Multi-frequency VLBA observations are described in greater detail by Rodriguez et al. (2006). A system mass of at least a few $10^8 M_\odot$ was estimated using VLBA and HET data, while observations of HI absorption (Rodriguez et al. 2009) yield a mass estimate $>7 \times 10^8 M_\odot$. The $M_*/M_{bulge}$ correlation predicts a larger mass for this system of $\sim 3 \times 10^9 M_\odot$ (Romani et al. 2014). At the redshift of 0402+379 of 0.055, for $H_0=75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ gives a scale of 1 mas = 1.06 pc.

2. Scientific Justification

To date we have obtained three epochs at 15 GHz spread over 6 years. Figure 3 shows a zoomed image centered on the position of the core component C2. Although the changes in position with time are very close to the errors (which are not shown but are on the order of 0.04 mas) and thus by no means conclusive, the progression of C2 in the same direction is extremely suggestive. Assuming this progress is real, these motions can be fit with an inclined circular orbit (solid line in Fig 3: radius $\sim 15$ mas, inclination $\sim 7$ degrees). This inclination is consistent with our detection of HI in absorption and the subluminal and rather symmetric jets. Using our system mass estimate of $3 \times 10^8 M_\odot$ we find from Kepler’s Laws that the period of rotation should be $\sim 1 \times 10^5$ y. This period corresponds to a relative velocity between components C1 and C2 of $\sim 0.003c$, consistent with the upper limit found for component C2 relative to C1 of $\leq 0.02c$. 

\textit{Constraining the Orbits of the Supermassive Binary Black Holes in 0402+379}
This preliminary orbit model allows us to make a prediction for the position of the C2 component in 2015 (Fig. 3). If confirmed the velocity of $\sim0.02c$ would require an extremely large ($10^{11} M_\odot$) enclosed mass. Our knowledge of the enclosed mass and orbital parameters is still very poor, and other scenarios are possible that could produce a large relative velocity. Rather than a greater enclosed mass, a highly elliptical orbit would mean that we have caught C1 and C2 closer to pericenter so that the velocity is higher than that predicted by circular orbits. We also have some indication (Rodriguez et al. 2009) that the radial velocities are $\sim1000$ km/s ($0.003c$). The proposed VLBA observations will provide the 4th epoch of an observational campaign aimed at constraining the relative motions of the two nuclei, which in turn will help us to better constrain the system mass and orbits. Such a determination will also solidly confirm the binary black hole nature of this system.

The motions of the jet components have been determined using the 15 GHz data taken in 2003, 2005 and 2009 (Fig. 2). The jet features have a large component of motion along the jet axis, as expected. The proposed observations will allow us to increase the accuracy of the expansion studies of the northern and southern hot spots. These expansion studies will refine our estimates of the kinematic age of the pc-scale radio emission, currently 500 - 1500 years (Rodriguez et al. 2006).

Because the source structure is dominated by the two compact cores at 15 and 22 GHz, these observations will be free of the systematics (primarily blending of components) that plague the determination of component positions at lower frequencies. At even higher frequencies (43 GHz) the decrease in flux density of the two cores, along with reduced telescope performance, make the relative astrometry problematic, thus we believe 15 and 22 GHz to be optimal for this campaign.

Here we propose for the 4th epoch of a monitoring campaign on 0402+379 at 15 and 22 GHz. This epoch will double the secular baseline, making these observations particularly timely. We further request 8 and 5 GHz in order to study the spectral evolution, and variability, of the two cores, and to verify the possible offset in core position with frequency shown in Fig 4. Here we find the 8, 15 and 22 GHz positions of the C2 components each show a small change in position with time, but also appear systematically shifted from the simultaneously measured positions at the other frequencies. At present we have no clear explanation for this offset, although we suspect it may be related to a "core shift" (Fromm et al. 2013) as we are detecting the very base of the jet close to the black hole.

3. Technical Considerations

The two compact components that are of primary interest peak between 8 and 15 GHz with flux densities of 60 and 15 mJy for C1 and C2 respectively. Obtaining high signal to noise ratios for all components at these moderate flux density levels will be possible observing at 1 Gbps using the new continuum capabilities. We will observe the nearby ($3.1''$) compact flat-spectrum calibrator J0419+3955 hourly to improve the calibration. To carry out high quality imaging, with similar ($u,v$) coverage as in the previous 3 epochs, we will require roughly 1-5 hours integration at each band (more at the high frequencies) spread over a wide range in hour angle. Our total request is for 12 hours.

References

Figure 1: Naturally weighted 2005 VLBA images of 0402+379 at 5, 8, 15 and 22 GHz. Contours are drawn beginning at $3\sigma$ and increase by factors of 2 thereafter. The labels shown in the 5 GHz map indicate the positions of the two strong, compact, central components. See Rodriguez et al. (2006) for further details.

Figure 2: Component positions for the VLBA observations of 0402+379 at 15 GHz. The arrows shown represent the motion found for each component (magnified by a factor of 3), relative to the position of C1, obtained from a time baseline of 6 yrs.
Figure 3: A closeup of the region centered on the position of the C2 core component. Although the changes in position with time are very small, the progression of C2 in the same direction is extremely suggestive. The solid line represents a possible orbit with radius $\sim 15$ mas and inclination $\sim 7$ degrees, consistent with our detection of HI in absorption and the slow moving and rather symmetric jets. This preliminary orbit model allows us to make a loose prediction for the position of the C2 component in 2015, indicated with a star symbol, which these observations will allow us to confirm.

Figure 4: Similar to Fig. 3, but also showing 8 GHz (red x’s) and 22 GHz (blue k’s) in addition to 15 GHz (green u’s). A small but systematic offset in position with frequency may be a spectral index effect if we are detecting the very base of the jet close to the black hole. Another epoch of observations at 5 - 22 GHz will determine if this effect is significant.