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High angular resolution studies of stellar-mass black holes

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Abstract. X-ray binaries provide nearby laboratories to study the launching and evolution of relativistic jets on human timescales. High angular resolution VLBI observations are critical in determining the motions of these jets, allowing us to track them back to their launch point and determine an ejection time. This can be compared with the contemporaneous X-ray behaviour to determine the causal connection between the changing geometry of the accretion flow and the evolving properties of the jets. However, the rapid variability of the jets in both brightness and morphology can in some cases violate the fundamental assumptions of aperture synthesis, precluding high-precision measurements of the jet properties. Recent algorithmic advances are allowing us to overcome these challenges, providing a wealth of new information on the properties of the jets. In this review I will give a brief summary of recent progress in this field. I will also discuss the use of X-ray binary jets as astrometric probes, allowing us to measure the proper motions, parallaxes, and even orbital parameters of these systems. Together with systemic radial velocities determined from the optical band, these measurements can be used to calculate the binaries' motion through the Galaxy, and hence place constraints on the formation of their black holes.

1. Jet launching and propagation

Jets are observed throughout the visible Universe, yet key questions remain about how they are launched, and how they couple to the accretion flow. Since timescales around accreting black holes scale with the black hole mass, stellar-mass black holes in X-ray binary systems allow us to observe the launching and evolution of their jets on timescales of hours to days.

The mid-1980s saw some of the first high-resolution observations of X-ray binaries, finding the radio emission in Cygnus X-3 to arise from moving jet sources that were expanding over time (e.g. Spencer et al. 1986, Molnar et al. 1986). This picture was spectacularly confirmed following the detection of apparent superluminal motion in the sources GRS 1915+105 (Mirabel & Rodríguez 1994) and GRO J1655−40 (Tingay et al. 1995, Hjellming & Rupen 1995). However, these observations also demonstrated the challenges associated with aperture synthesis of time-variable sources. Such challenges were further exacerbated by the low Galactic latitudes and large distances of many X-ray binaries, leading to substantial angular broadening and loss of information on the longest baselines at the standard VLBI observing frequencies of a few GHz (e.g. Mioduszewski et al. 2001, Miller-Jones et al. 2004).

The observed ejections of radio-bright, rapidly-moving jets were associated with X-ray flaring events, together with marked changes in the X-ray spectra. The rapid (day-timescale) evolution of these bright outbursts opened up the prospect of tracking the changes in both jets and accretion flow in real time, determining the causal sequence of events in the accretion flow that led to the ejection of relativistic jets. Fender et al. (2004) synthesised a large body of work over the previous decade to propose a unified model, in which black hole X-ray binaries powered steady, core-dominated jets (Blandford & Königl 1979) in their hard accretion states. In contrast, bright, relativistic ejecta were launched at the transition to the soft accretion states, when the inner accretion flow collapsed from a vertically-extended, optically thin geometry to a standard thin accretion disk (Shakura & Sunyaev 1973) that extended down to the innermost stable circular orbit.

While efforts were made to identify a single event in the accretion flow that led to the launching of jets, initial efforts relied primarily on photometry (Fender et al. 2009). Such studies found no clear association with any definitive X-ray spectral or timing signature, other than a possible correspondence with periods of low X-ray variability. However, the timing of radio flares is affected by the time taken for internal shocks to form in the flow (if indeed the observed jet ejecta are indeed internal shocks; Kaiser et al. 2000) and the delay associated with the radio-emitting regions evolving to become optically thin at the observing frequency. Furthermore, it is not possible to disentangle multiple components during rapid flaring sequences from GHz-frequency photometry alone (e.g., Tetarenko et al. 2017). High angular resolution imaging with VLBI can mitigate these issues, extrapolating the proper motions of jet ejecta with sufficient accuracy to infer (in the absence of deceleration) a precise launch time. That can then be compared with contemporaneous X-ray data to search for the sequence of events in the accretion flow that could have caused the launching of jets. This was attempted during the 2009 outburst of H1743−322, and determined the ejection time to ±12 hr, finding a possible correspondence between the disappearance of Type-C quasi-periodic oscillations from the X-ray power density spectrum and the inferred time of jet launching (Miller-Jones et al. 2012). However, more precise measurements were hindered by the intrinsic time variability of black hole X-ray binary jets and the low cadence of observations.

2. VLBI observations of time-variable sources

The sparse nature of VLBI arrays requires the use of Earth rotation synthesis to provide sufficient *uv*-coverage for high-fidelity imaging. The fundamental assumption of this technique is that the radio emission remains unchanged throughout the observation, such that the changing projected baselines as the Earth rotates measure different Fourier components of the same sky brightness distribution. This assumption is violated for sources such as X-ray binary jets, which vary in both brightness and morphology on timescales of minutes to hours (Tingay et al. 1995). Similar challenges affected the recent efforts to directly image Sgr A* (Event Horizon Telescope Collaboration et al. 2022), and required new techniques to either directly model the variability (e.g. Johnson et al. 2017) or parameterize it such that the underlying, non-variable structure could be determined (e.g. Broderick et al. 2022).

Initial approaches to this problem included imaging only subsets of data (Tingay et al. 1995), or convolving the images to a lower resolution to counteract the smearing effects arising from the proper motion of jet components (Hjellming & Rupen 1995), and were validated using extensive simulations. However, these approaches necessarily involved significant loss of information. A refined approach sought to subtract away the changing flux densities of a variable core component to improve the imaging of the static jet structure (Mioduszewski et al. 2001), and met with modest success in epochs with good amplitude calibration and core variability that was not too extreme.

2.1. Time binning

Fortunately, the structure of X-ray binary jets at typical VLBI resolutions of a few mas is typically relatively simple, and can be represented via a small number of simple point-like or Gaussian components whose properties can be ascertained even with relatively sparse *uv*-coverage. Efforts to image such jets without substantial information loss could therefore adopt a simple (albeit labour-intensive) process of snapshot imaging, breaking the observation into a series of time bins in which the source structure and amplitude were assumed to be relatively stable, such that standard aperture synthesis techniques remained valid. This approach was deployed to great effect by Fomalont et al. (2001), who imaged the moving jets from the neutron star X-ray binary system Sco X-1 using time bins varying from 50 min for the VLBA to 2.5 hr for the EVN and the Asia-Pacific Telescope. This work revealed a set of jet knots that moved outwards at mildly-relativistic speeds of $0.32 - 0.57c$, which were occasionally subject to an injection of energy from a faster-moving yet unseen beam that was inferred to travel at a speed exceeding $0.95c$. More recently, Motta & Fender (2019) reanalysed simultaneous X-ray data from RXTE, finding that the ejection of both the moving jet lobes and the ultrarelativistic flows could be associated with particular signatures in the X-ray spectral and variability properties.

A similar approach was adopted to analyse the rapidly evolving jets during the 2015 outburst of the black hole X-ray binary V404 Cygni (Fig. 1). The intrinsic luminosity of the system was shown to have exceeded the Eddington luminosity (Motta et al. 2017) during a two-week period of rapid radio flaring that culminated in the brightest flare of the entire outburst (Fender et al. 2023). Miller-Jones et al. (2019) analysed a four-hour 15-GHz VLBA observation, splitting the data into 2-minute time bins that were model fit individually in Difmap (Shepherd 1997), to reduce the number of degrees of freedom when compared to standard imaging algorithms such as CLEAN. This approach detected 13 separate jet ejecta, which were moving along different position angles with mildly-relativistic velocities of 0.3–0.5 c. The changes in jet position angles, which continued over the full two-week flaring period, suggested that the jets were precessing on timescales of seconds to hours. This was attributed to Lense-Thirring precession of an inner slim disk arising from the super-Eddington accretion rate, which exerted a torque on the jets, causing them to precess in turn.

While the time-binned imaging approach was thus able to reveal previously-undetected phenomena, it has several drawbacks. It suffers from low sensitivity and limited *uv*-coverage in individual time bins, restricting its applicability to bright and relatively simple sources. It does not by default enforce continuity between adjacent snapshots, and time bins with particularly complex structure required prior knowledge to guide the model fitting to a result that was consistent with surrounding images. Finally, it does not make optimal use of the available information.

2.2. Phase shifting

In an attempt to measure the proper motion of faint, fast-moving jets within an individual observation, Yang et al. (2011) corrected their *uv*-data on XTE J1752−223 for a range of proper motions, identifying the true value from the peak signal-to-noise ratio in the resulting dirty images. This allowed them to distinguish between jet ejecta observed in different epochs separated by a month, and thereby to show that the outburst of this system resulted in at least three separate ejection events.

Wood et al. (2021) independently developed a similar dynamic phase centre tracking technique to increase the signal-to-noise of faint, moving jets. They split their *uv*-data into a set of short time bins. The phase centre of each of these data sets was shifted to account for a user-defined proper motion, and the shifted data were then concatenated and imaged. This effectively allows the radio image to "follow" a moving component, maximising its

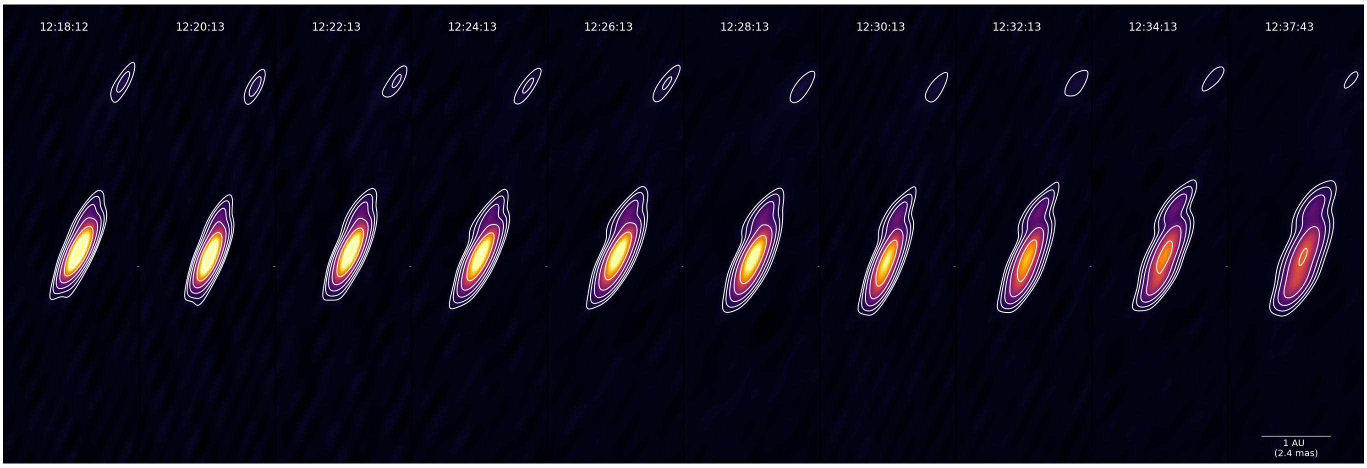

Fig. 1. Rapidly-evolving jets from the black hole X-ray binary system V404 Cyg (Miller-Jones et al. (2019)). The morphology and brightness of the jets evolve on timescales of minutes. Time binning was used to capture the evolution, but does not make optimal use of the full information contained in the visibilities. Figure taken from Venturi et al. (2020).

signal-to-noise, but smearing out in the opposite direction any other structures in the image.

Wood et al. (2021) used this technique to reconcile the difference between the low proper motion of a bright jet component seen in VLBI images of the black hole X-ray binary MAXI J1820+070, and the higher proper motion inferred from fitting the arcsecond-scale jets detected by eMERLIN and MeerKAT (Bright et al. 2020). The dynamic phase centre tracking detected a second, rapidly-moving jet component that was too smeared-out to be detected in the original images. This allowed more informed modelling of the jet propagation, pinpointing the ejection time of the faster-moving component to ± 30 min. This is the most well-constrained radio ejection time to date for a canonical black hole X-ray binary state transition (i.e. not including the rapid flaring events seen in V404 Cygni; Miller-Jones et al. (2019)). Interestingly, the correspondence with X-ray variability changes (specifically a change in the nature of the quasi-periodic oscillations seen in the power density spectra; Homan et al. 2020) provided the best link to date between jet ejection events and the changes in the accretion flow that could have caused them.

2.3. Visibility modelling

While the dynamic phase centre tracking technique can be used to track individual ejecta, its utility is restricted to relatively simple jet morphologies, with few moving components. Furthermore, it accounts only for the proper motion of a jet component, and cannot provide information on other important jet parameters, such as the expansion or flux density evolution of the component over time. The measurements are made in image space, maximising the signal-to-noise of a moving source to determine its proper motion.

A more powerful approach has recently been developed by Wood et al. (2023), adopting a Bayesian approach to directly fit the visibility data in the uv-plane with a moving jet model. By fitting simple models, this technique reduces the complexity relative to standard image-based solutions. It can in principle be extended to fit multiple components, accounting for expansion, deceleration, and even arbitrarily complicated flux density evolution, restricted only by signal-to-noise and available computing power. The Bayesian approach allows the use of prior information (e.g. from preliminary imaging) to place informed constraints on the fitting process.

This technique was first demonstrated by Wood et al. (2023) on the 2021 outburst of the black hole candidate X-ray binary MAXI J1803−298, in which they were able to model both the proper motion and flux density evolution of a moving jet component in just 2–4 hr of observations. The fits were hindered by the sparse uv-coverage arising from the angular broadening of the source, the difficulties of calibrating low-elevation data, and the faintness of the radio emission, which peaked at just 6 mJy. Nonetheless, it provided a first indication of the power of this technique, determining the jet ejection date to within a 2.6-hr period. The sparse (daily) X-ray coverage proved insufficient to associate the jet ejection with any particular X-ray spectral or variability changes.

A refined version of the technique was subsequently adopted by Wood et al. (2024) to measure the proper motion of a rapidly-fading jet knot observed during the hard state of the black hole X-ray binary Swift J1727.8−1613. The knot was found to be fading over the course of the three-hour observation, with no evidence for significant expansion or deceleration. It was not detected in an LBA observation that started a few hours later, attesting to the value of techniques that can probe source evolution within a single observation. Such discrete jet knots have not previously been observed so early in an X-ray binary outburst (i.e. prior to the main state transition), and these were attributed to either an internal shock in the jet, or interactions between the jet and the surrounding medium.

The above summary demonstrates the power of these new visibility modelling techniques in extracting a wealth of information from VLBI observations of time-variable sources. However, they are tailored primarily to relatively simple structures that can be easily parameterised (e.g. as simple point source or Gaussian components). More complex structures, such as the extended hard state jets presented by Wood et al. (2024), are more difficult to parameterise and hence model in the visibility data. However, from causality arguments, such extended structures are less likely to vary on the timescale of an individual observation, so can be deconvolved via standard image-plane algorithms such as CLEAN, and then subtracted from the visibility data prior to modelling any more compact, variable components.

Further development of these visibility modelling techniques is underway, with the aim of applying them to transient jets in both new and archival data (Wood et al. in prep.). They are tailored for the case of relatively simple X-ray binary jets, whose trajectories are straightforward to model. However, they would not be appropriate for more complex evolving morphologies, as seen in AGN jets or the accretion flows around supermassive black holes, for which dynamical imaging and Bayesian inference approaches have been developed (e.g. Bouman et al. 2017, Arras et al. 2022). These may be appropriate for imaging better-resolved jets, as seen in the bright hard state of X-ray binaries (e.g. Wood et al. (2024)), or as observations with facilities such as the GMVA or the ngEHT push to higher frequencies.

3. Astrometry

As sources of bright, steady radio emission, the compact core jets from X-ray binaries (as distinct from the transient ejecta discussed in Section 2) can be used as astrometric targets, allowing their proper motions and parallaxes to be measured using VLBI. While the advent of *Gaia* (Gaia Collaboration et al. 2016) has provided such information for over a billion optical sources (Gaia Collaboration et al. 2023), many X-ray binaries are located in the Galactic Plane, at distances of several kpc, behind several magnitudes of optical extinction. Furthermore, low-mass X-ray binaries tend to be optically faint in quiescence, such that astrometric measurements with Gaia can only be made during their brief periods of outburst. Moreover, the different emission components contributing to the optical emission from X-ray binaries mean that the photo-centre of an X-ray binary system may subject to change over the course of an outburst, depending on the prominence of the disk, jet, and stellar companion in the optical spectrum (e.g. Markoff et al. 2020). Therefore, despite the wealth of information provided by *Gaia*, VLBI still has a significant role to play in X-ray binary astrometry.

3.1. Proper motions and natal kicks

The proper motions of X-ray binaries represent an observable probe of their natal formation mechanism. While neutron stars are believed to form in supernovae, black holes can form either in a supernova explosion, or by direct collapse. When a compact object forms in a binary system, any ejection of matter in a supernova explosion will exert a recoil kick on the host binary (assuming that it remains bound). The supernova mechanism itself can impart an additional natal kick to the compact object, as inferred from the proper motions of young pulsars (Hobbs et al. (2005)). However, the double Maxwellian kick distribution inferred from these results underpredicts the observed neutron star population in globular clusters, whose low escape velocities could not retain systems receiving natal kicks $> 50\,\mathrm{km\,s^{-1}}$. To address this issue, Mandel & Müller (2020) proposed a probabilistic recipe for neutron star kicks that depends on the carbon/oxygen core mass of the progenitor, the neutron star remnant mass, and a normalisation factor. This prescription significantly increased the predicted population of low-kick neutron star systems. Observational tests of this prescription will require analysis of a range of systems, from isolated pulsars to microlensing systems, neutron stars in binaries, and gravitational wave merger events. O'Doherty et al. (2023) used VLBI and Gaia data to compile the most complete observational census to date of the kicks of neutron stars in binary systems, fitting the overall sample with a beta-distribution that peaked below $100\,\mathrm{km\,s^{-1}}$, in contrast to the high-velocity Maxwellian determined from young pulsars. Given the importance of natal kicks in determining compact object merger rates, it will be important to include this lower-kick population in population synthesis codes, which still rely predominantly on the Maxwellian distribution first determined by Hobbs et al. (2005).

The kicks of stellar-mass black holes will depend on their formation mechanism. Early work identified individual black hole X-ray binaries with high peculiar velocities (Mirabel et al. 2001, Mirabel et al. 2002), which were inferred to have formed in a natal supernova. These proper motion measurements of XTE J1118+480 and GRO J1655−40 were then combined with other known properties of the systems to model their full evolution from the time of black hole formation through to the present day (Willems et al. 2005, Fragos et al. 2009), finding strong evidence for asymmetric natal kicks. However, in the case of Cygnus X-1, its very low peculiar velocity with respect to its inferred birthplace in the Cygnus OB3 association was taken as evidence for formation via direct collapse (Mirabel et al. 2002).

The first population-level study of black hole natal kicks was performed by Atri et al. 2019, who analysed a sample of 16 black hole X-ray binaries observed with VLBI or *Gaia* and traced back their motions in the Galactic potential to determine the velocity kicks they could have received at formation, assuming that the systems formed in the Galactic plane. They found that the sample kick distribution could be fit with a unimodal Gaussian with a mean of $107 \pm 16\,\mathrm{km\,s^{-1}}$. This is somewhat higher than would be inferred from the prescriptions of Mandel & Müller (2020), who found that two-thirds of isolated black holes should receive no significant natal kicks, with a high-velocity tail extending to $150\,\mathrm{km\,s^{-1}}$. However, extinction in the Galactic plane could select against low-kick systems (Jonker et al. 2021), and the recoil kicks affecting binary systems would augment the natal kicks arising from the supernova mechanism itself, while the overall kick would be diluted by the increased inertia of the binary. Further work, as well as a larger sample of systems, is required to account for these effects and interpret the observed population in light of the theoretical predictions.

3.2. Parallax distances

Accurate distances remain essential for understanding the properties of X-ray binaries. With an accurate distance, the approaching and receding proper motions of intrinsically-symmetric jet ejecta can be combined to determine the jet speed and inclination angle (e.g., Miller-Jones et al. (2019)). Distance is required to determine accurate estimates of natal kicks (e.g., Atri et al. 2019) and black hole spins (e.g., McClintock et al. 2014), and to convert fluxes into luminosities.

The first accurate parallax distance to a black hole X-ray binary was measured with the VLBA (Miller-Jones et al. 2009), with four additional black hole parallax measurements having been made with VLBI over the following 15 years (Reid et al. 2011, Reid et al. 2014, Atri et al. 2020, Miller-Jones et al. 2021, Reid & Miller-Jones 2023). And while *Gaia* provides a wealth of astrometric information, the intrinsic optical faintness of low-mass X-ray binaries in quiescence has meant that only five black hole X-ray binaries have *Gaia*-measured parallaxes with significance $> 5\sigma$ (Gaia Collaboration et al. 2023). This makes additional VLBI parallax measurements invaluable. However, most known black hole X-ray binaries are transient, and their neutron star counterparts are typically a factor ~ 20 fainter in the radio for a given X-ray luminosity (e.g., Migliari & Fender 2006). This restricts new parallax observations to long-lived black hole transient outbursts, which spend sufficient time in the hard X-ray spectral state or in reflaring events that it is possible to trace out the full annual parallax ellipse on the sky (e.g., Atri et al. 2020). Furthermore, for systems in highly-scattered regions of the Galactic plane (e.g., Reid & Miller-Jones 2023), successful parallax measurements can only be made at high frequencies, where the calibrator grid is significantly sparser, requiring new techniques such as multi-view calibration (Rioja et al. 2017) to provide sufficient astrometric accuracy.

Despite the inherent challenges in determining parallax distances to X-ray binaries, a high-significance parallax measurement represents the gold standard in distance determination techniques, with the inferred distance being close to model-independent. Lower-significance measurements ($\lesssim 10\sigma$) carry some model-dependence due to their reliance on an appropriate prior to convert the parallax to a distance estimate (Astraatmadja & Bailer-Jones 2016).

In cases where a parallax cannot be measured directly, a kinematic distance estimate can be determined under the assumption that the source has a relatively low peculiar velocity relative to the Galactic rotation. Reid (2022) showed that with accurate measurements of proper motion (whose cumulative signal increases over time, in contrast to a parallax signal) and line-of-sight radial velocity (from the optical band), a Bayesian approach can be used to infer a three-dimensional kinematic distance that minimises the deviation from Galactic rotation. For sources on the far side of the Galaxy, this technique can provide a more precise distance estimate than is possible from parallax measurements with existing facilities.

3.3. Orbital motion

With sufficiently accurate astrometry, it is possible to directly measure the binary orbit on the plane of the sky. The best targets for such measurements are high-mass X-ray binaries (where the black hole powering the jets exhibits a larger orbital displacement) that are nearby, and with a long orbital period. These conditions were all fulfilled for the first astrometric detection of an X-ray binary orbit in Cygnus X-1 (Reid et al. 2011). However, while these observations served to determine the sense of the orbit on the plane of the sky, they was unable to constrain any of the orbital parameters independently. With additional observations covering a full binary orbit, Miller-Jones et al. 2021 were able to improve upon this measurement. By mitigating the scatter along the jet axis due to orbital phase-dependent absorption in the stellar wind of the donor star, they were able to refine the parallax distance, and measure the orbit at a 3σ significance. While further improvement could in principle measure the orbital inclination angle, this would require moving to higher observing frequencies to reduce the scatter along the jet axis due to both intrinsic jet variability and free-free absorption in the donor star wind.

The only other such system with an astrometrically-measured orbit is the gamma-ray binary system PSR B1259−63 (Miller-Jones et al. 2018). VLBI was able to uniquely measure the sense of the orbit, the source distance, the orbital inclination, and the longitude of the ascending node, which were not possible to ascertain from pulsar timing measurements alone. More recently, *Gaia* has measured the orbits of the binary companions of three detached black hole systems (El Badry et al. 2023a), El Badry et al. 2023b), Gaia Collaboration et al. 2024), none of which have detectable radio emission. Together, these discoveries demonstrate the value of high-precision astrometry in identifying and characterising black hole systems. Within the next two years, *Gaia* DR4 should allow the combination of radio- and *Gaia*-derived astrometric orbits to fully solve for the masses of both components in radio-detected systems such as Cygnus X-1 or PSR B1259−63, yielding some of the most precise compact object masses measured to date.

4. Conclusions

VLBI remains a powerful technique for investigating the properties of X-ray binaries and their jets, providing an unambiguous characterisation of jet morphologies, speeds, expansion, and deceleration. Such measurements play a unique and critical role in linking jet launching to the changing properties of the accretion flow during X-ray binary outbursts. However, such studies have to date been limited by the time-variable nature of the jets. Recent algorithmic developments have mitigated these issues, enabling high-fidelity reconstructions of the evolving jet structure within an individual observation. This allows us to probe jet evolution on timescales of minutes, rather than the standard daily cadence that was the state of the art for many years. With ever-improving constraints on jet ejection times, and the availability of intensive X-ray monitoring campaigns from facilities such as *INTEGRAL*, *NICER*, or *Swift*, it may finally be possible to pin down the causal sequence of events that leads to the launching of relativistic jet ejecta.

Beyond direct imaging, astrometric VLBI observations are able to provide accurate distances to X-ray binaries (enabling precision astrophysics) and probe the formation mechanisms of the black holes that they host. Larger samples of X-ray binary proper motions and natal kick constraints are required to understand the selection effects affecting the existing population, and thereby provide meaningful comparisons to theoretical models. Even in the era of *Gaia*, VLBI has a role to play in providing accurate astrometric measurements of such systems, and the combination of both optical and radio astrometry holds great promise for precision mass measurements over the coming years.

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