Discovery and Long-term Broadband X-Ray Monitoring of Galactic Black Hole Candidate MAXI J1803–298

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Abstract

We report the results from the broadband X-ray monitoring of the new Galactic black hole candidate MAXI J1803–298 with MAXI/GSC and Swift/BAT during its outburst. After the discovery on 2021 May 1, the soft X-ray flux below 10 keV rapidly increased for ~10 days, then gradually decreased over five months. In the brightest phase, the source exhibited the state transition from the low/hard state to the high/soft state via the intermediate state. The broadband X-ray spectrum during the outburst is well described with a disk blackbody plus its thermal or nonthermal Comptonization. Before the transition, the source spectrum is described by a thermal Comptonization component with a photon index of ~1.7 and an electron temperature of ~30 keV, while a strong disk blackbody component is observed after the transition. The spectral properties in these periods are consistent with the low/hard state and the high/soft state, respectively. A sudden flux drop with a duration of a few days, unassociated with a significant change in the hardness ratio, was found in the intermediate state. A possible cause of this variation is that the mass accretion rate rapidly increased at the disk transition, which induced a strong Compton-thick outflow and scattered out the X-ray flux. Assuming a nonspinning black hole, we estimate the black hole mass of MAXI J1803–298 to be 5.8 ± 0.4 (cos i/cos 70°)−1/2(D/8 kpc) M⊙ (where i and D are the inclination angle and the distance, respectively) from the inner disk radius obtained in the high/soft state.

Unified Astronomy Thesaurus concepts: X-ray binary stars (1811); Accretion (14); Black hole physics (159)

1. Introduction

Most of the known Galactic black hole X-ray binaries (BHXBs) exhibit transient behaviors. They are usually dormant in X-rays, but suddenly enter into an outburst, increasing their X-ray luminosities by several orders of magnitude. Because the X-rays are produced in the inner parts of the accretion disk, through the release of the gravitational energy of the accreted gas, the X-ray luminosity and energy spectra depend on the mass accretion rate and the structure of the inner disk, and the spacetime in the vicinity of the black hole. X-ray observations of BHXBs therefore provide clues to understanding black hole accretion flows and the nature of the black holes themselves. In particular, monitoring broadband X-ray spectra during their outbursts is helpful for studying the evolution of the accretion flows over a wide range of mass accretion rates.

The Galactic black hole candidate MAXI J1803–298 was discovered on 2021 May 1 (Serino et al. 2021) with the nova search system (Negoro et al. 2016) of MAXI (Matsuoka et al. 2009).

Its position was then localized by NICER multiple pointings (Gendreau et al. 2021) and further constrained with Swift (Gropp et al. 2021). Many follow-up observations were performed in X-ray (Bult et al. 2021; Chand et al. 2021, 2021; Chenevez et al. 2021; Feng et al. 2021; Homan et al. 2021; Jana et al. 2021; Miller & Reynolds 2021; Sguera & Sidoli 2021; Shidatsu et al. 2021; Steiner et al. 2021; Ubach et al. 2021; Wang et al. 2021; Xu & Harrison 2021; Jana et al. 2022) and other wavelengths (Buckley et al. 2021; Espinasse et al. 2021; Hosokawa et al. 2021; Saikia et al. 2021; Mata Sánchez et al. 2022). NuSTAR and NICER found periodic absorption dips, and Swift detected absorption lines likely originating in a disk wind (Miller & Reynolds 2021), both suggestive of a high inclination angle above ~70°. A sign of an outflow was also detected in optical spectroscopy (Buckley et al. 2021), where p Cygni-like profiles were detected in hydrogen Balmer lines.

In this article, we report the results from the long-term, broadband X-ray monitoring of MAXI J1803–298 over almost the entire outburst, using the MAXI/Gas Slit Camera (GSC) and Swift/Burst Alert Telescope (BAT) data. We used Heasoft version 6.28 and XSPEC version 12.11.1 for the data reduction and analysis, and adopted the solar abundance table given by Wilms et al. (2000). Throughout the article, errors represent the 90% confidence ranges for one parameter, unless otherwise specified.
2. Observations and Data Reduction

2.1. Localization of the MAXI J1803−298 Position

At 19:50 UT on 2021 May 1, the MAXI/GSC nova search system triggered an uncatalogued X-ray transient source. The source position determined by MAXI was (\(\alpha_{2000} = 18^h03^m44^s\), \(\delta_{2000} = -29^\circ48'14''\)) with a statistical error of about \(\pm 0.3\) and a systematic uncertainty of \(\pm 0.1\). Following the MAXI alert of a new transient, NICER performed multiple pointings to localize the source position from 03:36 UT on 2021 May 2, using the nonimaging NICER/XTI. Starting from the nominal coordinates reported by MAXI, NICER performed 37 offset pointings with a step interval of 6', which is the same as the size of NICER’s field of view (FoV). The exposure time for each pointing was about 15 s. Figure 1 (left) shows the time evolution of the NICER raw counts and the pointing direction coordinates, whereas Figure 1 (right) shows the count rate map created from the raw counts and the exposure map. The vignetting effect in each pointing was corrected using the vignetting profile of the NICER X-ray concentrator, obtained from ray-tracing simulations that considered the calibration test results obtained with the 1.5 keV X-rays at the NASA/GSFC 100 m X-ray beamline. The image was smoothed with a Gaussian filter of a standard deviation of 1 pixel (1'). The coordinates of the source estimated from the maximum value of the count rate map are (\(\alpha_{2000} = 18^h03^m09^s\), \(\delta_{2000} = -29^\circ48'43''\)). After further follow-up observations by Swift (Gropp et al. 2021), the position of MAXI J1803−298 was determined to be (\(\alpha_{2000} = 18^h03^m02^s79^m\), \(\delta_{2000} = -29^\circ49'49.9''\)), or \((l, b) = (1^\circ47184, -3^\circ727501)\). This is consistent with the coordinates obtained from the NICER multiple pointing observations within their FoV of 3' radius.

2.2. MAXI

MAXI has been monitoring MAXI J1803−298 since its discovery on 2021 May 1 (MJD 59335). In this work, we have used all of the available GSC data taken from 2021 April 26 (MJD 59330) to October 19 (MJD 59506). We have produced MAXI/GSC long-term light curves through a point-spread function (PSF) fit method (Mori et al. 2010). To extract the GSC spectra, we utilized the MAXI on-demand software (Nakahira et al. 2013) and the latest Calibration Database (CALDB) as of 2021 May. The source and background extraction regions were defined as a circle with a 1.6 radius and an annulus within radii from 1.7 to 3°, respectively, both centered at the source position.

Although the source region includes the neighboring source XTE J1807−294, located 0°6 away, its contamination is likely to be negligible. To evaluate the contamination flux level from XTE J1807−294, we extracted the time-averaged spectrum for 1 yr before the discovery (MJD 58970–59334) from the same source region. However, we did not detect any significant source signals, and obtained an upper limit for the 2−10 keV flux of 0.8 m Crab (\(2.4 \times 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\)), assuming the Crab spectrum (\(\Gamma = 2.1, N_H = 3 \times 10^{21}\) cm\(^{-2}\)). This is a negligible level in our analysis. To avoid source contamination of the background data, we excluded from the background region areas within certain radii (depending on the source fluxes) around the nearby bright sources: 1°0, 1°5, 1°8, 1°4, and 2°3 around SAX J1747.0−2853, 1A 1742−294, XTE J1751−305, H 1755−338, and GX 5−1, respectively, all of which are located 3°5−5°0 away from MAXI J1803−298. We determined these exclusion radii based on the 2−10 keV GSC image in MJD 59335−59350, obtained with the on-demand software, so that the PSFs of the sources were sufficiently covered.

2.3. Swift

We also used the Swift/BAT survey-mode data for the same period as the MAXI/GSC data. The BAT data were downloaded from the HEALPix archive,\(^{10}\) and were reduced with the Swift/BAT CALDB released on 2017 October 16. The data were first processed with the tool batsurvey. The tool produces files that list the count rates of the sources in the BAT FoV for the individual scans. From these products, we calculated the 1 day averaged count rates of MAXI J1803−298 using the tool ftscalc and compiled them into a light curve. The time-averaged spectrum and the response file for each continuous scan were produced with the dedicated script make_surveypha from the batsurvey products. We created time-averaged spectra for longer time intervals by merging the spectra and response files via ftools mathpha.

\(^{10}\) https://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/
addrmf, and used them in the spectral analysis (see Section 4). In this analysis, we discarded the spectral bins when only upper limits on the count rates were obtained.

3. Light Curves and Hardness–Intensity Diagram

Figure 2 presents the MAXI light curves and hardness ratios, and the Swift/BAT hard X-ray light curve of MAXI J1803−298. In the initial phase of the outburst, the source flux rapidly increased by ∼2 orders of magnitude. The Swift/BAT data suggest that the outburst started at least a few days before the discovery with the MAXI/GSC on MJD 59335. After the source was out of MAXI’s FoV, from MJD 59338 to MJD 59346, it reached the peak with ∼0.6 Crab in 2–4 keV and ∼0.4 Crab in 4–10 keV. The hardness ratio dropped in this data gap, suggesting that the source started the state transition from the low/hard state to the high/soft state, as reported by Shidatsu et al. (2021). The Swift/BAT hard X-ray flux reached its peak around MJD 59339, ∼10 days before the flux peak below 10 keV. Following the flux peaks, the source has gradually dimmed over five months, with a slight rebrightening around MJD 59440. Using the NICER data, Steiner et al. (2021) reported that the source returned to the low/hard state between MJD 59500 and MJD 59506, although this transition is not very clear in Figure 2, due to low statistics.

In Figure 3, we plot the hardness–intensity diagram, where a counterclockwise path is seen, as for other transient BHXBs. On the basis of the behavior of the source fluxes and the hardness ratios, we define six phases, listed in Table 1, and use them in the following spectral analysis. Here, the data gaps of MAXI/GSC were omitted. The data before the discovery (until MJD 59334) and after MJD 59500 were also ignored, because we were unable to obtain statistically meaningful spectra due to the too low flux. Considering the hardness–intensity diagram, the source was likely to be in the low/hard state and the high/soft state in Phases A and C–F, respectively, in which the source had high and low hardness ratios. In Phase B, the hardness ratio was between the values in Phases A and C–F, indicating that the source was likely to be in the intermediate state. These are confirmed in the following spectral analysis.

We also created 6 hr bin light curves (Figure 4) in Phase B to study the variability during the intermediate state. Interestingly, the source exhibited a flux drop of ∼40% during MJD 59355–59358, without significantly changing the level of the...
Figure 4. The same as Figure 2, but with 6 hr bins and limited to MJD 59345–59362 (Phase B). The shaded regions indicate the phases of the highest soft X-ray flux with relatively weak hard X-rays (Phase B-0), the flux drop in the soft X-rays (Phase B-1), and after the drop (Phase B-2), as used in Section 4.2.

4.1. Time-averaged Spectra in the Individual Phases

Figure 5 shows the time-averaged MAXI/GSC and Swift/BAT spectra in the individual phases. For the MAXI/GSC data, we discarded the spectral bins at high energies when the source count rate was below ~10% of the background level. In the Appendix (Figure 10), we show the MAXI/GSC response-folded spectra and their background contributions. The Swift/BAT data for Phases D, E, and F were unavailable. In these phases, all of the spectral bins gave only upper limits on the count rates. In Phase A, the sources exhibited a hard, power-law-shaped spectrum with a cutoff at ~50 keV. Then, in Phase B, a strong thermal component, likely originating in the standard disk, emerged in the soft X-ray band. Meanwhile, the spectral cutoff disappeared in the hard X-ray band. A strong, steep, power-law-shaped component, with a photon index of ~2.5, was seen in the Phase B spectrum, while in the later phases the hard X-ray component became weak and harder.

We analyzed the broadband X-ray spectra of MAXI J1803–298 using a standard model for BHXBs: the multicolor disk blackbody emission (diskbb; Mitsuda et al. 1984) and its Comptonization. The diskbb model is parameterized by the disk temperature and the normalization that is determined by the inner disk radius $r_{in}$, the distance $D$, and the inclination angle $i$. For the Comptonization component, we adopted nthcomp for Phase A (Zdziarski et al. 1996; Życki et al. 1999) and simpl (Steiner et al. 2009) for Phases B–F. The nthcomp model calculates a thermally Comptonized spectrum using the photon index $\Gamma$, the electron temperature $kT_e$, and the seed photon temperature (the inner disk temperature $kT_{in}$ when the seed spectrum is set to be a disk blackbody). Because the direct disk component is not seen in the soft X-ray band, the diskbb model was not used and $kT_{in}$ was fixed at 0.1 keV for the Phase A spectrum. The simpl model is a convolution model redistributing a fraction ($F_{\text{seed}}$) of the input seed photons into a power-law profile with photon index $\Gamma$. When using this model, we extended the energy range used in the calculation down to 0.01 keV and up to 1000 keV, so that the spectral fit was not affected by uncertainties at the upper and lower boundaries of energy.

We also used the TBabs model to account for interstellar absorption. Since the MAXI/GSC has sensitivity only above 2 keV, it is difficult to determine the column density. The column density was therefore fixed at $N_H = 3 \times 10^{21}$ cm$^{-2}$, which was obtained from a NICER observation (Homan et al. 2021). We have confirmed that the uncertainty in $N_H$ has only a small effect on the fit parameters; they do not change beyond their 90% error ranges when $N_H = 2 \times 10^{21}$ cm$^{-2}$ and $N_H = 4 \times 10^{21}$ cm$^{-2}$ are adopted. The cross-normalization factor of the Swift/BAT data with respect to the MAXI/GSC data varied to account for the uncertainties in the instrumental cross-calibration and that caused by flux variation.

Homan et al. (2021), Xu & Harrison (2021), and Jana et al. (2021) have reported that the source showed strong absorption dips, with a ~7 hr interval and a ~5000 s duration, in which the X-ray intensity was reduced by ~50%–100%. However, we found that the effect in our spectral analysis was negligible. The conclusion of the analysis did not change when the data in the dip phases (assuming the above interval and duration, and the center of the dip as reported by Homan et al. 2021) were excluded. This is likely because the strong dips were short-lived compared with the data periods that we employed. Actually, previous studies of other transient BHXBs have found that dips were only seen in limited periods during outbursts (e.g., Kuulkers et al. 2013).

As shown in Figure 5, the TBabs+nthcomp model and the TBabs+simpl+diskbb model were able to reproduce the observed spectra. The best-fit parameters in each phase are summarized in Table 2. The Phase C–F spectra were dominated by the diskbb component in the soft X-ray band below 10 keV. In Phases D–F, the photon index $\Gamma$ was not constrained at all, because the hard tail was not clearly observed due to the lack of hard X-ray data. For these phases, we adopted the best-fit value in Phase C, $\Gamma = 2.1$. Many previous works on BHXBs have indicated that the inner disk radius remains constant when the X-ray spectrum is dominated by disk blackbody emission (e.g., Ebisawa et al. 1993; Kubota & Makishima 2004; Steiner et al. 2010; Shidatsu et al. 2011). Considering this, we attempted to fit the Phase C–F spectra simultaneously, linking the diskbb normalizations of all of the phases. In this fit, $\Gamma$ were also linked to one another. As shown in Table 2, we obtained an acceptable fit, which gave $r_{in} = 44 \pm 3$ (cos $i$ / cos $70^\circ$)$^{-1/2}$ (D/8 kpc) km.

4.2. Short-term Variation in Phase B

Next, to study the spectral variation in the intermediate state, we made 1 day averaged MAXI/GSC and Swift/BAT spectra in Phase B, and applied the same model as in Section 4.1: the TBabs+simpl+diskbb model. The model successfully reproduced all of the data. Figure 6 shows two representative spectra at different X-ray fluxes and their best-fit models, and Figure 7 presents the time variation of the best-fit parameters. At the brightest phase in the soft X-rays (around MJD 59350; hereafter, we call this Phase B-0), the spectrum was dominated by the thermal component below 10 keV and the hard tail had a photon index of ~2.0, while a steep power-law-shaped spectrum with a photon index of 2.3–2.7 was seen in the other time periods in Phase B.
Figure 5. Top: unfolded MAXI/GSC (black) and Swift/BAT (open red square) spectra for the individual phases given in Table 1, fitted with the TBabs+nthcomp model (for Phase A) or the TBabs+simple+diskbb model (for Phases B–F). The units of the ordinate axes are keV (Photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$). Bottom: residuals for the best-fit models.

Table 2

| Phase | $\Gamma$ | $kT_{in}$ keV | $F_{scat}$ | $kT_{out}$ keV | $r_{in}$ km | Cross-norm. | $\chi^2$/dof | $F_{x}$ $10^{-9}$ erg s$^{-1}$ cm$^{-2}$ |
|-------|----------|--------------|------------|---------------|-------------|-------------|-------------|----------------------------------|
| A     | 1.7 ± 0.1 | 26$^{+18}_{-17}$ | ...       | 0.1 (fixed)   | ...         | 1.0$^{+0.3}_{-0.2}$ | 38/35     | 5.5$^{+0.6}_{-0.5}$            |
| B     | 2.46$^{+0.08}_{-0.07}$ | ... | 0.22$^{+0.03}_{-0.02}$ | 0.88 ± 0.03 | 46$^{+3}_{-4}$ | 0.8 ± 0.1 | 155/154 | 19.8 ± 0.5        |
| C     | 2.1 ± 0.2 | ... | 0.04 ± 0.02 | 0.86 ± 0.04 | 40 ± 4       | 0.5$^{+0.4}_{-0.2}$ | 65/77    | 11.7$^{+0.8}_{-0.7}$         |
| D     | 2.1 (fixed) | ... | <0.03 | 0.81$^{+0.02}_{-0.01}$ | 38$^{+2}_{-3}$ | ... | 77/75    | 7.5$^{+0.9}_{-0.4}$          |
| E     | 2.1 (fixed) | ... | <0.02 | 0.64$^{+0.02}_{-0.00}$ | 50$^{+1}_{-1}$ | ... | 52/49    | 4.8$^{+0.7}_{-0.2}$         |
| F     | 2.1 (fixed) | ... | <0.04 | 0.56$^{+0.04}_{-0.03}$ | 42$^{+17}_{-2}$ | ... | 30/41    | 2.1$^{+0.4}_{-0.3}$        |
| B-1   | 2.7 ± 0.2 | ... | >0.3 | <0.72 | 93$^{+0.20}_{-0.34}$ | 1.1 ± 0.3 | 46/33 | 17.5$^{+2.7}_{-1.9}$     |
| B-2   | 2.5 ± 0.1 | ... | 0.26$^{+0.05}_{-0.04}$ | 0.85 ± 0.06 | 51$^{+8}_{-6}$ | 0.8 ± 0.1 | 38/35 | 21.7$^{+2.4}_{-0.9}$    |

(Simultaneous Fit)

| C     | 2.1 ± 0.2 | ... | 0.05$^{+0.02}_{-0.01}$ | 0.83 ± 0.02 | 44 ± 3$^{d}$ | 0.5$^{+0.2}_{-0.1}$ | 234/245$^{e}$ | 11.7$^{+0.8}_{-0.7}$ |
| D     | (linked) | ... | 0.019$^{+0.009}_{-0.018}$ | 0.77 ± 0.02 | (linked) | ... | ... | 7.5$^{+1.0}_{-0.4}$ |
| E     | (linked) | ... | <5 × 10$^{-3}$ | 0.67$^{+0.01}_{-0.00}$ | (linked) | ... | ... | 5.0$^{+0.4}_{-0.3}$ |
| F     | (linked) | ... | <3 × 10$^{-2}$ | 0.56$^{+0.01}_{-0.00}$ | (linked) | ... | ... | 2.2$^{+0.3}_{-0.2}$ |

Notes.

a The TBabs+nthcomp model was applied for Phase A, while the TBabs+simple+diskbb model was adopted for the other phases. The $N_{H}$ value of TBabs was fixed at 3.0 × 10$^{22}$ cm$^{-2}$.
b The inner disk radius estimated from the relation $r_{in} = \sqrt{N_{h}/\cos i} (D/10 \text{kpc})$, where $N_{h}$, $D$, and $i$ are the normalization of diskbb, the distance, and the inclination angle, respectively. $i = 70^\circ$ and $D = 8 \text{kpc}$ were assumed here.
c Unabsorbed 0.01–100 keV flux.
d The normalizations of diskbb and $\Gamma$ of simple were linked among the four phases.
e The total $\chi^2$/d.o.f. value of all the four spectra.

To investigate the cause of the flux drop seen in Figure 4, we also made time-averaged spectra for MJD 59355.5–59358.0 (during the deepest flux drop; hereafter, we call this Phase B-1) and for MJD 59358.5–59362.0 (after the drop; Phase B-2), and applied the same spectral model as above. The two spectra and their best-fit models are shown in Figure 8, and the best-fit parameters are given in Table 2. We found that $T_{in}$ was lower in Phase B-1 than in Phase B-2. By contrast, $r_{in}$ and $F_{scat}$ favored...
larger values in Phase B-1, although they were marginally consistent each other between the two phases when the 90% uncertainties were considered.

The bottom panel in Figure 8 shows the ratio of the raw spectra folded by the instrumental responses. The Phase B-1 spectrum has a slightly larger soft X-ray fraction below 3 keV than the Phase B-2 spectrum, which is consistent with the change in $T_{\text{in}}$. We note that this flux drop cannot be explained by the increase in the absorption column density alone. In such a case, softer X-rays would be more strongly absorbed, and thus the spectrum would become significantly harder in the flux drop. To test whether the absorption can explain at least some fraction of the flux drop at low energies, we fit the spectra with the same model above, allowing $N_{\text{H}}$ to vary. The fit only gave upper limits, $N_{\text{H}} \sim 4 \times 10^{21}$ cm$^{-2}$, for both spectra, but this value suggests that the absorption was not strongly enhanced in the flux drop.

5. Discussion

5.1. Long-term Evolution and Spectral States

We have performed long-term X-ray monitoring of the new Galactic black hole candidate MAXI J1803−298 over five months following its discovery, using MAXI/GSC and Swift/BAT. The long-term light curves were characterized by a rapid rise and slow decay, and the spectral softening was observed at the brightest phase (Figure 2). In the hardness−intensity diagram, the source drew a counterclockwise path (Figure 3), like other transient BHXBs (e.g., Miyamoto et al. 1995). Recently, the soft-to-hard transition has been reported, from NICER observations, to have occurred between MJD 59500 and 59506 (Steiner et al. 2021). The low statistics of the MAXI/GSC data hampered the determination of the exact time of the transition, but the hardness−intensity diagram suggests that the luminosity of the soft-to-hard transition was $\sim 1$ order of magnitude lower than that of the opposite transition.

The combination of the two instruments enabled us to study the broadband X-ray spectrum in 2–200 keV and its evolution during the outburst. At the initial rise of the soft X-ray flux (Phase A), the source showed a typical low-/$T_e$ (1.7 keV) and the direct disk emission component was not observed. At the highest flux phase (Phase B), the soft X-ray fraction increased, and the time-averaged spectrum was characterized by a steep power-law model with $\Gamma \sim 2.5$, consistent with the spectral profile in the intermediate or very high state. Although previous studies suggest disk truncation in this state (Tamura et al. 2012; Hori et al. 2014), we did not detect a significant increase in $r_{\text{in}}$, likely due to the insufficient quality of the data. We note that the $r_{\text{in}}$
values obtained from the simpl*diskbb model include the contributions of the scattered disk photons.

Due to the data gap from MAXI/GSC, it is unclear exactly when the onset of the transition occurred, but it most likely occurred around the middle of the data gap from MAXI/GSC; NuSTAR observed a typical low/hard-state spectrum for MJD 59339–59340 (Xu & Harrison 2021), while for MJD 59345–59346 AstroSAT detected a significant disk blackbody component with an inner disk temperature of \( \sim 0.6\, \text{keV} \), suggesting that the source was already in the intermediate state (Jana et al. 2021). We have investigated the 1 day averaged Swift/BAT spectra in the data gap from MAXI, but have detected no significant spectral variation, due to low statistics.

In the decaying phase after the intermediate state (Phases C–F), the spectrum was described by dominant multicolor disk blackbody emission in the soft X-ray band and a weak power-law tail, with \( \Gamma \sim 2.0 \) in the hard X-ray band. These spectral properties are consistent with the high/soft state. Applying the disk blackbody and its nonthermal Comptonization model, we obtained the inner disk temperature \( T_{\text{in}} \sim 0.5–1\, \text{keV} \) and the scattering fraction \( F_{\text{scat}} < 10\% \), in agreement with typical BHXBs in the high/soft state (McCintock & Remillard 2006). Unlike the case of neutron star low-mass X-ray binaries, no additional blackbody component was required in this period, supporting the nature of the source being a black hole. The idea that the source contains a black hole is consistent with the fact that no coherent pulsation has been detected so far (e.g., Xu & Harrison 2021). We note that searching for pulsation using the MAXI/GSC data is difficult, because of the insufficient statistics and the very large time gaps between each scan (MAXI observes a source for only a few minutes in a 92 minute orbit; see Sugizaki et al. 2011). A systematic search for pulsation from MAXI J1803–298 is beyond our scope, and we leave this for future work. We have also searched the MAXI 2–10 keV light curve over the entire outburst period, but found no X-ray bursts. This also indirectly supports the nature being a black hole.

### 5.2. Variation in the Intermediate State

Significant spectral variation on timescales of \( \sim 1\, \text{day} \) was observed in the intermediate state (Phase B). Around Phase B-0, which corresponds to the flux peak in the soft X-ray band, the spectrum was characterized by a dominant thermal disk component and a relatively weak hard tail with \( \Gamma \sim 2.0, \) reminiscent of the high/soft-state spectrum. At lower luminosities, the source exhibited a steep power-law-shaped spectrum with \( \Gamma \sim 2.5, \) consistent with the very-high-state spectrum, which is normally seen at a higher luminosity than that of the high/soft state. Given that the steep power-law spectrum is usually seen at sub-Eddington luminosities (\( \Gamma < 2 \)), the hard component may have been launched in the inner disk region. If such an outflow was really launched, and was Compton-thick and almost completely ionized, strong scattering could reduce the apparent X-ray flux without a great change in the spectral shape. A candidate of Compton-thick wind was actually observed in GRO J1655–40 at similar luminosities (Neilsen et al. 2016; Shidatsu et al. 2016).

We note, however, that the very-high-state spectra are more complex than the simpl*diskbb model (e.g., Gierliński & Done 2003; Tamura et al. 2012; Hori et al. 2014), and that the spectral parameters that we have estimated are to be taken with caution. The application of more realistic models to high-quality broadband spectra would be required to investigate the details of the accretion flow structure at this epoch.

### 5.3. Constraint on the Black Hole Mass

Previous studies have suggested that the standard disk extends stably down to the ISCO in the high/soft state. Since the ISCO depends on the mass of the central compact object, we can constrain the black hole mass of MAXI J1803–298 from the inner disk radius estimated in the high/soft state. In our spectral analysis, we obtained \( r_{\text{in}} = 44 \pm 3 \, \text{(cos} \, \text{i} / \cos 70^\circ)^{-1/2} \, (D/8 \, \text{kpc}) \, \text{km} \), from the normalization of diskbb. Considering the correction factor of the boundary condition at the inner disk edge and the color–temperature correction factor (\( K \) in total), the actual inner radius was estimated to be \( R_{\text{in}} = K r_{\text{in}} = 52 \pm 4 \, \text{(cos} \, \text{i} / \cos 70^\circ)^{-1/2} \, (D/8 \, \text{kpc}) \, \text{km} \). Here, we adopted \( K = 1.19, \) assuming a color–temperature correction factor (\( f_{\text{col}} \) of 1.7 (Shimura & Takahara 1995) and a torque-free inner boundary (Kubota et al. 1998). Assuming a Schwarzschild black hole, we obtain a black hole mass of \( M_{\text{BH}} = 5.8 \pm 0.4 \, \text{(cos} \, \text{i} / \cos 70^\circ)^{-1/2} \, (D/8 \, \text{kpc}) \, M_{\odot} \).
In the above discussion, we only considered the 90% error of \( r_\text{in} \) obtained in the spectral fit, but the color–temperature correction factor could be an additional source of uncertainty. Davis et al. (2005) obtained \( f_\text{col} = 1.4 - 1.7 \) from the calculation of the disk spectrum, considering radiation transfer in the disk atmosphere and comparisons with observations. If we adopt the lowest value, 1.4, \( K \) is reduced by \( \sim 30\% \), and \( M_\text{BH} \) thereby decreases by the same factor. Another uncertainty could be posed by the relativistic effects, which are not considered in the disk bb model. To investigate these effects, we fit the Phase C-F spectra simultaneously, in the same manner as in Section 4.1, but replaced disk bb with the relativistic disk emission model kerrbb (Li et al. 2005). In this fit, we allowed both the mass accretion rate and \( M_\text{BH} \) to vary, and fixed all of the other parameters of kerrbb: \( f_\text{col} = 1.7, i = 70^\circ \) or \( 85^\circ \), \( D = 8 \) kpc, and \( a_\ast = 0 \), where \( a_\ast \) is the dimensionless spin parameter of the black hole defined as \( J_\ast/GM^2 \) (\( J \) is the angular momentum of the black hole). We assumed a torque-free inner boundary and considered the self-irradiation effect, but ignored the limb-darkening effect. From this model, \( M_\text{BH} \) was estimated to be \( 6.1_{-0.3}^{+0.4} \) and \( 10.5_{-0.5}^{+0.7} \) for \( i = 70^\circ \) and \( 85^\circ \), respectively. These values, although having large errors, are consistent with the values that we obtained from the disk bb model, and hence the relativistic effects can be considered to be weak in a nonrotating black hole.

In the case of a Kerr black hole with a prograde spin, the relativistic effects can be stronger, because the ISCO radius decreases with the spin and the observed disk spectrum can significantly deviate from what disk bb predicts. Generally, the black hole mass estimated from the relativistic disk model increases as the spin increases and the ISCO radius decreases, but the exact value depends on the black hole spin and the inclination angle in a complicated way (e.g., Shidatsu et al. 2011; Wang et al. 2018). Estimating the black hole mass and spin and the inclination simultaneously is difficult for the MAXI/GSC data, due to insufficient statistics and the lack of data in the soft X-ray band below 2 keV. The application of the relativistic disk model to better-quality soft X-ray spectra is left for future work.

In Figure 9, we plotted the \( M_\text{BH} \) versus \( D \) relation obtained above. While the inclination angle of MAXI J1803–298 is likely to be \( i \gtrsim 70^\circ \), because of the presence of winds and absorption dips, the distance has not been constrained so far. Considering that the luminosity at the soft X-ray peak (MJD 59350) was likely close to the Eddington luminosity (see Section 5.2), we can obtain another constraint on \( M_\text{BH} \) and \( D \). This is also plotted in Figure 9. Here, the unabsorbed 0.01–100 keV flux at the soft X-ray peak, \( 2.4 \times 10^{-8} \) erg cm\(^{-2}\) s\(^{-1}\), was adopted and converted to the luminosity \( L_\text{peak} \) by assuming emission from a geometrically thin disk surface.

The combination of the \( D \) versus \( M_\text{BH} \) relations from the ISCO radius and peak luminosity favors moderate or large distances, \( \gtrsim 11 \) kpc for \( i = 70^\circ \) and 6 kpc for \( i = 85^\circ \), when \( L_\text{peak} > 0.5L_\text{Edd} \) is assumed. The source is therefore likely located near the Galactic center or farther away. This is in agreement with the fact that the absorption column density estimated with a NICER spectrum is consistent with the total Galactic column \( N_\text{H} \gtrsim 3 \times 10^{21} \) cm\(^{-2}\) obtained from the 2D HI4PI map, a full-sky HI survey (HI4PI Collaboration et al. 2016). A relatively large black hole mass, \( \gtrsim 8M_\odot \), was obtained in both cases of inclination angles.

6. Summary

Using MAXI/GSC and Swift/BAT data, we have studied the X-ray spectral evolution of the new Galactic black hole candidate MAXI J1803–298. The source showed the state transition from the low/hard state to the high/soft state via the intermediate state. Flux variation on a timescale of \( \sim 1 \) day was detected in the intermediate state, which could be interpreted as a rapid change in the mass accretion rate (and possibly the launch of a Compton-thick outflow) at the transition between the standard disk and the slim disk. Using the inner disk radius in the high/soft state and the peak luminosity, we estimated the black hole mass and distance of MAXI J1803–298 to be \( \sim 8M_\odot \) and \( \gtrsim 6 \) kpc (where a nonspinning black hole, an inclination of \( \gtrsim 70^\circ \), and the peak luminosity of \( \gtrsim 0.5 \) times the Eddington luminosity are assumed), suggesting that the source is a black hole X-ray binary located near to or farther away than the Galactic center region.

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Facilities: MAXI (GSC), Swift (BAT, NICER (XTI)).
Software: XSPEC (v12.11.1; Arnaud 1996), HEASoft (v6.28; HEASARC 2014).

Appendix

MAXI/GSC Folded Spectra in the Individual Phases

Figure 10 shows the folded MAXI/GSC and Swift/BAT spectra (with the background contributions for the MAXI/GSC) in the individual phases given in Table 1.
Figure 10. The MAXI/GSC response-folded, background-subtracted spectra of MAXI J1803$-$298 in Phases A–F. The background spectra are shown with open red squares.

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