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Measuring fundamental jet properties with multiwavelength fast timing of the black hole X-ray binary MAXI J1820+070

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ABSTRACT

We present multiwavelength fast timing observations of the black hole X-ray binary MAXI J1820+070 (ASASSN-18ey), taken with the Karl G. Jansky Very Large Array (VLA), Atacama Large Millimeter/Sub-Millimeter Array (ALMA), Very Large Telescope (VLT), New Technology Telescope (NTT), Neutron Star Interior Composition Explorer (NICER), and *XMM–Newton*. Our data set simultaneously samples 10 different electromagnetic bands (radio – X-ray) over a 7-h period during the hard state of the 2018–2019 outburst. The emission we observe is highly variable, displaying multiple rapid flaring episodes. To characterize the variability properties in our data, we implemented a combination of cross-correlation and Fourier analyses. We find that the emission is highly correlated between different bands, measuring time-lags ranging from hundreds of milliseconds between the X-ray/optical bands to minutes between the radio/sub-mm bands. Our Fourier analysis also revealed, for the first time in a black hole X-ray binary, an evolving power spectral shape with electromagnetic frequency. Through modelling these variability properties, we find that MAXI J1820+070 launches a highly relativistic ($\Gamma = 6.81^{+1.06}_{-1.15}$) and confined ($\phi = 0.45^{+0.13}_{-0.11}$ deg) jet, which is carrying a significant amount of power away from the system (equivalent to $\sim 0.6 L_{1-100\text{keV}}$). We additionally place constraints on the jet composition and magnetic field strength in the innermost jet base region. Overall, this work demonstrates that time-domain analysis is a powerful diagnostic tool for probing jet physics, where we can accurately measure jet properties with time-domain measurements alone.

Key words: black hole physics – stars: individual: MAXI J1820+070, ASASSN-18ey – ISM: jets and outflows – radio continuum: stars – submillimetre: stars – X-rays: binaries.

1 INTRODUCTION

One of the key open questions in high-energy astrophysics is the nature of the connection between accretion and relativistic jets launched from compact objects. Determining how jets arise as a result of accretion, and quantifying how much energy they inject into the local environment, are important problems, as jet feedback can affect many other astrophysical processes (such as star formation and galaxy evolution; Silk & Rees 1998; Mirabel et al. 2011). However, we still do not understand the complex relationship between the

properties of the accretion flow (geometry, mass accretion rate), and the properties of relativistic jets (kinetic power, bulk speed).

A crucial step towards understanding the inner workings of these jets is characterizing jet properties and how they evolve with the accretion flow. Black hole X-ray binaries (BHXBs) are ideal test-beds to study jets, as they are close in proximity, display a wide range of accretion and jet launching environments, and evolve on human time-scales. BHXBs contain a stellar-mass black hole accreting matter from a companion star, where a portion of the accreted material can be ejected in the form of a relativistic jet. The majority of these systems are transient, evolving from periods of minimal activity into bright outbursts (over time-scales of days to months), during which the system evolves through several different accretion states

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(Fender, Belloni & Gallo 2004; Remillard & McClintock 2006; Fender, Homan & Belloni 2009; Belloni 2010; Corral-Santana et al. 2016; Tetarenko et al. 2016). Compact jet emission observed in the hard accretion state of a BHXB outburst is produced as a result of synchrotron radiation (Hjellming & Johnson 1988; Corbel & Fender 2002), and displays a characteristic spectrum consisting of an inverted optically thick portion ($\alpha > 0$, where flux density scales as ν^α), which breaks to an optically thin ($\alpha \sim -0.7$) portion (this synchrotron spectral break is thought to mark the most compact jet base region where particle acceleration begins; Markoff, Falcke & Fender 2001; Markoff, Nowak & Wilms 2005; Russell et al. 2013a,b). Therefore, jet synchrotron emission tends to dominate in the lower electromagnetic frequency bands (radio, sub-mm, infrared, and possibly optical; Fender 2001; Russell et al. 2006; Tetarenko et al. 2015), while emission from the accretion flow dominates in the higher electromagnetic frequency bands (optical, UV, X-ray; Done, Gierlinski & Kubota 2007).

The jet launched during a BHXB outburst is known to produce highly variable emission, and thus time-domain analyses can offer a new avenue to probe detailed jet properties (Casella et al. 2010; Gandhi et al. 2017; Tetarenko et al. 2019). For instance, Fourier domain measurements can probe physical scales not accessible with current imaging capabilities (sub-AU scales at kpc distances). This allows us to map out the jet size scale with respect to the distance downstream from the black hole, and in turn make geometric measurements of the jet cross-section and opening angle (in the case of a conical jet). Further, due to optical depth effects, emission originating from a BHXB jet displays a distinct observational signature where the signal at lower electromagnetic frequencies will appear as a delayed version of the signal at higher electromagnetic frequencies. Through combining size scale constraints at different electromagnetic frequencies, with time-lag measurements between emission features (e.g. flares) at these electromagnetic frequencies, we are able to place constraints on jet power and speed (also possibly jet acceleration over different scales; Blandford & Königl 1979; Heinz 2006; Uttley & Casella 2014). Lastly, with simultaneous radio, sub-mm, infrared/optical (OIR), and X-ray observations, we are also able to cross-correlate multiband jet/accretion flow variability signals. This type of analysis allows us to directly link changes in the accretion flow (probed by X-ray variability) with changes in the jet on different scales (OIR probes the jet base, radio probes further along the flow).

Multiwavelength spectral timing studies on BHXBs were first performed in the optical bands (e.g. Motch, Ilovaisky & Chevalier 1982; Kanbach et al. 2001; Gandhi et al. 2008), but it was only recently that the first unambiguous detection of (stationary¹) IR variability (Casella et al. 2010; Vincentelli et al. 2018) originating in a compact jet came from GX 339-4 (as optical frequencies can at times contain contributions from other emission sources, such as the accretion disc). These works discovered that IR emission originating from the base of the jet varied significantly on sub-second time-scales, IR variability was highly correlated with X-ray variability, and the IR jet variability properties (i.e. time-lags and variability amplitude) appeared to be vastly different at different stages of the outburst (Kalamkar et al. 2016). With similar sub-second correlated variability signatures now also seen in several outbursting sources in the optical (Gandhi et al. 2010, 2017; Paice

et al. 2019), there is little doubt that a common mechanism must be driving this variability. Further, Malzac et al. (2018) have recently shown that IR variability properties measured in the Fourier domain (e.g. power spectra, coherence, and lags) can be reproduced by a jet model, where the variability is driven by internal shocks in the jet flow created through the collision of discrete shells of plasma injected at the base of the jet with variable speeds (the behaviour of these shells is directly linked to the amplitude of X-ray variability at different time-scales; see also Jamil, Fender & Kaiser 2010; Malzac 2014; Drappeau et al. 2015, 2017; Péault et al. 2019; Bassi et al. 2020; Marino et al. 2020). The same model can also explain broadband IR spectral properties, including the presence of the synchrotron spectral break, which under the assumption of a single-zone model is an estimator of the magnetic field strength in the jet plasma and the size of the emitting region in this first acceleration zone at the base of the jet (Chaty, Dubus & Raichoor 2011; Gandhi et al. 2011). This new work opens up the possibility of studying internal processes in the jet through measuring variability properties in the Fourier domain. Overall, all of these results suggest that variability in the accretion flow is subsequently driving variability in the jet, and confirmed the diagnostic potential of time domain studies for studying jet and accretion physics in BHXBs.

Recently, Tetarenko et al. (2019) expanded these BHXB spectral timing studies into the radio frequency bands (probing further out along the jet flow when compared to OIR frequencies), by repeating this spectral timing experiment using simultaneous radio and X-ray observations of the BHXB Cygnus X-1. Due to the vastly different instruments and observing techniques used at radio frequencies (when compared to OIR frequencies), to enable a radio timing study the authors implemented a new technique whereby a full interferometric array was split into separate sub-arrays, allowing for the periods of continuous, multiband data needed to use Fourier and cross-correlation analyses to study the variability. This work was able to connect rapid variability properties in radio light curves to real jet physics in a BHXB for the first time. In particular, the jet speed and opening angle were measured through detecting and modelling time-lags between the radio/X-ray signals at different bands, and a Fourier analysis of the radio signals further allowed the authors to track how matter propagates through the radio emission regions, revealing new information about the internal processes occurring in the jet. These new results show that not only is time-domain analysis possible in the lower electromagnetic frequency bands, but it is a powerful tool that can provide an unprecedented view of a BHXB jet.

In this work, we build on the success of this first radio spectral timing study by using the sub-array technique to observe the BHXB MAXI J1820+070 during its 2018–2019 outburst. Here, we further improve upon the Cygnus X-1 experiment by adding sub-mm, infrared, and optical observations to sample more electromagnetic frequency bands, in turn allowing us to connect variability properties across different scales in the jet (from the jet base probed by the infrared/optical, to regions further out along the jet flow probed by the radio/sub-mm).

1.1 MAXI J1820+070

MAXI J1820+070 (also known as ASASSN-18ey) is a dynamically confirmed, low-mass BHXB, containing a K-type dwarf donor star and a $8.48^{+0.79}_{-0.72} M_\odot$ black hole (Torres et al. 2019, 2020). This source was first discovered as a bright optical transient by the All-Sky Automated Survey for Supernovae (ASASSN; Kochanek et al. 2017) when it entered into outburst in 2018 March (Denisenko 2018; Tucker

¹ Alternatively, see for example Fender & Pooley (1998) studying IR quasi-periodic oscillations detected in the BHXB GRS 1915+105.

et al. 2018). Archival photographic plates² have since presented evidence of two past outbursts of this system, in 1898 and 1934 (Kojiguchi et al. 2019). An X-ray counterpart to the optical source was subsequently detected by the Monitor for All-sky X-ray Image (MAXI; Kawamuro et al. 2018; Shidatsu et al. 2018), while a radio counterpart was detected with the Arcminute Microkelvin Imager Large Array (AMI-LA; Bright, Fender & Motta 2018) and the RATAN-600 radio telescope (Trushkin et al. 2018). The radio source was shown to have a flat spectrum extending up to the submillimetre bands (Tetarenko et al. 2018a), consistent with the presence of a partially self-absorbed compact jet. MAXI J1820+070 remained in a hard accretion state, with a compact jet present, from 2018 March until early 2018 July (Homan et al. 2020), when it began transitioning to the soft accretion state. At this point, the compact jet was quenched (Tetarenko et al. 2018b), and superluminal discrete jet ejections were launched (Bright et al. 2020; Espinasse et al. 2020). Recent radio parallax measurements indicate that MAXI J1820+070 is located at a distance of 2.96 ± 0.33 kpc, and the jets have an inclination angle of 63 ± 3 deg³ to our line of sight (Atri et al. 2020). The recently released *Gaia* EDR3 (*Gaia* Collaboration et al. 2020) distance of $2.66^{+0.85}_{-0.52}$ kpc (calculated using the recommended zero-point correction and a prior that models the XB density distribution in the Milky Way; Grimm, Gilfanov & Sunyaev 2002; Atri et al. 2019; Lindegren 2020) is consistent with this radio parallax estimate, improving upon the larger uncertainties reported in DR2 (Gandhi et al. 2019).

MAXI J1820+070 has been found to be highly variable down to sub-second time-scales in the X-ray and optical bands (Kajava et al. 2019; Paice et al. 2019; Mudambi et al. 2020; Stiele & Kong 2020; Buisson et al. 2021). In this work, we focus on connecting variability from across the electromagnetic spectrum, combining fast timing observations at radio, sub-mm, infrared, optical, and X-ray frequencies. In Section 2, we outline the data collection and reduction processes. In Section 3, we present high time resolution light curves of MAXI J1820+070, and characterize the variability we observe in these light curves with Fourier domain and cross-correlation analyses. In Section 4, we model the jet timing properties derived from our Fourier and cross-correlation analyses, placing constraints on jet power, speed, geometry, and size scales. In Section 5, we discuss the time-domain properties of the jet in MAXI J1820+070, and highlight important considerations in designing future spectral timing experiments of BHXB jets. A summary of the results is presented in Section 6.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 ALMA sub-mm observations

MAXI J1820+070 was observed with the Atacama Large Millimeter/Sub-Millimeter Array (ALMA; Project Code: 2017.1.01103.T) on 2018 April 12, for a total on-source observation time of 2.0 h. Data were taken in Band 7 at a central frequency of 343.5 GHz. The ALMA correlator was set up to yield 4×2 GHz wide base-bands, with a 2.0-s correlator dump time. During our observations, the array was in its Cycle 5 C3 configuration, with 46 antennas. We reduced and imaged the data within the Common Astronomy Software Application package (CASA v5.4; McMullin

Table 1. Time-averaged radio and sub-mm flux densities of MAXI J1820+070.

Electromagnetic frequency band	Average flux density (mJy) ^a	Systematic Error (%) ^b
5.25 GHz	46.0 ± 0.1	5
7.45 GHz	48.1 ± 0.2	5
8.5 GHz	48.3 ± 0.2	5
11.0 GHz	49.2 ± 0.2	5
20.9 GHz	58.7 ± 1.1	10
25.9 GHz	60.5 ± 1.1	10
343.5 GHz	125.3 ± 0.05	5

Notes. ^aErrors on the VLA and ALMA average flux density measurements are calculated from the local rms in images made from data taken over the entire observation period.

^bAdditional systematic errors added (in quadrature) to the average flux density error measurements to account for absolute flux calibration uncertainties at the VLA and ALMA.

et al. 2007), using standard procedures outlined in the CASA Guides for ALMA data reduction.⁴ We used J1751+0939 as a band-pass/flux calibrator and J1830+0619 as a phase calibrator. To obtain high time resolution flux density measurements, we used our custom CASA variability measurement scripts.⁵ These scripts perform multifrequency synthesis imaging for each time-bin with the `tclean` task, using a natural weighting scheme to maximize sensitivity. Flux densities of the source in each time bin are then measured by fitting a point source in the image plane (with the `imfit` task). We performed phase-only self-calibration (down to a solution interval of 60 s) prior to running the imaging scripts. To check that any variability observed in these MAXI J1820+070 sub-mm frequency light curves is dominated by intrinsic variations in the source, and not due to atmospheric or instrumental effects, we also ran additional tests on a check source (see Appendix A for details). An time-averaged flux density measurement over the whole observation period is shown in Table 1.

2.2 VLA radio observations

MAXI J1820+070 was observed with the Karl G. Jansky Very Large Array (VLA; Project Code: 18A-470) on 2018 April 12 for a total on-source observation time of 6.0 h. The array was in the A configuration at the time of our observations, where we split the full array into three sub-arrays of 10, 9, and 8 antennas. Observations in each sub-array were made with the 8-bit samplers, where each sub-array observed exclusively in one frequency band: C (4–8 GHz), X (8–12 GHz), or K (18–26 GHz) band. Each band was comprised of 2 base-bands, with 8 spectral windows of 64 2-MHz channels each, giving a total bandwidth of 1.024 GHz per base-band. The sub-array set-up allows us to push to shorter correlator dump times than would be possible if we were using the full array. In these observations, we set a 0.15-s correlator dump time, providing the highest time resolution possible, while staying within the standard 25 Mb s^{−1} data rate limit. With our sub-array set-up, we record data fast enough to probe time-scales down to hundreds of ms. We implemented a custom non-periodic target/calibrator cycle for each sub-array, alternating observing MAXI J1820+070 and calibrators, at one band per sub-array, such that we obtained simultaneous data

²Digital Access to a Sky Century at Harvard (DASCH; <http://dasch.rc.fas.harvard.edu>).

³This inclination angle estimate was derived using the combination of jet proper motions and the known distance.

⁴<https://casaguides.nrao.edu/index.php/ALMAGuides>

⁵https://github.com/Astroua/AstroCompute_Scripts

in all three bands. We reduced and imaged the data within CASA, using standard procedures outlined in the CASA Guides⁶ for VLA data reduction (i.e. a priori flagging, setting the flux density scale, initial phase calibration, solving for antenna-based delays, bandpass calibration, gain calibration, scaling the amplitude gains, and final target flagging). We used 3C 286 (J1331+305) as a flux/bandpass calibrator, and J1824+1044 as a phase calibrator. To obtain high time resolution flux density measurements, we follow the same procedure as for the ALMA data, using our custom CASA variability measurement scripts. We performed phase-only self-calibration (down to a solution interval of 10 s) prior to running the imaging scripts. To check that any variability observed in these MAXI J1820+070 radio frequency light curves is dominated by intrinsic variations in the source, and not due to atmospheric or instrumental effects, we also ran additional tests on a check source (see Appendix A for details). An time-averaged flux density measurement over the whole observation period is shown for each band in Table 1.

2.3 VLT HAWK-I infrared observations

HAWK-I is a wide-field photometer operating in the near-IR band (0.97–2.31 μm) made by four HAWAII 2RG 2048 $\times$ 2048 pixel detectors (Pirard et al. 2004). High time resolution near-IR (K_s band; 2.2 μm ; 1.4×10^5 GHz) data of MAXI J1820+070 was collected on 2018 April 12 between 07:32:58 and 08:31:39 UTC with the HAWK-I instrument mounted on the Very Large Telescope (VLT; Project Code: 0100.D-0308(A)) UT-4/Yepun. The instrument was set up in *Fast-Phot* mode: i.e. the detector was limited only to a stripe made of 16 contiguous windows of 64 $\times$ 64 pixels in each quadrant, permitting a time resolution of 0.0625 s. In order to read out the data, the final light curve has periodic gaps of ≈ 3 s every 15–16 s. We pointed the instrument in order to place the target and a bright reference star ($K_s = 11.9$) in the lower left quadrant (Q1). We extracted photometric data using the ULTRACAM data reduction pipeline v9.14 tools⁷ (Dhillon et al. 2007), deriving the parameters from the bright reference star and its position (the position of the target was linked in each exposure). To avoid seeing effects, we used the ratio between the source and the reference star count rate. Finally, we put the time of each frame in the Barycentric Dynamical Time (BJD_TDB) system. We also derive a rough estimate of the time-averaged flux density from these data, to help put our longer wavelength measurements into context, by comparing the target to the reference star. With $E(B - V) = 0.18$ (Tucker et al. 2018), this leads to a de-reddened flux density of ~ 101 mJy.

2.4 NTT ULTRACAM optical observations

ULTRACAM is a fast-timing optical instrument which uses three channels for simultaneous multi-wavelength monitoring, and can observe at a high frame rate (Dhillon et al. 2007). High time resolution optical (i_s band;⁸ 0.7711 μm ; 3.9×10^5 GHz) data of MAXI J1820+070 was collected on 2018 April 12 between 06:28 and 10:01 UTC with the ULTRACAM instrument mounted on the 3.5 m New Technology Telescope in La Silla, Chile (NTT; Project Code: 0101.D-0767). The instrument was used in two-window mode

(one each for the target and the comparison star), with both window sizes of 50 $\times$ 50 pixels with a 2 $\times$ 2 binning for sensitivity, and speed at 96.5 Hz in i_s band (using ULTRACAM's 'co-adding' feature, i_s band was observed with an exposure time of 8.96 ms, and a total cycle time of 10.4 ms, giving 1.44 ms of dead time and a sampling rate of ~ 96.5 Hz).

The data were reduced using the ULTRACAM pipeline v9.14 (Dhillon et al. 2007). The bias was subtracted from each frame, and flat-field corrections were also applied. Aperture sizes scaled to the instantaneous seeing were used, with radii between 0.7 and 3.5 arcsec, with an annulus of between 12 and 6.3 arcsec to calculate the background. These apertures had variable centre positions that tracked the centroids of the sources on each frame, with a two-pass iteration (where an initial pass is made to track the sources on the CCD before a second photometry pass) used for accuracy. Our times were then adjusted to BJD_TDB system using methods given in Eastman, Siverd & Gaudi (2010).

Our comparison star is listed as PSO J182026.430+071011.742 in the PANSTARRS survey catalogue (Magnier et al. 2020). We extracted the target count rates and count rates for the comparison star using aperture photometry with a variable aperture size dictated by the seeing conditions. The aperture also tracked the centroid of the source of interest by using a bright star in the field as a reference source. We also derive a rough estimate of the time-averaged flux density from these data, to help put our longer wavelength measurements into context, by comparing the target to the reference star. With $E(B - V) = 0.18$ (Tucker et al. 2018), this leads to a de-reddened flux density of ~ 62 mJy.

2.5 NICER and XMM-Newton X-ray observations

NICER (Neutron star Interior Composition ExploreR) is an X-ray instrument aboard the International Space Station (ISS). It comprises 52 functioning X-ray concentrator optics and silicon drift detector pairs, arranged in seven groups of eight. Individual photons between 0.2 and 12 keV, and their energies, can be detected to a time resolution of 40 ns (Gendreau et al. 2016).

For this work, we reduced NICER data from ObsID 1200120127 using NICERDAS, a collection of NICER-specific tools which is apart of the HEASARC software package.⁹ Full Level2 calibration and screening was conducted with the *nicerl2* task, which calibrated, checked the time intervals, merged, and cleaned the data. Barycentric correction was carried out using BARYCORR.

XMM-Newton observed MAXI J1820+070 with the EPIC-pn camera for approximately 2 h, between 07:39:28–9:39:28 UTC on 2018 April 12. These observations were set up in *Burst Mode*. Events were extracted with a PATTERN ≤ 4 , FLAG==), in the 0.2–15 keV energy range. We used a box of angular size ≈ 86 arcsec (RAWX between 28 and 48). The event file was barycentred using the command *barycen*, and the XMM-Newton X-ray light curve was extracted with 1 ms time resolution. Due to the very high count rate, the source showed several telemetry drop outs lasting ≈ 14 s every ≈ 30 –50 s.

To acquire a rough estimate of the X-ray flux, for comparison with our other multi-wavelengths measurements, we fit the XMM-Newton X-ray spectrum with a powerlaw + diskbb model, finding an X-ray flux in the 1–10 keV band of $\sim 4.9 \times 10^{-8}$ erg cm⁻²s⁻¹ (~ 4 mJy).

⁶https://casaguides.nrao.edu/index.php/Karl.G._Jansky_VLA_Tutorials.

⁷<http://deneb.astro.warwick.ac.uk/phsaap/ultracam/>

⁸Please note that u_s and g_s band data were also obtained from these observations. These data will be reported in a separate paper; Paice et al. (in preparation).

⁹<https://heasarc.gsfc.nasa.gov>

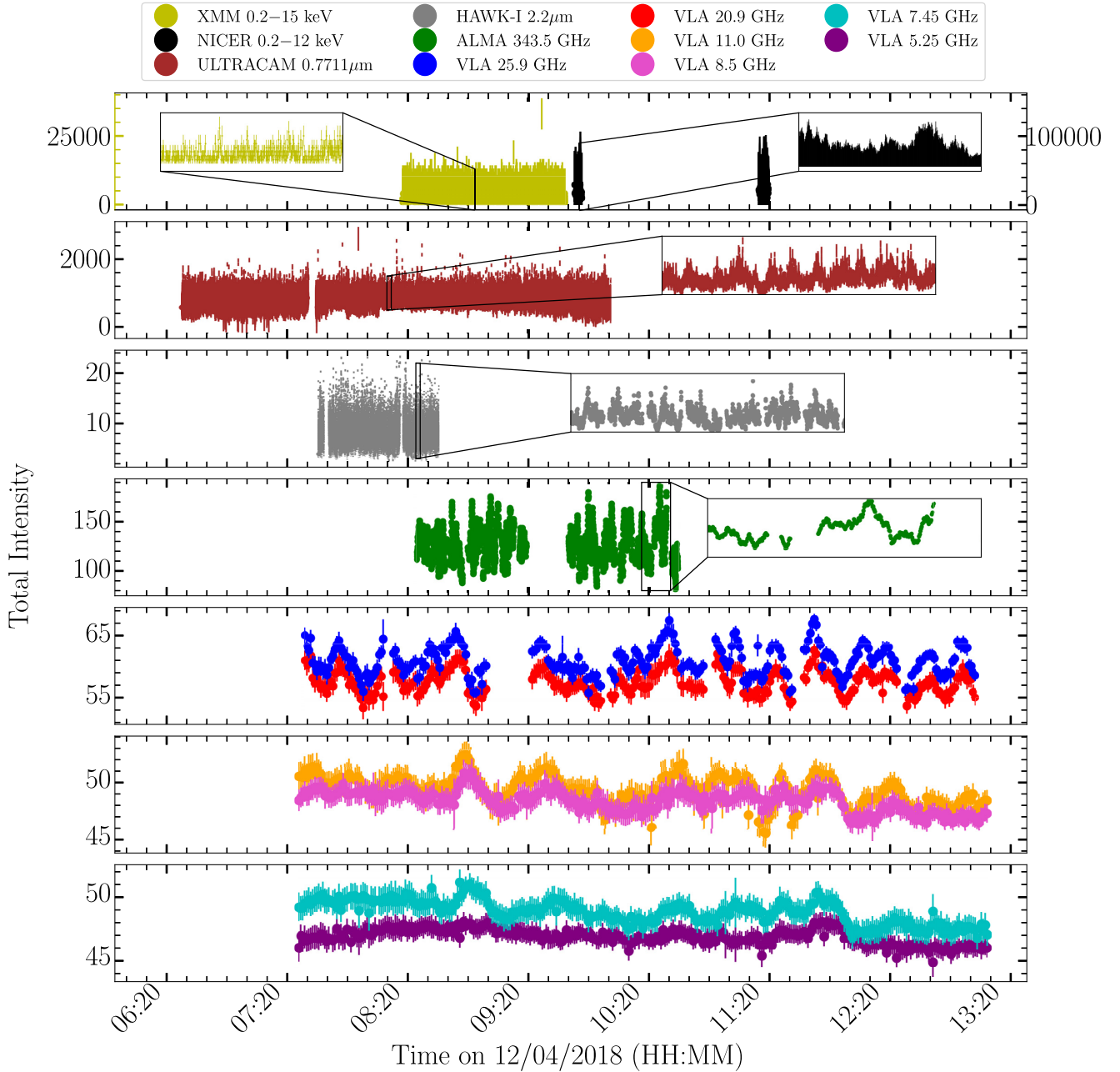


Figure 1. Simultaneous multiband light curves of the BHBX MAXI J1820+070 taken on 2018 April 12 in the X-ray (*XMM-Newton* 0.2–15 keV and NICER 0.2–12 keV), optical (0.7711 μm), infrared (2.2 μm), sub-mm (343.5 GHz), and radio (5.25–25.9 GHz) bands. The main panels from top to bottom show light curves for progressively decreasing electromagnetic frequency bands, and the inset panels show zoomed in versions of the light curves. The total intensity units for VLA/ALMA are mJy bm^{-1} , HAWK-I is amplitude with respect to the reference star, ULTRACAM is arbitrary instrumental units, and NICER/*XMM-Newton* are counts s^{-1} . The time resolution for the VLA, ALMA, HAWK-I, ULTRACAM, NICER, and *XMM-Newton* light curves are: 5, 2, 0.0625, 0.01, 0.01, and 0.004 s, respectively. We observe clear variability in the emission from MAXI J1820+070, taking the form of rapid flaring across all of the electromagnetic bands sampled.

3 MEASURING JET TIMING CHARACTERISTICS

3.1 Light curves

Time-resolved multiband light curves of MAXI J1820+070 are displayed in Fig. 1 and an average broad-band spectrum is displayed in Fig. 2. In the light curves, we observe clear structured variability at all electromagnetic frequencies in the form of multiple flaring

events. Similar flare morphology can be observed between the time-series signals (especially in the radio and sub-mm bands), suggesting that the emission in the different electromagnetic frequency bands is correlated and may show measurable delays. Upon comparing the signals across all of the electromagnetic bands sampled, the variability appears to occur on much faster time-scales in the higher electromagnetic bands when compared to the lower electromagnetic bands. When considering the radio and sub-mm bands, the variability is of higher amplitude in the higher frequency sub-mm band

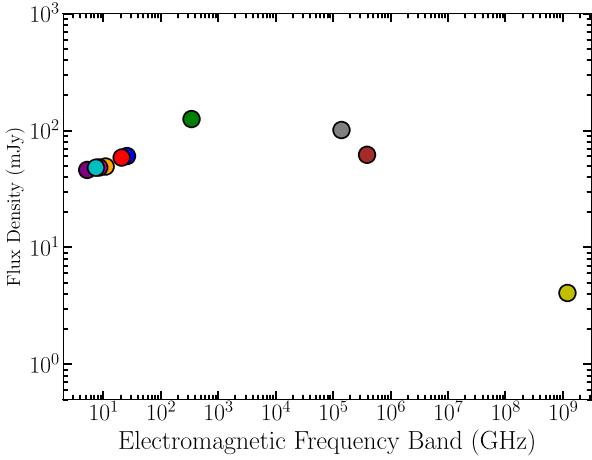


Figure 2. Time-averaged broad-band spectrum of our radio–X-ray data of MAXI J1820+070 (see Table 1 and Sections 2.3–2.5). The colours of the data points correspond to the same colours of the electromagnetic frequency bands in Fig. 1. The radio through sub-mm data appear to lie on the slightly inverted optically thick portion of the jet spectrum (spectral index $\alpha_{\text{thick}} \sim 0.25$), while the infrared and optical data appear to lie on the steep optically thin portion of the jet spectrum (spectral index $\alpha_{\text{thin}} \sim -0.5$).

(~ 100 mJy), when compared to the lower frequency radio bands (~ 5 –20 mJy). Further, the sub-mm band shows a higher average flux level when compared to the radio bands (~ 125 mJy in the sub-mm versus ~ 46 –60 mJy in the radio bands; see Table 1), indicating an inverted optically thick radio through sub-mm spectrum. The infrared and optical bands appear to not lie on the extension of the radio–sub-mm spectrum, but rather on the steep optically thin portion of the jet spectrum, indicating the jet spectral break lies between the sub-mm and infrared bands (see Fig. 2). This result is consistent with previous reports of bright mid-IR emission in excess of the optical emission during the hard state of the outburst (Russell et al. 2018). All of these emission patterns are consistent with the radio, sub-mm, infrared, and optical emission originating in a compact jet, where the higher electromagnetic frequency emission is emitted from a region closer to the black hole (with a smaller cross-section), while the lower electromagnetic frequency emission is emitted from regions further downstream in the jet flow (with larger cross-sections).

3.2 Fourier power spectra

To characterize the variability we observe in the light curves of MAXI J1820+070, we opted to perform a Fourier analysis on the data. We use the STINGRAY software package¹⁰ for this Fourier analysis (Huppenkothen et al. 2016, 2019), and Figs 3 and 4 display the resulting power spectral densities (PSDs).

As our light curves contain gaps, to build the PSDs over a wide range of Fourier frequencies we stitch together PSD segments created from light curves imaged/extracted with different time-bin sizes. In particular, by building light curves on time-scales larger than the gaps, we can manufacture a continuous time-series with which we are able to probe a lower Fourier frequency range. For the radio frequency VLA data, we use three PSD segments, built from light curves with 5 s (final PSD segment is an average over 100 s chunks), 60 s (final PSD segment is an average over 15 min chunks), and

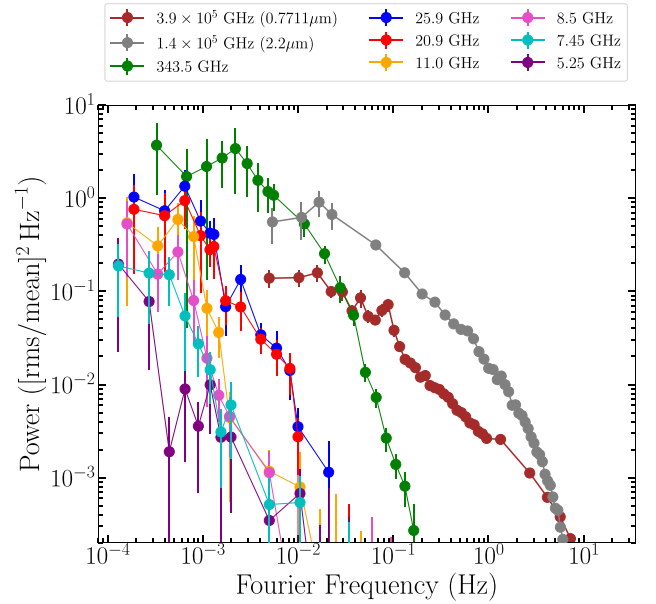


Figure 3. Fourier power spectra (PSDs) of optical (0.7711 μm ; ULTRACAM), infrared (2.2 μm ; HAWK-I), sub-mm (343.5 GHz; ALMA) and radio (5.25–25.9 GHz; VLA) emission from MAXI J1820+070. Note that PSDs of the X-ray bands are shown separately in Fig. 4 for clarity. The PSDs shown here were built by stitching together PSD segments created from data imaged/extracted with different time-bin sizes (with the shortest time-scales sampled being 0.01/0.065/2/5 s for the optical/infrared/sub-mm/radio bands; see Section 3.2 for details), in order to circumvent the gaps in the light curves and sample the lower Fourier frequencies. In these PSDs, we observe a clear trend in the shape of the PSDs with electromagnetic frequency band, where the break in the PSDs moves to lower Fourier frequencies as we shift to lower electromagnetic frequency bands. Note that all PSDs shown here have been white-noise subtracted, and the pre-white noise subtracted PSDs are shown in Appendix B.

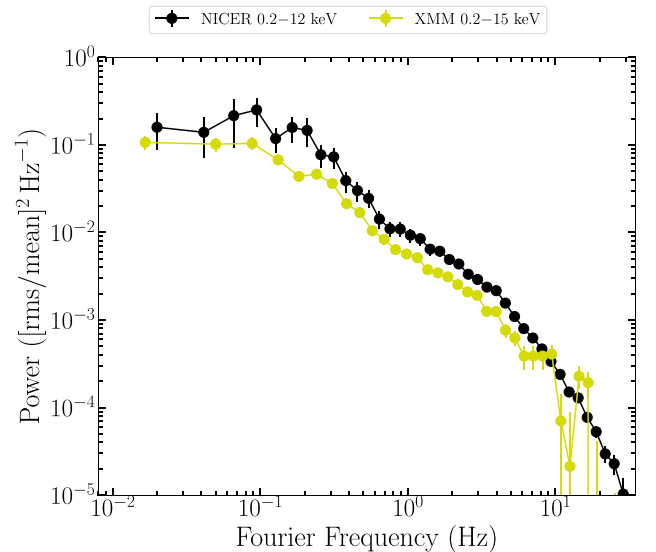


Figure 4. Fourier power spectra (PSDs) of the NICER and *XMM-Newton* X-ray emission from MAXI J1820+070. Note that the X-ray PSDs shown here have been white-noise subtracted, and the pre-white noise subtracted PSDs are shown in Appendix B.

¹⁰<https://stingray.readthedocs.io/en/latest/>

240 s (final PSD segment is an average over 90, 108, 132 min chunks for 20.9/5.9, 8.5/11, 5.25/7.45 GHz bands, respectively) time-bins. For the sub-mm frequency ALMA data, we use two PSD segments, built from light curves with 2 s (final PSD segment is an average over 180 s chunks) and 90 s (final PSD segment is an average over 50 min chunks) time-bins. For the infrared/optical frequency data, we use two PSD segments, built from light curves with 0.0625/0.01 s (final PSD segment is an average over 15/0.75 s chunks) and 10/0.5 s (final PSD segment is an average over 200 s chunks for both) time-bins. For the NICER/*XMM-Newton* X-ray frequency data, we use only one PSD segment, built from light curves with 0.01/0.004 s time-bins (final PSD segment is an average over 50/30 s chunks). The number of segments/chunk sizes were chosen based on the gap time-scales, and to reduce the noise in the PSDs. Further, a geometric re-binning in frequency was applied (factor of $f = 0.2$ for radio-sub-mm, $f = 0.05$ for infrared/optical, and $f = 0.15$ for X-ray, where each bin-size is $1 + f$ times larger than the previous bin size) to reduce the scatter at higher Fourier frequencies in all the PSDs. The PSDs are normalized using the fractional rms-squared formalism (Belloni & Hasinger 1990), and white noise has been subtracted.¹¹ White noise levels were estimated by fitting a constant to the highest Fourier frequencies (see Appendix B).

The PSDs all appear to display a broken power-law type form, where the highest power occurs at the lowest Fourier frequencies (corresponding to the longest time-scales sampled). However, there are clear differences between the PSD shape for the different bands, where the break in the PSDs moves to lower Fourier frequencies as we shift to lower electromagnetic frequency bands. The same effect can be seen when examining the smallest time-scales (or highest Fourier frequencies) at which significant power is observed in each band (i.e. 10 s at 343.5 GHz, 100 s at 20.9/25.9 GHz, and 500 s at 5.25–11 GHz). This is the first time an evolving PSD with electromagnetic frequency has been observed from a BHXB.

To quantitatively characterize the evolving PSDs with electromagnetic frequency band that we observe in our data, we consider two different metrics: (1) integrated fractional rms amplitude (computed in the Fourier frequency range 10^{-4} –50 Hz) and (2) location of the PSD break. Fig. 5 displays each of these metrics as a function of electromagnetic frequency band (and also shows the slope after the PSD break as a function of electromagnetic frequency band). To estimate the break frequencies (and slopes after the break) in the PSDs, we have used a Markov Chain Monte Carlo algorithm (MCMC; implemented in the EMCEE python package; Foreman-Mackey et al. 2013) to fit each PSD with a phenomenological model.

It is commonplace in the BHXB literature to fit X-ray PSDs with Lorentzian components (Belloni et al. 2002). However, we found that for the radio, sub-mm, infrared, and optical PSDs a Lorentzian component could not fit the highest Fourier frequencies well, as we observe a much steeper damping of the power at these Fourier frequencies when compared to the X-ray PSDs (although see a discussion in Appendix B of how windowing and oversubtraction of white noise can impact the PSDs at higher Fourier frequencies). Therefore, to better model the more severe damping in the power that we see in the radio-optical PSDs, we choose to use a broken power-law component rather than a Lorentzian. Specifically, to fit the radio and sub-mm PSDs, we use only a broken power-law component, to fit the infrared/optical PSDs we use a broken power-law component

¹¹For the X-ray/optical/IR data, the white noise should be dominated by Poisson/counting noise, while in the radio/sub-mm the white noise is likely due to a combination of atmospheric/instrumental effects.

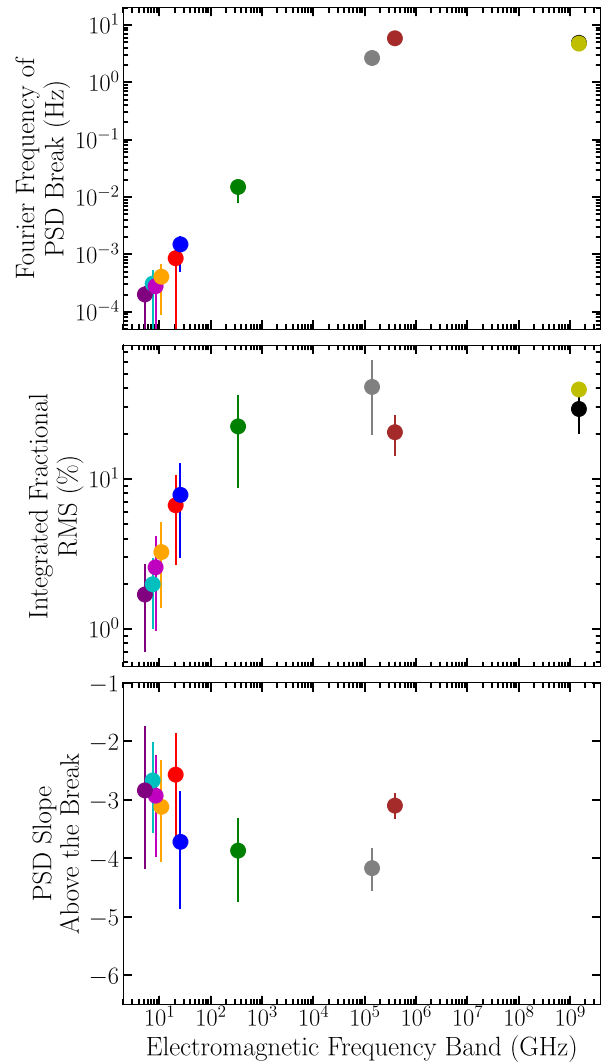


Figure 5. Variability characteristics of the emission from MAXI J1820+070, derived from the PSDs shown in Figs 3 and 4. From top to bottom: The panels show the Fourier frequency of the PSD break, integrated fractional RMS, and the slope above the PSD break (as we only fit the X-ray PSDs with Lorentzian components, no PSD slope is shown for these bands). The colours of the data points in all panels correspond to the same colours of the electromagnetic frequency bands in Figs 3 and 4. We observe a clear trend with electromagnetic frequency in all of these quantities, except for the slope above the PSD breaks, which remains relatively constant (within error) across the radio-optical bands.

for the highest Fourier frequencies+Lorentzian component(s) for the lower Fourier frequencies, and to fit the X-ray PSDs we use only Lorentzian components. Additionally, we tested how the PSD break varies with the chosen model, finding that different models do not lead to significant differences in the inferred PSD break (see Appendix C). In our fitting process, we use wide uniform priors for all parameters. The best-fitting result is taken as the median of the resulting posterior distributions, and the uncertainties are reported as the range between the median and the 15th percentile (–), and the 85th percentile and the median (+), corresponding approximately to 1σ errors. The best-fitting model parameters can be found in Table 2, while the fits are displayed with residuals in Appendix C.

Fig. 5 clearly shows that the PSD break frequency and integrated fractional rms amplitude both change with electromagnetic

Table 2. PSD modelling results.

Electromagnetic frequency band	f_{break} (Hz) ^a	Slope above break	z_{ν} ($\times 10^{12}$ cm) ^b	z_{cross} ($\times 10^{11}$ cm) ^c
5.25 GHz	$(2.0^{+2.1}_{-0.8}) \times 10^{-4}$	$-2.84^{+1.09}_{-1.34}$	$37.6^{+32.7}_{-19.0}$	$2.8^{+2.9}_{-1.5}$
7.45 GHz	$(3.1^{+2.6}_{-2.2}) \times 10^{-4}$	$-2.67^{+0.65}_{-0.89}$	$22.2^{+33.4}_{-11.2}$	$1.7^{+2.8}_{-0.9}$
8.5 GHz	$(2.8^{+3.5}_{-1.4}) \times 10^{-4}$	$-2.93^{+0.70}_{-1.04}$	$26.7^{+30.1}_{-15.0}$	$2.0^{+2.8}_{-1.2}$
11.0 GHz	$(4.1^{+3.2}_{-2.6}) \times 10^{-4}$	$-3.12^{+0.79}_{-0.94}$	$17.8^{+22.9}_{-8.6}$	$1.4^{+1.9}_{-0.7}$
20.9 GHz	$(8.6^{+4.9}_{-9.9}) \times 10^{-4}$	$-2.57^{+0.71}_{-1.12}$	$9.1^{+10.6}_{-3.8}$	$0.8^{+1.0}_{-0.4}$
25.9 GHz	$(1.5^{+0.9}_{-0.6}) \times 10^{-3}$	$-3.72^{+0.87}_{-1.14}$	$5.2^{+4.2}_{-2.1}$	$0.4^{+0.4}_{-0.2}$
343.5 GHz	$(1.5^{+0.7}_{-0.5}) \times 10^{-2}$	$-3.87^{+0.55}_{-0.87}$	$0.5^{+0.3}_{-0.2}$	$0.05^{+0.04}_{-0.02}$
2.2 μm	$2.7^{+0.4}_{-0.3}$	$-4.18^{+0.34}_{-0.39}$	$(2.9^{+0.8}_{-0.6}) \times 10^{-3}$	$(2.3^{+1.0}_{-0.8}) \times 10^{-4}$
0.7711 μm	$5.8^{+0.8}_{-0.5}$	$-3.10^{+0.22}_{-0.22}$	$(1.3^{+0.3}_{-0.2}) \times 10^{-3}$	$(1.2^{+0.5}_{-0.4}) \times 10^{-4}$
NICER 0.2–12 keV	$4.9^{+0.4}_{-0.4}$	...	...	...
XMM–Newton 0.2–15 keV	$4.7^{+0.8}_{-0.7}$	...	...	...

^aFor the NICER/XMM–Newton X-ray PSDs, we take the break frequency to be the ‘characteristic frequency’ defined in Belloni, Psaltis & van der Klis (2002)

as $f_{\text{break}} = \sqrt{\nu_0^2 + \Delta^2}$, where ν_0 is the central frequency and Δ is the FWHM of the highest Fourier frequency Lorentzian.

^bDistance downstream from the black hole to the $\tau_{\nu} = 1$ surface. Here, we use the formalism, $z_{\nu} = \frac{\beta c \delta}{f_{\text{break}}}$, and sample from the best-fitting β distribution along with the known θ distribution (see Sections 3.2 and 4 for details).

^cJet cross-section assuming a conical jet. Here, we use the formalism, $z_{\text{cross}} = z_{\nu} \tan \phi$, and sample from the best-fitting ϕ distribution (see Section 4 for details).

frequency band, following trends qualitatively consistent with what we might expect from jet model predictions (Blandford & Königl 1979; Malzac 2014). In particular, the higher variability amplitude observed at the higher electromagnetic frequency jet emitting bands (sub-mm/infrared/optical) reflects the fact that this emission originates from a region with a smaller cross-section, presumably closer to the black hole. The variability amplitudes we measure here in MAXI J1820+070 are consistent with other recent works as well (e.g. mid-IR variability amplitudes of 15–20 per cent in the BHXB MAXI J1535–571 at 4.85–12.13 $\mu\text{m}/2\text{--}6 \times 10^4$ GHz; Baglio et al. 2018). Additionally, the Fourier frequency of the PSD breaks appears to increase with electromagnetic frequency, before leveling off between the optical and X-ray bands. The factors that set the PSD break frequency for the jet emitting bands (radio-optical) is a complex question. In the internal shock model of Malzac (2014), flux variability is driven by the injection of discrete shells of plasma at the base of the jet with variable speeds. The fastest time-scale jet velocity fluctuations are dissipated closest to the base of the jet, as the most rapid variations have led to shells catching up with each other rather quickly. Further downstream in the jet, only the more slowly-varying jet velocity fluctuations still remain to catch up with one another, create shocks, and produce the varying radio emission we observe. As such, this argues that the PSD break must be related to the distance downstream in the jet (e.g. see equation 36 of Malzac (2014), where all the power in a given fluctuation at Fourier frequency, f , is dissipated at a distance downstream that scales as $1/f$). In fact, we do find that the PSD breaks scale inversely with electromagnetic frequency band, following the same trend we expect for the size-scale of the jet at different electromagnetic frequencies (i.e. distance downstream from the black hole to the $\tau = 1$ surface, z_{ν} ; see Table 2). However, the situation is likely much more complex, as the Malzac (2014) model also predicts that the distance downstream is connected to the properties of the injected velocity fluctuations (e.g. amplitudes of the fluctuations and power spectral shape of the fluctuations; see equations 36 and 45 of Malzac 2014), and when two shells collide they merge and form a new shell, indicating that different fluctuations can also be correlated with each other. In the following modelling sections of this paper, we will make the simplifying assumption that the PSD breaks are tracing the jet size-scale, but a more detailed investigation of all of the factors that may govern the PSD break will be considered in future work.

Unlike the PSD breaks and the variability amplitudes, the slope after the PSD break remains constant across the radio through optical PSDs.¹² This constant slope suggests that the mechanism that damps higher Fourier frequency variations in the jet, does not vary with electromagnetic frequency (or distance downstream from the black hole), possibly reflecting the self-similar nature of the jet.

3.3 Time lags

In the light curves of MAXI J1820+070 (Fig. 1), we observe similar flaring structures across the different electromagnetic frequency bands, suggesting the time-series signals may be correlated. To test this theory, and search for any time-delays between the different electromagnetic frequency bands, we created cross-correlation functions (CCFs). We follow the same procedure as outlined in Tetarenko et al. (2019) for our CCF analysis, whereby we use the z -transformed discrete correlation function algorithm (ZDCF; Alexander 1997; Alexander 2013) to build the CCFs, the maximum likelihood code of Alexander (2013) to estimate the peak of each CCF (signifying the strongest positive correlation and best estimate of any time-lag), and perform a set of simulations¹³ allowing us to quantify the probability of false detections in the CCFs. We note that the ZDCF method uses a different binning criterion when compared to the classic discrete correlation function of Edelson & Krolik (1988). In particular, equal population binning is used, where the bins are not equal in time-lag width.

¹²As a test of consistency in our fits, given the near constant slope after the break found in individual fits to the PSDs, we also performed a joint PSD fit. Here we ran the MCMC algorithm, this time tying the slope after the break parameter across the PSDs. This alternate fit yielded PSD breaks that were all consistent (within errors) with the individual fits.

¹³In these simulations, we randomize each light curve (Fourier transform the light curves, randomize the phases of both, then inverse Fourier transform back) to create simulated light curves that share the same power spectra as the real light curves, and then calculate the CCF for each randomized case. Significance levels are then based on the fraction of simulated CCF data points (at any lag) above a certain level. See §3.2 of Tetarenko et al. (2019) for more details.

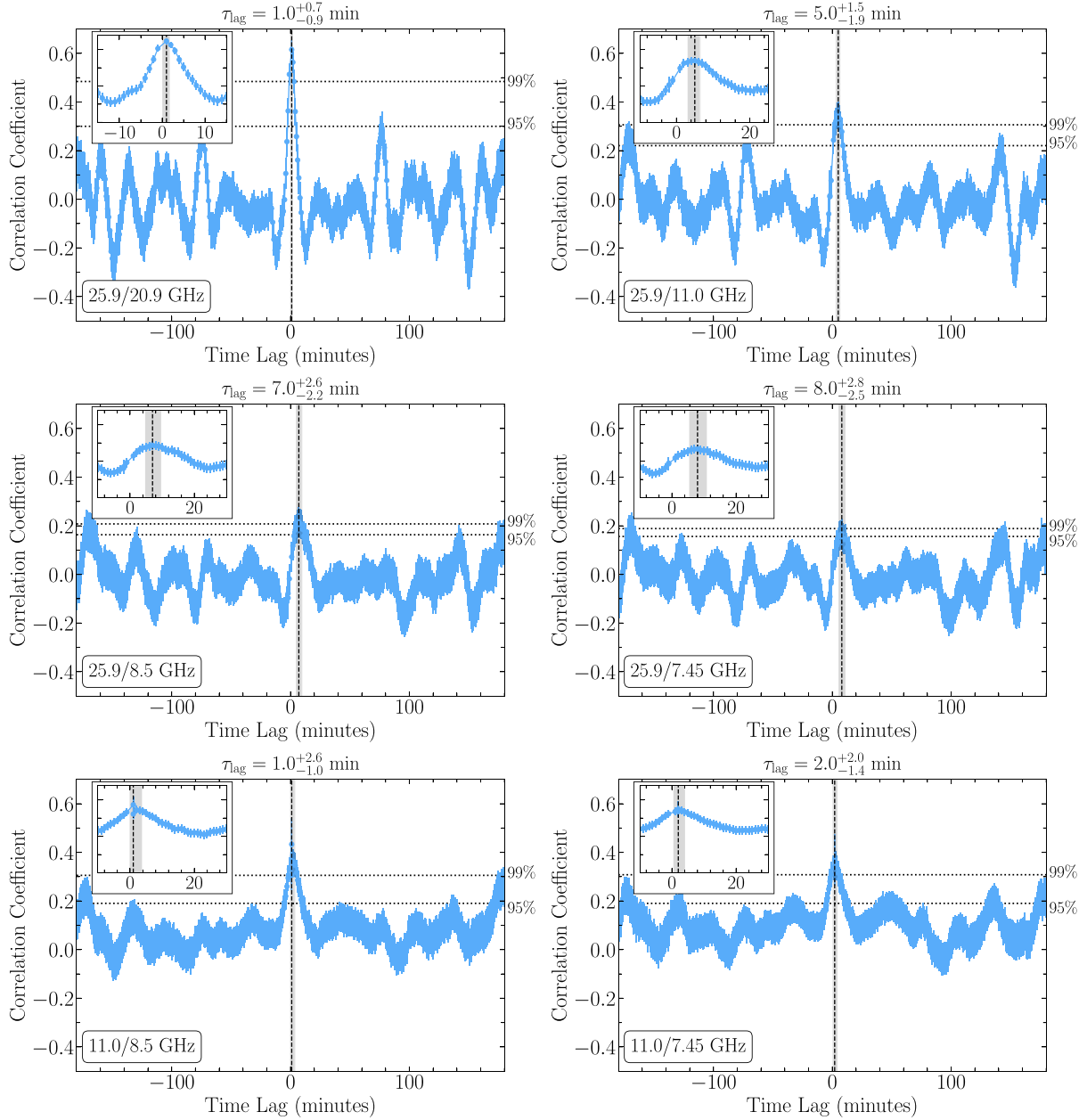


Figure 6. CCFs between emission at different radio frequency bands from MAXI J1820+070 (a positive lag indicates that the lower radio frequency band lags the higher radio frequency band). The panels compare radio signals between 25.9/20.9 GHz (top left), 25.9/11.0 GHz (top right), 25.9/8.5 GHz (middle left), 25.9/7.45 GHz (middle right), 11.0/8.5 GHz (bottom left), and 11.0/7.45 GHz (bottom right). The insets show a zoomed in version of the CCFs near the peak. The black dotted line and grey shading indicates the peak of the CCF and its associated confidence interval (where the measured lag is labelled at the top of each panel). The black dotted lines mark the 95/99 per cent significance levels (see Section 3.3). We measure clear time lags between the radio signals at various bands on the order of minutes.

3.3.1 Radio – radio lags

Fig. 6 displays the CCFs comparing the time-series signals between the different radio frequency bands sampled. We measure clear time-lags between several radio bands on time-scales between 1 and 8 min (see Table 3), indicating that the radio signals are correlated. The lower radio frequency bands always lag the higher radio frequency bands, and this lag increases as the observing frequency decreases in the comparison band. As lower radio frequencies probe further downstream from the black hole in the jet flow, these patterns in radio–radio time-lag are consistent with the measured lags tracing the

propagation of material along the radio emission regions in the jet. We note that all of our radio-radio CCFs display symmetric peaks at the measured time-lag, which reach or exceed the 99 per cent significance level, and also show roughly the same width, indicating that the observed lags likely correspond to variations on comparable time-scales. Therefore, we consider the detected time lags statistically significant, and are confident they are tracking a real correlation between the light curves. However, we also note that in all our CCFs there exist secondary peaks (which are likely the result of red noise) at $\sim -170/140$ min that can at times approach the 95/99 per cent significance levels, but still remain less significant than the measured

Table 3. Radio-radio time lag measurements.

Frequency bands Compared (GHz)	Time lag (min)
25.9/20.9	$1.0^{+0.7}_{-0.9}$
25.9/11.0	$5.0^{+1.5}_{-1.9}$
25.9/8.5	$7.0^{+2.6}_{-2.2}$
25.9/7.45	$8.0^{+2.8}_{-2.5}$
25.9/5.25 ^a	> 8.0
11.0/8.5	$1.0^{+2.6}_{-1.0}$
11.0/7.45	$2.0^{+2.0}_{-1.4}$
11.0/5.25 ^b	$2.0^{+4.5}_{-5.7}$

^aWe do not detect a clear lag between these bands, and thus use the value from the next highest frequency band (7.45 GHz) as an lower limit.

^bThe larger errors on this time lag measurement make the measured lag consistent with zero. Note that this CCF is not shown in Fig. 6.

lags. As the time-lags at these secondary peaks remain constant (within error) across the radio bands, and the characteristic radio flaring time-scale is a few hundred seconds (as seen in Fig. 1), we believe these secondary peaks are the result of the CCF algorithm matching the largest flares in each band to adjacent flares in the time-series, and thus do not represent physical lags.

3.3.2 Sub-mm – radio lags

When running the ZDCF algorithm to compare the ALMA sub-mm emission and the VLA radio emission, we did not detect any measurable lags. While we do tend to observe broad peaks in these CCFs, they do not reach the 95/99 per cent significance levels. This likely indicates that the lags are identified by the CCF algorithm, but they are not statistically significant. Upon examining the sub-mm and radio light curves in Fig. 1, it is clear that the sub-mm signal is flaring on much more rapid time-scales than the radio flaring. Therefore, we believe that the reason we cannot significantly detect a lag between the sub-mm and radio bands in the CCFs is that the frequency separation between the sub-mm and radio bands is too large, and the sub-mm signal has been significantly smoothed out by the time it reaches the radio bands.

As the CCF method does not appear to be sufficient to measure sub-mm – radio lags in this case, we designed an alternative method in which we essentially pass the sub-mm signal through a jet filter, and compare the resulting signal to our radio signals. To apply this jet filter, we delay and smooth the sub-mm signal with a Gaussian kernel (with smoothing time-scale, σ_{smooth}). To solve for the delays and smoothing time-scales (both of which will vary with the comparison radio band), we simultaneously fit our model to all radio frequencies (5.25–25.9 GHz) using an MCMC algorithm. In this fitting process, we use wide uniform priors for all parameters. As we wish to obtain a jet model independent estimate of the sub-mm-radio lags (mimicking the CCF algorithm), we do not tie the delays or smoothing time-scales between radio bands together in the fits (in a Blandford & Königl (1979) jet model, we would expect both delay and smoothing time-scale to inversely scale with radio frequency). Further, we only use the ALMA sub-mm signal from MJD 58220.365 (08:45 UT) onwards in our modelling, as we find that the ALMA observations do not start early enough to sample all of the sub-mm emission that, when smoothed and delayed, will contribute to the large radio flare at $\sim 08:55$.

The best-fitting jet filter parameters and lags are displayed in Fig. 7 and Table 4. The best-fitting result is taken as the median of the

resulting posterior distributions, and the uncertainties are reported as the range between the median and the 15th percentile (–), and the 85th percentile and the median (+), corresponding approximately to 1σ errors. Our jet filter method is able to reproduce the radio frequency signals extremely well, and the resulting sub-mm-radio lags follow the same pattern as the radio-radio lags (where lower radio frequencies lag the higher sub-mm frequency, and the lag increases as the radio frequency decreases in the comparison band). Therefore, we are confident that the modelled sub-mm-radio lags are tracking a real correlation between the sub-mm and radio light curves, and in turn represent the propagation of material along the jet flow. The best-fitting smoothing time-scales also scale inversely with radio frequency, and the characteristic length scales (z_{smooth} in Table 4) implied by these smoothing time-scales, are consistent with our estimates for the jet cross-sections (based on our PSD measurements; z_{cross} in Table 2), further reinforcing the validity of our jet filter method.

3.3.3 X-ray–optical–infrared lags

Fig. 8 displays the CCFs comparing the time-series signals between the X-ray, optical, and infrared bands. The X-ray/optical CCF displays a complex structure, including a peak at ~ 150 ms, an anticorrelation dip between ~ -2 and 4 s, and broad peaks at larger lags. These CCF features are similar to those reported in Paice et al. (2019) for observations taken 5 d after those reported in this paper. An X-ray/optical lag on the order of hundreds of ms has been seen in several BHXBs already (e.g. Gandhi et al. 2017), and is often interpreted as tracing the propagation of accreted material from the X-ray emitting regions in the accretion flow to the optical emitting regions in the jet base. The asymmetric anticorrelation dip could be a result of superposition of a symmetric anticorrelation with positive timing humps, due to reprocessing or QPOs (Veledina, Poutanen & Vurm 2011). The optical/infrared emission also appears to be highly correlated, displaying a strong CCF peak that indicates a lag consistent with zero (-18^{+30}_{-50} ms). These results, combined with the broad-band spectrum shown in Fig. 2, suggest that the infrared and optical emission may both originate in the optically thin innermost jet base region (although the jet may not be the only contributor to the optical emission from the system; Veledina et al. 2019; Kosenkov et al. 2020), and that any lag between the optical/infrared bands may be attributed to the synchrotron cooling time of the electrons in the jet. In this case, we can use the optical/infrared lag to estimate the magnetic field strength in the jet base region (B). The synchrotron cooling time is defined as

$$t_{\text{sync}} = \frac{6\pi m_e c}{\sigma_T B^2 \gamma} = 7.8 \left(\frac{10^4 \text{ G}}{B} \right) \left(\frac{1}{\gamma} \right) \text{ s}. \quad (1)$$

Here the Lorentz factor of the electrons, $\gamma = (9.1 \times 10^{-4})(\nu/B)^{1/2}$, where ν is in units of Hz and B is in units of Gauss. In turn, the synchrotron cooling induced lag can then be written as

$$\tau_{\text{opt/IR}} = (8.6 \times 10^{11}) B^{-3/2} \left(\nu_{\text{opt}}^{-1/2} - \nu_{\text{IR}}^{-1/2} \right) \text{ s}. \quad (2)$$

Substituting in $\tau_{\text{opt/IR}} < 68$ ms, yields a magnetic field strength constraint of $B > 6 \times 10^3$ G in the jet base region. This constraint is consistent with magnetic field strength estimates made using the measured spectral break frequency in the broad-band spectrum of the compact jet launched by several different BHXBs in the hard accretion state ($B \sim 10^4$ G; e.g. Chaty et al. 2011; Gandhi et al. 2011; Russell et al. 2014; Russell et al. 2020).

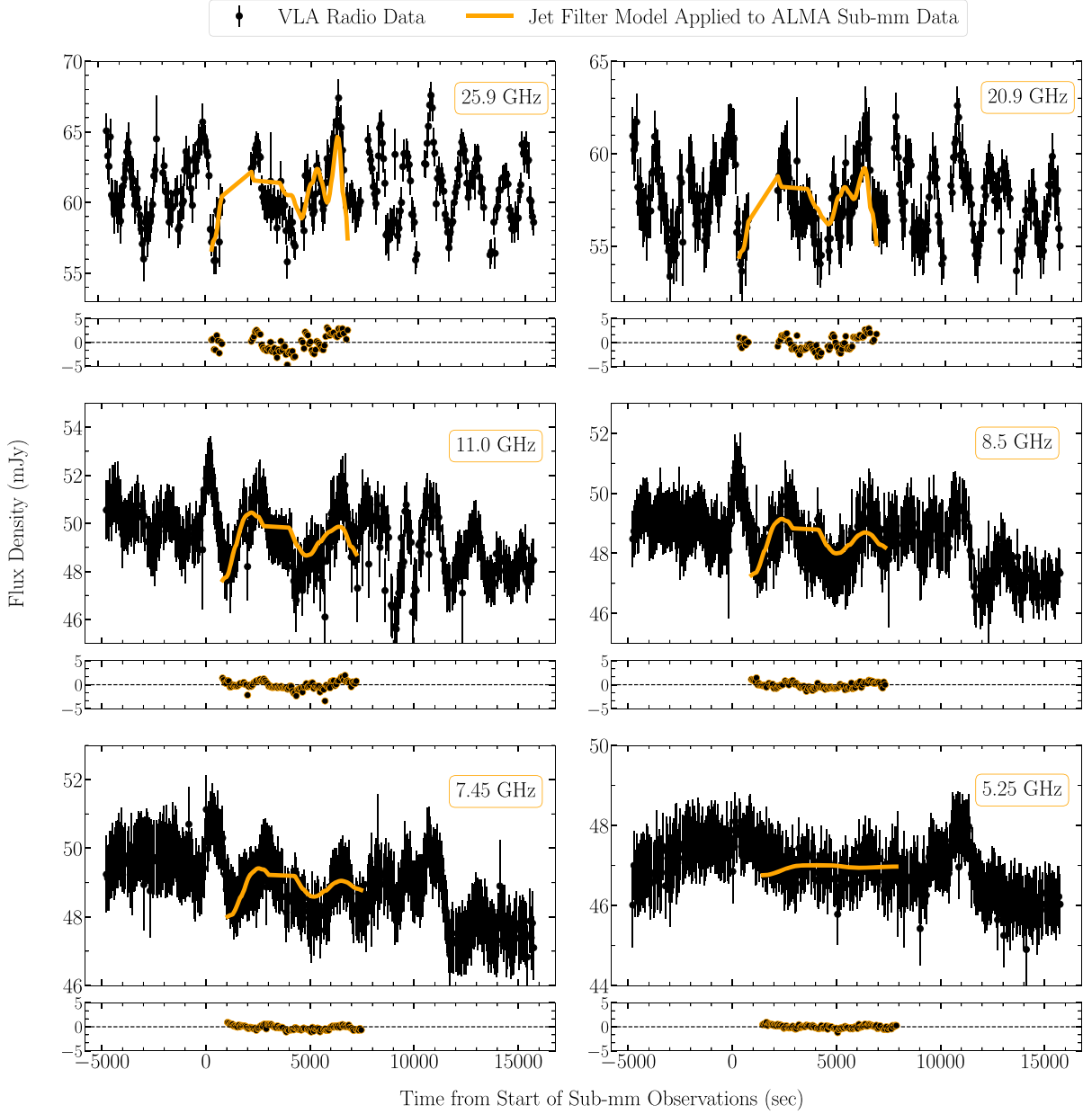


Figure 7. Modelling the sub-mm–radio lags in MAXI J1820+070. In each panel, the top sub-panel displays the VLA radio light curves (black circles), with the result of our jet filter model (solid orange line; best fit parameters in Table 4) overplotted, while the bottom sub-panel displays the residuals (data-model/uncertainties). By passing the ALMA sub-mm signal through our jet filter model, we can reproduce the observed radio signals extremely well, and in turn reliably estimate the sub-mm–radio lags in this case.

4 MODELLING JET TIMING CHARACTERISTICS

In Section 3, we presented measurements of several quantities characterizing the variable emission we observed from MAXI J1820+070 (e.g. PSD breaks and lags). All of these measured quantities can be predicted by the compact jet model of Blandford & Königl (1979), depending on jet properties: jet power (P), speed ($\beta = v/c$), opening angle (ϕ), inclination angle of the jet axis (i), distance (D), and particle properties (filling factor f , equipartition fraction¹⁴ between the particles and the magnetic field ξ_B).

¹⁴In this model, the particle pressure is a fixed fraction of the magnetic pressure, such that, $p_{\text{part}} = \frac{p_{\text{mag}}}{\xi_B}$.

Following the formalism outlined in Heinz (2006), the observed jet flux density (in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$) at electromagnetic frequency, ν , can be expressed as

$$F_\nu = \frac{5.1}{4\pi D^2} z_\nu^{17/8} \sin i^{7/8} \phi^{9/8} C_0 C_1^{-7/8} \delta^{1/4} \left(\frac{\nu}{\nu_{\text{ref}}} \right)^\alpha, \quad (3)$$

where z_ν represents the distance downstream (along the spine of the jet, in units of cm) from the black hole to the $\tau_\nu(z_\nu) = 1$ surface, $\delta = \Gamma[1 - \beta \cos i]^{-1}$ represents the Doppler factor, $\Gamma = [1 - \beta^2]^{-0.5}$ represents the bulk Lorentz factor, α represents the spectral index for

Table 4. Sub-mm-radio lag modelling results.

Frequency bands Compared (GHz)	Time lag (min)	σ_{smooth} (s)	z_{smooth} $\times 10^{11}(\text{cm})^a$
343.5/25.9	$4.5^{+0.2}_{-0.4}$	$6.5^{+0.6}_{-0.6}$	$0.5^{+0.1}_{-0.1}$
343.5/20.9	$5.5^{+1.2}_{-1.0}$	$9.2^{+1.6}_{-1.2}$	$0.7^{+0.2}_{-0.2}$
343.5/11.0	$12.6^{+1.2}_{-1.3}$	$13.8^{+2.1}_{-1.6}$	$1.1^{+0.3}_{-0.2}$
343.5/8.5	$15.7^{+1.7}_{-1.8}$	$17.7^{+3.1}_{-2.1}$	$1.4^{+0.4}_{-0.3}$
343.5/7.45	$16.7^{+2.2}_{-1.7}$	$21.8^{+3.8}_{-2.4}$	$1.8^{+0.5}_{-0.4}$
343.5/5.25	$23.6^{+4.5}_{-3.1}$	$37.5^{+8.6}_{-4.2}$	$3.1^{+1.0}_{-0.7}$

^aComputed using the formalism, $z_{\text{smooth}} = \beta_{\text{exp}} c \delta \sigma_{\text{smooth}}$. Here, we sample from the best-fitting Γ and ϕ distributions along with the known i distribution (see Sections 3.3.2 and 4 for details). The expansion velocity is computed using the relation, $\beta_{\text{exp}} = \tan \phi [1 - (\beta \cos i)^2]^{-1/2}$ (Tetarenko et al. 2017).

the time-averaged spectrum,¹⁵ ν_{ref} represents a reference frequency to anchor the time-averaged spectrum (we set $\nu_{\text{ref}} = 20.9$ GHz, in the middle of the electromagnetic frequency range covered), and C_0/C_1 are the constants (Rybicki & Lightman 1979),

$$\begin{aligned}
 C_0 &= (2.4 \times 10^{-17}) \left(\frac{2\xi_B^{3/4} f}{1 + \xi_p} \right) \left(\frac{2}{1 + \xi_B} \right)^{7/4} \left(\frac{8.4 \text{ GHz}}{\nu} \right)^{1/2} \\
 &\equiv (8.4)^{1/2} X_0 \nu^{-1/2} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1} \\
 C_1 &= (2.3 \times 10^{-12}) \left(\frac{2\xi_B}{1 + \xi_p} \right) \left(\frac{2}{1 + \xi_B} \right)^2 \left(\frac{8.4 \text{ GHz}}{\nu} \right)^3 f \\
 &\equiv (8.4)^3 X_1 \nu^{-3} \text{ cm}^{-1}.
 \end{aligned} \quad (4)$$

Here, ξ_B represents the equipartition fraction, we set the proton contribution term $\xi_p = 0$ to signify a purely leptonic jet with no protons,¹⁶ and we group constant terms (including ξ_p and ξ_B) into the X_0 and X_1 constants.

The kinetic jet power (including the counter-jet contribution, but not the kinetic energy from the bulk motion) can be expressed as a function of distance downstream in the jet (z) as

$$W = 2 [4p\Gamma^2\beta c\pi(\phi z)^2] \text{ erg s}^{-1}, \quad (5)$$

where jet pressure $p = \sqrt{\frac{\sin i}{2C_1\delta^2\phi z_\nu}} \left(\frac{z}{z_\nu} \right)^{-2}$ and c is the speed of light. The power contribution from the kinetic energy due to the bulk motion can be expressed as, $W_{\text{KE}} = [\Gamma - 1]W$. Therefore, the total power becomes $P = W + W_{\text{KE}} = \Gamma W$.

Rearranging equation (5), and substituting in the expression for jet pressure, yields

$$z_\nu = \left(\frac{W}{8\Gamma^2\beta c\pi\phi^{3/2}} \right)^{2/3} \left(\frac{2X_1(8.4)^3\delta^2}{\sin i} \right)^{1/3} \nu^{-1} \text{ cm}. \quad (6)$$

Note that in Section 3, we have discussed the factors that may govern the PSD break. While we realized that this was far from a simple question, to first order we interpret the PSD breaks at each electro-

magnetic frequency, ν , as tracing z_ν . To transform between the two quantities, we employ the prescription, $f_{\text{break}} = \frac{\beta c \delta}{z_\nu}$ (see Table 2).¹⁷

Lastly, an observed time lag between two electromagnetic frequency bands can be written as follows:

$$\tau_{\text{lag}} = z_{\text{norm}} \left(\frac{1}{\nu_{\text{low}}} - \frac{1}{\nu_{\text{high}}} \right) \frac{(1 - \beta \cos i)}{\beta c} \text{ s}, \quad (7)$$

where ν_{low} and ν_{high} represent the lower and higher electromagnetic frequency bands being compared, the $(1 - \beta \cos i)$ term represents a correction due to the transverse Doppler effect,¹⁸ and $z_{\text{norm}} = z_\nu \nu$ is the constant displayed on the right side of equation (6).

Overall, equations (3) through (7) can allow us to predict average flux densities, PSD breaks, and lags. However, if we fit these data dimensions separately, the jet parameters in the model (W , β , ϕ , i , D) will be highly degenerate. Alternatively, if we simultaneously fit all the data, tying the parameters between the data dimensions, we can help to break this degeneracy. Further, in the case of MAXI J1820+070, there exist independent constraints on the distance (D) and inclination angle (i) from radio parallax measurements (Atri et al. 2020; Bright et al. 2020), which also help to reduce degeneracy in the model.

To solve for the jet power, opening angle, and speed, we use a MCMC algorithm to simultaneously fit the average jet spectrum (Table 1), PSD breaks (Table 2), radio-radio lags (Table 3), and sub-mm-radio lags (Table 4). In this fitting process, we independently sample from the known distance ($D = 2.96 \pm 0.33$ kpc) and inclination angle ($i = 63 \pm 3^\circ$) distributions, fix the filling factor¹⁹ ($f = 1$) and particle properties ($\xi_B = 1$, $\xi_p = 0$), and leave the jet power (W), speed (Γ), opening angle (ϕ), and spectral index (α) as free parameters. We use wide uniform priors for all of our free parameters. Additionally, we take steps to make the model more computationally efficient, by choosing to fit for the bulk Lorentz factor Γ rather than β (thereby avoiding hard boundaries for the speed parameter), and choosing to fit for $\log W$ rather than W (thereby avoiding very large numbers). The best-fitting result is taken as the median of the resulting posterior distributions, and the uncertainties are reported as the range between the median and the 15th percentile (−), and the 85th percentile and the median (+), corresponding approximately to 1σ errors. Table 5 shows the best-fitting parameters, Fig. 9 displays the best-fitting model overlaid on the data, and corner plots displaying the posterior distributions and two-parameter correlations can be found in Fig. 10. The Blandford & Königl (1979) jet model can reproduce the different dimensions of our data quite well. Modelling our data with more complex jet models (e.g. Malzac et al. 2018) will be considered in future work.

As a further test of the accuracy of the model, we can compare the predictions of the best-fitting model to a jet elongation measurement made independently with Very Long Baseline Array (VLBA) imaging of the MAXI J1820+070 jet. We imaged MAXI J1820+070 with

¹⁷Under the assumption of a conical jet, the distance downstream and the jet cross-section will be linked. Therefore, we also ran an alternate version of our MCMC modelling, where we assume the PSD breaks are explicitly linked to the jet cross-section instead; $f_{\text{break}} = \beta_{\text{exp}} c \delta / 2z_\nu \tan \phi$. This alternate prescription produced best-fit parameters that were very similar to the original modelling runs, attesting to the robustness of our modelling results.

¹⁸The transverse Doppler effect describes the situation where the observed interval between the reception of two photons is smaller than the emission interval.

¹⁹Note that setting a lower filling factor value mainly affects the jet power parameter (where lower f values lead to higher power estimates), while the other parameters do not change as significantly.

¹⁵The Blandford & Königl (1979) jet model results in a flat spectrum ($\alpha = 0$), but the radio–sub-mm MAXI J1820+070 spectrum is clearly inverted, so we add an additional term to account for this here.

¹⁶ ξ_p is defined in terms of the proton contribution to the particle pressure; $p_{\text{proton}} = \frac{\xi_p}{1 + \xi_p} p_{\text{part}}$.

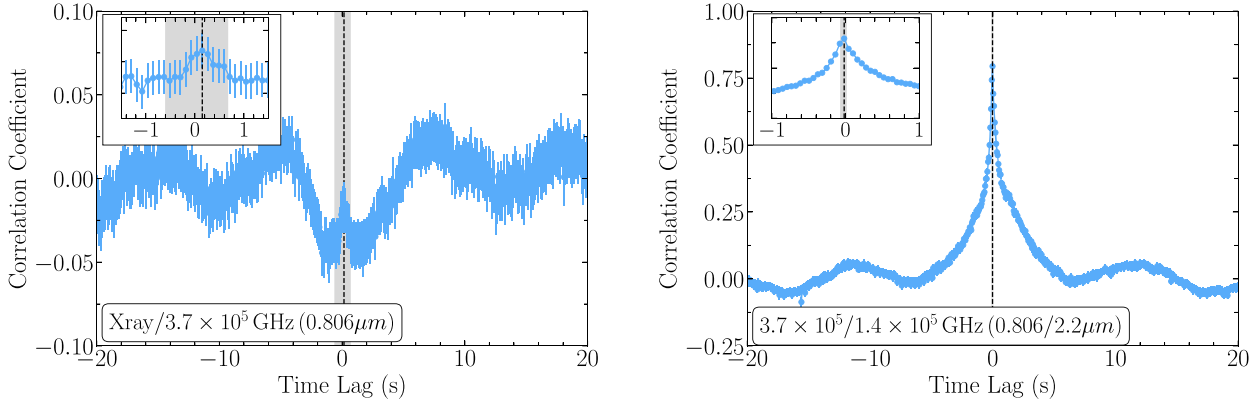


Figure 8. CCFs between *XMM-Newton* X-ray/optical (left) and optical/infrared (right) emission from MAXI J1820+070 (a positive lag indicates that the lower electromagnetic frequency band lags the higher electromagnetic frequency band). The insets show a zoomed in version of the CCFs near the peak, while the black dotted line and grey shading indicates the peak of the CCF and its associated confidence interval. The optical/infrared CCF shows a lag consistent with zero (-18^{+30}_{-50} ms), while the X-ray/optical emission shows a much more complex CCF structure [similar to that reported by Paice et al. (2019) for other observations of this source], including a peak at 151^{+500}_{-700} ms.

Table 5. Jet modelling results.

Parameter	Best-fitting value	Model status ^c
Jet power ($\log W$; erg s^{-1}) ^a	$36.98^{+0.27}_{-0.35}$	Free
Jet speed (Γ) ^b	$6.81^{+1.06}_{-1.15}$	Free
Jet opening angle (ϕ ; deg)	$0.45^{+0.13}_{-0.11}$	Free
Spectral index (α)	$0.25^{+0.02}_{-0.02}$	Free
Distance (D ; kpc)	2.96 ± 0.33	Known
Inclination angle (i ; deg)	63 ± 3	Known
Filling factor (f)	1	Fixed
Equipartition fraction (ξ_B)	1	Fixed
Proton contribution (ξ_p)	0	Fixed

^aGiven the posterior distribution of W , we estimate the distribution of the total power ($P = W\Gamma$), by performing Monte Carlo simulations sampling from the W and Γ distributions 10 000 times to yield, $\log P = 37.79^{+0.31}_{-0.38}$.

^bGiven the posterior distribution of Γ , we estimate the distribution of the corresponding bulk jet speeds (β), by performing Monte Carlo simulations sampling from the Γ distribution 10 000 times to yield, $\beta = 0.98^{+0.01}_{-0.01}$.

^cThis column indicates whether a parameter was left free, fixed, or known from an independent study (in this case we sampled from the known distribution in the fitting process).

the VLBA²⁰ on 2018 March 16 (about a month prior to the fast timing observations; see Fig. 11). Through fitting the source with a Gaussian in the image plane, we measure the jet size scale in the plane of the sky to be $l = 0.52 \pm 0.02$ mas at 15 GHz. To transform this measurement into a physical distance, we can use the following relation:

$$z_{\text{vlba}} = (1.49 \times 10^{13}) \frac{l_{\text{mas}} D_{\text{kpc}}}{\sin i} \text{ cm}, \quad (8)$$

Substituting in the known values of $D = 2.96$ kpc and $i = 63$ deg, results in $z_{\text{vlba}} = 25.7 \times 10^{12}$ cm, which is remarkably close to our best-fitting model prediction (cyan X in Fig. 9 middle).

5 DISCUSSION

In this work, we have discovered highly variable, correlated multi-band emission from the BHXB MAXI J1820+070. Using Fourier

and cross-correlation analyses, we measured the variability characteristics of the emission, and modelled these variability characteristics to directly estimate jet properties (e.g. power, speed, geometry, size scale). In the following sections, we discuss these jet properties, putting them into context with previous studies of MAXI J1820+070, as well as other BHXB systems. Additionally, we highlight the technical capabilities and instrumental advancements needed to push these types of BHXB spectral timing studies forwards.

5.1 Jet properties

5.1.1 Jet size-scales

In our Fourier analysis of the emission from MAXI J1820+070 (presented in Figs 3 and 4), we discovered a clear evolution in the shape of the PSDs with electromagnetic frequency band. In particular, the PSD break frequency appears to scale inversely with electromagnetic frequency band through the jet-emitting bands (radio-optical), before leveling off into a plateau as we reach the X-ray band (see Fig. 5). This trend matches the relationship we expect to see between the downstream distance of the emitting region from the black hole and electromagnetic frequency band. Thus, measuring the PSD break frequency at several bands has allowed us to, for the first time, map out the jet size scale with electromagnetic frequency (see Table 2; note that Vincentelli et al. 2019 have also previously suggested a tentative connection between high Fourier frequency IR PSD features and the jet size scale for GX 339-4).

Our jet size scale predictions show remarkable consistency with previous work on MAXI J1820+070. For example, Paice et al. (2019) presented optical (g_s band; equivalent to 6.4×10^5 GHz) observations of MAXI J1820+070, taken 5 d after our observations. The g_s band PSD displays a break ~ 5 –50 Hz, whereas our model predicts the PSD break at 12.4 Hz (although we note that there may be other sources of optical emission from the system; Veledina et al. 2019; Kosenkov et al. 2020). Additionally, Markoff et al. (2020) present an upper limit of <0.1 mas for the size scale of the infrared emitting region (in the plane of the sky) in MAXI J1820+070, from direct imaging with the GRAVITY instrument on the VLT Interferometer (observations taken between 2018 May 31 and June 1, while the system was still in the hard state). This measurement corresponds to physical scales of $\lesssim 10^{12}$ cm (assuming a distance of 2.96 kpc), in

²⁰For details on these VLBA observations (Project Code: BM467) and the data reduction process please see Atri et al. (2020).

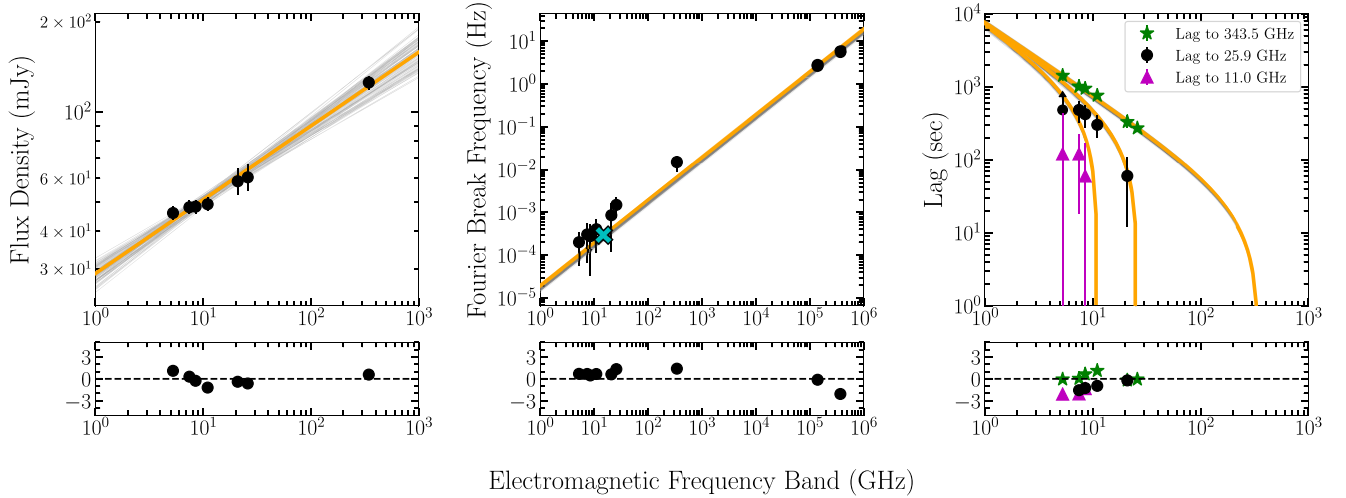


Figure 9. Modelling the jet timing properties in MAXI J1820+070. The panels from left to right display the time-averaged jet spectrum, the Fourier break frequency, and the time-lags to 343.5, 25.9, and 11 GHz, all as a function of electromagnetic frequency band. In each panel, the top sub-panel displays the data (black circles, green stars, and magenta triangles) with the result of the best-fitting jet model overplotted (solid orange line represents the model, where the thin grey lines show the final positions of all the walkers in the MCMC run, to represent the 1σ confidence interval; see Table 5), while the bottom sub-panel displays the residuals (data-model/uncertainties). The cyan X in the middle panel represents an independent measurement of the jet size scale at 15 GHz from VLBA imaging, projected on to this plane (i.e. $\beta c \delta / z_{\text{vlba}}$; see Section 4). We do not include infrared/optical fluxes in the modelling as a rigorous absolute flux calibration was not performed on this data, and we do not include X-ray/optical/infrared lags in the modelling as our model only describes the partially self-absorbed optically thick portions of the jet. The Blandford & Königl (1979) jet model can reproduce these three data dimensions reasonably well.

agreement with the infrared emission region measurements reported here. However, we do notice some deviations between our best-fitting model and the data (see Fig. 9), where the model can over/underpredict the z_v and lags. These deviations may be indicative of acceleration occurring in the jet flow, or alternatively a breakdown of the expected (linear) size scale to electromagnetic frequency relation farther out in the jet flow. Such a breakdown could possibly suggest a non-conical jet geometry. Interestingly, in a previous radio timing study of Cygnus X-1 (Tetarenko et al. 2019), a similar effect was observed, where a shallower²¹ $z_v \propto \nu^{-0.4}$ relation was needed to match the time lag measurements at lower (S Band; 2–4 GHz) electromagnetic frequencies. Further, possible evidence for a non-conical jet geometry has been reported recently for neutron star XB 4U 0614+091 (Marino et al. 2020).

5.1.2 Jet speed

Through modelling the jet timing characteristics, we have found that MAXI J1820+070 houses a highly relativistic compact jet. In particular, we estimate a bulk Lorentz factor of $6.81^{+1.06}_{-1.15}$. This far exceeds what was estimated²² for the transient jet ejections that occurred later on in the outburst ($\Gamma \sim 2.2$; Atri et al. 2020; Bright et al. 2020), and is also higher than compact jet speeds suggested by

the two other BHXBs with direct speed measurements; Cygnus X-1 ($\Gamma = 2.6$; Tetarenko et al. 2019) and GX 339-4 ($\Gamma > 2$; Casella et al. 2010; see also Saikia et al. 2019 who use an alternative approach with infrared emission to estimate $\Gamma = 1.3$ –3.5 for several BHXBs). It is thought that compact jet speed increases as the outburst progresses through the rising hard state (Vadawale et al. 2003; Fender et al. 2004, 2009). MAXI J1820+070 rose quickly (~ 10 d) through this rising hard state (Shidatsu et al. 2018; Kajava et al. 2019), in turn reaching a high luminosity/fast-jet state very early on in the outburst, where it remained for several months before transitioning to the soft state (when the compact jet is quenched). As our observations were taken when the source was in this high luminosity/fast-jet state, this could explain the higher jet speed measurement here, and suggests we have sampled the jet speed near the high end of its distribution in this outburst.

Considering the three BHXBs with compact jet speed constraints (GX 339-4, Cygnus X-1, and MAXI J1820+070; Casella et al. 2010; Tetarenko et al. 2019), we can compare the jet bulk Lorentz factors to the Eddington fraction when the jet speed measurements were made (see Fig. 12). To estimate the Eddington luminosity for each source, we use $M_{\text{BH}} = 21.2 M_{\odot}$ for Cygnus X-1 (Miller-Jones et al. 2021), $M_{\text{BH}} = 2.3$ –9.5 $M_{\odot}$ for GX 339-4 (Corral-Santana et al. 2016), and $M_{\text{BH}} = 8.48 M_{\odot}$ for MAXI J1820+070 (Torres et al. 2019, 2020). To estimate bolometric X-ray luminosity, we use $D = 2.2$ kpc for Cygnus X-1 (Miller-Jones et al. 2021), $D = 8$ kpc for GX 339-4 (Corral-Santana et al. 2016), and $D = 2.96$ kpc for MAXI J1820+070 (Atri et al. 2020), as well as the conversion $F_{\text{Bol}} \sim 5 \times F_{2-10\text{keV}}$ for BHXBs in the hard accretion state (Migliari & Fender 2006). As the source sample is small, it is difficult to definitively determine whether jet speed increases with Eddington fraction, in line with past predictions (Vadawale et al. 2003; Fender et al. 2004, 2009), measurements of two tracks in the radio/X-ray correlation for BHXBs (Russell et al. 2015), and more recent modelling (Péault et al. 2019). However, Fig. 12 does hint at the presence of a positive correlation between jet speed and Eddington fraction in BHXBs.

²¹We note that the Cygnus X-1 system contains a high-mass donor star with a strong stellar wind, which is known to at least partially absorb radio signals (Pooley, Fender & Brocksopp 1999; Brocksopp, Fender & Pooley 2002). Therefore, it is a possibility that this shallower relation may be related to the wind absorption effects.

²²Note that the transient and compact jet speeds are measured with different methods here. Further, Fender (2003) have shown that for any significantly relativistic source (which must be located close to d_{max}), the Lorentz factor varies rapidly with distance, and thus could be a lot higher.

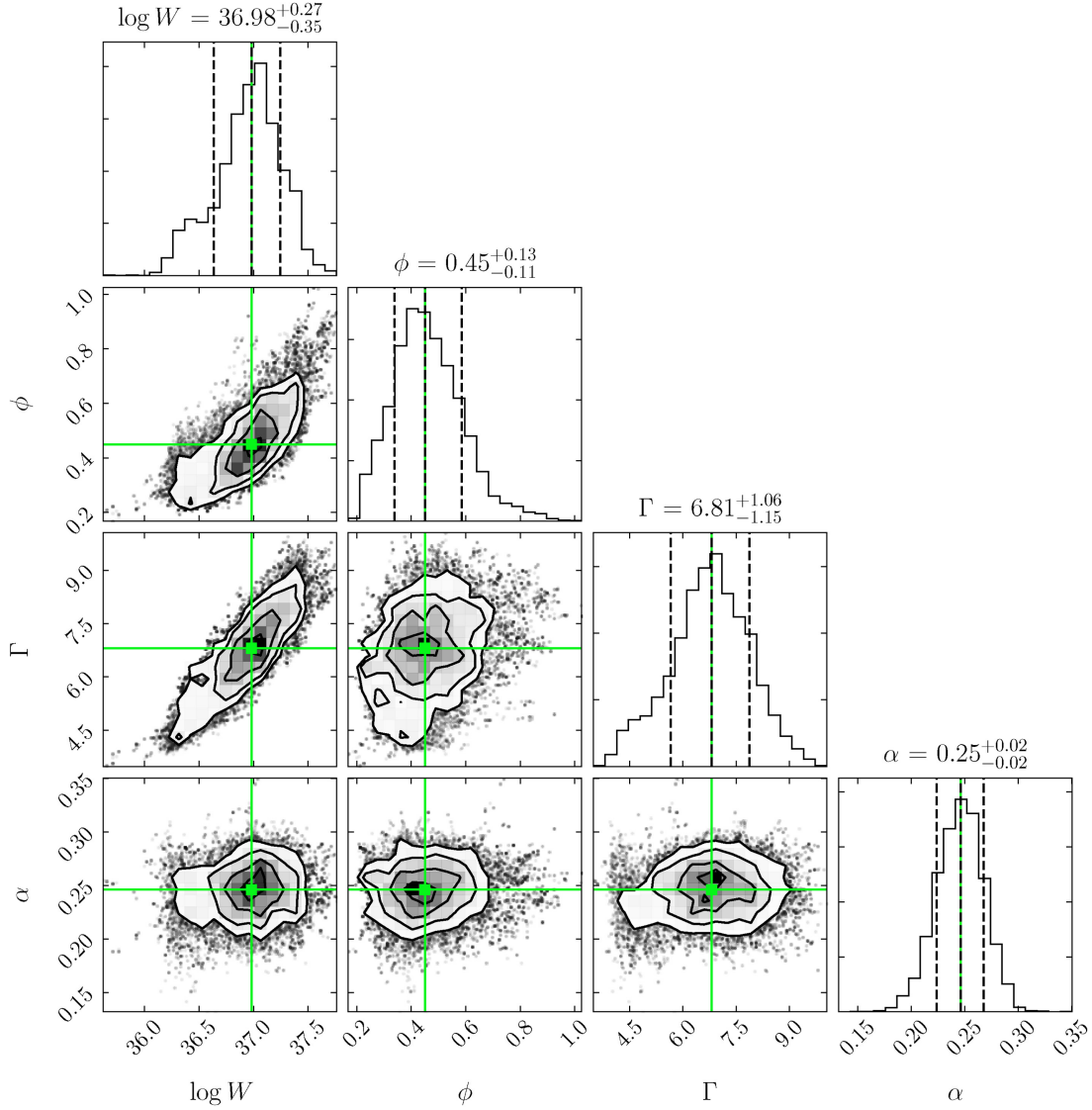


Figure 10. Corner plots displaying the results of the MCMC, Blandford & Königl (1979) jet model fit (see Table 5). The panels show the histograms of the one-dimensional posterior distributions for the free model parameters, and the two-parameter correlations, with the best-fitting values of the free parameters indicated by green lines/squares. These corner plots were created with the CORNER plotting package (Foreman-Mackey 2016).

5.1.3 Jet power

Our modelling has also allowed us to estimate the jet kinetic power, where we find $P = (6.2^{+6.4}_{-3.6}) \times 10^{37} \text{ erg s}^{-1}$. Upon comparing this jet power estimate to X-ray studies closest in time to our observations in the hard state of this outburst, we find that the power output of the MAXI J1820+070 jet is a significant fraction of the bolometric X-ray luminosity ($f_x = P_{\text{jet}}/L_{1-100\text{keV}} \sim 0.6$, where $L_{1-100\text{keV}} \sim 1.0 \times 10^{38} \text{ erg s}^{-1}$; Shidatsu et al. 2018; Kajava et al. 2019), and similar to the power estimated to be carried in the transient jet ejecta ($\sim 4 \times 10^{37} \text{ erg s}^{-1}$; Bright et al. 2020).²³ The discovery of such a high-power compact jet (especially when compared to the X-ray

output) in MAXI J1820+070 is reminiscent of the jet launched from the BHXB Cygnus X-1, which is known to carry energies on par ($f_x \sim 0.06-1$) with the bolometric X-ray luminosity in the system, and has carved out a large pc-scale cavity in the surrounding ISM as a result (Gallo et al. 2005). In the several-month period that MAXI J1820+070 spent in the hard state, with its compact jet turned on, it would have deposited a large amount of energy into the local ISM (over 4 months, $\sim 6 \times 10^{44} \text{ erg}$), and thus we might expect to observe a similar feedback effect here, where the jet may have carved out an ISM cavity (if MAXI J1820+070 is located in a dense enough environment and not moving supersonically relative to the ISM; e.g. the Cygnus X-1 jet is propagating through the tail of an H II region; Gallo et al. 2005). This theory is consistent with the discovery of X-ray hot-spots later on in the MAXI J1820+070 outburst, which could be produced by shocks between the edge of this ISM cavity and the jet ejecta (Espinasse et al. 2020).

²³Note that this power estimate assumes that the jet ejecta are associated with an optically thin radio flare, and were launched over a time period $\lesssim 6.7$ hours (equivalent to the rise-time of this flare).

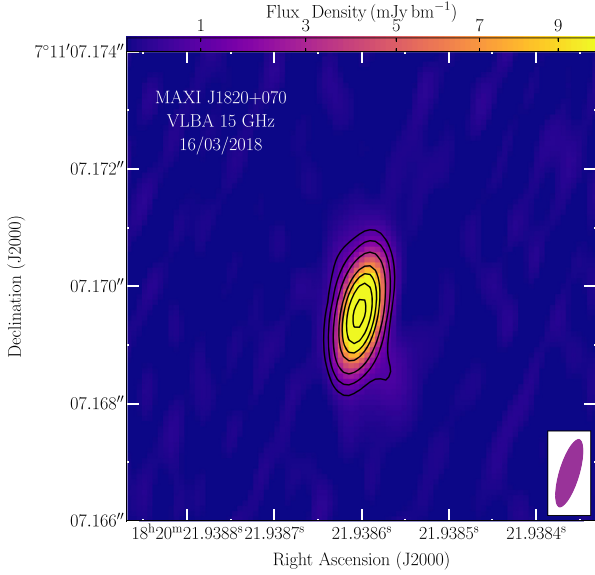


Figure 11. VLBA image of the marginally resolved MAXI J1820+070 jet at 15 GHz, created with observations taken on 2018 March 16 (Project Code: BM467). Contour levels are $2^{n/2} \times$ the rms noise level of 0.1 mJy bm^{-1} ($n = 6, 8, 10, 12, 13, 14, 15$). The VLBA beam is shown in the *bottom right* corner. From this image, we measure a jet elongation of $l = 0.52 \pm 0.02 \text{ mas}$ (PA = $25.9 \pm 2.8 \text{ deg}$).

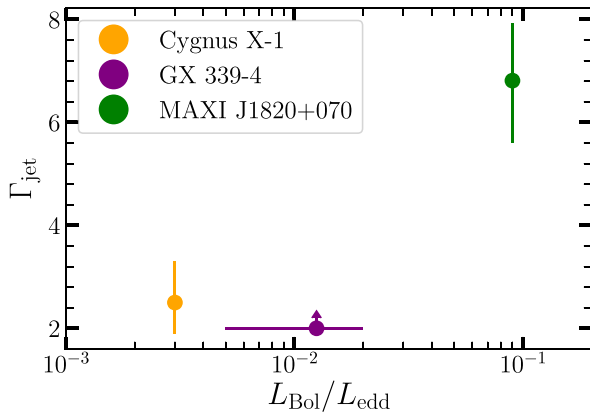


Figure 12. Comparison between jet bulk Lorentz factors and Eddington fractions for the three BHXBs with compact jet speed constraints: Cygnus X-1 (Tetarenko et al. 2019), GX 339-4 (Casella et al. 2010), MAXI J1820+070 (this work; Shidatsu et al. 2018; Kajava et al. 2019). The horizontal error bars for the Eddington fraction of GX 339-4 represent the range of black hole masses estimated for this source (see Section 5.1.2 for details). Given the small sample of sources with jet speed constraints so far, it is difficult to definitively determine if we observe direct evidence for the jet speed being correlated with the Eddington fraction.

5.1.4 Jet geometry

We were also able to constrain the jet opening angle in MAXI J1820+070, finding $\phi = 0.45 \text{ deg}$. While the majority of opening angle constraints in the BHXB population are upper limits (Miller-Jones, Fender & Nakar 2006), the MAXI J1820+070 opening angle is one of the narrowest opening angles measured to date (although see Malzac et al. 2018, which predicts opening angles as low as 0.05 deg in GX 339-4). This small opening angle could suggest a

highly confined jet. While it is difficult to pinpoint the confinement mechanism, given that a strong accretion disc wind was detected during the hard state of this outburst (Muñoz-Darias et al. 2019), it is possible that this wind could have played a significant role in inhibiting the transverse expansion of the jet.

5.1.5 Jet composition

The high jet power and bulk jet speed that we have found for MAXI J1820+070 can allow us to place constraints on the composition of the jet (i.e. proton content). In particular, if there are too many protons (positron to proton ratio is too low), then the bulk kinetic power in the jet will become physically unreasonable.

We know that the jet kinetic power cannot be dramatically higher than the accretion power near the hard to soft accretion state transition, as this would suggest a discontinuity in the mass accretion rate across the transition, which is ruled out observationally by the smoothness of X-ray light curves across the transition for many BHXB sources (Maccarone 2005). In Section 4, we have shown that for a purely leptonic (pair-dominated) jet, the kinetic power is already a significant fraction of the accretion power ($\sim 0.6 L_{\text{acc}}$). In fact, if the jet were proton-dominated (no pairs), then the kinetic power would be $\frac{m_p}{\gamma_{\text{min}} m_e} \sim 30$ times the purely leptonic jet power (where the low energy cut-off of the electron energy distribution $\gamma_{\text{min}} \sim 70(\nu/8.4 \text{ GHz})^{0.5}(p/1 \text{ erg cm}^{-3})$, and we set $\nu = 5.25 \text{ GHz}$, corresponding to our lowest sampled electromagnetic frequency; Heinz 2006). Therefore, a proton-dominated jet would have a kinetic power that exceeds the accretion power. If we use the accretion power as an upper limit, we can place quantitative constraints on the proton to electron ratio (N_p/N_e) in the jet. Including the proton content, the total kinetic power can be written as (Heinz 2006),

$$W_{\text{total}} = W + 2\rho c^3 \Gamma \beta (\Gamma - 1) \pi \phi^2 z^2, \quad (9)$$

where W is the power in the purely leptonic jet estimated from our modelling (equation 5 and Table 5). Through rearranging equation (9), and setting $W_{\text{total}} = L_{\text{acc}}$, we find a density $\rho = 6.5 \times 10^{-20} \text{ g cm}^{-3}$, which corresponds to $N_p/N_e \sim 0.6$. Therefore, this approach suggests that the jet in MAXI J1820+070 cannot be proton dominated.

5.1.6 Strength of the counter-jet signal

Lastly, given our measurements of the jet speed, inclination angle, and spectral index ($\beta = 0.98$, $i = 63^\circ$, and $\alpha = 0.25$; see Table 5), we can constrain the strength of the signal from the counter-jet (the portion of the bi-polar jet travelling away from us). We estimate a ratio of the flux densities between the approaching and receding jets for MAXI J1820+070 of $\frac{F_{\text{app}}}{F_{\text{rec}}} = \left(\frac{1+\beta \cos i}{1-\beta \cos i} \right)^{2-\alpha} = 5.3$. This suggests that the counter-jet signal is not negligible. Analysing the effect of the counter-jet signal on our timing analysis will be explored in future work.

5.2 Designing future spectral timing experiments

While spectral timing studies of BHXBs continue to provide new insights into accretion driven jets, these studies, especially in the lower electromagnetic frequency bands, are very much in their infancy. Therefore, it is important that we continue to evaluate how these experiments can be improved, and how we can design future observing campaigns to overcome any challenges we currently face.

In this study, we discovered that a significant smoothing effect between the sub-mm and radio signals can make measuring a sub-mm-radio lag infeasible with the CCF method. This issue highlights the need to simultaneously sample more closely spaced frequency bands in between the two regimes (30–100 GHz). At present, this would entail adding more instruments to a campaign (and the added difficulty that comes with synchronizing more telescopes). But with planned next generation instruments, like the next generation VLA (Selina et al. 2018), we could observe these intermediate bands with one instrument, and in turn make these types of observations much more feasible. Additionally, if we could have the ability to implement a VLA-type sub-array technique with ALMA, this could also help sample a wider range of bands simultaneously.

Further, the majority of spectral-timing studies (including this one) have been one-shot observations, and thus unable to probe how jet variability evolves during outburst. The formalism we have developed here, to measure jet properties using timing characteristics alone, could allow us to map out for the first time how quantities such as jet power and speed change throughout an outburst. While repeating this spectral timing experiment several times throughout an outburst would require significant time commitment from several observatories, implementing dedicated large multi-semester observing programs presents a viable option in this respect (e.g. JCMT large program PITCH-BLACK;²⁴ Tetarenko et al., in preparation).

Lastly, this work has shown the importance of combining timing studies at lower electromagnetic frequency bands (radio, sub-mm) with those at higher electromagnetic frequency bands (OIR), to connect variability properties across different scales in the jet/accretion flow. Therefore, the inauguration of highly sensitive next generation instruments, like the Square Kilometre Array (SKA) and James Webb Space Telescope (JWST), present exciting prospects for continuing to develop multi-wavelength spectral timing experiments.

6 SUMMARY

In this paper, we present high time resolution multi-wavelength measurements of the BHXB MAXI J1820+070 during the hard state of its 2018–2019 outburst. These observations were taken with the VLA, ALMA, VLT HAWK-I, NTT ULTRACAM, NICER, and XMM-Newton, sampling a total of ten different electromagnetic frequency bands simultaneously. We find that the emission from MAXI J1820+070 is highly variable, showing multiple structured flaring events over a 7-hour observation period.

To characterize the variability we observe, we use a combination of cross-correlation and Fourier analyses. Through these analyses, we discovered that the emission is highly correlated between the different electromagnetic frequency bands, showing clear time-lags ranging from minutes between the radio/sub-mm bands to hundreds of ms between the X-ray/optical bands. A Fourier analysis of the emission revealed a clear trend in the PSD break frequency with electromagnetic frequency band, which has allowed us to map out the jet size scale for the first time in a BHXB. Additionally, through modelling the multi-band variability properties in MAXI J1820+070 with a Bayesian formalism, we directly measured jet speed, geometry, and energetics, finding a highly relativistic ($\Gamma = 6.81^{+1.06}_{-1.15}$), confined ($\phi = 0.45^{+0.13}_{-0.11}$ deg) jet, which carries a significant amount of energy away from the black hole ($\log P = 37.79^{+0.31}_{-0.38}$ erg s^{−1}, equivalent to $\sim 0.6 L_{1-100\text{keV}}$). We use this high jet power and bulk jet speed to place constraints on the jet composition, finding that the jet in MAXI

J1820+070 can not be proton dominated. Lastly, we put constraints on the magnetic field strength in the jet base region of $B > 6 \times 10^3$ G.

Overall, this work demonstrates that it is possible to accurately measure key jet properties using only time-domain measurements. To take full advantage of these time-domain tools, it is essential that we continue to develop these spectral timing techniques, and repeat these experiments throughout different outburst states and across different BHXB systems.

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DATA AVAILABILITY

The radio/sub-mm data presented in this work are available in the ALMA (<http://almascience.nrao.edu/aq/>) and NRAO (<https://archive.nrao.edu/archive/>) online data archives. Raw HAWK-I cubes can be found in the ESO online archive (http://archive.eso.org/eso/eso_archive_main.html). The ULTRACAM data can be made available upon reasonable request to the authors. XMM-Newton and NICER event files can be downloaded from their respective online archive repositories (<http://nxsasac.esa.int/nxsa-web/#search> and <https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl>).

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²⁴<https://www.eoobservatory.org/jcmt/science/large-programs/pitch-black/>

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APPENDIX A: RADIO AND SUB-MM CALIBRATOR LIGHT CURVES

Given the flux variability that we detected in our radio and sub-mm light curves of MAXI J1820+070, we wanted to ensure that the variations observed represent intrinsic source variations, rather than atmospheric or instrumental effects. Therefore, we created time resolved light curves of check sources, which are bright calibrators that are treated as science targets in the data reduction (see Fig. A1). While the ALMA observations were set up specifically with a check source that differed from the phase calibrator (J1832+0731), the

VLA observations did not have a specific check source in the observational set-up. Therefore, to mimic the check source in our VLA data, we re-ran the reduction, treating every other phase calibrator (J1824+1044) scan as a science target. We find that all of the check sources display a relatively constant flux density throughout our observations, with any variations (<1 per cent of the average flux density) being a very small fraction of the variations we see in MAXI J1820+070. Based on these results, we are confident that our light curves of MAXI J1820+070 are an accurate representation of the rapidly changing intrinsic flux density of the source.

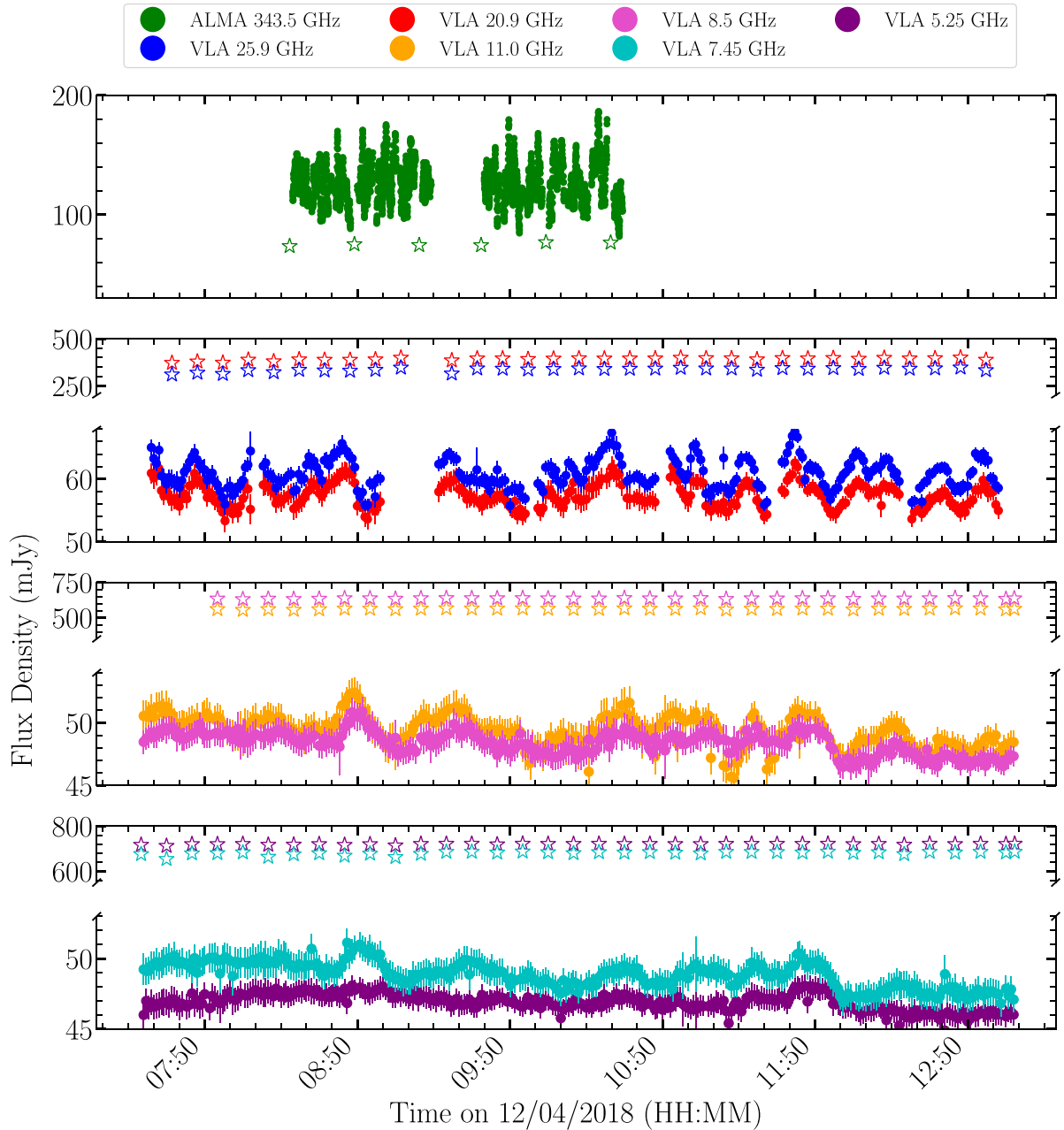


Figure A1. Multi-band radio and sub-mm light curves of MAXI J1820+070 and our calibrator check sources (J1832+0731 for 343.5 GHz and J1824+1044 for 5.25–25.9 GHz). The panels from top to bottom show light curves for progressively decreasing electromagnetic frequency bands (as indicated by the legend). All of the check sources are plotted as star symbols. As all of the check source observations show relatively constant flux densities over the course of the observations, the variations we observe in MAXI J1820+070 are most likely intrinsic to the source, and not the result of atmospheric or instrumental effects.

APPENDIX B: PSD WHITE NOISE LEVELS

In this section, we show the PSDs prior to white noise subtraction, and indicate the measured white noise levels (see Fig. B1). We have estimated the white noise levels by fitting a constant to the highest Fourier frequencies.

Note that for the infrared/optical data ($2.2/0.7711\mu\text{m}$), we notice that this procedure tends to slightly overestimate the white noise levels. This is especially apparent in our PSD fits (see Fig. C1), where we see a slight excess in the residuals at the highest Fourier frequencies, and also measure quite a steep PSD slope after the break. This effect is likely due to some non-flat component of the noise, potentially caused by the instrument readout. A precise estimate of this component goes beyond the scope of this work, but to ensure that this does not bias our key PSD measurement of the break frequency, we repeated the fit to these PSDs prior to white noise subtraction (i.e. equivalent to adding a constant component into the model). We find that the best-fit PSD break in these secondary fits is consistent with the original fits within the 1σ uncertainties.

Additionally, given the steep slopes after the PSD breaks that we measure, we opted to also investigate the effect of leakage caused by windowing on our PSD slopes. To test if this windowing effect is sufficiently strong to hide slopes steeper than 2 (in turn suggesting that incorrect white noise subtraction could be producing our steep slopes), we ran a set of simulations where we simulated light curves from a PDS with our measured breaks and slopes (and with the same windowing and sampling properties of our true light curves). We then calculated the PDS of these simulated light curves again, to check if the steep slope had disappeared. In our simulations, we find that we are still able to recover the steep slopes in the Fourier frequency range where we have significant power, before the white noise floor dominates, and thus this effect does not seem to be strong enough to fully hide the steeper slopes in our case.

APPENDIX C: PSD FITS

In this section, we show the results of the final fits to our PSDs (Fig. C1), as well as a comparison between the PSD break frequencies found using different PSD models (Fig. C2).

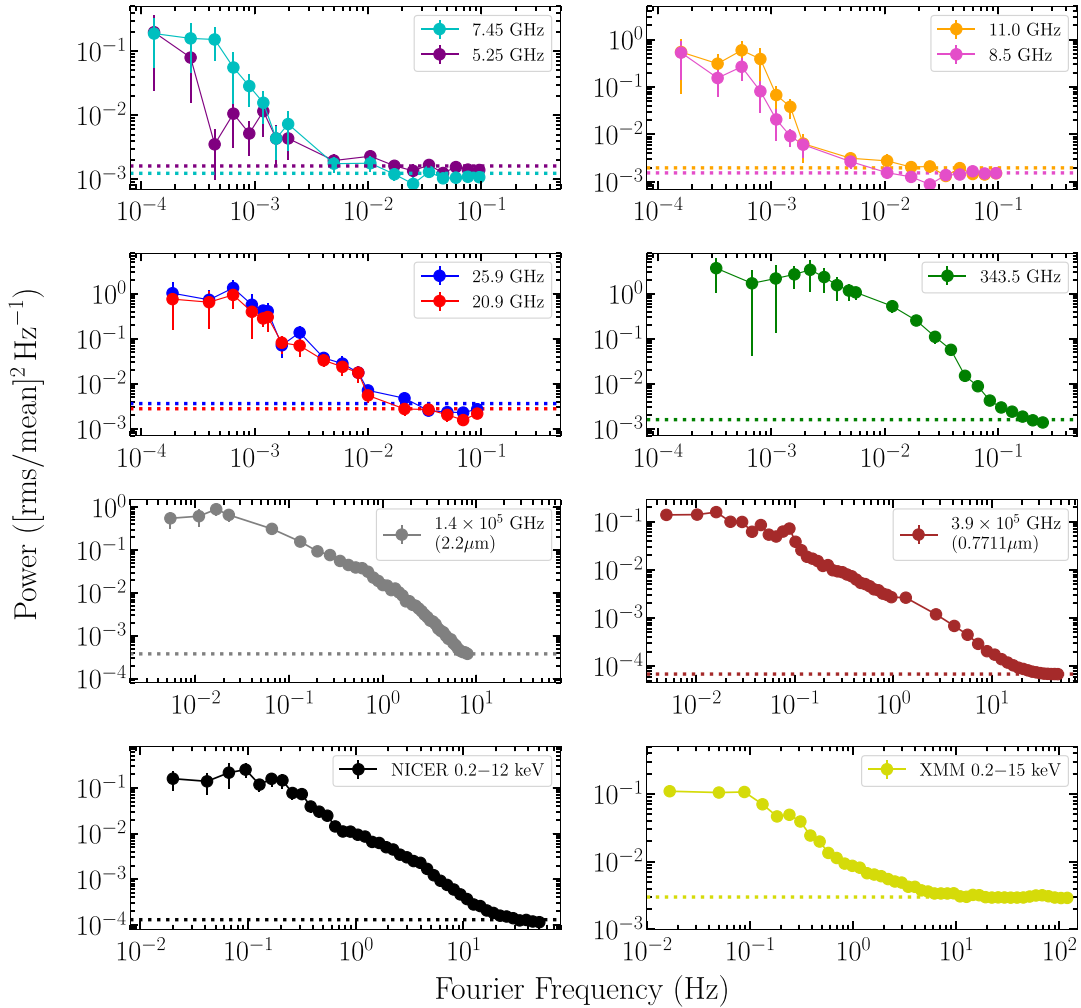


Figure B1. Fourier power spectra (PSDs) of emission from MAXI J1820+070, prior to white noise subtraction. The estimated white noise levels are indicated by the dotted lines in each panel.

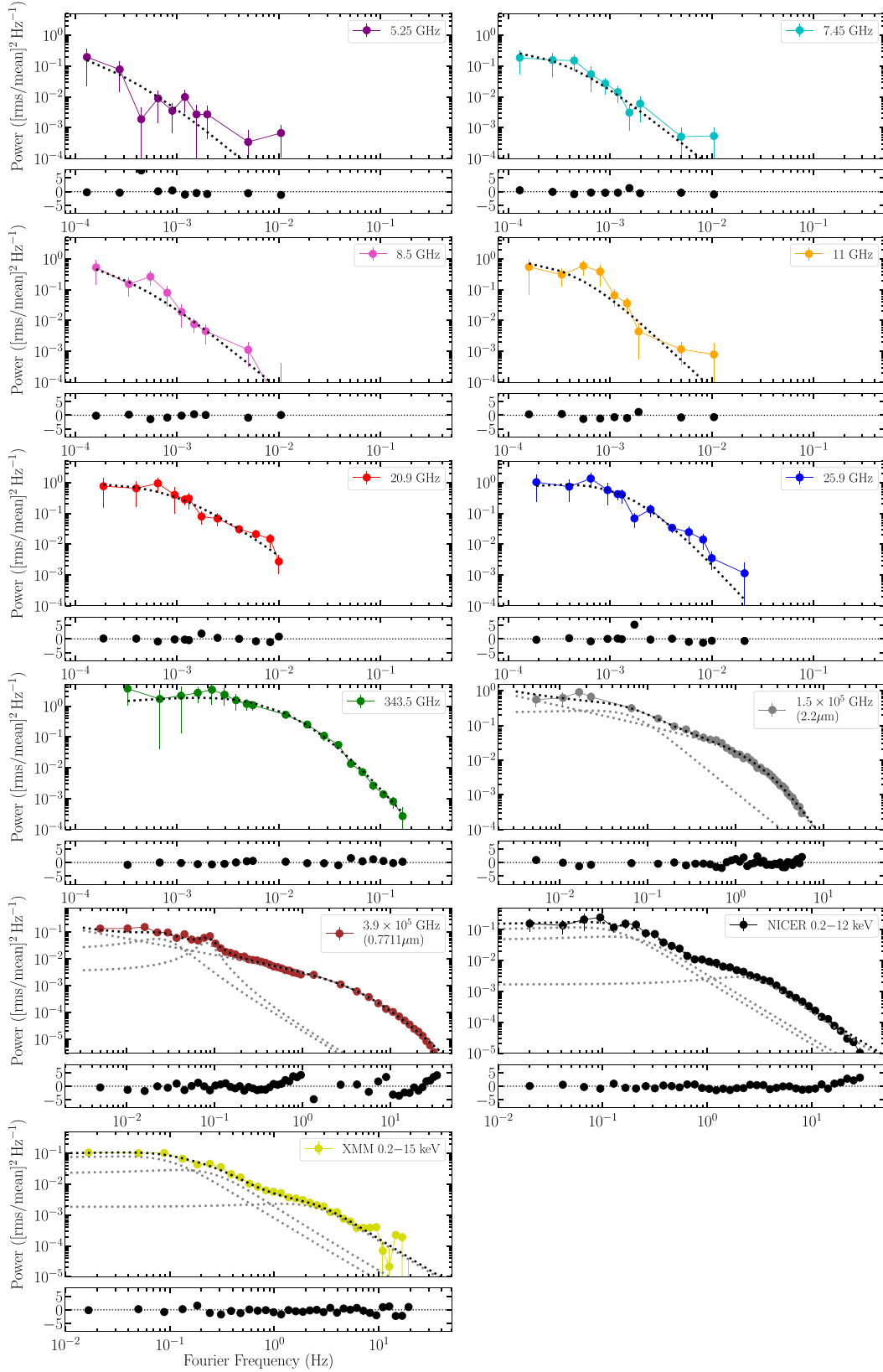


Figure C1. Fits to the MAXI J1820+070 Fourier power spectra (PSDs). In each panel, the PSDs and best-fit model (indicated by the dashed black line) are shown in the top sub-panels, while the residuals for the fits (data-model/uncertainties) are shown in the bottom sub-panels. The radio/sub-mm PSDs (5.25–343.5 GHz) are fit with a broken power-law, the infrared/optical ($2.2\mu\text{m}/0.7711\mu\text{m}$) PSDs are fit with a broken power-law for the higher Fourier frequencies + Lorentzian(s) for the lower Fourier frequencies, and the X-ray PSDs are fit with Lorentzians (see Section 3.2 for details). In the cases where more than one component (e.g. broken power-law + Lorentzian) is needed to fit the total PSD, the individual components are displayed by grey dashed lines.

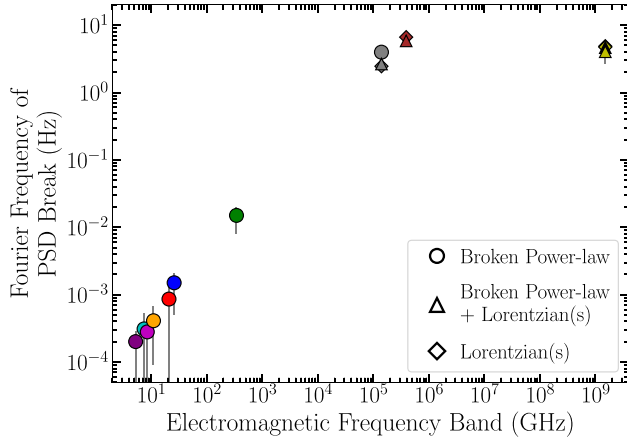


Figure C2. Fourier frequency of the PSD break inferred from using different models to fit the PSDs; broken power-law (*circles*), broken power-law for the higher Fourier frequencies + Lorentzian(s) for the lower Fourier frequencies (*triangles*), and strictly Lorentzian components (*diamonds*). For the strictly Lorentzian component fits, we take the break frequency to be the ‘characteristic frequency’ defined in Belloni et al. (2002) as $f_{\text{break}} = \sqrt{\nu_0^2 + \Delta^2}$, where ν_0 is the central frequency and Δ is the FWHM of the highest Fourier frequency Lorentzian. The colours of the data points correspond to the same colours of the electromagnetic frequency bands in Figs 3 and 4. Overall, we find that the PSD break measurements do not change drastically when different PSD models are used.

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