



# X-Ray, Optical, and Near-infrared Monitoring of the New X-Ray Transient MAXI J1820+070 in the Low/Hard State

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## Abstract

We report X-ray, optical, and near-infrared monitoring of the new X-ray transient MAXI J1820+070 discovered with MAXI on 2018 March 11. Its X-ray intensity reached  $\sim 2$  crab at 2–20 keV at the end of March, and then gradually decreased until the middle of June. In this period, the X-ray spectrum was described by Comptonization of the disk emission, with a photon index of  $\sim 1.5$  and an electron temperature of  $\sim 50$  keV, which is consistent with a black hole X-ray binary in the low/hard state. The electron temperature was slightly decreased, and the photon index increased, with increasing flux. The source showed significant X-ray flux variation on a timescale of seconds. This short-term variation was found to be associated with changes in the spectral shape, and the photon index became slightly harder at higher fluxes. This suggests that the variation was produced by a change in the properties of the hot electron cloud responsible for the strong Comptonization. Modeling a multi-wavelength spectral energy distribution around the X-ray flux peak at the end of March, covering the near-infrared to X-ray bands, we found that the optical and near-infrared fluxes were likely contributed substantially by the jet emission. Before this outburst, the source was never detected in the X-ray band with MAXI (with a  $3\sigma$  upper limit of  $\sim 0.2$  mcrab at 4–10 keV, obtained from seven years of data from 2009 to 2016), whereas weak optical and infrared activity was found at flux levels  $\sim 3$  orders of magnitude lower than the peak fluxes in the outburst.

**Key words:** accretion, accretion disks – black hole physics – X-rays: binaries – X-rays: individual (MAXI J1820+070)

## 1. Introduction

Transient Galactic black hole binaries (BHBs) provide opportunities to study the evolution of black hole accretion flows over a wide range of mass accretion rates (e.g., McClintock & Remillard 2006; Done et al. 2007, for reviews). They are usually too faint to detect in the X-ray band, but suddenly increase their X-ray luminosity by orders of magnitude on timescales of days to weeks. At low luminosities, they stay in the so-called low/hard state and show a power-law-shaped hard spectrum, often with an exponential cutoff at  $\sim 100$  keV. This spectral profile is often interpreted as thermal Comptonization of the soft X-ray photons from the truncated standard disk, in a hot electron cloud developed somewhere around the disk. However, the geometry of the Comptonized region is not yet clear. Moreover, energetic electrons and the synchrotron emission produced in jets may contribute to

the Comptonized component, but the extent to which they do is still in debate. Multi-wavelength observations are important for tackling these questions, because the main part of the jet synchrotron emission is normally located in the radio to optical band.

MAXI J1820+070 was discovered with the MAXI (Matsuoka et al. 2009)/Gas Slit Camera (GSC; Mihara et al. 2011). The MAXI Nova Search System (Negoro et al. 2016) first triggered the source at 2018 March 11 UT 12:50 (Kawamuro et al. 2018). Soon after the discovery, the source was associated with the optical variable source ASSASN-2018ey (Denisenko 2018), discovered by All-Sky Automated Survey for SuperNovae (ASAS-SN) on 2018 Mar 6 in optical (Tucker et al. 2018). The position of the X-ray source was precisely determined in follow-up observations with *Swift*, as  $(\alpha^{2000}, \delta^{2000}) = (18^{\text{h}}20^{\text{m}}21^{\text{s}}.88, +07^{\circ}11'08''.3)$ , which was consistent with the position of ASSASN-2018ey.

The relatively small interstellar absorption/extinction, with a hydrogen column density of  $\sim 10^{21} \text{ cm}^{-2}$ , and the high flux, exceeding 1 crab at 2–20 keV at the peak, have motivated extensive multi-wavelength follow-up observations of MAXI J1820+070 during the outburst (Baglio et al. 2018; Bahramian et al. 2018; Berdyugin et al. 2018; Bozzo et al. 2018; Bright et al. 2018; Casella et al. 2018; Del Santo & Segreto 2018; Floers et al. 2018; Gandhi et al. 2018a; Garnavich & Littlefield 2018; Kennea et al. 2018; Kennea & Siegel 2018; Kennea 2018; Kuulkers et al. 2018; Littlefield 2018; Mandal et al. 2018a, 2018b; Mereminskiy et al. 2018; Munoz-Darias et al. 2018; Paice et al. 2018; Russell et al. 2018; Sako et al. 2018; Tetarenko et al. 2018; Trushkin et al. 2018; Uttley et al. 2018). Until the middle of June, the source always showed a power-law-shaped X-ray spectrum with a photon index of  $\sim 1.5$ , consistent with BHB spectra in the low/hard state. The source was found to show strong optical and X-ray short-term variability on timescales of less than 1 s (Gandhi et al. 2018a; Sako et al. 2018), and low-frequency quasi-periodic oscillations (QPOs) were detected in both X-ray and optical bands at 10–50 mHz (Gandhi et al. 2018a; Mereminskiy et al. 2018; Yu et al. 2018). A radio counterpart was also detected (Bright et al. 2018; Tetarenko et al. 2018; Trushkin et al. 2018), suggesting the presence of jets. After the decay in X-ray flux until the middle of June, the source started to increase its X-ray flux again. Then, it showed an X-ray spectral softening in July, at a flux comparable to the first peak (Homan et al. 2018).

In this article, we investigate the nature of MAXI J1820+070, mainly focusing on the period before the X-ray re-brightening, using X-ray data obtained from monitoring observations with MAXI, *Swift*, and optical and near-infrared (IR) data from ground-based telescopes participating in the collaboration of Optical and Infrared Synergetic Telescopes for Education and Research (OISTER) in Japan. Throughout this work, we utilized HEASoft version 6.23 for the X-ray data reduction, and XSPEC version 12.10.0 with the solar abundance table given by Wilms et al. (2000) for the spectral analysis. Errors represent the 90% confidence ranges for one parameter, unless stated otherwise.

## 2. X-Ray Data

### 2.1. Observations and Data Reduction

#### 2.1.1. MAXI Data

We reduced the MAXI/GSC event data with the processed version 1.3.6.6, through the MAXI analysis tools implemented in “MAXI/GSC on-demand web interface”<sup>18</sup> (Nakahira et al. 2013). The source events were extracted from a circular region with a radius of  $2^\circ$ , centered at the target position. Background events were collected from the source-free region within  $3^\circ$  of the source position, determined by excluding the source region and  $2^\circ$  from nearby bright sources.

Figure 1 shows the MAXI/GSC light curves of MAXI J1820+070 at 2–6 keV and 6–20 keV and their hardness ratios (HRs), together with the *Swift*/BAT light curve at 15–50 keV, downloaded from the “BAT Transient Monitor” website (Krimm et al. 2013),<sup>19</sup> with a time bin the length of their orbital periods ( $\sim 92$  minutes; black points in Figure 1). The

soft and hard X-ray fluxes rapidly increased in the initial phase of the outburst, and around March 20, they reached their peak level of  $\sim 5 \text{ photons s}^{-1} \text{ cm}^{-2}$  at 2–20 keV, corresponding to  $\sim 2$  crab. The source started dimming in early April, then from the middle of June it increased its flux again. The HR was almost constant before the re-brightening. To reduce the statistical errors, we binned 1–40 adjacent data points that have similar flux levels, as shown in red in Figure 1, and created time-averaged GSC spectra in these individual bins.

We also investigated whether or not the source was detected with MAXI/GSC before the 2018 outburst. We created light curves with bins of 72 days at 3–4 keV, 4–10 keV, and 10–20 keV, applying the image fitting technique to the GSC data from 2009 September to 2016 July, in the same manner as those adopted in the MAXI Galactic and extragalactic X-ray source catalogs (Hori et al. 2018; Kawamuro et al. 2018). We found, however, that the source was not detected significantly at any period, and estimated  $3\sigma$  upper limits of the seven-year averaged fluxes as  $\sim 0.2$  mcrab at 4–10 keV,  $\sim 0.1$  mcrab at 3–4 keV, and  $\sim 1.0$  mcrab at 10–20 keV.

#### 2.1.2. Swift Data

To acquire information at higher energies, we created hard X-ray spectra of MAXI J1820+070 from *Swift*/BAT-survey data. We processed the BAT-survey data downloaded from the HEADAS archive<sup>20</sup> via the `ftool batsurvey`, and then generated the time-averaged spectra and their response files in the individual continuous scans using the script `make_survey pha`. We selected the scans that partially or totally overlapped with the intervals of MAXI/GSC spectra, and used those scan data in the spectral analysis. If multiple BAT scans overlapping the interval of a MAXI spectrum were present, we adopted the one with the longest overlapping time. If there were no overlapping scans, we discarded the MAXI data. In the end, we obtained 63 quasi-simultaneous MAXI/GSC and *Swift*/BAT-survey spectra, covering the 3–200 keV band.

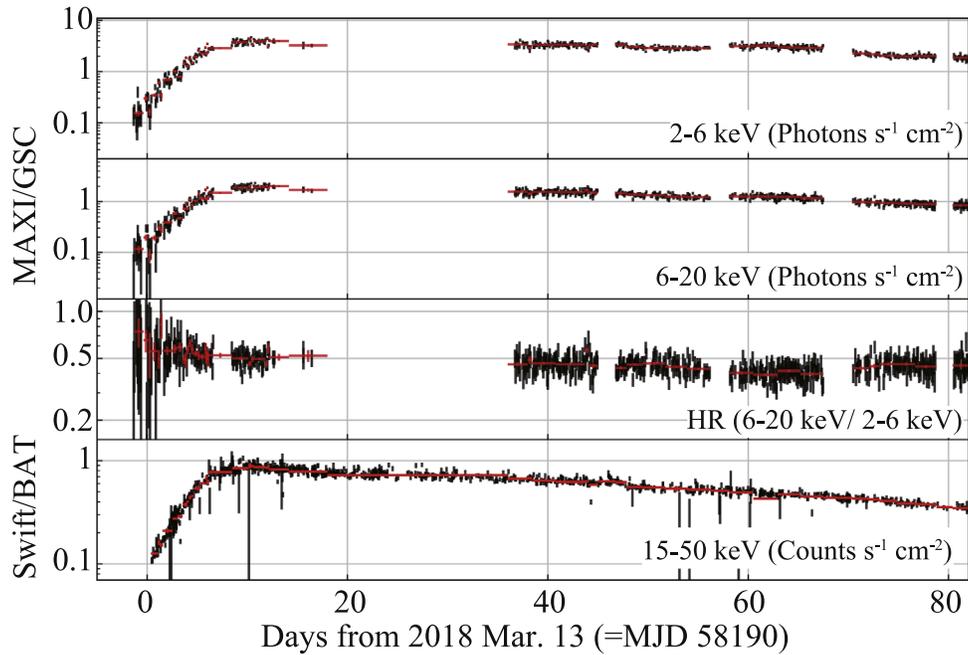
To investigate the more detailed spectral profile and X-ray variations on shorter timescales, we also analyzed the simultaneous *Swift*/XRT and BAT *event-by-event* data (hereafter called BAT-event data), occasionally taken during the outburst. We picked out the observation IDs (OBSIDs) containing both XRT and BAT-event data (OBSID = 00010627014, 00010627015, 00010627018, 00010627026, 00010627035, 00010627036, 00010627045, 00088657002, 00814259000, 00815603000) to create their light curves and spectra.

The OBSID = 00814259000 data were acquired on March 14, one day after the discovery with MAXI, and the other data sets were taken after March 19, when the source flux almost reached its peak level. We found that all the data sets obtained after March 19 had similar spectral and temporal properties and gave similar results. In the following, we just show the results from the data with OBSID = 00814259000 (hereafter Data-1) and 00010627014 (Data-2), as representative data at the beginning of the outburst and at about the first flux peak, respectively. The former observation was performed from March 14 UT 19:14:16 to 20:55:54, with net exposures of  $\sim 1.0$  ks for the XRT and  $\sim 0.5$  ks for the BAT, and the latter was from March 25 UT 04:07:30 to 04:23:56, with a  $\sim 2.4$  ks exposure for the XRT and  $\sim 0.5$  ks for the BAT. The XRT was operated in the Windowed Timing mode in both observations.

<sup>18</sup> <http://maxi.riken.jp/mxondem>

<sup>19</sup> <http://swift.gsfc.nasa.gov/docs/swift/results/transients>

<sup>20</sup> <https://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/>



**Figure 1.** MAXI/GSC light curves of MAXI J1820+070 at 2–6 and 6–20 keV, their hardness ratio, and the *Swift*/BAT light curve at 15–50 keV, from top to bottom. The black points present the data with orbital time bins ( $\sim 92$  minutes) and the red points show binned data. The error bars represent  $1\sigma$  statistical errors.

The XRT data were first reprocessed through the `fool xrtpipeline` with the calibration database (CALDB) downloaded in 2018 February. Then, the source signals were extracted from a circular region with a radius of 30 pixels, centered at the source position. To avoid pileup effects, we excluded the events in the core of the point-spread function (PSF) with a radius of 5 pixels for Data-1 and 15 pixels for Data-2, so that the count rate is well below  $150 \text{ counts s}^{-1}$  (see Evans et al. 2009). The background region of each data set was defined as an annulus with inner and outer radii of 80 and 120 pixels, respectively, centered at the target position. We employed `swxwt0to2s6psf3_20131212v001.rmf` in the CALDB as the XRT response matrix file. The ancillary response files (ARFs) of the individual observations were created via `xrtmkarf` by considering the PSF profile.

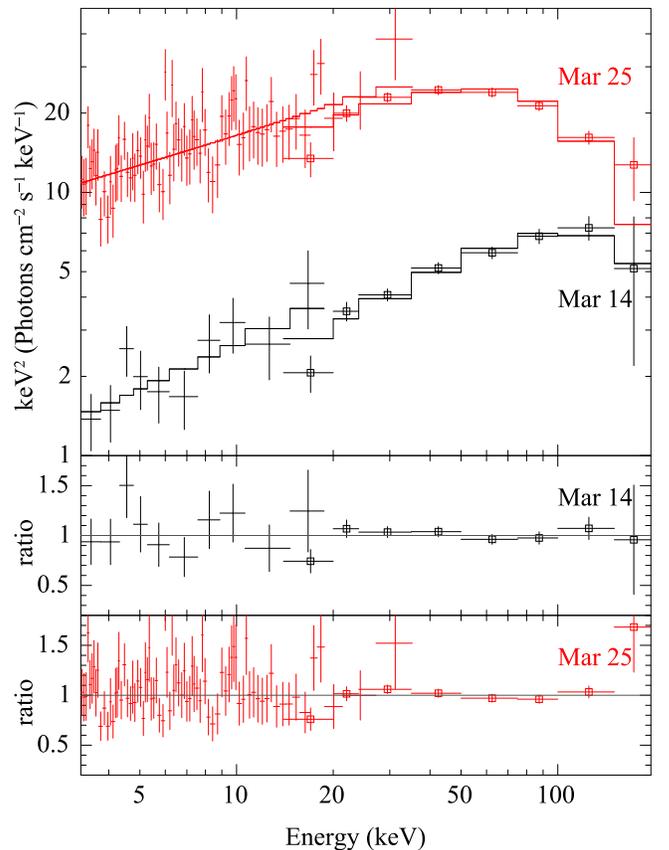
By using the *Swift*/BAT-event data, energy spectra and light curves were produced in the standard manner as described in Sakamoto et al. (2007). We created the energy response files with the `fool batdrngen` and added systematic error vectors to the spectral files with `batphasyserr`, before the spectral analysis.

## 2.2. Analysis and Results

### 2.2.1. Long-term Evolution Studied with MAXI/GSC and *Swift*/BAT-survey Data

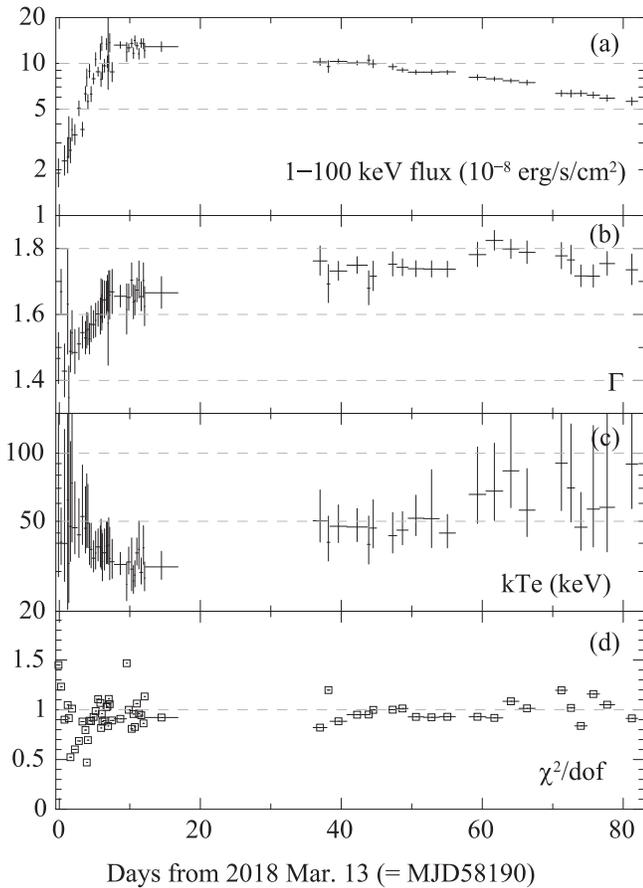
We first analyzed the MAXI/GSC and *Swift*/BAT-survey spectra to study the long-term spectral evolution, before the re-brightening in June. Figure 2 displays two typical spectra at low and high luminosities, obtained on 2018 March 14 UT 9:42–17:44 and March 25 UT 03:45–19:51, respectively. Both of them have a power-law-like profile, as is usually seen in the low/hard state of BHBs. A significant spectral turnover can be seen in the March 25 spectrum at 50–100 keV, which is not very clear in the March 14 spectrum.

We applied the Comptonization model `nthcomp` to the individual GSC+BAT-survey spectra, assuming that the seed photons originate in the emission from the standard accretion disk.



**Figure 2.** MAXI/GSC (crosses) and *Swift*/BAT (open squares) spectra obtained on March 14 (black) and March 25 (red), with their best-fit `TBabs*nthcomp` models (top), and the data vs. model ratios for the former (middle) and latter (bottom) spectra. The spectra are *unfolded* ones, corrected for the effective area of the instrument.

The `nthcomp` model calculates a Comptonized spectrum from a photon index, an electron temperature, and a characteristic temperature of the seed photons (which is the inner disk



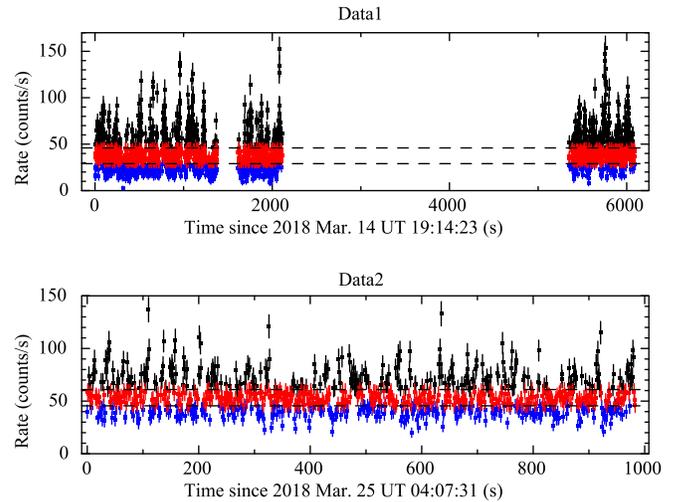
**Figure 3.** Time variations of the parameters in the best-fit  $\text{TBabs}^*\text{nthcomp}$  model. The unabsorbed 1–100 keV flux in units of  $10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$ , the photon index, the electron temperature in units of keV, and the reduced chi-squared, from top to bottom.

temperature  $T_{\text{in}}$  in the case of the disk blackbody radiation). We fixed  $T_{\text{in}}$  at 0.1 keV, because it cannot be constrained in the GSC +BAT spectra, covering energies only above 3 keV. We have confirmed that the results remained unchanged within the 90% error ranges when  $T_{\text{in}} = 0.5 \text{ keV}$  and  $0.05 \text{ keV}$  were adopted. To account for the interstellar absorption, we combined the  $\text{TBabs}$  model (Wilms et al. 2000) with a hydrogen column density of  $1.5 \times 10^{21} \text{ cm}^{-2}$ , which was determined from the spectrum of the Neutron Star Interior Composition Explorer (NICER) on March 12–14 (Uttley et al. 2018). We varied the cross-normalization factor of the BAT data with respect to the GSC data. We obtained  $\sim 1.0$  with a 90% confidence range of  $\pm \sim 20\%$  as its typical value.

The model reproduced the spectra well. In Figure 2, we show the best-fit models and the data versus model ratios of the March 14 and 25 data. Figure 3 presents the overall trend in the fit parameters and the reduced chi-squared values. During the rise of the outburst, the electron temperature and the photon index showed a slight decrease and increase, respectively. After the flux peak, the electron temperature increased slightly, whereas the photon index was nearly unchanged within the error range, during the gradual decay of the unabsorbed 1–100 keV flux by a factor of  $\sim 2$ .

### 2.2.2. Short-term Variation Studied with *Swift*/XRT and BAT-event Data

We next analyzed the simultaneous *Swift*/XRT and BAT-event data occasionally acquired in the outburst. Figure 4 presents the



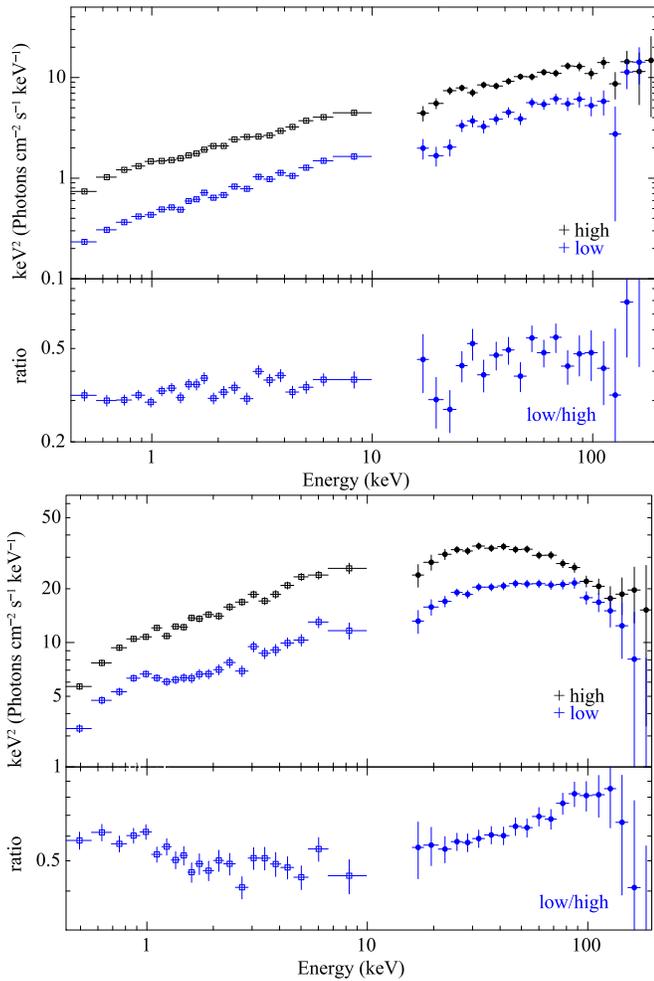
**Figure 4.** *Swift*/XRT light curves of MAXI J1820+070 at 0.3–10 keV obtained from Data-1 (top) and Data-2 (bottom) with 1 s bins. The dashed lines indicate the thresholds to extract the intensity-sorted spectra in Figure 6, and the black and blue points are included in high- and low-flux phases, respectively.

XRT light curves with 1 s bins of MAXI J1820+070 on March 14 and 25, obtained from Data-1 and Data-2, respectively. The flux varied by a factor of  $\sim 2$ – $5$  on timescales of a few to  $\sim 100 \text{ s}$  in both epochs. To investigate the energy dependence of the rapid flux variation, we sorted the time bins in these light curves in terms of their count rates. In each observation, we defined the upper and lower 30% time bins among all the data points as the high- and low-flux phases, respectively, and produced time-averaged spectra in these two phases (see Figure 4 for thresholds of the count rates for these phases).

In Figure 5, we plotted the time-averaged spectra in the low- and high-intensity phases, and the ratio of the former to the latter, produced from the individual data sets. Both spectra in Data-1 can be approximated by a single power law, and the spectral ratio increases with energy, indicating that the photon index in the low-intensity phase is slightly lower than that in the high-intensity phase. For Data-2, both spectra show a clear spectral cutoff at around 30–50 keV. Remarkably, the spectrum in the low-intensity phase displays a hump at  $\sim 1 \text{ keV}$ , and the spectral ratio below  $\sim 2 \text{ keV}$  decreases with increasing energy, suggesting that a less variable component than the main cutoff power-law component is present in the soft X-ray band.

We applied a Comptonization model to these intensity-sorted spectra and investigated which physical parameter(s) made the spectral differences. Here we adopted a sophisticated Comptonization model,  $\text{compps}$  (Poutanen & Svensson 1996), instead of  $\text{nthcomp}$ . This model calculates a Comptonized spectrum produced in a hot electron cloud, based on exact numerical solutions of the radiative transfer equation, for a given electron temperature  $kT_e$ , Compton  $y$ -parameter, geometry of the cloud, and energy distribution of the seed photons. We assumed spherical geometry ( $\text{geom} = 4$  in the XSPEC terminology) of the Comptonization component, and a multicolor disk blackbody as the seed spectrum. We ignored the reflection component, whose strength was not constrained, likely due to the uncertainties in the cross-normalization between the XRT and BAT-event spectra.

For Data-2, we combined the  $\text{diskbb}$  model (Mitsuda et al. 1984) with  $\text{compps}$ , as a direct disk blackbody component, to model the hump seen in the soft X-ray band. The inner disk temperature of  $\text{diskbb}$ ,  $kT_{\text{in}}$ , was linked to the seed temperature



**Figure 5.** (Top) Simultaneous *Swift*/XRT (open squares) and *Swift*/BAT (filled squares) intensity-sorted spectra on March 14 (Data-1; left) and 25 (Data-2; right). They are unfolded with a power-law model having a photon index of 2. (Bottom) Ratios of the unfolded spectra in the low-intensity phases with respect to those in the high-intensity phases.

$kT_{\text{bb}}$  of the `compps` model. We also employed the `TBabs` model for interstellar absorption, leaving  $N_{\text{H}}$  as a free parameter. In this analysis, we varied the cross-normalization factor of the BAT with respect to the XRT, which was found to be consistent with 1.0, with a 90% error of  $\pm 0.1$ – $0.2$ , in both Data-1 and Data-2.

These models, `TBabs*(compps)` and `TBabs*(diskbb+compps)`, successfully reproduced the Data-1 and Data-2 spectra, respectively. Figure 6 shows the folded spectra with their best-fit models, and the ratio of data to model. Table 1 lists the best-fit parameters of each phase. In both data sets, the Compton  $y$ -parameters in the low-intensity phases were larger than those in the high-intensity phases.

We estimated the inner disk radius for Data-2, from the photon fluxes of the direct disk component and the Comptonized component, via the equation given in Kubota & Makishima (2004):

$$P_{\text{d}} + P_{\text{c}} \times 2 \cos i = 0.0165 \left[ \frac{r_{\text{in}}^2 \cos i}{(D/10 \text{ kpc})^2} \right] \left( \frac{kT_{\text{in}}}{1 \text{ keV}} \right)^3$$

photons  $\text{s}^{-1} \text{cm}^{-2}$

(where  $P_{\text{c}}$  and  $P_{\text{d}}$  are photon fluxes of the Comptonized component and the direct disk component, respectively), by assuming a spherical geometry of the Comptonization component and the conservation of the number of disk photons after Comptonization.

### 3. Optical and Near-IR Data

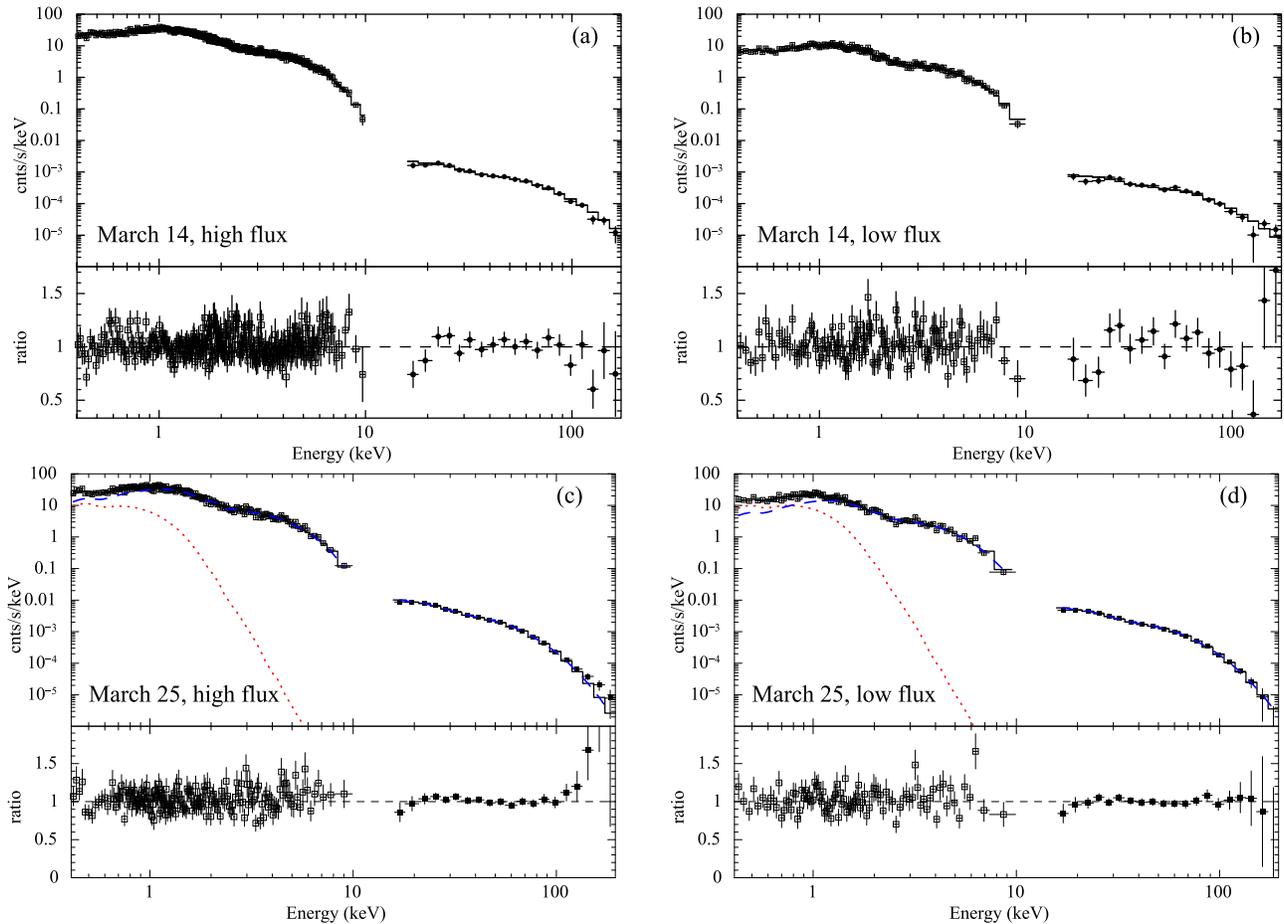
#### 3.1. Observations and Data Reduction

Optical and near-IR observations in the  $g'$ ,  $R_c$ ,  $I_c$ ,  $r$ ,  $i$ ,  $z$ ,  $J$ ,  $H$ , and  $K_s$  bands were carried out with ground-based telescopes through the target-of-opportunity program in the Optical and Infrared Synergetic Telescopes for Education and Research (OISTER). The  $g'$ -,  $R_c$ -, and  $I_c$ -band data were taken with the three-color imaging system developed for the MITSuME project (Kotani et al. 2005; Yatsu et al. 2007; Shimokawabe et al. 2008; Yanagisawa et al. 2010) on the MITSuME 50 cm telescope in Akeno, the 50 cm telescope at the Okayama Astrophysical Observatory (OAO), and the MURIKABUSHI 105 cm telescope at the Ishigakijima Astronomical Observatory. The  $r$ -,  $i$ -, and  $z$ -band data were taken with the Multi-wavelength Simultaneous High Throughput Imager and Polarimeter (MuSaSHI), installed on the 55 cm SaCRA telescope at Saitama University. The  $J$ -,  $H$ -, and  $K_s$ -band data were taken with the Nishiharima Infrared Camera (NIC; Ishiguro et al. 2011; Takahashi et al. 2013) on the 2.0 m Nayuta telescope at the Nishi-Harima Astronomical Observatory. The data were reduced on IRAF by following standard procedures including bias and dark subtraction, flat-fielding, and bad pixel masking. Photometry was performed with IRAF. The magnitudes of MAXI J1820+070 were calibrated with nearby reference stars. The magnitudes of the reference stars were taken from the UCAC4 catalog (Zacharias et al. 2013) for the  $g'$ -,  $R_c$ -, and  $I_c$ -band data, from Pan-STARRS1 Surveys (Chambers et al. 2016) for the  $r$ -,  $i$ -, and  $z$ -band data, and from the Two Micron All Sky Survey Point Source Catalog (Cutri et al. 2003) for the  $J$ -,  $H$ -, and  $K_s$ -band data. The statistical photometric errors of MAXI J1820+070 and the systematic errors of the reference star magnitudes were taken into account in assessing the observational errors.

Figure 7 shows the  $g'$ -,  $R_c$ -, and  $I_c$ -band light curves of MAXI J1820+070, together with the MAXI/GSC light curve at 2–20 keV. The optical fluxes were found to gradually increase as the X-ray flux became higher, and they show a significant variation on each night by 0.5–1 mag (by a factor of 1.6–2.5 in the flux units). As described in the following section, we studied the averaged properties of the multi-wavelength spectral energy distribution (SED) around the flux peak, by combining the one-night averaged optical and near-IR data, and the quasi-simultaneous X-ray data obtained with MAXI/GSC and *Swift*/BAT. Investigation of the short-term variations of the optical fluxes and their correlation to those in X-rays is left for future work.

We also searched the archival optical and IR data<sup>21</sup> for possible activity of MAXI J1820+070 before the 2018 outburst. The source was detected multiple times by Palomar Transient Factory (PTF) in 2013 May with  $R$ -band magnitudes of 18.3–18.7 mag and typical errors of  $\sim 0.06$  mag. It was also detected in the mid-IR band with *Wide-field Infrared Survey Explorer* (*WISE*)/Near-Earth Object *WISE* (NEOWISE) in

<sup>21</sup> At <http://irsa.ipac.caltech.edu/frontpage/>.



**Figure 6.** (a), (b) The time-averaged folded spectra in the high- and low-intensity phases of Data-1, and their best-fit  $\text{TBabs}^*\text{comppps}$  models. The lower panels present the ratio of data to model. (c), (d) Same as the top panels, but for Data-2 with the best-fit  $\text{TBabs}^*(\text{disk}+\text{comppps})$  models. The  $\text{diskbb}$  and  $\text{comppps}$  components are plotted separately with red dotted and blue dashed lines, respectively.

2010 September/2014–2017 March and September. The *WISE*/*NEOWISE* apparent magnitudes were 15.3–16.3/13.7–14.8 mag with typical errors of  $\sim 0.3/0.08$  mag in the W1 band ( $3.4\ \mu\text{m}$ ), and 14.7–15.4/13.4–14.6 mag with typical errors of  $\sim 0.3/0.2$  in the W2 band ( $4.6\ \mu\text{m}$ ). The fluxes in both the W1 and W2 bands showed significant variations by 0.5–1 mag (a factor of  $\sim 2$  in the flux units) within a few to several days.

### 3.2. Analysis of Multi-wavelength SEDs

Figure 8(a) shows the multi-wavelength SED on 2018 March 24, when the data in the  $g'$ ,  $r$ ,  $i$ ,  $z$ ,  $J$ ,  $H$ , and  $K_s$  bands, together with the X-ray data from *MAXI*/*GSC* and *Swift*/*BAT*, were available. The X-ray data were corrected for interstellar absorption using the  $\text{TBabs}$  model with  $N_{\text{H}} = 1.5 \times 10^{21}\ \text{cm}^{-2}$  (Uttley et al. 2018), and optical/IR data for interstellar extinction using the  $\text{redden}$  model in *XSPEC* with the extinction  $E(B - V) = 0.26$ , which was converted from the  $N_{\text{H}}$  value through the relation in Bohlin et al. (1978). As is noticed from the figure, the SED in the IR to optical band is not smoothly connected to the X-ray spectrum. For comparison, we also plotted, in Figure 8(b), an SED obtained from the archival optical/IR data before the 2018 outburst, and the upper limits of the X-ray fluxes estimated with the *MAXI*/*GSC*.

The optical and IR photons of BHBs can originate in the accretion disk, jet, or companion star. In the case of the disk emission, the optical and IR bands correspond to the radiation

from the outer disk region, which is often irradiated by the X-rays from the inner disk region. To obtain the upper limit of the contribution of the disk emission to the optical/IR fluxes, we applied the irradiated disk model  $\text{diskirr}$  (Gierliński et al. 2008, 2009) to the multi-wavelength SED on 2018 March 24 (see Section 4.3 for discussion of the contributions of the other emission components).

The  $\text{diskirr}$  model computes the spectrum of the disk emission and its Comptonization, considering the irradiation of the disk. The model has nine input parameters: the inner disk temperature  $kT_{\text{in}}$ , the photon index  $\Gamma$  and electron temperature  $kT_{\text{e}}$  of the Comptonized component, the luminosity ratio  $L_{\text{c}}/L_{\text{d}}$  of the Comptonized component to the disk component, the fraction  $f_{\text{in}}$  of the luminosity of the Comptonized component that is thermalized in the inner disk, the fraction  $f_{\text{out}}$  of the bolometric flux illuminating the outer disk, the radius  $r_{\text{irr}}$  of the inner disk irradiated by the Comptonized component with respect to the inner disk radius, the outer disk radius  $R_{\text{out}}$ , and the normalization, determined by the inner disk radius  $R_{\text{in}}$  in the same manner as  $\text{diskbb}$ .

Following previous works (e.g., Shidatsu et al. 2017), we fixed  $r_{\text{irr}}$  and  $f_{\text{in}}$ , which were unconstrained with our data, at default values, 1.1 and 0.1, respectively, which are appropriate for spectra of the low/hard state (Poutanen et al. 1997). The other parameters were left as free parameters. We multiplied  $\text{TBabs}$  with  $N_{\text{H}}$  fixed at  $1.5 \times 10^{21}\ \text{cm}^{-2}$  and  $\text{redden}$  with  $E(B - V)$  at 0.26 to the

**Table 1**  
Best-fit TBabs\*compps and TBabs\*(diskbb+compps) Parameters for Data-1 and Data-2, Respectively, in the High- and Low-intensity Phases

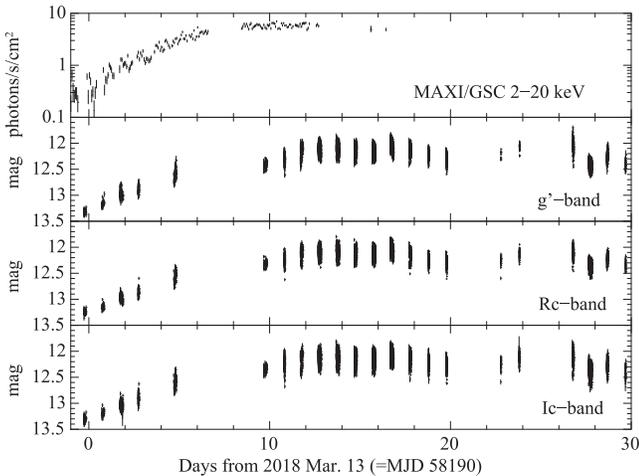
Parameters		Data-1		Data-2	
		High	Low	High	Low
TBabs	$N_{\text{H}}$ ( $10^{22}$ cm $^{-2}$ )	$0.10^{+0.05}_{-0.04}$	<0.1	$0.12 \pm 0.10$	$0.15^{+0.09}_{-0.07}$
compps <sup>a</sup>	$kT_{\text{e}}$ (keV)	>240	>48	$27^{+3}_{-2}$	$35^{+8}_{-5}$
	y-parameter	$1.1 \pm 0.2$	$1.6^{+0.1}_{-0.2}$	$0.77 \pm 0.02$	$0.87^{+0.03}_{-0.02}$
	$kT_{\text{bb}}$ (keV)	$0.22 \pm 0.02$	$0.2^{+0.2}_{-0.1}$	$0.18^{+0.12}_{-0.04}$	$0.21^{+0.05}_{-0.04}$
diskbb	norm ( $10^4$ )	$8^{+4}_{-3}$	$1.3^{+6.8}_{-1.0}$	$53^{+90}_{-27}$	$17^{+22}_{-10}$
	norm ( $10^5$ )	...	...	$5.3^{+41.0}_{-5.1}$	$4^{+14}_{-3}$
	$r_{\text{in}}$ (km) <sup>b</sup>	...	...	$372^{+168}_{-198}$	$240^{+192}_{-48}$
$\chi^2/\text{d.o.f.}$		356/328	168/144	200/190	108/107
Flux <sup>c</sup> ( $10^{-8}$ erg s $^{-1}$ cm $^{-2}$ )		4.1	2.1	18	10

### Notes.

<sup>a</sup> The seed spectrum was assumed to be a disk blackbody, and the inner disk temperature of compps ( $kT_{\text{bb}}$ ) was linked to that of diskbb ( $kT_{\text{in}}$ ) in Data-2. The reflection component was ignored.

<sup>b</sup> Inner radius estimated from the total photons of the disk blackbody emission, including the Comptonized photons in a spherical corona (see Section 2.2.2). A distance of 3 kpc and an inclination angle of  $30^\circ$  are assumed. The color-temperature correction and the correction of the inner boundary condition are not considered.

<sup>c</sup> Unabsorbed 0.01–100 keV flux.



**Figure 7.** X-ray and optical light curves of MAXI J1820+070, obtained with MAXI/GSC and in the MITSuME project, respectively. The light curves at 2–20 keV, and in the optical  $g'$ ,  $R_c$ , and  $I_c$  bands are presented, from top to bottom. The magnitudes are expressed in the AB system. The error bars of the optical light curves include both the statistical photometric errors of MAXI J1820+070 and the systematic errors of the reference star magnitudes.

diskir model, as X-ray interstellar absorption and optical/IR extinction, respectively. We have confirmed, however, that the conclusions below do not change if we increase or decrease  $N_{\text{H}}$  by a factor of 2, and change  $E(B - V)$  accordingly.

As shown in Figure 8(a), the model was able to reproduce the SED on March 24, giving a  $\chi^2/\text{d.o.f.}$  value of 106/122. In this best-fit model, the reprocessed emission from the outer disk dominates the flux in the IR bands, where a profile flatter than the optical SED is seen. The parameter values were constrained to be  $kT_{\text{in}} = 0.23^{+0.03}_{-0.13}$  keV,  $\Gamma = 1.67^{+0.01}_{-0.03}$ ,  $kT_{\text{e}} = 29^{+2}_{-3}$  keV,  $L_{\text{c}}/L_{\text{d}} = 0.24 \pm 0.06$ ,  $f_{\text{out}} = 6.4^{+4}_{-2} \times 10^{-5}$ , and  $R_{\text{out}} > 3 \times 10^4 R_{\text{in}} = 2 \times 10^7 (D/3 \text{ kpc})(\cos i / \cos 30^\circ)^{-1/2}$  km. The  $\Gamma$  and  $kT_{\text{e}}$  values were consistent with those obtained in the analysis of the X-ray spectra alone, and the  $kT_{\text{in}}$  value was the same as that determined from the *Swift*/XRT and BAT-event data on March 25, within the 90% error ranges.

## 4. Discussion

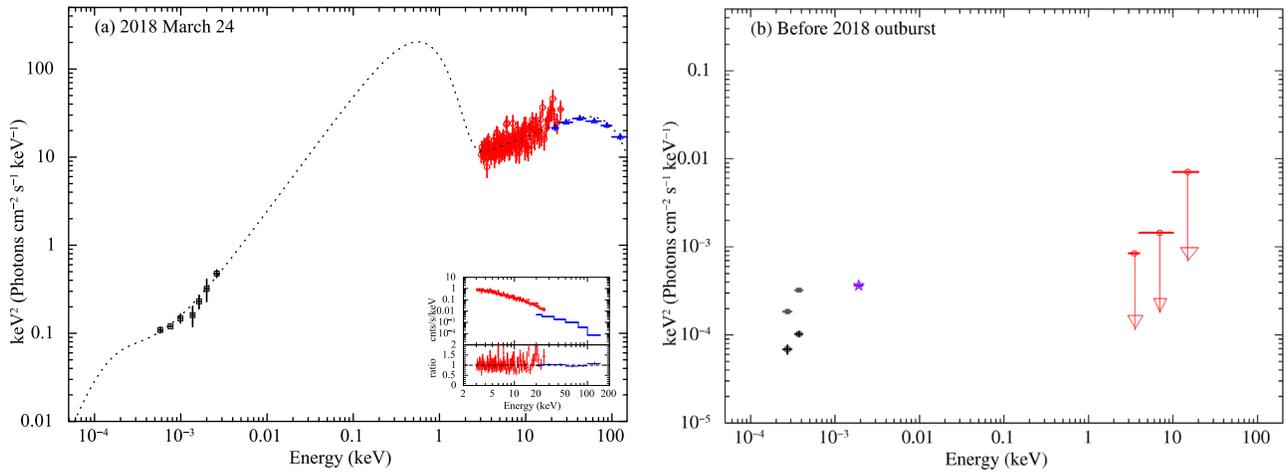
### 4.1. Overall X-Ray Properties

Like other X-ray novae, the new X-ray source MAXI J1820+070 displayed a rapid rise in flux, up to as high as  $\sim 2$  crab at 2–20 keV, and then a slower decay for  $\sim 3$  months. Using MAXI/GSC data, we found that the source increased its X-ray flux by  $\gtrsim 4$  orders of magnitude from the quiescent level, to  $\sim 2$  crab in the 2–20 keV band, at the peak at the end of 2018 March. Before the re-brightening in the middle of June, the source did not show any drastic spectral softening, and kept presenting a hard spectrum roughly characterized by an exponentially cutoff power-law model with a photon index of  $\sim 1.5$  and a cutoff energy of  $\sim 50$  keV, which is consistent with those of black hole X-ray binaries in the low/hard state.

The observed peak flux of MAXI J1820+070 was quite high, compared with typical flux levels at which many known BHBs in the central regions of the Galaxy show the transition to the high/soft state ( $\sim 0.1$  crab; e.g., Yu et al. 2007; Zhou et al. 2013). This can be explained if MAXI J1820+070 is located closer to us than they are. Indeed,  $D \approx 3$  kpc has recently been obtained from the astrometry with *Gaia* data (Gandhi et al. 2018b). Using the unabsorbed 1–100 keV flux, obtained with the best-fit *nthcomp* model of the simultaneous MAXI/GSC and *Swift*/BAT spectrum on 2018 March 25, the peak luminosity at the end of March is calculated to be  $\sim 2 \times 10^{38} (D/3 \text{ kpc})^2 \text{ erg s}^{-1}$ , which is converted to an Eddington ratio of  $L_{\text{X}}/L_{\text{Edd}} \sim 0.1 (D/3 \text{ kpc})^2 (M_{\text{BH}}/10 M_{\odot})^{-1}$ .

After the period of  $\sim 3$  months in the low/hard state, the source caused re-brightening and entered into the state transition, at a luminosity similar to the first peak in March. Such a long period before the state transition is unusual in transient BHBs, although similar behavior was observed in the 2009 outburst of XTE J1752–223 (Nakahira et al. 2010), where the source stayed in the low/hard state for three months before the transition, with two plateau phases in its X-ray light curve. In that case, the complex evolution was explained by a gradual increase in the mass accretion rate for some unknown reasons.

What caused the two-step rise of MAXI J1820+070 is still unclear, but possibly the first rise was caused by an enhancement



**Figure 8.** (a) Multi-wavelength SED of MAXI J1820+070 on 2018 March 24. The black squares indicate the optical/IR data in the  $K_s$ ,  $H$ ,  $J$ ,  $z$ ,  $i$ ,  $r$ , and  $g'$  bands, from left to right. Red circles and blue triangles show the MAXI/GSC and *Swift*/BAT data, respectively. The best-fit `diskir` model is indicated by the dotted line. The inset presents the same X-ray data folded with the instrumental responses, in units of counts  $s^{-1} \text{keV}^{-1}$  (upper), and their ratio of data to model (lower). (b) SED before the start of the 2018 outburst, obtained from the archival PTF  $R$ -band data (purple star), and the *WISE* (black open squares)/*NEOWISE* (gray filled squares) IR data, combined with the  $3\sigma$  upper limits of the seven-year averaged X-ray fluxes derived with the MAXI/GSC (see Section 2.1.1).

in the mass transfer from the companion star, and the second rise by a rapid increase in the mass accretion rate caused by the disk instability that was triggered somewhere in the outer disk during the first rise and propagated inward. The viscous timescale of the disk is expressed as  $t_v(R) \sim \alpha^{-1} \Omega_K^{-1} (H/R)^{-2}$ , where  $\alpha$ ,  $H$ , and  $\Omega_K$  are the viscosity parameter, the disk scale height, and the Keplerian angular velocity at the radius  $R$ , respectively. The timescale  $t_v \sim 90$  days corresponds to  $R \sim 2 \times 10^{10}$  cm for  $H/R \sim 0.01$  and  $\sim 4 \times 10^{11}$  cm for  $H/R \sim 0.1$ , when a black hole mass of  $10 M_\odot$  and  $\alpha = 0.1$  are assumed.

An alternative interpretation for the two-step flux increase may be provided in terms of the irradiation of the companion star, as invoked by Nakahira et al. (2014) to explain the re-flare observed in the outburst of *Swift* J1910.2–0546 (or MAXI J1910–057). The first rise in flux could be produced by the enhancement of the mass accretion rate through the inner disk due to the disk instability, and the fact that the strong X-rays irradiated and inflated the companion star, causing an increase in the gas supply to the accretion disk. The second flux enhancement could then be produced by triggering the disk instability again.

#### 4.2. Implications for Long- and Short-term X-Ray Variations

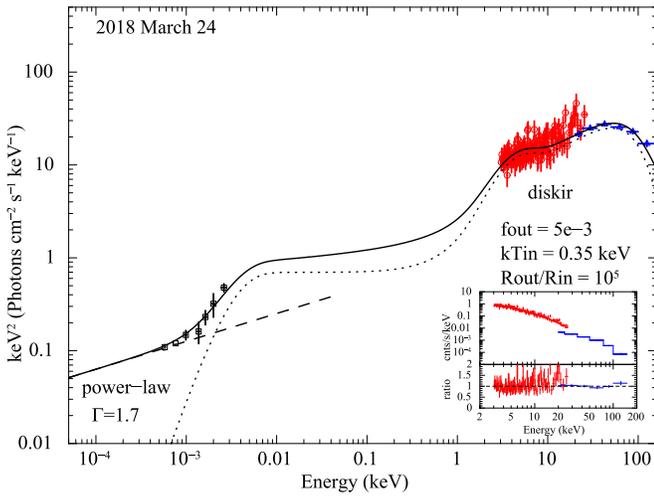
Looking at the MAXI/GSC and *Swift*/BAT spectra during the low/hard state in more detail, we found that the spectrum became slightly softer and bent at lower energies and higher luminosities. According to the best-fit `nthcomp` models for the individual spectra (Section 2.2.1), the photon index increased from 1.4 to 1.7 and the electron temperature decreased from 50 to 30 keV, during the rise phase of the outburst. This long-term spectral evolution would be explained by the change in the mass accretion rate; the standard disk is developed inwards as the mass accretion rate increases, and the soft X-rays from the standard disk cool the hot inner flow and/or corona around the standard disk, providing a softer Comptonized spectrum with a lower electron temperature.

We also detected spectral variation on much shorter timescales, a few to  $\sim 100$  s, using the *Swift*/XRT and BAT-event data taken on March 14 and 25, corresponding to the beginning and the peak of the outburst. In both periods, the

spectrum of MAXI J1820+070 was softer/harder in the high-/low-intensity phases of the short-term variation. Applying the `compps` model, a smaller  $\gamma$ -parameter (and a lower electron temperature on March 25) were obtained during phases of higher flux. Similar trends were obtained in the shot analysis of Cyg X-1 (Negoro et al. 1994, 2001; Yamada et al. 2013b), and the density fluctuation in the radiation-inefficient accretion flow was suggested as one possibility to drive the variation, on the basis of the evolution of the spectrum and X-ray time lags during the shots. Further studies of timing properties of MAXI J1820+070 would be required to understand the actual cause of its short-term variation.

Thanks to the good statistics of the *Swift*/XRT data, we detected, in the March 25 spectrum, a structure below  $\sim 2$  keV that cannot be reproduced by the `TBabs*nnthcomp` model and is less variable than the main Comptonization component. Assuming it to be the component due to direct disk emission, we obtained the inner disk temperature as  $\sim 0.2$  keV and the inner disk radius as  $\sim 180\text{--}540(D/3 \text{ kpc})(\cos i / \cos 30^\circ)^{-1/2}$  km, which was estimated from the photon flux of the component due to total intrinsic disk emission, including both the direct and Comptonized emission. This radius can be converted to  $\sim 12\text{--}36 R_g(M_{\text{BH}}/10 M_\odot)^{-1}(D/3 \text{ kpc})(\cos i / \cos 30^\circ)^{-1/2}$ , where  $R_g = GM_\odot/c^2$ , and this means that the standard disk is truncated, around the flux peak at the end of March.

We cannot rule out the possibility, however, that the soft component seen on March 25 was not the direct standard disk emission but a Comptonized emission produced around the inner edge of the standard disk, as discussed (Chang et al. 2010; Yamada et al. 2013a; Shidatsu et al. 2014). If this is the case, the direct disk component was below the energy range of the XRT, and the standard disk was further truncated, with a lower inner disk temperature than what we estimated above. The mass accretion rate at the flux peak can then be close to the Eddington rate, considering the radiation efficiency of the standard disk,  $\sim 0.1 R_{\text{ISCO}}/R_{\text{in}}$  (where  $R_{\text{in}}$  and  $R_{\text{ISCO}}$  the radii of the inner edge of the standard disk and the innermost stable circular orbit, respectively), and the peak luminosity estimated in Section 4.1.



**Figure 9.** Same data as Figure 8(a), with the powerlaw+diskir model (solid line). The power-law and diskir components are indicated by the dashed and dotted lines, respectively.

### 4.3. Origin of Optical and Near-IR Emission in the Outburst and Jet Energetics

The optical and near-IR flux of BHBs is considered to originate in the blackbody emission from the companion star, jet emission, and/or the emission from the outer region of the accretion disk, which is often enhanced by the irradiation of X-rays from the inner disk region. In the case of MAXI J1820+070 during the outburst, the contribution of the companion star is negligible, because the previous PTF data suggest that the optical flux in the quiescent phase was at least  $\sim 3$  orders of magnitude smaller than at the peak of the outburst (see Section 3.2). The multi-wavelength SED around the X-ray flux peak could technically be fit with an irradiated disk model. However, the resultant value of  $f_{\text{out}}$ , the strength of the reprocessed component, was unusually small compared with those of typical BHBs in the low/hard state ( $>10^{-3}$ ; e.g., Gierliński et al. 2009).

Considering the above results, we suggest that the optical and near-IR emission of MAXI J1820+070 in the outburst was not entirely produced by the disk emission, but substantially contributed by the jet emission, particularly in the near-IR band. A similar conclusion was also obtained from optical polarimetry (Veledina et al. 2018). Indeed, as shown in Figure 9, the SED can be fairly well reproduced, for example, by adding a power-law component (as the optically thin synchrotron emission from jet) with a photon index of 1.7 and a normalization adjusted to the  $K_S$ -band flux, and setting  $f_{\text{out}}$ ,  $kT_{\text{in}}$ ,  $L_c/L_d$ , and  $R_{\text{out}}$  of diskir to be  $5 \times 10^{-3}$ , 0.35 keV, 70, and  $10^2 R_{\text{in}}$ , respectively. In this model, the inner disk region is efficiently irradiated by the Comptonization component dominating the X-ray luminosity, and the heated disk produces a weak hump seen around  $\sim 5$  keV. We note that the parameters related to the irradiation of the outer disk are not significantly changed by the irradiation efficiency of the inner disk alone, because they are determined by the bolometric flux. Remarkably, the stronger contribution of the jet component at longer wavelengths, indicated by this model, is consistent with the observed sub-second optical variations (Gandhi et al. 2018a) likely originating in the jet activity, which was found to be stronger in redder bands.

Indeed, previous studies of BHBs suggest that steady compact jets are present during the low/hard state, and that their emission dominates the radio to IR or optical fluxes (see Fender 2010; Gallo 2010; Markoff 2010, and references therein). The SEDs of BHBs in the low/hard state exhibit a flat, power-law profile at the radio frequencies (e.g., Corbel et al. 2000; Fender 2001), with a spectral index of  $\beta \sim 0$  (where the flux density  $F_\nu \propto \nu^\beta$ ), and have a break in the submillimeter to IR band, above which a smaller  $\beta$  is obtained (Corbel & Fender 2002; Migliari et al. 2010; Gandhi et al. 2011; Shidatsu et al. 2011; Russell et al. 2013, 2014). As discussed also for jets in active galactic nuclei (Blandford & Königl 1979), this SED profile can be described with the synchrotron radiation from conical jets, where optically thick and thin synchrotron components are observed below and above the break, respectively.

Such an SED with the shape of a broken power law, extending from the radio to the near-IR band, was actually obtained in MAXI J1820+070 (Russell et al. 2018) around the X-ray flux peak at the end of March, with spectral indices of  $\beta \sim 0.3$  and  $\beta \sim -0.7$ , below and above the break frequency  $\nu_b$  of  $\sim 3 \times 10^{13}$  Hz. Following Shidatsu et al. (2011), we attempt here to estimate the physical parameters of the jet base, from  $\nu_b$  and the flux density at  $\nu_b$  of  $F_{\nu_b} \sim 400$  mJy. For simplicity, we assume a single-zone jet base and ignore the effects of relativistic beaming by the bulk motion of the jet. If the electron number density at the Lorentz factor  $\gamma$  is proportional to  $\gamma^p$ , the synchrotron luminosity in an optically thin part,  $\nu L_\nu$ , depends on  $\nu$ ,  $p$ , the magnetic field strength  $B$  and the volume  $V$  of the emission region (where  $V = 4\pi R^3/3$  in the case of a spherical region), and the pitch angle  $\theta$  of the jet, while the synchrotron self-absorption coefficient  $\alpha_\nu$  is expressed as a function of  $\nu$ ,  $p$ ,  $B$ , and  $\theta$  (see Shidatsu et al. 2011 for complete expressions). The former parameter,  $\nu L_\nu$ , is proportional to  $\nu^{(3-p)/2}$ , and thus we obtain  $p = 2.4$  for MAXI J1820+070, from the observed spectral index,  $\beta \sim -0.7$ .

Assuming the equipartition of the magnetic field energy and the kinetic energy of electrons in the jet, and considering the condition of the optical depth and the luminosity at  $\nu_b$  as  $\sim \alpha_{\nu_b} R \sim 1$  and  $\nu_b L_{\nu_b} \sim 1 \times 10^{35} (D/3 \text{ kpc})^2 \text{ erg s}^{-1}$ , respectively, we obtain  $B = 1 \times 10^4 (D/3 \text{ kpc})^{-0.22} (\sin \theta / \sin 30^\circ)^{0.55} \text{ G}$  and  $R = 2 \times 10^9 (D/3 \text{ kpc})^{0.94} (\sin \theta / \sin 30^\circ)^{0.11} \text{ cm}$  for the jet base of MAXI J1820+070. These values are comparable to those estimated in GX 339-4 (Shidatsu et al. 2011), XTE J1550-564 (Chaty et al. 2011), and MAXI J1836-194 (Russell et al. 2014) during the low/hard state.

The magnetic energy density is derived from the above  $B$  value as  $u_B = B^2/8\pi \sim 8 \times 10^6 \text{ erg cm}^{-3}$ . The Lorentz factor of electrons emitting  $\nu_b = 3 \times 10^{13}$  Hz photons is  $\sim 10$ . Following Chaty et al. (2011), we can calculate the timescales of adiabatic cooling and radiative cooling at the jet base as  $\gtrsim B/c \sim 70$  ms and  $\propto u_B^{-1} \gamma^{-1} \sim 400$  ms, respectively. This indicates that the former is the dominant cooling process.

The total synchrotron luminosity  $L_{\text{sync}}$  is roughly estimated as  $\sim 10^{36} \text{ erg s}^{-1}$ , from the SED profile obtained in Russell et al. (2018), and the energy density of the synchrotron radiation,  $u_{\text{sync}} \sim L_{\text{sync}}/(4\pi R^2 c)$ , is calculated to be  $3 \times 10^5 \text{ erg cm}^{-3}$ . The luminosity of the synchrotron self-Compton radiation,  $L_{\text{SSC}}$ , is thus estimated as  $L_{\text{sync}} u_{\text{sync}}/u_B \sim 0.05 L_{\text{sync}}$ . This suggests that the synchrotron self-Comptonization emission is negligible, contributing only  $\sim 0.05\%$  to the X-ray flux. The energy density of external photons from the accretion disk is roughly estimated as

$9 \times 10^7 \text{ erg cm}^{-3}$ , from the 1–100 keV X-ray luminosity,  $\sim 1 \times 10^{38} \text{ erg s}^{-1}$ . The contribution of the external Comptonization emission is thus  $\sim 1 \times 10^{37} \text{ erg s}^{-1}$ , which is still only  $\sim 10\%$  of the total X-ray luminosity. As noticed in Figure 8(a), the observed near-IR fluxes are somewhat lower than what is expected from the simple extrapolation of the power-law component seen in the X-ray band, suggesting that the jet synchrotron emission itself is also unlikely to be a main contributor to the X-ray flux. These results would justify the assumption in our X-ray spectral modeling that the X-ray photons were predominantly produced by Comptonization of the disk emission.

#### 4.4. Implications for the Weak IR and Optical Activity before the Outburst

We found weak optical and IR emission of MAXI J1820+070 before the start of the 2018 outburst, using the archival PTF, *WISE*, and NEOWISE data. The source exhibited *R*-band flux variation by 0.4 mag (by 0.4 in the flux units) on a timescale of  $\sim 1$  day, and mid-IR variations by  $\sim 1$  mag (by 2.5) on a timescale of  $\lesssim$  several days and a few years. Assuming a distance of 3 kpc, the averaged PTF apparent magnitude in the *R* band,  $\sim 18.5$  mag, is converted to an absolute magnitude of  $\sim 6$  mag. This magnitude corresponds to a K-type companion star if it is a main-sequence star and dominated by the optical flux in the PTF observations. Because of the significant variations, however, we suggest that a large fraction of the optical and IR fluxes did not originate in the blackbody emission from the companion star, but perhaps in the outer disk and/or jet emission.

### 5. Summary and Conclusion

We have studied the new BHB candidate MAXI J1820+070 utilizing X-ray data from MAXI and *Swift* and optical/near-IR data taken in the OISTER collaboration. What we have found can be summarized as follows.

1. The source stayed in the low/hard state for  $\sim 3$  months, from its discovery in 2018 March until the start of the second brightening in the middle of June.
2. The X-ray spectrum in that period was successfully described with the Comptonization of the disk emission in the hot inner flow or corona with an electron temperature of  $\sim 50$  keV.
3. The source showed X-ray short-term variation on a timescale of seconds, which is likely associated with a change in the properties of the Comptonized cloud.
4. The source exhibited weak activity in the optical and near-IR bands before the 2018 outburst, when the source was not detected in X-rays.
5. In the outburst, its optical and near-IR fluxes were correlated with the X-ray flux. By modeling the multi-wavelength SED at the X-ray flux peak at the end of March, the optical and near-IR fluxes were found likely to be contributed by the jet synchrotron emission.

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*Facilities:* MAXI(GSC), *Swift*(XRT and BAT).

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