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A radio parallax to the black hole X-ray binary MAXI J1820+070

P. Atri,1,2 J. C. A. Miller-Jones,1,2 A. Bahramian,1,2 R. M. Plotkin,1,2 A. T. Deller,3 P. G. Jonker,4,5 T. J. Maccarone,6 G. R. Sivakoff,7 R. Soria,8,9 D. Altamirano,10 T. Belloni,11 R. Fender,12 E. Koerding,13 D. Maitra,14 S. Markoff,15 S. Migliari,16,17 D. Russell,18 T. Russell,15 C. L. Sarazin,19 A. J. Tetarenko,20 and V. Tudose21

1International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
2Department of Physics, University of Nevada, Reno, NV 89557, USA
3Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail Number H11, PO Box 218, Hawthorn, VIC 3122, Australia
4SRON, Netherlands Institute for Space Research, Sorbonnelaan 2, NL-3584 CA Utrecht, the Netherlands
5Department of Astrophysics/IMAPP, Radboud University Nijmegen, PO Box 9010, NL-6500 GL Nijmegen, the Netherlands
6Department of Physics, Texas Tech University, Box 41051, Science Building, Lubbock, TX 79499-1051, USA
7Department of Physics, University of Alberta, CCIS 4-183, Edmonton, AB T6G 2E1, Canada
8School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, 52 Sanlihe Rd., Beijing 100864, China
9Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, Sydney, NSW-2006, Australia
10Physics and Astronomy, University of Southampton, Southampton, Hampshire SO17 1BJ, UK
11INAF - Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate, Italy
12Astrophysics, Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
13Department of Astrophysics/IMAPP, Radboud University Nijmegen, PO Box 9010, NL-6500 GL Nijmegen, the Netherlands
14Department of Physics and Astronomy, Wheaton College, Norton, MA 02766, USA
15Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, Science Park 904, NL-1098XH Amsterdam, the Netherlands
16XMM–Newton Science Operations Centre, ESA/ESAC, Camino del C仿sillo s/n, Urb. Villafranca del Castillo, E–28691 Villanueva de la Cañada, Madrid, Spain
17Institute of Cosmos Sciences, University of Barcelona, Martí i Franquès 1, E-08028 Barcelona, Spain
18Center for Astro, Particle and Planetary Physics, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE
19Department of Astronomy, University of Virginia, 530 McCormick Road, Charlottesville, VA 22904, USA
20East Asian Observatory, 660 N. Aohōka Place, University Park, Hilo, HI 96720, USA
21Institute for Space Sciences, Atomistilor 409, PO Box MG-23, 077125 Bucharest-Magurele, Romania

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ABSTRACT
Using the Very Long Baseline Array and the European Very Long Baseline Interferometry Network, we have made a precise measurement of the radio parallax of the black hole X-ray binary MAXI J1820+070, providing a model-independent distance to the source. Our parallax measurement of $(0.348 \pm 0.033)$ mas for MAXI J1820+070 translates to a distance of $(2.96 \pm 0.33)$ kpc. This distance implies that the source reached $(15 \pm 3)$ per cent of the Eddington luminosity at the peak of its outburst. Further, we use this distance to refine previous estimates of the jet inclination angle, jet velocity, and the mass of the black hole in MAXI J1820+070 to be $(63 \pm 3)^\circ$, $(0.89 \pm 0.09)c$, and $(9.2 \pm 1.3)M_\odot$, respectively.

Key words: astrometry – parallaxes – stars: black holes – radio continuum: transients – X-rays: binaries – high angular resolution.

1 INTRODUCTION
The distances to astronomical systems are essential quantities that allow us to draw a connection between observed and physical parameters (e.g. flux and luminosity, angular, and physical speeds). In particular, for black hole X-ray binaries (BHXBs) the relation between different accretion phases and Eddington luminosity fractions can then be studied (Maccarone 2003), and the systems can be accurately placed on the X-ray/radio luminosity plane (Gallo, Degenaar & van den Eijnden 2018) to probe jet/accretion coupling. With accurate distances, we can break the degeneracy between the inclination angles of radio jets and their speeds (Fender 2003).
A well-constrained inclination angle can also help in obtaining accurate mass estimates of the black hole (BH) from the mass function of the system (Cantrell et al. 2010). An accurate distance helps in obtaining a well-constrained three-dimensional space velocity and hence the potential kick velocity (PKV) distribution of the system (Atri et al. 2019), providing clues as to the BH formation mechanism (Nelemans, Tauris & van den Heuvel 1999).

Distances to BHXBs are often estimated by studying the optical/infrared spectra of the donor star (Jonker & Nelemans 2004). The proper motion of the receding and approaching jets can also be used to place an upper limit on the distance of the BHXBs (Mirabel & Rodríguez 1994). Lower limits on the distance can be estimated by measuring either the interstellar extinction (Zdziarski et al. 1998, 2004) or the velocities of H I absorption (e.g. Chauhan et al. 2019) towards the source. X-ray dust scattering halo has also been used to constrain the distance to some the BHXBs (e.g. Xiang et al. 2011). However, these methods are all model dependent, involving certain assumptions. The only model-independent method of distance determination is measuring a high-significance trigonometric parallax. However, given their typical distances (several kpc), such high-precision observations can only be carried out using Very Long Baseline Interferometry (VLBI) or by satellites like Gaia (Gaia Collaboration 2018; Gandhi et al. 2019). The Gaia’s capabilities to conduct high-precision astrometry of BHXBs in the Galactic plane can be limited due to high extinction and low optical brightness outside of outburst. Gaia also has a global zero-point offset in its parallax measurements, the magnitude of which is still under debate (Chan & Bovy 2019). Therefore, targeted VLBI astrometry campaigns on outbursting BHXBs remain crucial. Of the ∼60 BHXB candidates (Tetarenko et al. 2016), only V404 Cyg (Miller-Jones et al. 2009), Cyg X–1 (Reid et al. 2011; and low optical brightness outside of outburst.

In 2018 March (MJD 58188), the BHXB MAXI J1820+070 (ASASSN-18ey, hereafter MAXI J1820) went into outburst and was detected as a bright X-ray (Kawamuro et al. 2018) and optical (Tucker et al. 2018) transient. Archival photographic plates show two past outbursts in 1898 and 1934 (Grindlay et al. 2012), suggesting an outburst recurrence time-scale of ∼40 yr for this source (Kojiguchi et al. 2019). In its 2018 March outburst, the transient made a complete hard (until MJD 58303.5) to soft (MJD 58310.7–58380.0) to hard state (from MJD 58393.0) outburst cycle (Shidatsu et al. 2019). Radio observations during and after the transition from hard to soft state revealed an apparently superluminal approaching jet (Bright et al. submitted). The source almost faded to quiescence hard to soft state revealed an apparently superluminal approaching jet (Bright et al. submitted). The source almost faded to quiescence hard to soft state revealed an apparently superluminal approaching jet (Bright et al. submitted). The source almost faded to quiescence hard to soft state revealed an apparently superluminal approaching jet (Bright et al. submitted).

We monitored MAXI J1820 (see Table 1) with the Very Long Baseline Array (VLBA), using both the Jet Acceleration and Collimation Probe of Transient X-ray Binaries (JACPOT-XRB) programme (e.g. Miller-Jones et al. 2012, 2019, proposal code BM467), and a long-running astrometry programme (e.g. Atri et al. 2019, proposal code BA130), supplemented with a targeted European VLBI Network (EVN) campaign (proposal code EA062). All observations used a combination of J1821+0549 (J1821 hereon) and J1813+065 (J1813 hereon) as the phase reference and astrometric check sources. The calibrator positions were taken from the Radio Fundamental catalogue (rfc2015a1). Our assumed positions (J2000) were RA = 18°21′27″:305837, Dec = 05°49′10″.65156 for J1821, and RA = 18°13′33″:411619, Dec = 06°15′42″.03366 for MAXI J1813. We imaged the calibrated data and determined the target position by fitting a point source in the image plane for every epoch.

### 2.1 VLBA campaigns

In the hard state at the start and end of an outburst, the radio jets are compact and ideal for astrometry. We took four epochs (2018 March, October, November, and December) of observations via the JACPOT-XRB program in which the first three epochs (proposal codes BM467A, BM467O, and BM467R) were observed at 15 GHz. These observations used J1813 (1.93° away from MAXI J1820) as the phase interferometer (being brighter at 15 GHz), and cycled every ∼2 min between it and the target, observing the check source J1821 (1.39° away from MAXI J1820) once every eight cycles. We observed geodetic blocks (Reid et al. 2009) for half an hour at the beginning and end of each observation to better model the troposphere. The data were correlated using DiFX (Deller et al. 2011) and standard calibration steps were followed using the Astronomical Image Processing System (AIPS 31DEC17; Greisen 2003). As the source faded in 2018 December, we took the final epoch in the more sensitive 5 GHz band with the observing scheme J1821–J1813–MAXI J1820.

We also observed under the astrometry program BA130 during its 2019 August refiex. We cycled through all these sources at 5 GHz for 1.5 h, and then at 15 GHz for 2.5 h, with geodetic blocks at the start and end of the observation. We followed standard calibration techniques within AIPS (31DEC17). MAXJ1820 was phase referenced separately to J1821 and J1813. Data from the Mauna kea dish were removed for the complete duration of BA130B due to very high dispersive delays that were calculated by the task TECOR.

### 2.2 Parallax campaign: EVN data

We were also approved to observe with the EVN at 5 GHz during the expected peaks of parallax offset in RA in the months of March and September, and in declination in the months of June and December. The source was observed in 2018 October, 2018 December, and 2019 March, but faded below the detection capability of the EVN before the scheduled 2019 June epoch. J1821 was chosen as the phase reference source due to its close proximity to MAXI J1820 and was observed every 4 min, with J1813 used as a check source. The data were reduced using AIPS (31DEC17). We used the bandpass, a

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priori amplitude, and parallactic angle corrections produced by the EVN pipeline, and corrected for ionospheric dispersive delays. We then performed phase, delay, and rate calibration using standard procedures in AIPS and extrapolated the phase and delay solutions derived from J1821 to both J1813 and MAXIJ1820.

### 2.3 Mitigating systematic astrometric biases

To mitigate against systematic errors arising from low elevations, we removed all data below 20° in elevation. We also removed half an hour of data around the sunrise/sunset times at each station when the ionosphere could be changing rapidly. To prevent source structure from affecting our astrometry, we made global models of the two phase reference sources by stacking all EVN data at 5 GHz, and all VLBA data at each of 5 and 15 GHz. These global models were used to derive our final phase and delay solutions for each epoch, which were then extrapolated to MAXIJ1820 and the relevant check source.

The JACPOT-XRB program (see Section 2.1) and the EVN parallax campaign (see Section 2.2) observed different extragalactic sources as phase calibrators. Hence, we scheduled the BHXB astrometry program observations (BA130B and BA130C; see Section 2.1) such that MAXIJ1820 could be independently phase referenced to both J1813 and J1821. Combining these two observations with BM467S (which also cycled between all three sources), we measured an average shift of +0.29 ± 0.08 mas in RA and +0.05 ± 0.02 mas in Dec in the position of MAXIJ1820 when it was phase referenced to J1813 as compared to when it was phase referenced to J1821. To account for this astrometric frame shift, we shifted the target positions measured when phase referenced to J1813 by −0.29 ± 0.08 and −0.05 ± 0.02 mas in RA and Dec, respectively.

To estimate the systematics arising from the troposphere (σ_{sys, trop}), we used the simulations of Pradel, Charlot & Lestrade (2006) for both the VLBA and EVN measurements, as appropriate for our target-phase calibrator angular separation and target declination. To this, we added in quadrature a conservative estimate of the ionospheric systematics (Reid et al. 2017), taken as σ_{sys, ion} = 50 μas (ν/GHz)^{-2} (θ/°)^{-1}, where ν is the observing frequency and θ is the angular separation between target and phase reference calibrator. The rms of the position of our check source (J1821 for BM467A, BM467O, BM467R, and J1813 for the remaining data sets) was in all cases less than the conservative upper limits calculated from the combined effect of σ_{sys, trop} and σ_{sys, ion}.

### 3. RESULTS AND ANALYSIS

#### 3.1 A Bayesian approach for parallax fitting

To derive the proper motion (μ_{α, cos δ}, μ_{δ}), parallax (π), and reference position (RA_0, Dec_0) of MAXIJ1820, we fit the position as a function of time (e.g. Loinard et al. 2007), with a reference date equivalent to the mid-point of the observing campaign (MJD 58474). To perform the fit, we adopted a Bayesian approach, using the PYMC3 python package (Salvatier, Wiecki & Fonnesbeck 2016) to implement a Hamilton Markov chain Monte Carlo (MCMC; Neal 2012) technique with a No-U-Turn Sampler (NUTS; Hoffman & Gelman 2011). The Gaia DR2 proper motion and parallax measurements were used as priors in the procedure. We had observations at 15 and 15 GHz and so fit for any potential core shift in the calibrator peak emission from 15 to 15 GHz (α_s, δ_s), and used a flat prior from −1 to 1 mas for both α_s and δ_s. We checked for convergence in our MCMC using the Gelman–Rubin diagnostic (Gelman & Rubin 1992). The posterior distributions for all parameters are Gaussian, and the median and the 68 per cent confidence interval of each of the fitted parameters are given in Table 2. All error bars reported hereafter are at 68 per cent confidence, unless otherwise stated. The resulting fits to the sky motion are shown in Fig. 1.

#### 3.2 Distance from parallax

Distances inferred by inverting low-significance parallax measurements suffer from Lutz–Kelker bias and can thus be underestimated (Lutz & Kelker 1973). Thus, the use of appropriate priors is essential to obtain meaningful distances (Bailer-Jones 2015; Astraatmadja &
We use a prior that models the X-ray binary density distribution in the Milky Way (MW prior hereon; Atri et al. 2016). We determine the distance posterior distribution to that obtained using the parallax measurement made by Gaia DR2, which gave a larger median value and a wider distribution ($5.1 \pm 2.7$ kpc). The mode and the 68 per cent higher confidence intervals are $4.13^{+2.57}_{-1.45}$ kpc. We also tested an exponentially decreasing volume density (EDVD) prior (Bailer-Jones 2015) using the scaling length parameter $L$ for BHXBs from Gandhi et al. (2019) and find that unlike the Gaia DR2 distance posterior distribution (median of $4.4 \pm 2.4$ kpc; mode of $3.46^{+1.13}_{-1.06}$ kpc), our new distance measurement is unaffected by the chosen prior (see Fig. 2). This shows that the high significance of our parallax measurement has led to a model-independent distance to the source.

4 DISCUSSION

With our much improved distance measurement for MAXI J1820, we now consider the physical implications of our result.

4.1 Transition and peak outburst luminosities

The main outburst of MAXI J1820 was observed to have a peak X-ray flux of $(14 \pm 1) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ in the 1–100 keV band (Shidatsu et al. 2019). A distance of $2.96 \pm 0.33$ kpc implies that the system only reached $0.15 \pm 0.03 L_{\text{Edd}}$ at the peak of its outburst, where $L_{\text{Edd}}$ is the Eddington luminosity for a 10 $M_{\odot}$ BH (see Section 4.3). The soft-to-hard state transition luminosity, from a flux of $(2.5 \pm 0.4) \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, implies that the system made this transition at $3 \pm 1$ per cent $L_{\text{Edd}}$, in agreement with the average luminosity fraction of $1.58 \pm 0.93$ per cent $L_{\text{Edd}}$ for BHXBs (Vahdat Motlagh, Kalemci & Maccarone 2019; Maccarone 2003). Thus, for MAXI J1820 the state transition luminosity provides a good distance indicator.

4.2 Jet parameters

Assuming intrinsic symmetry, the measured proper motions of corresponding approaching and receding jet ejecta along with a distance can be used to uniquely determine the jet speed and inclination angle between the jet and the line of sight (Mirabel & Rodríguez 1994; Fender et al. 1999), via $\beta \cos i = \mu_{\text{app}}/\mu_{\text{rec}}, \tan i = d \mu_{\text{app}}/\mu_{\text{rec}}$, where $\beta$ is the velocity of the jet (normalized to the speed of light $c$), $\mu_{\text{app}}$ and $\mu_{\text{rec}}$ are the proper motions of the approaching and receding components of the jet, respectively, $i$ is the inclination angle of the jet to the line of sight, and $d$ is the distance to the system. Bright et al. (2020) measured the proper motions of corresponding jet ejecta event during the transition phase of MAXI J1820 $\mu_{\text{app}} = 77 \pm 1$ mas d$^{-1}, \mu_{\text{rec}} = 33 \pm 1$ mas d$^{-1}$. We use this with our distance constraint to estimate $\beta = 0.89 \pm 0.09$ and $\theta = (63 \pm 3)^\circ$.
4.3 Implications for BH mass
Torres et al. (2019) conducted optical spectroscopy on MAXI J1820 and reported a mass function of \( f(M) = \frac{\text{d}N}{\text{d}\log M} = 5.18 \pm 0.15 \, M_\odot \), where \( f(M) \) is the mass function, \( i \) is the inclination angle, and \( M_1 \) and \( M_2 \) are the masses of the BH and its companion, respectively. Assuming a mass ratio \( q = M_2/M_1 = 0.12 \), they constrained the inclination angle to be \( 69^\circ < i < 77^\circ \), and the BH mass to be \( 7-8 \, M_\odot \). Using our derived inclination angle of \( 63 \pm 3^\circ \), we re-calculated the BH mass to be \( (9.2 \pm 1.3) \, M_\odot \). Torres et al. (2019) suggested that the value \( q = 0.12 \) needs confirmation, so we also calculated the mass of the BH for the full suggested range of \( q (0.03-0.4) \) to be \( (10 \pm 2) \, M_\odot \). We used this updated inclination angle \( i \) and distance \( D \) to estimate the inner disc radius in the high/soft state, \( R_{\text{in}} = 77.9 \pm 1.0 \, \text{D}_{\text{Mpc}} \cos i \) km (Shidatsu et al. 2019). Equating this to the innermost stable orbit data presented in this publication are derived from the following North American radio astronomy institutes. Scientific results from under cooperative agreement by Associated Universities, Inc. The Observatory is a facility of the National Science Foundation operated by NRAO. We would like to thank J. S. Bright for allowing us to use their natal kick.

4.4 PKV
The velocity distribution of BHXBs at Galactic plane crossing has been used to determine the potential kick the system might have received at the birth of the BH (Atri et al. 2019), which is an indicator of the birth mechanism of the BH (Nelemans et al. 1999; Fragos et al. 2009; Janka 2017). A robust PKV distribution requires good constraints on the proper motion, systemic radial velocity, and the distance to the system. We used the parallax and proper motion measured in this work, combined with the systemic radial velocity of \( (−21.6 \pm 2.3) \, \text{km s}^{-1} \) (Torres et al. 2019) to determine a PKV distribution with a median of \( 120 \, \text{km s}^{-1} \), and 5th and 95th percentiles of \( 95 \) and \( 150 \, \text{km s}^{-1} \). This velocity is higher than the typical velocity dispersion of stars in the Galaxy \( (50 \, \text{km s}^{-1}; \text{Mignard 2000}) \) and suggests that the system likely received a strong kick at birth, consistent with formation in a supernova explosion.

5 CONCLUSIONS
We report a precise VLBI parallax measurement of \( (0.348 \pm 0.033) \) mas to the BHBX MAXI J1820. Using this parallax and a Bayesian prior, we inferred a distance of \( (2.96 \pm 0.33) \, \text{kpc} \). We showed that MAXI J1820 reached \((15 \pm 3) \) per cent \( L_{\odot \text{dd}} \) at the peak of its outburst. We constrained the jet inclination angle and velocity to be \( (63 \pm 3^\circ) \) and \( (0.89 \pm 0.09) \, \text{c} \), respectively. We also report an updated BH mass estimate of \( (9.2 \pm 1.3) \, M_\odot \), and suggest the BH is slowly spinning and likely received a strong natal kick.

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