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Supplementary Materials for

Black hole spin–orbit misalignment in the x-ray binary MAXI J1820+070

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Materials and Methods

DIPol-UF/NOT observations

We have performed polarimetric observations of the black hole x-ray binary MAXI J1820+070 (*13,34,35*) both during the bright stages of the outburst in 2018 as well as in the quiescence. The data during the outburst (*20, 21*) were obtained with the Double Image Polarimeter-2 (DIPol-2) polarimeter (*18*) mounted on the Tohoku 60-cm telescope (T60) at Haleakala observatory, Hawaii. During the quiescence MAXI J1820+070 was observed with the DIPol Ultra Fast (DIPol-UF) (*19*) at the 2.56-m Nordic Optical Telescope (NOT) in July 2019, April and July 2020, and July 2021 (Table **S1**) (*32*). Both polarimeters have similar design: incoming light passes through a modulator (superachromatic half-wavelength plate, HWP), it is then split by the plane-parallel calcite plate into two orthogonally polarized rays (ordinary and extraordinary) and further is reflected by two dichroic beam splitters to produce o- and e-images on three charge-coupled devices (CCDs) simultaneously in the B, V, R bands. This design optically eliminates the sky polarization at the registration stage (even if it is variable), reaching up to 10^{-5} polarization precision (*18, 19, 36*). The instrumental polarization is below 10^{-4} level and can be accounted for using zero-polarization standards (*19*) but is negligible for our study. The zero point of the PA was determined by observing high polarization standards HD 161056 and HD 204827 (*19*).

For each independent measurement of linear polarization, four sequential images with the HWP rotated by $22\overset{\circ}{.}5$ in each step are obtained. Each measurement cycle consists of 16 images recorded simultaneously by three CCDs for one full rotation of the HWP modulator (0°–360°) giving four independent measurements of the normalized Stokes parameters (q, u) in the B, V, and R bands. This algorithm helps eliminate effects arising from dust particles on the retarder, nonparallelism of rotating components, etc. The images produced by DIPol-UF require standard CCD calibrations (*36*).

The average normalized Stokes parameters (q, u) are then obtained from 16 to 40 individual measurements using a 2σ weighting algorithm (*19,37*). The typical duration of an observational window where the data were averaged was one hour. The polarization produced by the interstellar medium (ISM) has been estimated from numerous (more than 400) observations of sample of field stars (stars #2, 3, 6, 7, 9 from fig. 9 of ref. (*20*)), which are close in distance to the target as indicated by their parallaxes (*38*). These normalized Stokes parameters $(q_{\rm ISM}, u_{\rm ISM})$ were subtracted from the measured values of the normalized Stokes parameters to obtain the intrinsic polarization information of the source $(q_{\rm intr}, u_{\rm intr})$. We then define the complex linear polarization quantity as $\mathcal{P} = q_{\rm intr} + i u_{\rm intr}$. Intrinsic polarization degree (PD) P and polarization angle (PA) θ are then obtained from the formulae

$$P = |\mathcal{P}| = \sqrt{q_{\rm intr}^2 + u_{\rm intr}^2}, \quad \theta = \frac{1}{2}\arg(\mathcal{P}). \tag{S1}$$

Because our PD measurements typically have significance 5–10σ, the bias in the measured PD is negligible and the uncertainty in PD ΔP is the same as the uncertainty on individual Stokes parameters. The uncertainty of the PA is estimated as $\Delta\theta = \Delta P/(2P)$ (*39*). The intrinsic PD and PA computed following this procedure are reported in Table **S1**.

Polarization observed during quiescence shows no clear dependence on the orbital phase (Fig. **2**), apart from some spread of the points in close orbital phases. The PD has a blue spectrum depending on frequency ν as $\propto \nu^3$, which is inconsistent with the red spectra expected from a jet or accretion disk. The PA is very stable in the B-band, where the PD is the highest and the relative uncertainty is smallest. Therefore, we computed the average PA in that band as a inverse-variance weighted mean of individual PAs. Since the deviations of individual measurements exceed the measurement uncertainties, the standard error of the weighted mean was corrected for overdispersion by the square root of the reduced χ^2, resulting in $\langle \mathrm{PA} \rangle = -19\overset{\circ}{.}7 \pm 1\overset{\circ}{.}2$. We also computed the mean and its uncertainty using a bootstrap (sampling with replacement) method (*40*) arriving at an identical value. The mean PA in the V- and R-bands have similar values, but larger uncertainties (Table **S1**).

Using the images from DIPol-UF we also measured photometry of MAXI J1820+070 relative to two nearby stars (#1 and 2 from table 2 in ref. (*20*)). Absolute photometry during July 2020 observations was obtained using simultaneous observations by the Liverpool Telescope (LT), see Fig. **S1** and Table **S2**. The flux of MAXI J1820+070 in all bands is anti-correlated with the PD (Fig. **S1**). This anti-correlation together with the spectral dependence of the PD can be interpreted as an interplay between two components: one, polarized, with contribution growing towards blue and another, unpolarized or, possibly, weakly polarized, variable component dominating the flux in the red. Following the spectral decomposition (Fig. **2**), the UV component produces only 20% of the total flux in the R band. This makes PA measurements of the UV component less reliable in this band. Stronger variations of the PA in R may be caused by the presence of a red and polarized at a level of 0.1–0.3% component, whose PA is different from that of the UV component. Such red and polarized component, with the PA consistent with the jet position angle, has been observed during the outburst (Table **S1**).

Liverpool Telescope observations

Photometric observations in the optical band were performed using the optical imaging component of the Infrared-Optical suite of instruments (IO:O) with the Sloan Digital Sky Survey (SDSS) $i'r'z'$, Bessel V and B filters on the LT (*41*) on La Palma, Spain. The object was observed during four nights from 2020 July 20 to 24, i.e. Modified Julian Dates (MJD) 59050–59054. LT image reduction was provided by the basic IO:O pipeline (*42*). As the photometric standards, we used four stars with known Panoramic Survey Telescope and Rapid Response System (PS1) point spread function magnitudes. To convert PS1 magnitudes to SDSS and Johnson-Cousins magnitudes we used equation (6) and table 6 from ref. (*43*). To obtain fluxes of the object from its magnitudes we used standard zero-points for SDSS and Johnson-Cousins systems (*44, 45*). The fluxes and their uncertainties are presented in Table **S3**.

Swift/UVOT observations

The *Neil Gehrels Swift Observatory* (*Swift*) (*46*) observed MAXI J1820+070 in the low state with the X-ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT) instruments (partly quasi-simultaneously with DIPol-UF/NOT) between 2020 July 20 – September 6. All the XRT data were taken in the photon counting mode with about 9 ks of total exposure. An averaged spectrum was extracted using the online tools (*47*) provided by the UK Swift Science Data Centre. The spectrum was rebinned to have at least 1 count per energy channel in order to apply W-statistic (*48, 49*). The data were fitted with a model consisting of a power law modified by the interstellar absorption TBABS*POWERLAW in the 0.5–10 keV band using the XSPEC package (*50*). Fixing the hydrogen column density to $N_{\rm H} = 1.6 \times 10^{21}$ cm^{-2} (*51*) we obtained a power-law photon index $\Gamma = 1.62 \pm 0.24$ with W-statistics of 42.7 for 46 degrees of freedom. We find flux corrected for absorption of $(3.3 \pm 0.7) \times 10^{-13}\,{\rm erg\,cm^{-2}\,s^{-1}}$ in the 0.5–10 keV energy range.

The UVOT data were processed with the UVOTPRODUCT tool (*52–54*). We used a $5''$ source aperture around the known position of MAXI J1820+070 (*38*), and a circular source-free $10''$ background aperture about $40''$ east of it. After comparing the magnitudes obtained between July 20 – September 6 to other quiescence data taken when the x-ray counting rate was low, we found that during this period MAXI J1820+070 was roughly 0.5–1 magnitude fainter in all the UV filters than in the data taken in 2019 or earlier in 2020. The same trend was observed in the V-band and, to a lesser extent, in the R-band. Therefore, we decided to stack all the 2020 July 20–September 6 UVOT data together to obtain time averaged fluxes in the *u*, *uvw1*, *uvm2* and *uvw2* filters for the spectral energy distribution (SED). Conversion of the background corrected count rates obtained from the UVOTPRODUCT to the fluxes is non-trivial, as it depends on the assumed spectral shape (*53*). Therefore, for reliable estimate of the fluxes we performed direct spectral fitting with a broad-band SED model using the XSPEC package (Fig. **2**).

Decomposition of the broadband spectrum

The broad-band average spectrum obtained with the LT and *Swift*/UVOT is shown in Fig. **2**. The spectrum was corrected for reddening using model of ref. (*55*) with extinction $A_V = 0.89$ (corresponding to the color excess $E(B-V) = 0.29$) obtained from the hydrogen column density $N_{\rm H} = (0.16 \pm 0.02) \times 10^{22}{\rm cm^{-2}}$ (*51*) using transformation $A_V = 5.59\,N_{\rm H}/10^{22}\,{\rm cm^{-2}}$ (*56*). The optical/infrared SED obtained with the LT is very red and can be described by a joined contribution of companion star and multicolor accretion disk, but the UVOT data show a UV excess. The excess is also seen in the non-dereddened data and is not an artefact of dereddening procedure. A similar excess has been detected previously in quiescent-state observations of the black hole x-ray binary A 0620$-$00 (*57*), but its nature remained a mystery.

The blue PD spectrum differs from the red (even after correcting for the reddening) spectrum of the infrared to UV continuum. This rules out accretion disk as the source of polarized light. We infer that the component producing the UV excess is responsible for polarization. To extract the average shape of the polarized component, we calculated the polarized fluxes as

$$(PF)_k = P_k F_k, \tag{S2}$$

where k is the index corresponding to one of the BVR-bands, P_k is the average PD and F_k is the average flux in this band. If PD of the polarized component is wavelength-independent, then the computed PF directly replicates its total spectral shape, with the normalization being smaller by the polarization fraction. The average PD was computed from the average Stokes parameters $(q_{\rm intr}, u_{\rm intr})$ obtained in 12 individual measurements in July 2020 during quiescence with DIPol-UF (Table **S1**). Because absolute photometry with DIPol-UF is not very reliable, the average flux was obtained from the LT observations. The averages were computed as a inverse-variance weighted mean of individual measurements and their standard errors were corrected for overdispersion by the square root of the reduced χ^2.

Published spectroscopy obtained during quiescence indicates a K-type spectral type for the companion star, which contributed about 20% to the flux in the r-band (*12, 22*). The average observed r-band flux during the spectroscopy was about 0.33 mJy, higher than the average flux of 0.24 mJy in our LT observations. Thus, the contribution of the companion star to the r-band flux rose to 27%. The radius of the companion star, which fills its Roche lobe, can be established from the measured orbital period $P_{\rm orb} = 0.68549 \pm 0.00001$ d, projected rotational velocity $v_{\rm rot} \sin i_{\rm orb} = 84 \pm 5$ km s^{-1}, and orbital inclination $i_{\rm orb} = 73° \pm 6°$ (*12*)

$$R_{\rm c} = \frac{P_{\rm orb}(v_{\rm rot} \sin i_{\rm orb})}{2\pi \sin i_{\rm orb}} = (1.19 \pm 0.08) R_\odot = (8.3 \pm 0.6) \times 10^{10} \text{ cm}. \tag{S3}$$

A moderately evolved late-type star of spectral class K7 can satisfy the constraint on radius and contribute about 27% to the r-band flux. A star with higher temperature overpredicts the companion star contribution in the r-band. For the fitting purposes, we approximate the stellar spectrum (*24*) by the blackbody with $T_* = 4000$ K and $R_* = R_{\rm c} = 8.3 \times 10^{10}$ cm (see Fig. **2**).

Using XSPEC v.12.11 (*50*), we modelled the total SED from LT and *Swift*/UVOT and, jointly, the three points of the PF. The total spectrum is described by the model REDDEN (BBODYRAD$_1$+DISKBB+BBODYRAD$_2$). The REDDEN model describes interstellar extinction (*55*). Component BBODYRAD$_1$ corresponds to the spectrum of the stellar companion, modeled as a blackbody of fixed temperature T_* and radius R_*. The DISKBB corresponds to the multicolor accretion disk. It has two free parameters: normalization, which is related to the inner radius $R_{\rm in}$, and temperature at that radius $T_{\rm in}$. Component BBODYRAD$_2$ corresponds to the UV excess that is modeled by a blackbody with two free parameters: temperature $T_{\rm bb}$ and radius $R_{\rm bb}$. The PF is modeled by the reddened second blackbody multiplied by the polarization fraction $P_{\rm UV}$. Blackbody and disk normalizations were converted to radii assuming the distance to the source of 2.96 kpc as determined by the radio parallax (*15*) and disk inclination $i_{\rm orb} = 73°$ (*12*).

The best-fitting model parameters with the corresponding uncertainties are listed in Table **S4**. We find the accretion disk temperature of about 6200 K, which is very close to that expected for the disk in quiescence (*58*). The inner radius of the disk $R_{\rm in} \approx 6 \times 10^{10}$ cm, which is 30% smaller than the estimate of the circularization radius for the measured $P_{\rm orb}$ and companion-to-black hole mass ratio $q = 0.072 \pm 0.012$ (*12*). The outer radius has to be at least 2–3 times larger to avoid underpredicting the red part of the spectrum. This is consistent with the expectation that the accretion disk size does not exceed the tidal radius of about 2.4×10^{11} cm (*58*).

The temperature of the additional blackbody is $T_{\rm bb} \sim 15,000$ K and the characteristic size $R_{\rm bb} \sim 9 \times 10^9$ cm. This reproduces the shape of the polarized flux SED and the UV excess. The PD of this component is $P_{\rm UV} = 0.055^{+0.023}_{-0.011}$, corresponding to 5–8% intrinsic PD (on average) of the polarized component. The broad-band SED and the best-fitting spectral components are shown in Fig. **2**. The computed values of PF were divided by the constant $P_{\rm UV}$ to demonstrate the fit with the UV excess component.

For lower and higher values of the color excess of 0.25 and 0.325, corresponding to the 1σ uncertainties in $N_{\rm H}$, the best-fitting spectral parameters change. The lower $E(B-V)$ leads to the 8% smaller disk temperature $T_{\rm in}$ and 13% larger inner radius $R_{\rm in}$, 8% smaller blackbody temperature $T_{\rm bb}$ and 3% larger radius $R_{\rm bb}$. For the higher $E(B-V)$, the effect is opposite: $T_{\rm in}$ is 7% larger, $R_{\rm in}$ is 9% smaller, $T_{\rm bb}$ is 7% larger and $R_{\rm bb}$ is smaller by 3%. This uncertainty does not affect any of our conclusions.

The source of polarized light and the nature of the spectral components

In this section we seek to answer two questions: what is the nature of the UV excess and what is the source of polarized radiation? The accretion disk itself cannot be the source of the UV emission, because in quiescence its temperature is lower as we see from the red optical spectrum. Another possibility is a hotspot (or hot line), the place where the accretion stream hits the disk. This component could be responsible for the UV excess. However, whether it can also be the source of polarization is questionable. The high temperature of this component implies that the matter is ionized. The PD from the optically thick electron-scattering dominated atmosphere (*59, 60*) depends on the cosine of the viewing angle $\mu = \cos i_{\rm orb}$ approximately as $11.7\% \times (1-\mu)/(1+3.582\mu)$ (*61*). For inclination angles permitted by the absence of eclipses (*12*), $i_{\rm orb} < 81^\circ$, the expected PD is $\lesssim 6\%$. A high implied PD, $P_{\rm UV} \approx$5–8%, is barely consistent with that.

On the other hand, high PD can be produced by synchrotron radiation in the ordered magnetic field. The blue spectrum indicates that we might see the optically thick part of this radiation, with the possible transition to optically thin part at $\nu \gtrsim 10^{15}$ Hz. Self-absorption becomes important at the turn-over frequency (*62–64*), $\nu_{\rm t} \approx 3 \times 10^{15} B_6^{\frac{p+2}{p+4}} (\tau_{\rm t}\gamma_{\rm t}^p)^{\frac{2}{p+4}}$, where B_6 is the magnetic field in units of 10^6 G, $\tau_{\rm t}$ is the Thomson optical depth of electrons emitting at the turn-over frequency, $\gamma_{\rm t}$ is their Lorentz factor and p is the index of the power-law distribution of electron number density on the Lorentz factor γ, $dn_{\rm e}/d\gamma \propto \gamma^{-p}$. For the observed $\nu_{\rm t} \approx 10^{15}$ Hz, this requires highly opaque source with $\tau_{\rm t}\gamma_{\rm t}^p \sim 1$ and/or high magnetic field with $B_6 \sim 1$, which would be expected in the bright hard state, but inconsistent with the relevant values for the source in (near-)quiescence, when both optical depth and the magnetic field drop by 2 to 4 orders of magnitude (*65*). The highest theoretically possible PD below the self-absorption frequency (*66*) of $P_{\max} = 3/(6p + 13) \sim 10\%$ requires highly ordered – and constant – magnetic field during two years, July 2019–July 2021. Hence, we find the synchrotron radiation to be an implausible source of the observed polarized flux.

Substantial polarization could instead be produced by electron scattering of radiation in an optically thin slab if the seed photons are injected along the slab plane (*67*). The PD$= (1 - \mu^2)/(3 - \mu^2)$ reaches 33% edge-on and is a weak function of orbital inclination (for $i_{\rm orb} \gtrsim 66°$, i.e. $\mu \lesssim 0.41$, the PD is larger than ~30%). Scattering in the Thomson regime means that the scattered radiation does not gain a systematic shift in energy with respect to the incident continuum, and hence the peak of the spectrum of the polarized component directly probes the characteristic energy and spectral shape of the incident radiation. Hence, the source of the incident light should have narrow, blackbody-like shape, with characteristic temperature $T \sim 15,000$ K. Because this temperature is much higher than the disk inner temperature, and the polarization angle is independent of orbital phase, the location and physical properties of such a component are unclear.

The additional polarized component may instead arise from Compton up-scattering of soft photons by hot electrons, which is related to a systematic shift in energy. A hot, geometrically thick accretion flow can exist in low-luminosity black hole binaries and active galactic nuclei (*25,65*). Alternatively, a hot layer (corona) atop of the cold disk, heated by the unwinding stream of matter, could be present. In both cases, the hot medium is expected to be optically thin, and may Compton up-scatter the photons coming from the cold accretion disk. We calculate the spectra and polarization properties of Compton scattering using iterative scattering method (*68*). We assume the spectrum of incident, non-polarized photons is a blackbody with temperature equal to the disk inner temperature $T_{\rm in} = 6200$ K. For these seed photons, to explain the peak of the first scattering order at $\sim 10^{15}$ Hz (as demanded by the spectral decomposition), we need to have electrons with temperature of about 200 keV. For such a high temperature, the PD is expected to drop with respect to the maximal, Thomson-regime PD by a factor of 3 (*69*). In the case of inner hot flow, only the photons travelling at inclinations α to the disk normal that are larger than some critical value $\alpha_{\rm crit}$ can interact with the hot matter. This limiting angle is related to the scale-height H of the hot medium $\cot\alpha_{\rm crit} \sim (H/R_{\rm in})$. Increasing the flow scale-height leads to a drop of PD. In Fig. **S2** we show the resulting flux, polarized flux and PD spectra at different viewing angles $i_{\rm orb} = 66°$, 73° and 81°. In this case the polarization is parallel to the disk normal. We find that the PD of scattered radiation is nearly independent of the photon frequency up to its peak at $\nu \sim 10^{15}$ Hz and therefore the spectral shape of the flux and PF of the scattered component are nearly identical in the optical band.

For the slab-corona geometry, an appropriate parameter determining PD is the Thomson optical depth of the hot slab $\tau_{\rm T}$. Only for $\tau_{\rm T} \gtrsim 0.5$ a substantial polarization exceeding 5% can be produced and the dominant electric-field oscillations are perpendicular to the projection of the disk normal. However, Comptonization in a slab of $\tau_{\rm T} = 0.1$ and electron temperature $kT_{\rm e} = 200$ keV overproduces the observed x-ray flux. This would imply that a more probable model that is more consistent with the observed spectral energy distribution and polarization properties is scattering of the disk radiation in the inner hot flow. Such a geometry favors the measured PA being parallel to the orbital axis.

Finally, the blue PD spectrum could be produced by dust scattering of the accretion disk radiation. This process is thought to be responsible for similarly blue polarization spectra observed from supermassive black holes in Seyfert galaxies and quasars (*26, 70–74*). The dust would likely be located in a flattened envelope (equatorial wedge) around the accretion disk (*73*), where it is shielded from the inner disk radiation, or in a circumbinary disk (*27*). In this case, the polarization vector lies in the meridional plane. If instead the dust has a more spherical distribution, the PD is expected to be smaller and the polarization to be perpendicular to the meridional plane. The dust scattering model, however, does not explain the UV excess.

Geometry

Here we define the coordinate systems and derive the formulae to compute the misalignment angle between the black hole spin and the orbital angular momentum, and the azimuthal angle of the black hole spin projection in the orbital plane. We consider a Cartesian system with the $x-y$ plane coinciding with the orbital plane. Thus the unit vector of the orbital angular momentum is $\hat{\boldsymbol{\Omega}} = (0,0,1)$. We choose the direction to an observer to lie in the $x-z$ plane at inclination angle $i_{\rm orb}$ as measured from the orbital axis (see Fig. **S3** for geometry), so the observer unit vector is

$$\hat{\boldsymbol{o}} = (\sin i_{\rm orb}, 0, \cos i_{\rm orb}). \tag{S4}$$

We assume that the black hole spin is directed at an angle β from the z-axis at azimuthal angle $\Phi_{\rm bh}$, which is measured from the x-axis in the counter-clockwise direction in the $x-y$ plane as viewed from the top. The unit vector of the black hole spin is

$$\hat{\boldsymbol{s}} = (\sin\beta\cos\Phi_{\rm bh}, \sin\beta\sin\Phi_{\rm bh}, \cos\beta). \tag{S5}$$

We define the polarization basis with the unit vector $\hat{\boldsymbol{e}}_1$ directed on the sky in the direction of the projection of the orbital spin, vector $\hat{\boldsymbol{e}}_2$ being directed to the left on the sky, and the third vector coincides with the observer direction:

$$\begin{aligned} \hat{\boldsymbol{e}}_1 &= \frac{\hat{\boldsymbol{\Omega}} - \cos i_{\rm orb}\,\hat{\boldsymbol{o}}}{\sin i_{\rm orb}} = (-\cos i_{\rm orb}, 0, \sin i_{\rm orb}), \\ \hat{\boldsymbol{e}}_2 &= (0,-1,0), \\ \hat{\boldsymbol{e}}_3 &= \hat{\boldsymbol{o}}. \end{aligned} \tag{S6}$$

In this vector basis, the black hole and the orbital spin vectors can be represented as

$$\hat{\boldsymbol{s}} = (\sin i_{\rm bh}\cos\Delta, \sin i_{\rm bh}\sin\Delta, \cos i_{\rm bh}), \tag{S7}$$

$$\hat{\boldsymbol{\Omega}} = (\sin i_{\rm orb}, 0, \cos i_{\rm orb}), \tag{S8}$$

where $\Delta = \theta_{\rm bh} - \theta_{\rm orb}$ is the difference in position angles of the black hole and the orbital spins. The misalignment angle β between the black hole and the orbital axis is then given by the scalar product:

$$\cos\beta = \hat{\boldsymbol{\Omega}} \cdot \hat{\boldsymbol{s}} = \cos i_{\rm bh} \cos i_{\rm orb} + \sin i_{\rm bh} \sin i_{\rm orb} \cos\Delta. \tag{S9}$$

The direction cosines of the black hole spin vector $\hat{\boldsymbol{s}}$ in polarization basis are

$$\begin{aligned}
\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{e}}_1 &= \sin i_{\rm bh} \cos\Delta = \cos\beta \sin i_{\rm orb} - \sin\beta \cos i_{\rm orb} \cos\Phi_{\rm bh}, \\
\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{e}}_2 &= \sin i_{\rm bh} \sin\Delta = -\sin\beta \sin\Phi_{\rm bh}, \\
\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{e}}_3 &= \cos i_{\rm bh} = \cos\beta \cos i_{\rm orb} + \sin\beta \sin i_{\rm orb} \cos\Phi_{\rm bh},
\end{aligned} \tag{S10}$$

allowing us to obtain the azimuthal angle of the black hole spin:

$$\begin{aligned}
\cos\Phi_{\rm bh} &= \frac{\sin i_{\rm orb} \cos i_{\rm bh} - \cos i_{\rm orb} \sin i_{\rm bh} \cos\Delta}{\sin\beta}, \\
\sin\Phi_{\rm bh} &= -\frac{\sin i_{\rm bh} \sin\Delta}{\sin\beta}.
\end{aligned} \tag{S11}$$

We assume that the black hole spin is aligned with the jet. If the spin is directed along the southern approaching jet, then its inclination $i_{\rm bh} = i_{\rm jet} = 63^\circ \pm 3^\circ$ and its position angle is $\theta_{\rm bh} = 180^\circ + \theta_{\rm jet} = 205\overset{\circ}{.}1 \pm 1\overset{\circ}{.}4$ (*15–17*). If, on the other hand, the black hole spin points along the northern receding jet, then $i_{\rm bh} = 180^\circ - i_{\rm jet} = 117^\circ \pm 3^\circ$ and its position angle is $\theta_{\rm bh} = \theta_{\rm jet} = 25\overset{\circ}{.}1 \pm 1\overset{\circ}{.}4$.

The polarimetric data provide us with the average polarization angle $\langle{\rm PA}\rangle = -19\overset{\circ}{.}7 \pm 1\overset{\circ}{.}2$, which carries information about orientation of the orbital axis on the sky. If dominant oscillations of the electric field lie in the meridional plane formed by the orbital spin and photon propagation direction, the position angle of the orbital spin can be either $\theta_{\rm orb} = \langle{\rm PA}\rangle$ or $\langle{\rm PA}\rangle + 180^\circ$. The electric field oscillations can also be perpendicular to the meridional plane, then the orbital spin position angle is $\langle{\rm PA}\rangle + 90^\circ$ or $\langle{\rm PA}\rangle + 270^\circ$. Furthermore, the radial velocity measurements are not able to differentiate between inclinations $i_{\rm orb}$ and $180^\circ - i_{\rm orb}$. The possible combinations result in 16 different geometrical arrangements of the black hole and orbital spins that satisfy the observational constraints. These 16 cases can be reduced to eight different values for the misalignment angle β: four for misalignment less than 90° and four for misalignment between 90° and 180° for the retrograde rotation of the black hole (Table **S5**).

The probability distribution for the orbital inclination $i_{\rm orb}$ was assumed to be a Gaussian with the peak at 73° with 1σ error of 6° and a cutoff at 81° (*12, 22*). For an alternative case of inclination exceeding 90°, the distribution mirror reflected relative to 90° is considered. Other parameters are assumed to follow a Gaussian distribution with corresponding 1σ errors. Using Monte-Carlo simulations (*33*), we obtain the probability distributions for β and $\Phi_{\rm bh}$ using Equations (S9) and (S11), respectively. Their mean and standard deviation are given in Table **S5**. In Fig. **S4** we show the posterior probability distribution for β for the eight different cases from Table **S5**. The probability distributions for $\Phi_{\rm bh}$ for the 16 cases from Table **S5** are shown in Fig. **S5**.

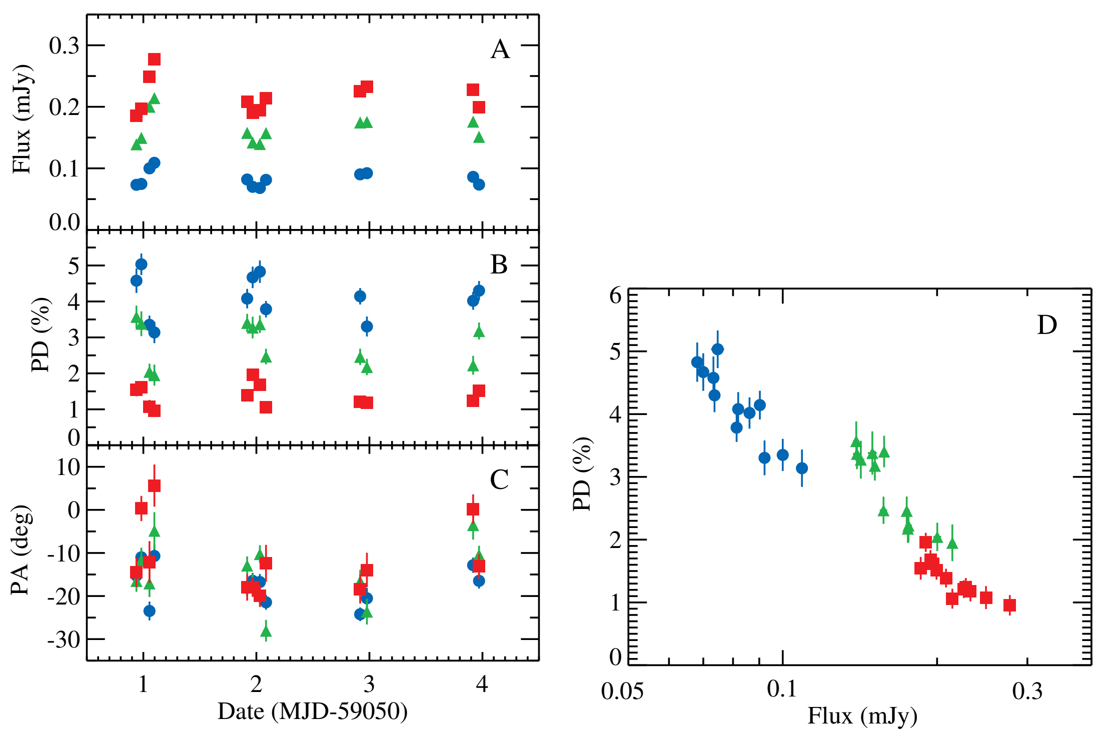

Figure S1: **Variation of flux and polarization.** **(A)** The dependence of the observed flux (not corrected for reddening), **(B)** intrinsic source PD and **(C)** PA on time during the July 2020 observations of MAXI J1820+070 with DIPol-UF in three filters: B (blue circles), V (green triangles), and R (red squares). **(D)** Dependence of the PD on flux in the same three filters. An anticorrelation is evident.

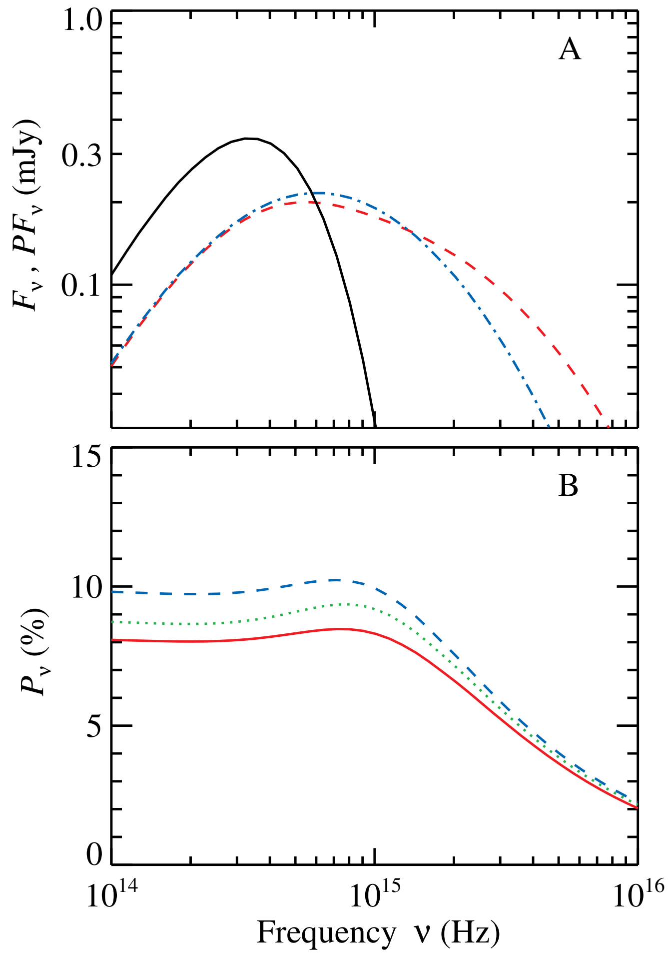

Figure S2: **Polarization properties of the hot accretion flow model.** **(A)** Flux from the spectral components: blackbody ($T_{\rm in} = 6200$ K, black solid line) and first Compton scattering of these photons by hot medium (red dashed line) with $kT_{\rm e} = 200$ keV and scale-height given by parameter $\cos\alpha_{\rm crit} = 0.5$, and spectrum of the polarized flux of the first scattering component (blue dot-dashed line) that has been scaled up to match the low-energy part of the intensity spectrum (divided by the PD at low energies). This shows that the polarized flux has the same shape as the scattered component flux, justifying our joint model fitting of the UV flux together with the polarized flux (shown in Fig. **2**). Only results for inclination of $i_{\rm orb} = 73°$ are shown, as the dependence on the inclination in its allowed range is minor. **(B)** PD of the scattered component as a function of frequency is shown for different inclinations $i_{\rm orb} = 81°$ (blue dashed line), $73°$ (green dotted) and $66°$ (red solid). PD for energies below the peak of the scattered component is nearly frequency-independent. The observed strong dependence of the PD on frequency is caused by the dilution of the polarized scattered radiation by the unpolarized accretion disk.

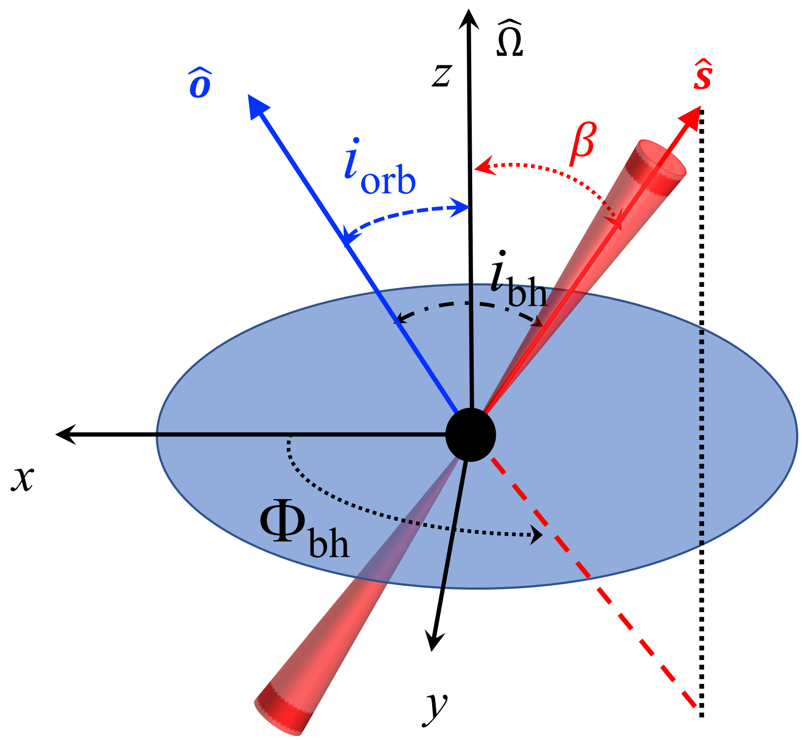

Figure S3: **Geometry of the system from the point of view of the binary.** The orbital plane here coincides with the $x-y$ plane of the Cartesian system with the orbital axis being along the z-axis. The observer is situated in the $x-z$ plane at inclination angle $i_{\rm orb}$ as measured from the orbital axis. The black hole spin is directed at angle β from the z-axis at azimuthal angle $\Phi_{\rm bh}$ as measured from the x-axis in the counter-clockwise direction in the $x-y$ plane as viewed from the top. The red cones indicate the jet, and the blue disk indicates the binary orbit. Fig. **3** shows the same geometry from the observer's perspective.

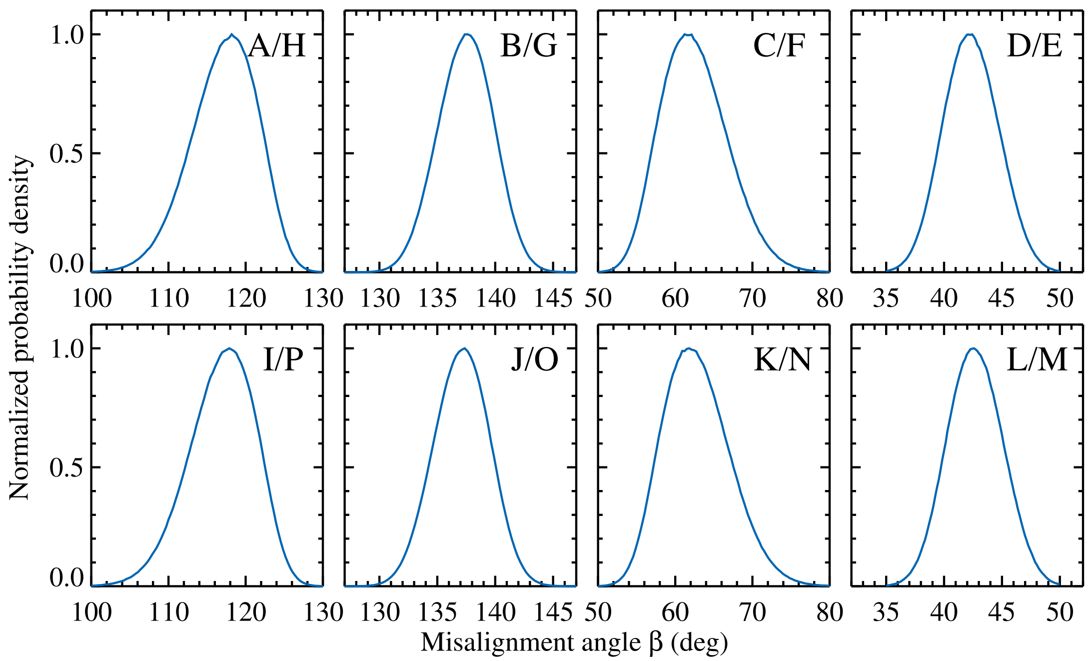

Figure S4: **Probability distribution function for the misalignment angle.** Distributions normalized to the peak values are shown for the eight different cases presented in Table **S5**.

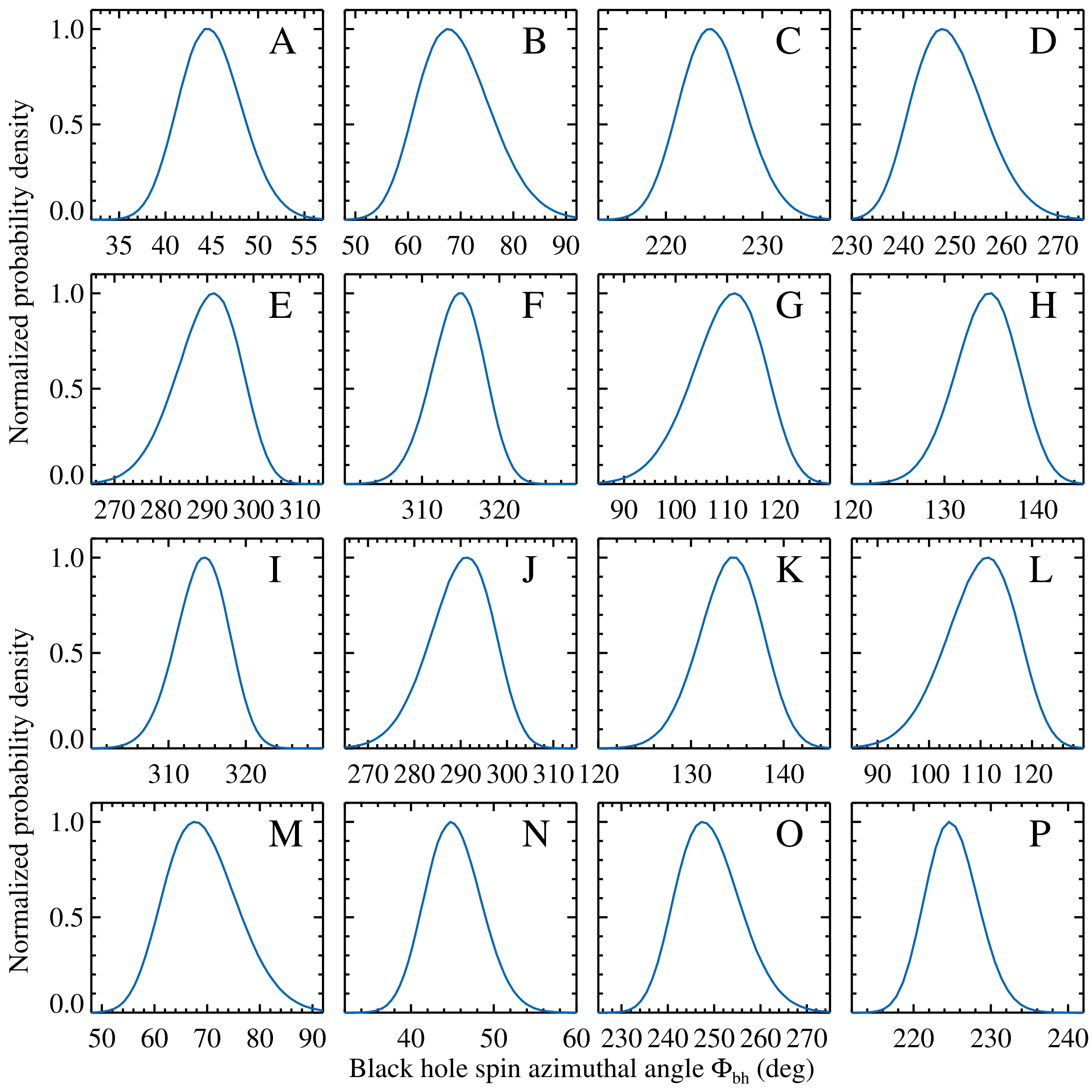

Figure S5: **Probability distribution function for the black hole spin azimuthal angle.** Distributions normalized to the peak values are shown for the 16 different cases **(A-P)** presented in Table **S5**.

Table S1: **Intrinsic polarization of MAXI J1820+070.** The intrinsic values of the PD and PA derived from observations of MAXI J1820+070 during the outburst with DIPol-2 (*20, 21*) and during quiescence with DIPol-UF at NOT. Uncertainties are 1σ. The Stokes parameters have been corrected for the interstellar polarization. The dates for observations during quiescence correspond to the middle of observing windows of a typical duration of one hour.

Date	B		V		R	
(MJD)	PD (%)	PA (deg)	PD (%)	PA (deg)	PD (%)	PA (deg)
			Outburst			
58195–58222	0.28 ± 0.01	9.2 ± 1.0	0.36 ± 0.01	22.9 ± 1.0	0.30 ± 0.01	29.0 ± 0.9
58223–58234	0.34 ± 0.02	8.8 ± 1.4	0.51 ± 0.02	23.4 ± 1.4	0.53 ± 0.02	23.9 ± 1.1
58312–58344	0.16 ± 0.01	-15.8 ± 1.6	0.15 ± 0.01	13.4 ± 2.3	0.02 ± 0.01	39.1 ± 11.0
58406–58428	0.06 ± 0.04	-3.0 ± 15.4	0.13 ± 0.06	2.8 ± 12.4	0.09 ± 0.04	44.8 ± 12.5
			Quiescence			
58686.93	3.86 ± 0.29	-23.8 ± 2.1	1.81 ± 0.24	-23.8 ± 3.8	0.70 ± 0.14	-24.1 ± 5.7
58688.01	2.35 ± 0.38	-25.9 ± 4.7	1.09 ± 0.25	8.0 ± 6.5	1.70 ± 0.10	-42.4 ± 1.7
58961.15	1.47 ± 0.28	-26.8 ± 5.4	0.52 ± 0.24	-4.2 ± 13.3	0.63 ± 0.19	8.5 ± 8.7
58964.16	4.31 ± 0.28	-18.5 ± 1.8	3.10 ± 0.29	-17.5 ± 2.7	1.05 ± 0.18	-2.0 ± 4.8
58965.11	2.81 ± 0.24	-23.5 ± 2.5	2.12 ± 0.21	-35.1 ± 2.9	0.84 ± 0.18	-26.3 ± 6.2
58967.12	4.53 ± 0.28	-24.1 ± 1.8	2.09 ± 0.39	-11.0 ± 5.3	1.09 ± 0.31	-27.0 ± 8.3
59050.94	4.58 ± 0.34	-15.3 ± 2.1	3.57 ± 0.31	-16.5 ± 2.5	1.54 ± 0.18	-14.5 ± 3.4
59050.98	5.03 ± 0.30	-11.0 ± 1.7	3.38 ± 0.34	-11.7 ± 2.9	1.62 ± 0.16	0.3 ± 2.9
59051.05	3.35 ± 0.26	-23.5 ± 2.2	2.04 ± 0.23	-17.1 ± 3.2	1.08 ± 0.18	-12.1 ± 4.9
59051.10	3.14 ± 0.30	-10.7 ± 2.7	1.95 ± 0.29	-4.8 ± 4.3	0.95 ± 0.16	5.6 ± 4.9
59051.92	4.08 ± 0.27	-18.1 ± 1.9	3.40 ± 0.25	-12.9 ± 2.1	1.39 ± 0.15	-18.0 ± 3.1
59051.97	4.67 ± 0.30	-16.5 ± 1.8	3.27 ± 0.30	-17.5 ± 2.6	1.96 ± 0.15	-17.9 ± 2.2
59052.03	4.83 ± 0.31	-16.7 ± 1.9	3.37 ± 0.24	-10.3 ± 2.1	1.68 ± 0.15	-20.0 ± 2.6
59052.09	3.78 ± 0.23	-21.5 ± 1.7	2.47 ± 0.22	-28.0 ± 2.5	1.06 ± 0.16	-12.4 ± 4.3
59052.92	4.14 ± 0.23	-24.2 ± 1.6	2.46 ± 0.23	-16.6 ± 2.7	1.21 ± 0.14	-18.4 ± 3.3
59052.98	3.30 ± 0.28	-20.5 ± 2.4	2.18 ± 0.23	-23.6 ± 3.0	1.18 ± 0.17	-14.0 ± 4.0
59053.92	4.02 ± 0.25	-12.8 ± 1.8	2.22 ± 0.26	-3.5 ± 3.4	1.24 ± 0.15	0.2 ± 3.4
59053.97	4.30 ± 0.27	-16.5 ± 1.8	3.18 ± 0.24	-10.4 ± 2.1	1.51 ± 0.15	-13.1 ± 2.9
59400.99	1.62 ± 0.12	-30.5 ± 2.0	0.77 ± 0.10	-17.1 ± 3.9	0.41 ± 0.07	6.4 ± 5.1
59401.94	2.86 ± 0.21	-25.4 ± 2.1	2.04 ± 0.20	-29.9 ± 2.8	0.36 ± 0.14	-6.1 ± 10.7
59051–59054	4.00 ± 0.19	-17.5 ± 1.3	2.65 ± 0.19	-14.7 ± 1.9	1.32 ± 0.08	-12.8 ± 2.3
58686–59402	3.18 ± 0.22	-19.7 ± 1.2	1.89 ± 0.19	-16.8 ± 1.9	0.94 ± 0.11	-18.6 ± 3.3
			Interstellar polarization			
58195–59054	0.81 ± 0.03	64.0 ± 1.1	0.71 ± 0.03	68.4 ± 1.2	0.60 ± 0.02	64.4 ± 0.8

Table S2: **Observed flux of MAXI J1820+070.** Mean fluxes and their 1σ uncertainties derived from observations of MAXI J1820+070 during quiescence in July 2020 with DIPol-UF at NOT.

Date	Flux (mJy)		
(MJD)	B	V	R
59050.94	0.0732 ± 0.0014	0.1391 ± 0.0019	0.1858 ± 0.0020
59050.98	0.0747 ± 0.0022	0.1495 ± 0.0030	0.1966 ± 0.0029
59051.05	0.1000 ± 0.0022	0.2002 ± 0.0034	0.2491 ± 0.0035
59051.10	0.1090 ± 0.0018	0.2142 ± 0.0030	0.2772 ± 0.0028
59051.92	0.0819 ± 0.0015	0.1577 ± 0.0021	0.2082 ± 0.0023
59051.97	0.0700 ± 0.0014	0.1420 ± 0.0022	0.1901 ± 0.0022
59052.03	0.0681 ± 0.0015	0.1395 ± 0.0024	0.1941 ± 0.0025
59052.09	0.0813 ± 0.0018	0.1572 ± 0.0026	0.2142 ± 0.0027
59052.92	0.0902 ± 0.0015	0.1745 ± 0.0023	0.2255 ± 0.0023
59052.98	0.0922 ± 0.0021	0.1754 ± 0.0031	0.2323 ± 0.0031
59053.92	0.0861 ± 0.0017	0.1759 ± 0.0027	0.2275 ± 0.0028
59053.97	0.0736 ± 0.0013	0.1512 ± 0.0020	0.1995 ± 0.0020

Table S3: **Log of observations with the Liverpool Telescope.** The observed fluxes of MAXI J1820+070 and their 1σ uncertainties in various filters.

Date (MJD)	Filter	Exposure (s)	Flux (mJy)	Date (MJD)	Filter	Exposure (s)	Flux (mJy)
59050.92075	i	100	0.2700±0.0014	59052.92842	z	100	0.3944±0.0033
59050.92213	i	100	0.2468±0.0015	59052.92980	z	100	0.4037±0.0033
59050.92350	i	100	0.2482±0.0015	59052.93193	V	200	0.1605±0.0011
59050.92505	z	100	0.3990±0.0028	59052.93463	B	200	0.0974±0.0007
59050.92642	z	100	0.4093±0.0029	59052.93637	r	40	0.3063±0.0018
59050.92780	z	100	0.3733±0.0029	59052.93705	r	40	0.2142±0.0018
59050.93052	V	300	0.1440±0.0009	59053.92120	i	100	0.3071±0.0017
59051.01279	i	100	0.3321±0.0014	59053.92257	i	100	0.3600±0.0018
59051.01417	i	100	0.3075±0.0014	59053.92395	i	100	0.3450±0.0018
59051.01554	i	100	0.3164±0.0014	59053.92550	z	100	0.3917±0.0033
59051.01709	z	100	0.4208±0.0027	59053.92687	z	100	0.3598±0.0033
59051.01846	z	100	0.5048±0.0028	59053.92825	z	100	0.3736±0.0034
59051.01984	z	100	0.4703±0.0027	59053.93038	V	200	0.1369±0.0011
59051.02254	B	300	0.1263±0.0005	59053.93308	B	200	0.0762±0.0007
59051.09342	i	100	0.3476±0.0016	59053.93482	r	40	0.2281±0.0019
59051.09479	i	100	0.3489±0.0016	59053.93550	r	40	0.2174±0.0019
59051.09617	i	100	0.3809±0.0015	59053.95474	i	100	0.2752±0.0016
59051.09771	z	100	0.4877±0.0032	59053.95612	i	100	0.2927±0.0016
59051.09909	z	100	0.4963±0.0033	59053.95750	i	100	0.2633±0.0017
59051.10047	z	100	0.4706±0.0033	59053.95904	z	100	0.3587±0.0032
59051.10168	r	40	0.2339±0.0019	59053.96042	z	100	0.3824±0.0030
59051.10236	r	40	0.2592±0.0018	59053.96180	z	100	0.4097±0.0033
59051.92206	i	100	0.3003±0.0015	59053.96393	V	200	0.1467±0.0010
59051.92343	i	100	0.2982±0.0015	59053.96663	B	200	0.0799±0.0007
59051.92481	i	100	0.2860±0.0015	59053.97116	i	100	0.3032±0.0042
59052.01060	i	100	0.2838±0.0016	59053.97254	i	100	0.3390±0.0016
59052.01197	i	100	0.2693±0.0015	59053.97391	i	100	0.3308±0.0016
59052.01335	i	100	0.2501±0.0016	59053.97546	z	100	0.4278±0.0032
59052.09336	i	100	0.2979±0.0015	59053.97684	z	100	0.4017±0.0032
59052.09474	i	100	0.2800±0.0016	59053.97821	z	100	0.4193±0.0031
59052.09611	i	100	0.2974±0.0015	59053.98035	V	200	0.1535±0.0010
59052.92275	i	100	0.3161±0.0017	59053.98305	B	200	0.0601±0.0007
59052.92412	i	100	0.3058±0.0016	59053.98479	r	40	0.2427±0.0017
59052.92550	i	100	0.3048±0.0017	59053.98546	r	40	0.2100±0.0017
59052.92705	z	100	0.3686±0.0034				

Table S4: **Best-fitting parameters of the SED model.** Distance of 2.96 kpc (*15*) and inclination $i_{\rm orb} = 73°$ (*12*) are assumed. The temperature and the radius of the blackbody approximating the SED of the stellar companion were fixed.

Parameter	Value	Units
$T_{\rm in}$	6200^{+1400}_{-1100}	K
$R_{\rm in}$	$(5.6^{+2.7}_{-1.8}) \times 10^{10}$	cm
$T_{\rm bb}$	14900^{+2300}_{-1400}	K
$R_{\rm bb}$	$(8.9^{+2.3}_{-2.1}) \times 10^{9}$	cm
T_{*}	4000	K
R_{*}	8.3×10^{10}	cm
$P_{\rm UV}$	$0.055^{+0.023}_{-0.011}$	

Table S5: **Geometrical parameters.** Geometrical parameters for the 16 possible cases identified by letters A–P of relative orientation of the orbital and the black hole spins.

	$i_{\rm bh}$		$i_{\rm jet} = 63° \pm 3°$				$180° - i_{\rm jet} = 117° \pm 3°$		
	$\theta_{\rm bh}$		$\theta_{\rm jet} + 180° = 205\overset{\circ}{.}1 \pm 1\overset{\circ}{.}4$				$\theta_{\rm jet} = 25\overset{\circ}{.}1 \pm 1\overset{\circ}{.}4$		
	$i_{\rm orb}$		$73° \pm 6°$		$107° \pm 6°$		$73° \pm 6°$		$107° \pm 6°$
			Polarization parallel to the meridional plane						
$\theta_{\rm orb} = \langle{\rm PA}\rangle$ =$-19\overset{\circ}{.}7 \pm 1\overset{\circ}{.}2$	β (deg)	A	117.3 ± 4.3	B	137.6 ± 2.4	C	62.7 ± 4.3	D	42.4 ± 2.4
	$\Phi_{\rm bh}$ (deg)		45.2 ± 3.4		69.7 ± 7.0		225.2 ± 3.4		249.0 ± 7.0
$\theta_{\rm orb} = \langle{\rm PA}\rangle$+180°	β (deg)	E	42.4 ± 2.4	F	62.7 ± 4.3	G	137.6 ± 2.4	H	117.3 ± 4.3
	$\Phi_{\rm bh}$ (deg)		289.8 ± 7.0		314.8 ± 3.4		110.3 ± 7.0		134.8 ± 3.4
			Polarization perpendicular to the meridional plane						
$\theta_{\rm orb} = \langle{\rm PA}\rangle$+90°	β (deg)	I	117.0 ± 4.3	J	137.2 ± 2.4	K	63.0 ± 4.3	L	42.8 ± 2.4
	$\Phi_{\rm bh}$ (deg)		314.5 ± 3.4		290.3 ± 6.9		134.5 ± 3.4		110.3 ± 6.9
$\theta_{\rm orb} = \langle{\rm PA}\rangle$+270°	β (deg)	M	42.8 ± 2.4	N	63.0 ± 4.3	O	137.3 ± 2.4	P	117.0 ± 4.3
	$\Phi_{\rm bh}$ (deg)		69.7 ± 6.9		45.5 ± 3.4		249.7 ± 6.9		225.5 ± 3.4

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