Discovery and state transitions of the new Galactic black hole candidate MAXI J1535–571

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Received (reception date); Accepted (acceptation date)

Abstract

We report on the detection and subsequent X-ray monitoring of the new Galactic black hole candidate MAXI J1535–571 with the MAXI/GSC. After the discovery on 2017 September 2 made independently with MAXI and the \textit{Swift}/BAT, the source brightened gradually, and in a few weeks, reached the peak intensity of $\sim 5$ Crab, or $\sim 1.6 \times 10^{-7}$ erg cm\textsuperscript{-2} s\textsuperscript{-1} in terms of the 2–20 keV flux. In the hardness-intensity diagram, the source drew two counter-clockwise circles at different 2–20 keV fluxes. On the initial outburst rise, the X-ray spectrum was described by a power-law model with a photon index of $\lesssim 2$, while after a hard-to-soft transition which occurred on September 18, the spectrum required a disk blackbody component in addition. At around the flux peak, the 2-8 keV and 15-50 keV light curves showed quasi-periodic and
anti-correlated fluctuations with an amplitude of 10–20 %, on a time scale of \( \sim 1 \)-day. Based on these X-ray properties obtained with the MAXI/GSC, we discuss the evolution of the spectral state of this source, and give constraints on its system parameters.

**Key words:** X-rays: individual (MAXI J1535−571) — X-rays: binaries — accretion, accretion disks — black hole physics

1 introduction

Transient black hole binaries (BHBs) sometimes exhibit dramatic outbursts, changing its X-ray luminosity over several orders of magnitude. Their outburst light curves typically consist of a rapid rise on timescales of a few days to a few weeks, and a subsequent slow decay on timescales of weeks to a few months. In their outbursts, they show distinct “states” with different spectral properties (e.g., McClintock & Remillard 2006; Done et al. 2007). The canonical two states are the so-called hard state and the soft state, where the spectrum below 10 keV is characterized by a hard power-law component with a photon index of \( < 2 \), and by a multi-color disk blackbody component (Mitsuda et al. 1984), respectively. BHBs are known to exhibit a hysteresis in their flux versus spectral evolution; they make state transitions from the hard state to the soft state and the opposite way at different luminosities, and consequently track a q-shaped curve on an X-ray hardness-intensity diagram (HID; Homan & Belloni 2005). Because the spectral properties are considered to reflect the structure and dynamics of accretion flows in the vicinity of the central black holes, probing the complex spectral evolution during outbursts gives us clues to the physics of black hole accretion over a wide range of mass accretion rates.

MAXI J1535−571 was detected on 2017 September 2 with the GSC onboard MAXI (Matsuoka et al. 2009), which is operating on the International Space Station (ISS). The MAXI/GSC nova alert system (Negoro et al. 2016) triggered on the source at UT 14:41 with a low significance. As reported by Negoro et al. (2017b), the detection was confirmed with subsequent scans, which recorded an X-ray intensity of \( 34 \pm 6 \) mCrab in 4–10 keV. Almost simultaneously and independently, the Swift/BAT also discovered the source (Markwardt et al. 2017; Kennea et al. 2017), and precisely determined its position at \(( \alpha, \delta ) = (15^h\ 35^m\ 19.73^s, -57^\circ\ 13'\ 48''\ .1)\) with the XRT and UVOT onboard. After the discoveries and a gradual increase of the flux, the source spectrum softened (Nakahira et al. 2017; Kennea 2017; Palmer et al. 2017) and a disk blackbody component became significant (Shidatsu et al. 2017), suggesting a state transition from the hard state into the soft state on about September 18.
Follow-up observations of the object were extensively performed in various wavelengths (Scaringi & ASTR211 Students 2017; Russell et al. 2017a; Dincer 2017; Nakahira et al. 2017; Shidatsu et al. 2017; Kennea 2017; Mereminskiy & Grebenev 2017; Russell et al. 2017b; Gendreau et al. 2017; Tetarenko et al. 2017; Britt et al. 2017). The counterpart of MAXI J1535−571 was found in the optical and infrared bands soon after the onset of the outburst, with a relatively low optical flux (∼21 mag in the $i'$ band; Scaringi & ASTR211 Students 2017; Dincer 2017). Radio emission from the object was also detected (Russell et al. 2017b; Tetarenko et al. 2017). The source was interpreted as a new black hole candidate in our galaxy, considering the X-ray spectral shapes and rapid X-ray variability (Negoro et al. 2017a), as well as the radio versus X-ray flux ratio (Russell et al. 2017a). The optical/near-infrared variations suggest that the companion is a low-mass star (Scaringi & ASTR211 Students 2017; Dincer 2017). As a working hypothesis, we here assume that the object is a new BHB.

Based mainly on the MAXI/GSC data, the present paper describes the X-ray behavior of MAXI J1535−571 over the 202 days from the outburst onset.

2 Data analysis and results

2.1 Data reduction

We studied the X-ray properties of MAXI J1535−571 using light curves and spectra obtained with the MAXI/GSC. The 15–50 keV light curve of the Swift/BAT was also employed to investigate the long-term trend in the hard X-ray band.

We analyzed the MAXI data with the processed version 1.3.6.6, which is a beta-test version released from DARTS at ISAS/JAXA¹. Light curves and spectral data were produced from the event data via MAXI specific tools implemented in “MAXI/GSC on-demand web interface ²(Nakahira et al. 2013)”. The on-source data were extracted from a circular region with a radius of 2°.1, centered on the source position. The background data of the same region were produced with a background event generator, which adopts the same method as used in the second MAXI/GSC extragalactic source catalog (Hiroi et al. 2013). To suppress statistical fluctuations, we generated 100 times more background counts than in the real data.

For the Swift/BAT data, we used the archived 15–50 keV light curve with a time resolution of ∼92 minutes (the spacecraft orbital period), available on the “BAT Transient Monitor” website (Krimm et al. 2013)³.

¹ http://darts.isas.jaxa.jp/astro/maxi/
² http://maxi.riken.jp/mxondem
³ http://swift.gsfc.nasa.gov/docs/swift/results/transients
2.2 Light curves and hardness ratios

Figure 1a shows background-subtracted MAXI/GSC light curves and hardness ratio (HR) of MAXI J1535−571, with the time origin \((T=0, \text{ where } T \text{ is in units of day})\) set to the onset of the outburst on 2017 September 2. Each data point represents one scan transit of the source, which takes place every 92 minutes and lasts for 40-100 s. MAXI was not able to observe the direction of MAXI J1535−571 for \(T =25–42, T =101–112, 120–121\) and 173-182. A Swift/BAT light curve in 15–50 keV is also presented to compare intensity variations at different energies. Because the data with the original sampling are subject to large statistical errors, we took averages typically over 2–20 adjacent data points. These binned data, 109 points in total, are shown in red in figure 1a.

The MAXI/GSC light curves and their HRs are converted to an HID in figure 2. There, colored data points represent the binned data in figure 1. Considering the behavior of the light curves and HID with MAXI, the entire outburst period can be classified into the following nine phases. Among them, H1 and H2 represent relatively hard phase typical of the hard state, S1 and S2 relatively soft phases to be interpreted as the soft state, and T1-T3 transient periods.

**H1a \((T=0–8):\)** the 2–8 and 8–20 keV intensities steadily increased, keeping an approximately constant HR \(\sim 0.6\).

**H1b \((T=8–10):\)** the 2–8 keV flux increased more rapidly than in H1a, and accordingly the HR rapidly declined to \(\sim 0.35\).

**H1c \((T=10–16):\)** the fluxes in both bands again increased steadily, with a slight decrease of the HR.

**T1 \((T=16–20):\)** the source declined rapidly in 2-8 keV and brightened in 8-20 keV simultaneously this is regarded as the first hard-to-soft state transition.

**S1 \((T=20–42):\)** the 2–8 keV flux was kept at the maximum level, while the 8–20 keV flux gradually decreased with small fluctuations (see below). The HR reached 0.1–0.2, the lowest value of the first circle in the HID.

**T2 \((T=42–46):\)** the HR rapidly increased, and the source returned to the hard state.

**H2 \((T=46–56):\)** the HR remained relatively constant, and the source made the second hard-to-soft state transition.

**T3 \((T=56–62):\)** the HR rapidly decreased.

**S2 \((T=62–):\)** the 2–8 and 8–20 keV fluxes both decreased steadily, while the HR marked the minimum value in the outburst, \(\sim 0.01\).

The behavior of the 15–50 keV flux was different from that in 8–20 keV; it decreased in H1b and then rose again in H1c. After the rapid decrease at the beginning of T1, it jumped among a few rather discrete intensity levels, and then gradually decreased during H2, T3 and S2 to undetectable levels.
Fig. 1. (a) The MAXI/GSC 2–8 keV and 8–20 keV light curves, hardness ratio between 8–20 keV and 2–8 keV band, and the 15–50 keV Swift/BAT light curve, from top to bottom. Black points indicate data with the finest time resolution (∼92 minutes), and red points are binned data. (b) Top: the zoomed 2–8 keV (black) and 15–50 keV (red) light curves around the first hard-to-soft state transition indicated in panel (a) by a pair of dashed vertical lines in green. The second order Bézier curves (solid lines) and its knots (circles) are superposed on the data. Middle and bottom: the ratios of the data to the Bézier curve. Errors in all panels represent 1σ confidence intervals.
Around $T=8–20$, the data were found to scatter much more than the statistical errors on a timescale of $\sim$one day. Figure 1b shows an expanded light curve for $T=8–22$, where superposed is a smoothed light curve produced using the second order Bézier curve. Anti-correlated oscillations can be seen between the 2–8 keV and 15–50 keV intensities with an amplitude of $\sim$10–20% and a period of $\sim$ one day.

2.3 Energy spectra

We extracted time-averaged MAXI/GSC spectra of MAXI J1535–571 from the 109 binned time points (defined in Section 2.2). The derived spectra were then fitted with the standard X-ray emission model for black hole X-ray binaries: a disk blackbody emission and its Comptonization, absorbed by cold interstellar medium. We adopted the multi-color disk model diskbb (Mitsuda et al. 1984), and convolved it with simpl (Steiner et al. 2009) in which a fraction of the input seed photons are redistributed by Comptonization into a power-law form. The interstellar absorption was expressed by the TBabs model, referring to the solar-abundance table given by Wilms et al. (2000). Because simpl is a convolution model, the energy band used in the spectral fitting was extended down to 0.01 keV and up to 100 keV. The spectral analysis was carried out with XSPEC version 12.9.1, and the errors represent 90% confidence limits.

In the fitting, the absorption columns density was fixed at $N_H=2.6 \times 10^{22}$ cm$^2$, a value which was favored by essentially all the spectra. When the 2–8 keV vs 8–20 keV HR is smaller than 0.22, we fixed $\Gamma$ at 2.40, a typical value during the soft state (McClintock & Remillard 2006), because the
direction disk emission was dominant in the GSC energy band and $\Gamma$ of the `simpl` model was poorly constrained. We confirmed that adopting $\Gamma$ from 2.2 to 2.6 instead of 2.40 does not affect our results. For the spectra in H1a and H1b, in which the direct disk component was not significant, a single `powerlaw` model was used instead of the `simpl*diskbb` model. The inner disk radius $R_{\text{in}}$ was estimated from the normalization of the `diskbb` component, by applying a correction factor of 1.18, obtained by combining an adjustment to express stress-free boundary condition ($\xi = 0.41$: see e.g., Kubota et al. 1998) with the color hardening factor ($\kappa = 1.7$: see e.g., Shimura 1995).  

Figure 3 and Table 1 present the spectra and the best-fit models for representative spectra in the individual phases. Analyzing all the spectra in the same way, we have obtained successful fits from most of them. The derived long-term evolution of the best-fit parameters is given in figure 4. For $T=16–25$, 42–45, and 55–202, the $R_{\text{in}}$ value, calculated assuming a distance $D=10$ kpc, stayed fairly constant, in spite of significant variations of the flux, Comptonized fraction, and the inner disk temperature. In Contrast, $R_{\text{in}}$ increased and varied significantly for $T = 45–53$, where rapid spectral hardening occurred. The results generally confirm our state assignments employed so far; H1 and H2 to hard state and S1 and S2 to the soft state.
Fig. 3. Representative MAXI/GSC spectra in phases H1a, H1b, H1c, T1, H2 and S2. The solid line shows the total model spectrum, and the dashed line indicates the intrinsic disk contribution.

3 Discussion

3.1 Overall properties of the outburst

We have observed a dramatic outburst of MAXI J1535−571, with a peak X-ray intensity of \( \sim 5 \) Crab, which is the 7th highest value among those of black hole candidates observed so far. The source reached the outburst peak more than two weeks after the discovery, which is relatively long compared with the typical flux-rise time scales in black hole candidates. Assuming a typical distance of \( D=10 \) kpc and an isotropic emission, the 2–20 keV peak luminosity is obtained as \( \sim 2.0 \times 10^{39} \) erg s\(^{-1}\), which is comparable to the Eddington luminosity of \( 10 M_{\odot} \) BH where \( M_{\odot} \) is the solar mass. Further discussion continues later on.

The evolution of the 2–20 keV flux is roughly characterized by a simple function of time, with a linear increase until \( T = 18.5 \) followed by an exponential decay and a re-flaring around \( T = 130 \).
However, more complex behavior, involving the three state transitions, can be seen when we compare the flux variations in different energy bands and examine the spectral evolution (see section 3.3).

As in many black hole transients, we can clearly see hysteresis patterns in the HID, in which the source roughly drew a counter-clockwise track. Meanwhile, its energy spectra exhibited sequential changes as shown in figures 3. At the beginning, MAXI J1535−571 brightened monotonically, accompanied by an increase of the photon index from $\Gamma \sim 1.5$ to $\sim 2.0$ (H1a through H1c), and then rapidly softened through the transition T1, to reach the soft state S1. Subsequently, it gradually declined in $\sim 180$ d with a decrease of $T_{\text{in}}$ from $\sim 1$ keV to 0.55 keV. However, during that course, it suddenly exhibited a spectral hardening (T2), stayed in the presumably hard state (H2) for about ten
days, and jumped back (T3) to the soft state (S2) to continue its decline. In H1c [$T=10–16$; figure 3 (3)] and H2 [$T=46–56$; figure 3 (7)], the source stayed for fairly long times, in a state of flat spectrum with $\Gamma \approx 2.0$ (equivalent to HR of 0.2–0.4), even though the HR changed widely from $\sim 0.8$ down to 0.01.

The overall behavior in the HID and the spectral evolution of MAXI J1535−571 supports the assumption that it is a BHB. The soft-to-hard transition, which is expected to take place at a lower X-ray luminosity has not been observed yet as of 2018 March 31, but will occur soon.

3.2 Constraint on the black hole mass

For $T=16–25$ (T1 to S1) and $T=55–202$ (T3 to S2) in figure 4, $R_{\text{in}}$ remained relatively constant at $\sim 100(D/10 \text{ kpc}) \cos i/\cos 0^\circ -1/2 \text{ km}$, which can be identified with the radius of ISCO (Innermost Stable Circular Orbit). This enables us to constrain the black hole mass $M_{\text{BH}}$ of MAXI J1535−571. If the black hole is a Schwarzschild black hole, the $R_{\text{in}}$ values can be identified with three times the Schwarzschild radius, to obtain $M_{\text{BH}} \sim 11M_\odot (D/10 \text{ kpc}) \cos i/\cos 0^\circ -1/2$. This relation is shown by black lines on a distance vs mass diagram in figure 5 assuming $i=0$ and $60^\circ$.

The minimum X-ray flux of $\sim 0.23 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$, corresponding to 1.5% of the peak flux ($15.7 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$), was obtained at the latest data point ($T=196–202$), when the source still remained in the soft state. If we assume that the soft-to-hard state transition usually seen at the end of the outburst occurs on the order of 1% of the Eddington luminosity (e.g., Maccarone 2003, Fender et al. 2004), the peak X-ray luminosity should be higher than $0.67 L_{\text{edd}} (D/10 \text{ kpc})^2 (M_{\text{BH}}/11M_\odot)^{-1}$, indicating that the source reached near or above the Eddington luminosity. In figure 5, red lines indicate the assumed Eddington ratios at the outburst peak. From these two sets of constraints, we obtain $D > 8.4 \text{ kpc}$ and $M > 9.5 \text{ M}_\odot$.

If the object is a highly spinning black hole, as suggested by modeling the reflection feature in the NuSTAR spectrum (Xu et al. 2017) on $T = 5.78$ in the hard state, we need to consider the relativistic effects to the disk emission. Generally, a high BH spin will lead to a high BH mass (Brenneman & Reynolds 2006), but too high a spin may be unfavored because the BH would then become too massive.

3.3 Interpretation of the Peculiar Behavior in the HID

The source drew two counter-clockwise circles on the HID (figure 2) with very different transition luminosities. The soft-to-hard transition T2 occurred when the luminosity decreased by a factor of $\sim 3$, from the peak value of T1 which is more or less close to Eddington limit (section 3.2). Then,
T3 roughly corresponds to the luminosity above which the intermediate state (so-called “very high state” or “soft/hard intermediate states”) usually starts to appear. Thus, the first cycle in the HID could be explained by an anomalous variation sometimes seen in other black hole X-ray binaries during the intermediate state (Fender et al. 2004, Hori et al. 2014). The spectra around the flux peak (T1) and between the first soft-to-hard transition and the second hard-to-soft transition (T2) were significantly contributed by both the direct disk and Comptonization components, in agreement with the intermediate state spectra seen in other BHBs. Interestingly, the softest phase in the first cycle (S1) has a spectrum similar to the softest spectrum in the second cycle (S2), as well as to the typical soft state spectra in other BHBs. The two spectra of MAXI J1535–571 are both dominated by the disk blackbody component, with similar $R_{\text{in}}$ but different $T_{\text{in}}$. Therefore, it appears as if the source, which was already in the canonical soft state in S1, made an excursion into a possibly quasi-steady state as $S1 \rightarrow T2 \rightarrow H2$, returned through $T3 \rightarrow S2$ to continue on of the same soft state. However, as is clear by comparing spectra (5) and (9) in figure 3 and inspecting figure 4, the power-law contribution (represented by $F_{\text{scat}}$) is considerably higher in S1, than in S2 when $F_{\text{scat}}$ was a few percent like in typical BHBS in the soft state. In addition, the power-law component in S1 exhibited the noticeable variability (figure 1b, section 2.2). Therefore, S1 and S2 could be somewhat different.

A pattern similar to the HID of MAXI J1535–571 is found in by figure 4 of Belloni & Motta 2016 as “generic HID”. According to this paper, our H1c and H2 could be classified as the hard-intermediate state, and S1 as the soft-intermediate state. The clue to a more precise classification of the spectral states would be the spectral shape above 10 keV and the short-term flux variability; these are left as future studies using the present data.

In H1c, the first period of that quasi-stable state, the 2–8 keV and 15–50 keV fluxes showed a
small, repetitive fluctuations on a timescale of \( \sim \) one day, with a sign of an anti-correlation (figure 1b). The time averaged spectra in H1c have a fairly flat profile, characterized by a single power-law component. Thus, the anti-correlated flux variation would be produced by the variation of the spectral index with a pivot energy at \( \sim 10 \) keV, the low statistics of the MAXI data hampered us to detect any significant differences at different phases of the fluctuation.

Variation on a similar timescale was found in MAXI J1659−152 (Kuulkers et al. 2012), but it has several different properties from that of MAXI J1535−571. The variation in MAXI J1535−571 was observed at around the flux peak, whereas that of MAXI J1659−152 was observed in the decaying phase of an outburst. Moreover, the case of MAXI J1659−152 is characterized by positive correlations between the soft and hard signals, and hence it was suggested to be produced by precession of the accretion disk induced by a 3:1 orbital resonance. The origin of the peculiar behavior in MAXI J1535−571 is hence still unclear, but could be associated with some change in the structure of the Comptonized corona, in response to fluctuations of the mass accretion rate due to some unspecified causes. A slight increase/decrease of the mass accretion rate would cause an increase/decrease of the number of seed photons for Comptonization in the corona, and thereby the corona is cooled/heated, leading to change the Comptonized continuum (e.g., Shidatsu et al. 2014).

4 acknowledgements

This research has made use of MAXI data provided by RIKEN, JAXA and the MAXI team. Part of this work was financially supported by Grants-in-Aid for Scientific Research 16K17672 (MS) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. MS acknowledges support by the Special Postdoctoral Researchers Program at RIKEN.

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