Constraining the Orbit of the Supermassive Black Hole Binary 0402+379

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Abstract

The radio galaxy 0402+379 is believed to host a supermassive black hole binary (SMBHB). The two compact-core sources are separated by a projected distance of 7.3 pc, making it the most (spatially) compact resolved SMBHB known. We present new multi-frequency VLBI observations of 0402+379 at 5, 8, 15, and 22 GHz and combine them with previous observations spanning 12 years. A strong frequency-dependent core shift is evident, which we use to infer magnetic fields near the jet base. After correcting for these shifts we detect significant relative motion of the two cores at $\beta = v/c = 0.0054 \pm 0.0003$ at PA = $-34^\circ$. With some assumptions about the orbit, we use this measurement to constrain the orbital period $P \approx 3 \times 10^4$ yr and SMBHB mass $M \approx 15 \times 10^7 M_{\odot}$. While additional observations are needed to confirm this motion and obtain a precise orbit, this is apparently the first black hole system resolved as a visual binary.

Key words: gravitational waves – quasars: supermassive black holes

1. Introduction

It is commonly believed that the later stages of galaxy evolution are governed by mergers. It is very common for galaxies to collide and interact with each other. Considering that most galaxies in the universe harbor supermassive black holes (SMBHs) at their centers (Richstone et al. 1998), it can be inferred that massive black hole pairs should be the outcome of such mergers through the hierarchical formation of galaxies (Begelman et al. 1980). This implies that supermassive black hole binaries (SMBHB) should be relatively common in the universe. However, despite very extensive searches, very few such systems have been observed (Burke-Spolaor 2011; Tremblay et al. 2016). The reason for this could be that black holes in a binary system either merge quickly, or that one of them escapes the system (Merritt & Milosavljević 2005). Hence, understanding these SMBHB systems is important for understanding a variety of processes ranging from galaxy evolution to active galactic nuclei (AGNs) to black hole growth.

There are two types of galaxy mergers: major and minor. Major mergers occur when the interacting galaxies are of similar sizes (mass ratio less than 3:1; Stewart et al. 2009, and references therein), whereas in minor mergers one galaxy is significantly larger than the other. A crucial expectation related to galaxy mergers is the emission of gravitational waves (GWs). When galaxies merge, due to the dynamical friction between them, the black holes at their corresponding centers sink toward a common center. This leads to the formation of a binary system, such that its orbit decays due to the interaction between the stars, gas, and dust of both galaxies. The two black holes may reach a small enough separation that energy losses from GWs allow the binary to coalesce into a single black hole (Begelman et al. 1980; Milosavljević & Merritt 2003).

Numerous simulations have been performed to study these SMBH mergers. These simulations deal with various aspects such as black hole mass ratios, self-gravitating or non-gravitating circumbinary disks, orbital spin, black hole spin, gas or stellar dynamics, etc. (Barnes 2002; Escala et al. 2004, 2005; Merritt & Milosavljević 2005; Sesana et al. 2006; Dotti et al. 2007; Callegari et al. 2009, 2011; Khan et al. 2011; Schnittman 2013). Despite several attempts, attaining the required resolution (the last parsec problem, $\sim 0.01$ pc) to study the black hole coalescence has been challenging. The fate of the merger at the parsec scale depends on the amount of surrounding stars and gas, and their interaction with the binary. In the case of a stellar background, due to three-body scattering, the formation of a loss cone takes place (Sesana et al. 2007), whereas in the case of gas-rich mergers tidal forces inhibit the gas from falling onto the binary, hence creating a gap (Dotti et al. 2012), and references within). The loss cone causes a decay period longer than the Hubble time (Milosavljević & Merritt 2003; Merritt et al. 2007). Hardening can be attained for a triaxial stellar remnant, with the loss cone being replenished (Merritt & Vasiliev 2011) and an expected coalescence time of $\sim 10^3$ years (Khan et al. 2011). For gas-rich mergers, the gap does not inhibit gas flow (Roedig et al. 2012) and a massive circumbinary disk around the binary promotes the decay, leading to a timescale for an equal-mass binary $\sim 10^7 M_{\odot}$ that is less than the age of the universe (Hayasaki 2009). For higher-mass black holes ($\sim 10^{8–9} M_{\odot}$) the timescales are greater. In a recent study by Khan et al. (2016), they reported that for massive galaxies at high redshifts ($z > 2$) it takes about a few million years for black holes to coalesce once they form a binary, whereas at lower redshifts where the nuclear density of the host is lower, it may take longer, on the order of a Gyr.

Gravitational waves from merging black holes are expected as a result of Einstein’s General Theory of Relativity (Einstein 1916, 1918, 1997, 2002).7 In 2015 September, the Laser Interferometer Gravitational Wave Observatory (LIGO) discovered a GW source GW150914, and identified it as a

7 http://einsteinpapers.press.princeton.edu/
merging binary black hole (Abbott et al. 2016). Although the masses of the two BHs are much smaller (∼30 \( M_\odot \)) in comparison to SMBHBs (∼10^7 – 10^9 \( M_\odot \)), this discovery provides the first observational evidence for the existence of binary BH systems that inspiral and merge within the age of the universe. It motivates further studies of binary BH formation astrophysics and with upcoming detectors such as the evolving Laser Interferometer Space Antenna (Amaro-Seoane et al. (2013)), it will be possible to detect low-frequency GWs (around one mHz), emitted from the inspirals of massive black holes (Klein et al. 2016). While mergers of SMBHBs are expected to be common emitters of GW radiation, modulating pulsar-timing observations have not yet detected any evidence for a GW signal (Arzoumanian et al. 2016). Pulsar-timing observations, unlike LIGO, should be more sensitive to SMBHB mergers (Shannon et al. 2015). 0402+379, with a separation of 7.3 pc between its core components, is one of the most important precursors of GW sources, and is important for understanding the reason behind the low incidence of such systems. From the elliptical morphology of the 0402+379 host galaxy (Andrade-Santos et al. 2016), we believe this object to be the result of a major merger.

The radio galaxy 0402+379 was first observed by Xu et al. (1995) as a part of the first Caltech Jodrell Bank Survey (CJ1), although at that time it was not identified as an SMBHB. This source first acquired attention as a compact symmetric object (CSO) candidate (small AGN with jets oriented close to the plane of the sky such that the radio emission from the jets is detected on both sides of the core) in 2003, in the full polarimetry analysis by Pollack et al. (2003). Subsequently, Maness et al. (2004) studied this source at multiple frequencies using the Very Long Baseline Array (VLBA), and on the basis of its properties, they classified it to be an unusual CSO. Rodriguez et al. (2006) studied this source in more detail and arrived at the conclusion that it is an SMBHB. This source contains two central, compact, flat spectrum and variable components (designated C1 and C2, see Figure 1), a feature that has not been observed in any other compact source. This is one of the only spatially resolved SMBHB candidates (Gitti et al. 2013; Deane et al. 2014). The milliarcsecond scale separation requires high resolving power available only with a telescope such as the VLBA. Although other systems like RBS 797 and J1502+1115 (a triple system), with separations of about 100 pc, have been detected, no system other than 0402+379 has been resolved at parsec scales. We believe that this SMBHB is in the process of merging.

Rodriguez et al. (2006) imaged this source at multiple frequencies, studying the component motion at 5 GHz, but finding no significant detection of core displacement. In this paper, we incorporate new 2009 and 2015 epochs of 0402+379 VLBA observations at 5, 8, 15, and 22 GHz, while reanalyzing the 2003 and 2005 observations. These data show strong evidence for a frequency-dependent core shift effect (Lobanov 1998; Sokolovsky et al. 2011). After accounting for this effect, our data set allows a detection of the relative motion of the two cores, making this the first visual SMBHB. We comment on the implications for the orbital period and masses. Throughout this discussion, we assume \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \) so that 1 mas = 1.06 pc.

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### 2. Observations and Data Reduction

#### 2.1. VLBA Observations

Observations were conducted on 2009 December 28 and 2015 June 20 with the VLBA at 4.98, 8.41, 15.35, and 22.22 GHz. For the 2015 observations, the total time on-source was 70 minutes at 5 GHz, 260 minutes at 8 GHz, 290 minutes at 15 GHz, and 330 minutes at 22 GHz. 3C84 and 3C111 were observed for bandpass and gain calibration, respectively. The data recording rate was 2048 Mbps, with two-bit sampling. Each frequency was measured over eight intermediate frequencies (IFs) such that every IF consisted of a bandwidth of 32 MHz across 64 channels in both circular and respective cross polarizations.

Standard data reduction steps including flagging, instrumental time delay, bandpass corrections, and frequency averaging were performed with the NRAO Astronomical Image Processing System (AIPS; Van Moorsel et al. 1996; Ulvestad et al. 2001). For all iterative self-calibration methods the initial model was a point source. Further cleaning, phase, and amplitude self-calibration were executed manually using Difmap (Shepherd et al. 1995). The source structure was later model-fitted in the visibility \((u, v)\) plane with Difmap using circular and elliptical Gaussian components.

Fully calibrated VLBI archival data from the 2003 epoch (Maness et al. 2004) at 15 GHz, and the 2005 (Rodriguez et al. 2006) epoch at 5, 8, 15, and 22 GHz, have been included to study the core-component motion with frequency and time. The visibilities were imaged and model-fitted in Difmap, as was done for the 2009 and 2015 data, to obtain the core positions. The calibrator 3C111 has been observed in the same configuration across all four epochs. Details of the observations can be found in Table 1.

### 3. Measurement and Fits

The new 2015 data set provides the most sensitive measurement of the source geometry. Using model fitting in Difmap to the visibilities, we determine the Gaussian size, axis ratio, and position angle for each core-component. These measurements are listed in Table 2. Additional Gaussian components are included in each model to account for the extended structure. We then follow Rodriguez et al. (2006) and Maness et al. (2004) in fixing these parameters in fits to the other epochs, while allowing only the positions and fluxes of C1 and C2 to vary. These are listed in Table 3, with the relative positions listed as angular separation \( r \) and position angle \( \theta \) measured north through east. The reported flux density errors combine the map rms \( \sigma_{\text{rms}} \) and an estimated systematic error in quadrature: \( \sigma_f = \sqrt{(0.1 S_f)^2 + (\sigma_{\text{rms}})^2} \).

The effective position errors are more difficult to estimate. The statistical errors \( \approx a/2(S/N) \) (Fomalont 1999) are very small (\( \sim 2 \mu\text{as} \)), and systematic effects certainly dominate. We made an initial check on these errors by redoing the previous Stokes I map analysis in Stokes LL and RR. 0402+379 is an unpolarized source, so we expect data from both Stokes RR and LL to yield similar distance measurements. Another way to obtain these error estimates is to split the data in time or frequency. However, these maps would have a different frequency. However, these maps would have a different systematic error in quadrature. Thus making it difficult to make a comparison between them. If the polarization-dependent structure differences are as small as expected, then any measured differences can be attributed to systematic errors. This technique has been...
Discussed previously by Roberts et al. (1991) and McGary et al. (2001). Decomposing the relative positions into R.A. (x) and decl. (y), we find that the median shifts in the core centroid positions are $\sigma_x = 7 \mu$as and $\sigma_y = 8 \mu$as for the higher frequencies, and $\sigma_x = 31 \mu$as and $\sigma_y = 34 \mu$as at 5 GHz.

3.1. Analysis

The core-component flux density arises from the surface at which the self-absorption optical depth is unity (Blandford & Königl 1979). Since this is strongly frequency-dependent, we expect an asymmetric extended structure, such as the jet base that defines the core, to have a frequency-dependent centroid. This effect is very obvious in the raw positions (Figure 2), where the lower-frequency centroids are shifted to the northeast along the larger-scale outflow position angle (Figure 1(a)).

Similar shifts have been detected in a number of AGNs (Lobanov 1998; Sokolovsky et al. 2011). Since we are measuring position relative to C1, any extension to that source may also contribute to the relative core shift; this need not be at the same position angle. However, the combined shift appears to be dominated by C2 and we indeed find that the frequency-dependent shift is along the 47° (north to east) position angle of the C2 outflow. According to Lobanov (1998), the shift can be parameterized as $r_c = a v^{-1/k}$, where $a$ is the shift amplitude and $k$ depends on the jet geometry, particle distribution, and magnetic field. For example, a conical jet with a synchrotron self-absorbed spectrum gives $k = 1$ (Lobanov 1998).

By correcting to an infinite frequency we can mitigate the effect of this core shift on the position of the nucleus (Figure 3). We are especially interested in the relative motion of C1 and
C2, so our model includes a fiducial relative position (at epoch 2000.0), as well as relative proper motion in R.A. and decl. Thus our model has six fit parameters (if we include the core-shift position angle as a fit parameter, we do indeed obtain 46° ± 1°, but prefer to fix this via the larger-scale jet axis). Our data set comprises the 13 observation frequencies and epochs. The plotted error ellipse in Figure 3 is semimajor axis, component orientation for both C1 and C2. All angles are measured from north through east.

Using our measurements and the position error estimates above, we performed a χ² minimization to determine the model parameters. These are listed in Table 4. The parameter error estimates are somewhat subtle. Since the fit minimum has χ²/DoF = 2.78, we must have systematic errors beyond those estimated above. The conventional approach is to uniformly inflate all errors until the effective χ²/DoF = 1. This is equivalent to estimating errors using the χ² surface with increases of +1, +2 ... × χ²/DoF. We list these “1σ” and “2σ” confidence intervals in Table 4.

However, this uniform inflation assumes that all errors have a Gaussian distribution and are equally underestimated. This is unlikely to be true. An alternative approach is to estimate errors via a bootstrap analysis (Efron 1987). This has the virtue of using only the actual data values (not the error estimates), but does pre-suppose that the observed data values are an unbiased draw from an (unknown) error distribution about the true values. Although our set of 13 position pairs is somewhat small for a robust bootstrap, we generated 10,000 re-sampled realizations of the data set, replacing five pairs in each realization with random draws from the remaining pairs. Each realization was subject to the full least-squares fit for all model parameters. The histograms of the fit values for the individual parameters were used to extract 95% confidence intervals for each quantity. These confidence intervals are listed in Table 4. They accord fairly well with the inflated χ² estimates.

In general, the parameters appear well-constrained. The core-shift coefficients a and k are estimated to ~3% accuracy (Table 4). The epoch position range is somewhat larger in the bootstrap error analysis, evidently as a result of the substantial offset of the 2009.9 position from the general trend.

The coefficient k depends on the shape of the electron energy spectrum, magnetic strength, and particle density distribution (Lobanov 1998). If k = 1, it implies that the jet has a conical shape, where synchrotron self-absorption is the dominant absorption mechanism. We have obtained k = 1.591 ± 0.232 (via the bootstrap technique), in accordance with the literature (Sokolovsky et al. 2011), where the highest reported k value is ~1.5. This implies that our observations are consistent with the synchrotron self-absorption mechanism.

The core shift depends mainly on the frequency as well as the magnetic field and spectral index (Lobanov 1998). All our measurements are derived from the same frequencies over time; however, there is a possibility of variation with magnetic field and spectral index. We calculated the spectral index for three epochs (2005, 2009, and 2015) using the peak intensities, and we have found these values to range from −0.58 to −0.98 and −0.43 to −0.50 for C1 and C2, respectively. From these ranges of spectral index, we can see that the variation over 10 years is quite small (~0.4). To our knowledge, no time-varying core-shift offsets have been reported in the literature. For our analysis, we assume that the core shift is constant over time.

In Figure 3 we plot the relative C2 core position, shifted to infinite frequency according to the best-fit a and k, for each of the 13 observation frequencies and epochs. The plotted error ellipses for the 8, 15, and 22 GHz observations are the formal σ and σγ from the polarization analysis. There are large outliers, especially the 2009.9 epoch. However, the overall shift is quite significant, with motion detected in both R.A. and decl., at >3σ in the χ² analysis and at well over 95% confidence in the bootstrap analysis. However, additional epochs, especially at high frequency, will be needed to make the motion visually clear.

To compare these above results, we also studied the motions of jet components. We find that the bright southern jet components continue to move away from the core, consistent with the trends seen in C1.
with the previous results (Rodriguez et al. 2006). For the weaker northern hotspot, the agreement is not as good, as it seems to exhibit inconsistent motion for some frequencies. However, this may be the result of errors in the previous measurements based on 5 GHz observations.

Using our best-fit \( \mu_{\text{R.A.}} \) and \( \mu_{\text{decl.}} \), we shift the raw data points (Table 3) to epoch 2000.0. For each frequency, we obtain an average relative R.A. and decl., which are subsequently subtracted from the fiducial 2000.0 point (Table 4), to obtain the distance from the core \( (r_c) \). This has been plotted to demonstrate our fitted frequency dependence, shown in Figure 4. The plotted errors have been obtained by error propagation using the above stated errors \( (\sigma_r \text{ and } \sigma_\theta) \).

### 3.2. Magnetic Field Estimate

The core shift effect is useful to deduce various jet-related physical parameters, including the magnetic field strength. The core shift effect is useful to deduce various jet-related physical parameters, including the magnetic field strength.

### Table 3

**Variable Gaussian Model Components**

| Epoch     | Frequency (GHz) | \( S_r (C1) \) (Jy) | \( S_r (C2) \) (Jy) | \( r \) (mas) | \( \theta \) (°) |
|-----------|-----------------|----------------------|----------------------|--------------|--------------|
| 2005.07   | 5               | 0.057 ± 0.005        | 0.014 ± 0.001        | 6.942        | -75.70       |
| 2009.99   | 5               | 0.058 ± 0.005        | 0.016 ± 0.001        | 6.841        | -75.93       |
| 2015.43   | 5               | 0.060 ± 0.006        | 0.013 ± 0.001        | 6.884        | -75.79       |
| 2005.45   | 8               | 0.067 ± 0.006        | 0.016 ± 0.002        | 6.913        | -76.46       |
| 2009.99   | 8               | 0.052 ± 0.004        | 0.017 ± 0.002        | 6.920        | -76.42       |
| 2015.43   | 8               | 0.083 ± 0.008        | 0.018 ± 0.002        | 6.913        | -76.33       |
| 2003.17   | 15              | 0.070 ± 0.007        | 0.020 ± 0.002        | 6.929        | -76.96       |
| 2005.07   | 15              | 0.054 ± 0.005        | 0.016 ± 0.002        | 6.959        | -76.81       |
| 2009.99   | 15              | 0.029 ± 0.003        | 0.012 ± 0.001        | 6.985        | -76.96       |
| 2015.43   | 15              | 0.058 ± 0.005        | 0.015 ± 0.001        | 6.956        | -76.77       |
| 2005.45   | 22              | 0.037 ± 0.003        | 0.011 ± 0.001        | 6.950        | -77.08       |
| 2009.99   | 22              | 0.020 ± 0.002        | 0.011 ± 0.001        | 6.984        | -77.16       |
| 2015.43   | 22              | 0.040 ± 0.003        | 0.012 ± 0.001        | 6.969        | -77.04       |

**Note.** Variable model parameters of Gaussian components for C1 and C2 of the model brightness distribution at different epochs and frequencies. These are as follows: \( S_r \), flux density at each frequency; \( r, \theta \), polar coordinates of the center of the component C2 relative to the center of component C1 (it has been assumed to be at a fixed position). Errors in flux have been estimated using both flux systematics and map rms \( (\sqrt{(0.1 \cdot S_r)^2 + \text{rms}^2)} \).

![Figure 2](image1.png)

**Figure 2.** We have plotted projected relative R.A. vs. decl. of component C2 with respect to C1 (at origin), at 5 GHz (c’-s’), 8 GHz (x’-s’), 15 GHz (u’-s’), and 22 GHz (k’-s’). These are the raw, uncorrected, model fit positions. An offset in position with frequency can be seen due to the core shift effect discussed in the text.

![Figure 3](image2.png)

**Figure 3.** Position of C2 relative to C1 in time after removing the effect of the core shift. The black line is a proper motion fit; the best-fit positions at each epoch are labeled by points along the line.

Lobanov (1998) and Hirotani (2005), for example, provided a derivation that assumes equipartition between the particle and magnetic field energy densities in the jet. An alternate formulation by Zdziarski et al. (2015) avoids the equipartition assumption, using the flux density \( F_v \) at a jet axis distance \( h \) to estimate the magnetic field strength as

\[
B_F(h) = \frac{3.35 \times 10^{-11} D_s[\text{pc}] \delta \Delta \theta[\text{mas}]^3 \tan \Theta^2}{h[\text{pc}] (\nu_1^{-1} - \nu_2^{-1})^5 [(1 + z) \sin i]^3 F_v[\text{Jy}]}.
\]

where \( z \) is redshift, \( D_s \) is the luminosity distance in parsecs, \( \delta = [\Gamma (1 - \beta \cos i)]^{-1} \) is the Doppler factor, \( \Gamma \) is the minimum Lorentz factor, \( \beta \) is the jet bulk velocity factor (obtained from Rodriguez et al. 2009), \( i \) is the inclination angle, \( \Delta \theta \) is the observed angular core shift (Lobanov 1998), and \( \Theta = \arctan \frac{\sqrt{d^2 - h^2}}{2r} \) is the jet half-opening angle (Pushkarev et al. 1998).
Table 4
Fitting Parameters

| Parameters       | Value       | Technique Bootstrap (95% ) | 1σ    | 2σ    |
|------------------|-------------|----------------------------|-------|-------|
| ΔR.A.0 (mas)     | −6.863      | −6.892, −6.855             | −6.859, −6.868 | −6.858, −6.869 |
| Δdecl.0 (mas)    | 1.474       | 1.448, 1.478               | 1.470, 1.478     | 1.468, 1.480 |
| \( \mu_{\text{R.A.}} \) (mas yr\(^{-1} \)) | −0.887   | −0.970, −0.831             | −1.245, −0.549     | −1.389, −0.405 |
| \( \mu_{\text{decl.}} \) (mas yr\(^{-1} \)) | 1.286    | 1.200, 1.401               | 0.878, 1.672     | 0.713, 1.836 |
| \( a \) (mas)   | 0.756       | 0.700, 0.818               | 0.739, 0.777     | 0.731, 0.785 |
| \( k \)         | 1.591       | 1.556, 1.823               | 1.565, 1.617     | 1.555, 1.628 |

Note. Fitted parameter values (Column 2) and their corresponding confidence intervals obtained from two different techniques: bootstrap analysis (Column 3) and \( \chi^2 \) minimization (Column 5 and 6). ΔR.A.0 and Δdecl.0 are infinite-frequency core offsets at epoch 2000.0; \( \mu_{\text{R.A.}} \) and \( \mu_{\text{decl.}} \) are proper motion estimates; \( a \) and \( k \) are core shift fitting parameters (\( r_c = a (\nu^{-1/2}) \)).

Figure 4. Plot of the core shift measurement in distance from the central engine for 0402+379 as a function of frequency. The black circles are the observed distance offset from the estimated infinite-frequency core position at each frequency, and the black solid curve is the fitted function, with \( r_c = a (\nu^{-1/2}) \) (See Table 4).

2012). From the latest 8 GHz map, we have obtained the FWHM of a Gaussian fitted to the transverse jet brightness component, \( d = 4.130 \pm 0.017 \) mas (minor axis of jet); the beam size along the jet direction, \( b_x = 1.26 \) mas; and the distance to the core along the jet axis, \( r = 26.320 \pm 0.017 \) mas. Since the extended jet components are not readily detected at 15 and 22 GHz, we assume the same opening angle for all frequencies. Table 5 gives our estimated values for these parameters, with the origins in the footnotes. The numerical constant in the above equation has been obtained for \( p = 2 \), where \( p \) is the index of the electron power law (see Zdziarski et al. 2012, 2015).

From a weighted linear fit of \( \delta \theta \) against \( \nu^{-1}_{1} - \nu^{-1}_{2} \), we obtain a slope \( 1.128 \pm 0.152 \) and intercept \( 0.008 \pm 0.010 \). Instead of calculating \( \frac{\delta \theta}{\nu^{-1} - \nu^{-2}} \) for each frequency separately, its slope has been used to calculate the magnetic field strength. Our fit indicates a magnetic field strength \( 0.71 \pm 0.25 \) G at \( h = 1 \) pc, similar to that for other jets (O’Sullivan & Gabuzda 2009).

3.3. Orbital Models

Our measured proper motion \( \mu_{\text{R.A.}} = −0.89 \pm 0.07 \) mas yr\(^{-1} \), \( \mu_{\text{decl.}} = 1.29 \pm 0.10 \) mas yr\(^{-1} \) (symmetric width of the 95% CL bootstrap range) corresponds to a proper motion \( \mu \) of \( 1.57 \pm 0.08 \) mas yr\(^{-1} \) at PA\( \mu = −34.76 \pm 2.79 \) (if we use the “10σ” \( \chi^2 \) errors, the amplitude uncertainty is \( \pm 0.38 \) mas yr\(^{-1} \)).

Thus, this is at least a 4σ detection. It is consistent with the non-detection of a proper motion in Rodriguez et al. (2006), where 15 years of 5 GHz data (1990–2005) were used to estimate \( \mu = 6.7 \pm 9.4 \) mas yr\(^{-1} \); our higher-frequency data and core shift correction are essential for measuring the much smaller motion.

We now ask if this proper motion is consistent with a shift due to the relative orbits of the two BHs. At \( z = 0.055 \), it corresponds to a projected space velocity of \( \beta = v/c = 0.0054 \pm 0.0003 \), so a Keplerian analysis suffices. First, the ratio \( 2\pi

Figure 4. Plot of the core shift measurement in distance from the central engine for 0402+379 as a function of frequency. The black circles are the observed distance offset from the estimated infinite-frequency core position at each frequency, and the black solid curve is the fitted function, with \( r_c = a (\nu^{-1/2}) \) (See Table 4).
The orbital eccentrcity grows as the orbit shrinks, since both stars and gas extract energy and angular momentum from the binary. For a stellar background, it depends on the mass ratio, with equal-mass binaries producing orbits that are usually circular or slightly eccentric with \(e < 0.2\) (Merritt et al. 2007). If a pair during the binary formation starts out with a non-zero eccentricity it may never become circular; instead, it tends to become more eccentric (Matsubayashi et al. 2007). In the case of gas-driven mergers, it depends on the disk thickness and the SMBBHs location inside the disk. The critical value of \(e\) is reported to be \(\sim 0.6\), such that systems with high eccentricities tend to shrink to this value (Armitage & Natarajan 2005; Cuadra et al. 2009; Roedig et al. 2012). In the case of \(0402+379\), it has been found to be embedded in cluster gas (Andrade-Santos et al. 2016), which makes it likely to have a non-zero eccentricity.

In Rodriguez et al. (2009) H I absorption measurements were used to infer kinematic motion about an axis inclined \(\sim 75^\circ\) to the Earth line of sight, passing through C2, the origin of the kiloparsec-scale jets. If we look at the solution derived here we see that the PA = 47° axis corresponds to \(i = 71.3^\circ\) (Figures 5 and 6), in reasonable agreement with the H I estimate. The
binary spin can be different from the orbital angular momentum; however, it has been found that if the amount of gas accreted is high (1%–10% of the black hole), on timescales of binary evolution it can change according to the orbital axis (Schnittman 2013, and references therein). Binary orbital axis and individual black hole spins tend to realign due to interaction with external gas except for when the mass ratios are extreme (>1), whereas torques from stars can cause misalignments of the binary orientation from the disk (Coleman Miller & Krolik 2013). For this fit we have $P = 49$ ky and $M = 16.5 \times 10^9 M_\odot$.

Because we find a large proper motion $\mu$ we expect the orbital motion to induce a substantial radial velocity in the relative orbit. Some values are given in Figure 6 and for PA = 47° we expect a relative $v_r = 700$ km s$^{-1}$. While the H$\alpha$ measurements do show velocity differences of this order, we do not see such large velocities in the optical line peaks. Examining the Keck spectra in Romani et al. (2014) we see that the stellar features of the elliptical host center on 16, 618 $\pm$ 53 km s$^{-1}$, while the Seyfert I-type narrow-line core emission centers on 16,490 km s$^{-1}$. Narrow-line emission extends several arcseconds from the core spanning $\sim$300 km s$^{-1}$ while in the unresolved kiloparsec core the velocity dispersion is $\sim$750 km s$^{-1}$. Thus, while at least 2 $\times 10^{10} M_\odot$ lies within the central kiloparsecs, we do not see multiple components shifted by $>500$ km s$^{-1}$. However, the full line width does accommodate such velocities and the wings of the H$\alpha$ complex are centered at $\sim$17,020 km s$^{-1}$, suggesting that fainter broad-line emission might include components spread over $>1000$ km s$^{-1}$. Furthermore, $v_r$ above is the relative velocity; if only the heavier component has bright optical emission, then the broad-line velocity shift from the background galactic velocity (arguably near the center of mass velocity) will be reduced to $m_v/M_{\text{tot}}$. Indeed, Rodríguez et al. (2009) assumed that the jet-producing C2 core is the dominant mass and the center of rotation. If this core also dominates the broad-line emission, then we expect that our VLBI relative velocity is dominated by the motion of C1 and the optical radial velocity shift from the host velocity may be small.

We must also compare with other core mass estimates. As noted above the optical lines indicate several $\times 10^{10} M_\odot$ in the central kiloparsecs. H$\alpha$ absorption velocities require $>7 \times 10^8 M_\odot$ (Rodríguez et al. 2009). And finally, the host bulge luminosity also indicates a large hole mass $M_{\odot} \sim 3 \times 10^9 M_\odot$ (Romani et al. 2014). All of these suggest substantial hole mass. The very large $M_\odot \sim 15$ masses implied by our fits are not excluded but do stretch the available mass budget.

### 3.4. Comments on the Resolved SMBHB Population

The process of hierarchical merging should make close SMBHB common, but to date few candidates at sub-kiloparsec separations have been seen. The resolved (massive) SMBHB seem to be preferentially in galaxy clusters or their products. For example, the SMBHB candidate RBS 797 (Gitti et al. 2013) resides in a cool-core cluster at $z = 0.35$. 0402+379 itself lies in a massive galaxy and dense X-ray halo (likely a fossil cluster) at $z = 0.055$. Thus, such environments seem to be a good place to look for additional systems. Another path to discovering multi-BH nuclei was described by Deane et al. (2014), who found J1502+1115 to be a triple system, with a closest-pair separation of 140 pc at redshift $z = 0.39$. Compact radio jets in the closest-pair of this source exhibit rotationally symmetric helical structure, plausibly due to binary-induced jet precession. However, the total number of resolved compact cores at parsec scales seems very small, with 0402+379 remaining as the only clear example out of several thousand mapped sources (Burke-Spolaor 2011; Tremblay et al. 2016).

Systems of even smaller separation are of the greatest interest since at $r \sim 0.01$ pc, losses from gravitational radiation will dominate and the merging binaries can be an important signal for pulsar-timing studies (Ravi et al. 2015). At present, we rely on arguments about the evolutions of the wider systems to infer the existence of merging SMBHBs. If such evolutions occur we might hope for a discovery of an intermediate $r \sim 0.1$ pc-scale massive $>10^9 M_\odot$ system at low $z$, where a sufficient resolution for a kinematic binary study is possible with high-frequency VLBI. Such a binary would have $P < 10^5$ yr and a well-constrained visual orbit would be achievable, making possible a precision test of its SMBHB nature (Taylor 2014). However, we should note that our study of the galactic halo of 0402+379 (Andrade-Santos et al. 2016) implies that it has stalled at its present 7 pc separation for several Gyr, so the path between resolvable and gravitational, radiation-dominated SMBHBs may not always be smooth.

### 4. Conclusion

In this study of 0402+379, we have focused on two aspects: frequency-dependent core shift and secular relative core motion. Both effects are observed, but the measured values present interpretation challenges.

The strong observed core shift matches well with the large-scale jet axis. It also provides quite typical estimates for the jet base magnetic field of $\sim$0.45–0.95 G. However, the core shift index 1.591 (1.556–1.823; 95% CL range) is somewhat large (expected $k \sim 1$), with the highest reported value in the literature being $k \sim 1.5$ (Sokolovsky et al. 2011). This may be an artifact of our constant core shift fit assumption, as perturbations could arise from the epoch-to-epoch variation in the underlying core-component fluxes.

After accounting for this core shift, the infinite-frequency relative positions of the C1 and C2 cores undergo a statistically significant secular proper motion. The motion corresponds to $\beta = 0.0054 \pm 0.0003$, and if orbital, it represents the first direct detection of orbital motion in a SMBHB, and promotes this system to a visual binary. Although we do not have sufficient observables to solve for an orbit, we can find plausible orbits, even assuming $e = 0$. Intriguingly, such orbits align well with the large-scale jet axis and have similar inclinations to those estimated with H$\alpha$ absorption VLBI. But the required masses are quite large (the highest reported mass is 21 billion $M_\odot$; McConnell et al. 2011). To test our orbital picture, additional VLBI epochs to confirm the consistency of the proper motion will be essential, and further studies of the core dynamics, especially at sub-kiloparsec scales, will also be very important. We should not forget that including a finite orbital eccentricity can allow smaller masses, but we will need additional kinematic constraints to motivate such solutions.

The discovery of possible orbital motion in 0402+379 presents the exciting prospect of probing an SMBHB’s kinematics. Extensions to our high-frequency VLBI campaign could certainly improve the measurements, but the proper motion is perhaps the most exciting finding for future searches.
for tighter, faster, and more easily measured examples of resolved SMBHBs.

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