High-resolution radio observations of X-ray binaries

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Abstract. I present an overview of important results obtained using high-resolution very long baseline interferometry (VLBI) observations of X-ray binary systems. These results derive from both astrometric observations and resolved imaging of sources, from black holes to neutron star and even white dwarf systems. I outline a number of upcoming developments in instrumentation, both new facilities and ongoing upgrades to existing VLBI instruments, and I conclude by identifying a number of important areas of investigation where VLBI will be crucial in advancing our understanding of X-ray binaries.

1. Introduction
Very Long Baseline Interferometry (VLBI) has provided us with some of the highest resolution observations to date of radio-emitting systems throughout the visible Universe. X-ray binary systems, accreting compact objects in orbit with less-evolved donor stars, emit synchrotron radiation from their relativistic jets. During outbursts, the radio emission from these sources becomes bright, reaching levels of several Jy in the brightest sources, and is often resolved with high-resolution observations, making such sources ideal targets for study with VLBI arrays.

Being Galactic systems, X-ray binaries are much closer than their scaled-up extragalactic analogues, the Active Galactic Nuclei (AGN). However, since they are typically $10^6$–$10^8$ times less massive than AGN, but only $10^4$ times closer (a few kpc compared to several tens to hundreds of Mpc), it is, counterintuitively, possible to probe closer to the compact object (in units of gravitational radii) in AGN than in X-ray binary systems, so the Galactic systems are in fact less useful for studying the close-in regions where the jets are accelerated and collimated. Furthermore, since the number of X-ray binaries with resolved radio emission is still small, studies of these sources are to some extent limited by the peculiarities of individual objects.

However, studies of X-ray binary systems do have some advantages over AGN. Their proximity means that fundamental parameters such as distance and space velocity can be determined by astrometric measurements. And since lengths and timescales close to the compact object scale with black hole mass, it is possible to observe the evolution of the jets in X-ray binaries on timescales of hours to days, rather than years to decades, following the evolution of the source through its entire duty cycle in a matter of months, and watching the evolution of the radio jets in real time as they move out and interact with their environments. Furthermore, since the class of X-ray binaries comprises accreting neutron stars as well as black hole systems, they allow us to probe the importance of a deep potential well and the existence of a solid surface and a stellar magnetic field in the acceleration and collimation of relativistic jets.

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In this article I will attempt to provide a brief overview of recent high-resolution studies of X-ray binary systems. In this definition, I choose to include all accreting Galactic compact objects, from black holes through neutron stars, and even white dwarf systems. I will outline new and upcoming developments in instrumentation, as well as their potential applications in solving some of the important open questions in the field of X-ray binary research.

2. Astrometry
2.1. Distances via trigonometric parallax
Distances to X-ray binary systems are notoriously poorly-constrained and model-dependent [1], despite being crucial to the interpretation of almost any astronomical measurement. Accurate distances are necessary for converting fluxes into luminosities, angular sizes into physical separations, and proper motions into speeds. A trigonometric parallax is the only direct, model-independent method of distance determination available, although at typical X-ray binary distances of a few kpc, the expected parallax signal is less than one milliarcsecond. Therefore, high-resolution astrometric VLBI observations can, in principle, provide a parallactic distance to relatively nearby Galactic sources. Unfortunately, black hole X-ray binary systems are not particularly well-suited to such measurements. They spend the majority of their lives in a quiescent state, only becoming sufficiently bright to be detected in the radio band in a reasonable integration time during occasional outbursts. During such outbursts, the sources exhibit relativistically-moving radio jets, making it difficult to accurately determine the position of the binary itself, adding scatter to any measurement of the parallax. Furthermore, occurring on an unpredictable and irregular basis, these outbursts are typically not sufficiently well-timed (i.e., not occurring at three- or six-month intervals) for a parallactic distance determination. For this reason, only two reliable parallactic distances have been measured to date, in the systems Sco X-1 [2] and Cyg X-1 [3].

Other methods of distance determination are subject to a variety of systematic errors, which were found to artificially enlarge the difference between the quiescent X-ray luminosities of black hole and neutron star systems [1]. If so, this would undermine the claimed evidence for black hole event horizons [4; 5]. Accurate distance determinations for black hole X-ray binaries would allow better estimations of their peak luminosities, thereby constraining the factor by which they can exceed their Eddington luminosities, which has important implications for whether the Ultraluminous X-ray sources (ULXs) in external galaxies are intermediate-mass black holes, or simply super-Eddington stellar-mass X-ray binaries. Constraining the systematics affecting other methods via model-independent parallax distance measurements to a handful of X-ray binaries would help tie down the distance scale for the majority of systems, allowing us to statistically verify the peak and quiescent luminosity distributions.

2.2. Kinematics via proper motion measurements
A second use of high-precision astrometry is to measure the proper motion of X-ray binary systems. Together with a radial velocity measurement, the Galactic co-ordinates and the distance of the source, a measured proper motion allows the full three-dimensional space velocity of the system to be calculated. Given other fundamental system parameters such as the constituent masses, and the luminosity and temperature of the donor star, the full evolutionary history of the binary can be reconstructed back to the time of compact object formation, as has been done for GRO J1655-40 [6].

Since the majority of X-ray binaries are at kiloparsec distances, their proper motions are of order a few milliarcseconds per year, so high-angular resolution VLBI measurements are typically required. This has so far been done for only a handful of X-ray binary systems [7; 8; 9; 10; 11], although optical observations (e.g., with the Hubble Space Telescope), occasionally in concert with radio data, have also yielded proper motions [12; 13; 14]. The measured proper motions...
can be compared with those expected from Galactic rotation, and the discrepancy (the peculiar motion) gives us information about the formation mechanism of the binary. Systems with a high velocity out of the plane or in an eccentric orbit about the Galactic Centre, such as Sco X-1 \cite{12}, XTE J1118+480 \cite{7} or LS 5039 \cite{9} must either have been born in the halo, or received a substantial natal kick during their formation in a supernova. On the other hand, the most massive black holes (> $10 M_\odot$) are believed to form without an energetic supernova explosion \cite{15}, as demonstrated by the case of Cygnus X-1, where $< 1 M_\odot$ is believed to have been ejected in the natal supernova \cite{10}. More statistics on black hole X-ray binary space velocities (from accurate proper motions, distances and black hole mass estimates) are needed to confirm or refute this scenario.

Without accurate proper motions, the radio morphologies exhibited by X-ray binaries can be difficult to interpret. For example, in the case of Cygnus X-3, a bright, well-studied radio-emitting X-ray binary, the morphology of the observed radio jets seems to change from epoch to epoch, likely owing to varying interactions with the dense, inhomogeneous circumstellar medium created by the Wolf-Rayet wind of the donor star. The source has been seen to show both one-sided \cite{16} and two-sided \cite{17} jets, with varying orientations and degrees of curvature of the jets at different epochs. An accurate core position for any given epoch (which can be obtained from a proper motion) will aid the interpretation of some of the more complicated VLBI structures seen from the jets [e.g., \cite{18}].

2.3. Resolving the binary orbit

Precision astrometry can even, in some cases, resolve the orbit of the compact object in a binary system, as done for the case of LSI+61°303 in a beautiful demonstration of the power of high-resolution VLBI techniques. This source is a high-mass X-ray binary system which has been observed at all wavelengths from the radio band up to gamma-ray and even TeV emission. It comprises a 1–3 $M_\odot$ accretor in an elliptical 26.5-d orbit (with a semi-major axis of $\sim 0.4$ mas) with a 12$M_\odot$ donor star. Resolved radio emission has been observed from the source, originally interpreted as a precessing, relativistic jet \cite{19; 20}. With Very Long Baseline Array (VLBA) observations at 10 epochs over the 26.5-d orbit, Dhawan et al. \cite{21} tracked the radio source over the course of the orbit. They found the radio emission to have a cometary morphology, with the axis of the emission pointing away from the high-mass donor star at all times, and varying dramatically at periastron. From this, they deduced that the radio emission arose not from a jet, but from electrons shock-accelerated in a pulsar wind where it interacts with the dense wind of the donor star. This proves that the source is a Be-star/pulsar binary, rather than a typical microquasar, which would be expected to have a resolved radio jet.

3. Imaging

Since X-ray binaries evolve on human timescales, we can observe their morphology change in real time. From the proper motions of components, we can constrain the jet velocity and orientation, probe the details of any interactions between the jets and their environment, and observe jet precession in the sources where it occurs. Furthermore, observations which can resolve the jets perpendicular to their direction of motion can, under the assumption of no confinement, place limits on the Lorentz factor of the jet flow \cite{22}.

3.1. Outflow morphology

High-resolution imaging is the only method to definitively ascertain the morphology of the radio emission from X-ray binaries. While jet synchrotron radiation, either from steady conical outflows, or from transient discrete ejecta, is the default interpretation of most unresolved radio emission, recent work has demonstrated that not all radio emission from X-ray binaries takes the form of collimated relativistic jets. LSI+61°303 (Section 2.3) shows a cometary morphology
due to interactions between a pulsar wind and the stellar wind of the donor, and high-resolution studies of the B[e] X-ray binary CI Cam [23] showed an ellipsoidal or double-ring morphology which expanded over the course of a year. This was interpreted as the propagation of a shock wave formed as the inner jets interacted with the dense surrounding circumstellar medium produced by the strong stellar wind of the donor star. Nevertheless, many systems do show jet-like emission, of which one of the most well-studied is SS 433. VLBI observations have significantly enhanced our understanding of the X-ray binary system SS 433. This source, accreting at super-Eddington rates, exhibits precessing, antiparallel jets moving at a speed of 0.26c. The jets are thought to have inflated the W 50 nebula surrounding the source. The precession of the jets is well described by the kinematic model [24; 25; 26; 27], and has been beautifully verified by VLBI imaging. Not only does the locus of radio emission follow the model predictions, but proper motion measurements on individual components give speeds which agree with the velocity derived from fits to the kinematic model. High-resolution imaging has also provided evidence for a wealth of new and unexpected phenomena in the source, including the existence of a brightening zone at $\sim 250$ AU from the core [27], and the presence of an equatorial outflow, possibly a wind from the accretion disc [28; 29].

In the most intensive VLBI monitoring campaign on an X-ray binary to date, SS 433 was observed with the VLBA at 1.5-GHz over one full quarter of its 162.5-d precession period\footnote{http://www.aoc.nrao.edu/~mrupen/XRT/SS433/ss433.shtml}. The proper motion of the equatorial emission was detected, implying a velocity of $\sim 10,000$ km s$^{-1}$, and an azimuthal dependence of the brightening region was observed [30]. A full analysis of this rich dataset is yet to be published.

3.2. Canonical black hole jets

High-resolution observations of black hole X-ray binaries have shown that the jets exist in two distinct forms. The most spectacular jets are the bright, optically-thin, relativistically-moving knots of emission seen during transient outbursts [e.g., 31; 32; 33; 34]. Such knots have always been seen to move ballistically away from the core, fading as they move outwards [35].

In the quiescent state, where the systems spend most of their time, the jets take the form of steady, partially self-absorbed, conical outflows. In this state, the jet length scales as $\nu^{-1}$, since we see the $\tau = 1$ surface at any frequency, which is closer to the core at higher frequencies. Such jets have only been directly imaged in the two systems, GRS 1915+105 [36] and Cygnus X-1 [37], but are inferred to exist in all hard-state and quiescent systems, due to the observed flat radio spectra and the unbroken correlation between X-ray and radio emission seen in hard and quiescent systems [38], extending from a few per cent of the Eddington luminosity ($L_{\text{Edd}}$), where the jets have been directly imaged [36; 37], all the way down to $10^{-8.5}L_{\text{Edd}}$. To date, no jets have ever been resolved in low-luminosity ($< 0.01L_{\text{Edd}}$) systems.

A unified picture of the jet-disc coupling puts these two types of jet into context, associating them with particular types of X-ray emission over the entire duty cycle of a black hole X-ray binary [39]. As a black hole system emerges out of quiescence, the power in the steady, partially self-absorbed, conical jets increases with the X-ray intensity, although the X-ray spectrum remains hard. The X-ray spectrum eventually begins to soften, and the jet velocity increases, causing internal shocks to appear within the flow as the fast-moving jets collide with slower material further downstream, which are seen as bright, transient, relativistically-moving ejecta. The radio core then switches off, and the source shows a soft, blackbody X-ray spectrum from the accretion disc. There may be several transitions between the soft and hard states at high X-ray intensity, each corresponding to a new transient ejection event, before the source fades, the X-ray spectrum gets harder, the core jet is re-established, and the system moves back into quiescence. However, the radio aspect of this picture still remains to be observationally verified,
since the jet morphology, of both the steady and transient jets, has only ever been resolved during the highest-luminosity part of the duty cycle.

### 3.3. Neutron star jets

While jets have been relatively well-studied in black-hole X-ray binary systems, their neutron-star counterparts remain much more enigmatic. The intrinsic faintness of the jets in neutron star systems, which are $\sim 30$ times fainter in the radio band at a given X-ray luminosity \([40]\), means that current instrumentation has the sensitivity to detect only the very brightest systems. These are the Z-sources, a subclass of the low magnetic field neutron star systems which are persistently accreting at or near the Eddington rate. A model for the jet-disc coupling has been proposed for neutron stars \([40]\), analogous to that developed for the black hole systems, which suggests that steady jets exist in the hardest X-ray states, which evolve to transient ejecta at transitions to softer states, when the nuclear jet switches off. Again, this picture remains to be verified by direct, high-resolution imaging.

The most detailed high-resolution study of a neutron star X-ray binary system to date was a set of monitoring observations of Sco X-1 \([41]\). The source was seen to be dominated by the emission from the working surfaces where a highly relativistic beam of plasma from the core impinged on the ISM. These lobes were stable in position angle over several years, although different lobe advance speeds were seen at different times. Intriguingly, the other confirmed neutron star system in which jets have been resolved, Cir X-1, also showed evidence for a highly-relativistic unseen outflow illuminating downstream radio lobes \([39]\), and has the highest Lorentz factor observed to date from an X-ray binary system ($v_{\text{app}} = 9.2c$ \([42]\)). This strongly argues against the theory that jet velocity should scale with the escape speed from the compact object.

### 3.4. White dwarf jets

Recent observations have demonstrated that jets are not only confined to black hole and neutron star systems. The recurrent nova RS Oph consists of a white dwarf accreting from the wind of its red giant companion. The white dwarf is close to the Chandrasekhar mass, and every $\sim 20$ y, a thermonuclear runaway occurs on its surface, burning the accreted layer of hydrogen. The ejected material from this explosion interacts with the wind of the red giant donor, and the resulting shocks generate radio emission. MERLIN and VLBA images of the 2006 outburst \([43; 44]\) showed an expanding spherical source, thought to be the shock where the explosion was propagating through the red giant wind, together with an additional collimated component moving at close to the white dwarf escape speed of $\sim 17,000$ km s\(^{-1}\). This is a clear demonstration of the presence of jets in a white dwarf system. Jets have previously been imaged in the symbiotic star CH Cyg \([45]\) and recent work shows strong indications of the presence of a jet during an outburst of the dwarf nova SS Cyg \([46]\), suggesting that high-resolution imaging of the many different classes of white dwarf systems could produce interesting new insights into such sources.

### 4. Polarization

Measurements of the polarization of the jets in X-ray binaries can give us information about the magnetic fields and how they align with the jet axis. As an example, full polarization imaging has been used in AGN jets to reconstruct the emissivity, velocity and magnetic field distributions in the jets \([47]\). Synchrotron radiation theory predicts a maximum fractional polarization of order 70 per cent for optically thin radiation. Observed degrees of polarization in radio observations of X-ray binaries (with typical resolutions of a few arcseconds), where it is detected at all, are typically of order a few to 20 per cent \([48; 49; 50; 51; 52]\). Such a discrepancy with the theoretical maximum implies that there must be some line-of-sight, beam, or external Faraday depolarization occurring. With higher-resolution (i.e., VLBI) observations, we can hope to
reduce the effect of beam depolarization, and obtain information about the true magnetic field structure. Full-polarization VLBI imaging of X-ray binaries has only been carried out in a limited number of cases to date. MERLIN observations found the central regions of SS 433 to be depolarized, whereas GRS 1915+105 and Cygnus X-3 showed between a few and 25 per cent polarization in the approaching jets. To have a hope of disentangling the magnetic field structure in X-ray binary jets, more high-resolution full-polarization observations are needed at high frequencies, where Faraday depolarization is less important.

5. New developments in instrumentation
5.1. e-VLBI
Recent years have seen the advent of eVLBI, very long baseline interferometry conducted in real time, transporting the data over the internet to a central location for correlation. This has made rapid-response science possible. Instead of waiting for a few weeks for the data to be shipped to the correlator, correlation is performed in real time, and the data can be reduced immediately. For sources such as X-ray binaries which evolve on a timescale of hours to days, this allows decisions on future observing strategies to be refined in the light of current data. As the source evolves from optically thick to thin, and expands, the observing frequency can be changed to provide optimal spatial sampling of the emitting regions. Decisions on the appropriate time sampling can be made according to the rate at which the source evolves. Should the source be scatter-broadened, or the phase reference calibrator be found to be too faint, adjustments to the observing strategy can be made. For long-term monitoring campaigns, this prevents telescope time from being used at times after the source has faded below detectability.

Early results of eVLBI imaging from both European and Southern Hemisphere arrays have now been published. The sustainable bit rate for the European VLBI Network (EVN) observations was only 128 Mbps, although this has now been upgraded to 512 Mbps, and the number of connected stations has increased from six to eight, providing enhanced uv-coverage and sensitivity. By way of comparison, the eVLBI observations with the Long Baseline Array (LBA) used a 1 Gbps data rate between the three mainland stations, with a reduced bandwidth link to the dish in Hobart.

5.2. Upgrade to the VLBA
The ongoing upgrade to the VLBA aims to increase the peak and standard sensitivities by a factor of 2.8 and 5.6 respectively, by increasing the data rate from 128 Mbps to 4 Gbps by 2011. This would provide an image noise level of < 10 $\mu$Jy beam$^{-1}$ in 8 h, and an astrometric accuracy of 10 $\mu$as on a 1-mJy source. With a comparable noise level, faster slew times, much greater ease of scheduling, better phase stability, and a larger field of view (permitting in-beam calibrators), this will allow the VLBA to rival or surpass the High Sensitivity Array (HSA) for astrometric observations.

The low-noise amplifiers for the 22-GHz VLBA receivers have already been replaced, resulting in a 38% decrease in the system noise, equivalent to increasing the integration time by a factor of 2.5. Further potential upgrades to wider bandwidth or lower noise levels are also being considered in other frequency bands where modern electronics can deliver enhanced performance. A new software correlator is being developed, which will be easily scaled (by adding more processors) to deal with increased bandwidth or data rates.

The improved instantaneous sensitivity will provide time-resolved lightcurves for faint sources, and allow us to detect jet components in a shorter integration time, such that they have not
moved significantly over the course of an integration. This will also allow the use of fainter calibrator sources, such that closer calibrators become available for the majority of sources, providing better phase referencing and allowing more accurate astrometry and the detection of weaker targets. We will be able to extend the existing studies of black hole X-ray binaries to the lower-luminosity hard and quiescent states, investigating how parameters such as the power, length, and degree of collimation of the jets vary with mass accretion rate. Furthermore, it will become feasible to study the jets of neutron star systems (typically a factor 30 fainter in radio luminosity) with VLBI, allowing us to probe how the effects of strong gravity, a solid surface and a stellar magnetic field affect the properties of the jets.

With the improved astrometric capability, parallactic distances will be feasible for all Galactic X-ray binaries accessible to the VLBA (10µas would give a 10σ detection of a parallax at 10 kpc). The orbits of long-period systems (> 90 h for a system containing a 10M⊙ black hole at 10 kpc) could be resolved, as was done for LSI+61°303 [21]. Positional shifts between quiescent and flaring states could also be used to determine the location along the jets responsible for the radio emission.

VLBI observations of Galactic X-ray binary systems at all but the highest frequencies are often degraded by interstellar scattering. Electron density fluctuations in the interstellar medium modify the refractive index of the plasma, giving rise to angular broadening of sources, temporal broadening of pulsed emission, and scintillation [e.g., 58, 59]. To mitigate these effects and attain the theoretical instrumental resolution and astrometric accuracy, it is necessary to observe at high frequencies. To this end, the upgrade to the 22 GHz receivers will allow us to overcome the scattering and image at full resolution sources in highly scatter-broadened regions such as the Galactic Plane, where most X-ray binaries are located. Since optically-thin synchrotron spectra tend to be steep ($S_\nu \propto \nu^{-0.7}$), sources are fainter at higher frequencies (where the best resolution is available for a given set of baselines), once again demonstrating the need for high sensitivity at the highest frequencies.

5.3. VSOP-2
The resolution of ground-based VLBI at a given frequency is limited by the maximum baseline, i.e., the Earth’s diameter. To attain higher resolution, it is necessary to use orbiting antennas, as done by HALCA from 1997–2003. A new space-based VLBI mission, VSOP-2/ASTRO-G is under development, as detailed by Tsuboi (these proceedings). The available frequencies of 8, 22, and 43 GHz will complement ground-based receiver bands, with a maximum resolution of 38µas at 43 GHz, and a phase-referencing capability to enable observations of faint sources at the high frequencies. While optically-thin emission from X-ray binary jets will necessarily be faint at such high frequencies, deep integrations using VSOP-2 will provide the opportunity to make the highest-resolution images ever taken of X-ray binary jets. This may be necessary to resolve the low-power jets inferred to exist in the hard and quiescent states.

6. Open questions
In this review, I have outlined the current state of the field, and recent developments in instrumentation. I will now close by highlighting a number of issues which I believe need to be addressed with high-resolution VLBI observations.

The existence of collimated jets in quiescent black hole X-ray binaries is commonly inferred from the flat radio spectra, but still remains to be directly tested by high-resolution radio imaging. At low luminosities, the jet is believed to be the dominant power output channel [60], and as such will affect the dynamics of the accretion flow. Whether the X-ray emission at low luminosities is dominated by a radiatively-inefficient accretion flow [e.g., 61] or whether it can be explained by synchrotron-emitting electrons at the jet base [62] is still under debate. Measuring
how the jet power, length, and degree of collimation vary with X-ray luminosity will provide important inputs to the theoretical models seeking to explain the quiescent state.

While the current paradigm for the jet-disc coupling throughout the duty cycle of black hole X-ray binary outbursts [63] has become widely accepted, questions are beginning to be raised over some of the underlying premises on which it is based [64]. While it was derived from a compilation of X-ray and radio behaviour from many different sources (mainly spectral information, with a limited set of high-resolution imaging observations taken during outburst or at the high-luminosity end of the hard state, when the sources are brightest), it has never been rigorously tested by high-resolution radio imaging from the rise out of quiescence all the way through to the end of the outburst. Similarly, the analogous “unified model” proposed to explain the phenomenology observed in the Z-sources [40] also needs to be verified via VLBI imaging. Despite their intrinsic faintness, the speed at which the Z-sources move through their duty cycles (switching states on a timescale of hours) makes such observations less time-intensive than similar studies on black hole systems.

Quantifying the differences in the jet morphology and behaviour between black hole and neutron star systems is another crucial issue which needs to be addressed by high-resolution observations. This will help quantify the role of a stellar surface, a magnetic field, and the depth of the potential well in jet formation, acceleration and collimation. The relative faintness of neutron star systems as compared to black hole X-ray binaries means that such studies will require the enhanced sensitivities of the new and upgraded instruments coming online.

The recent work on CI Cam [23], RS Oph [43; 44] and LSI+61°303 [21] has shown that radio emission from X-ray binaries should not be blindly interpreted as a collimated jet. Such systems exhibit a wide variety of radio morphologies, and high-resolution imaging of any new outburst is necessary to ascertain the geometry of the emission, and provide detailed information on the physical processes occurring in the source.

Verification of the systematics affecting the distance scale by measuring trigonometric parallaxes to Galactic radio-emitting X-ray binary systems will provide more accurate derivations of fundamental system parameters, allowing us to verify the claimed evidence for event horizons and casting light on the likely nature of ULXs.

Lastly, proper motion measurements for a larger sample of X-ray binaries are needed to improve the statistics on natal supernova kicks, and to help constrain black hole formation mechanisms and binary evolution scenarios.

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