MAXI/GSC Discovery of the Black-Hole Candidate MAXI J1305–704

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Abstract

We present the first results on a new black-hole candidate, MAXI J1305–704, observed by MAXI/GSC. The new X-ray transient, named as MAXI J1305–704, was first detected by the MAXI-GSC all-sky survey on 2012 April 9 in the direction to the outer Galactic bulge at \((l, b) = (304^\circ.2, -7^\circ.6)\). A Swift/XRT follow-up observation confirmed the uncatalogued point source, and localized to the position at \((13^h06^m56.4^s, -70^\circ 27'4.9''1)\). The source continued its activity for about five months, until 2012 August. The MAXI/GSC light curve in the 2–10 keV band and the variation of the hardness ratio of the 4–10 keV to the 2–4 keV flux revealed the hard-to-soft state transition on the sixth day (April 15) in the brightening phase and the soft-to-hard transition on the ~60th day (June 15) in the decay phase. The luminosity at the initial hard-to-soft transition was significantly higher than that at the soft-to-hard transition in the decay phase. The X-ray spectra in the hard state are represented by a single power-law model with a photon index of ~2.0, while those in the soft state need such an additional soft component as represented by a multi-color disk blackbody emission with an inner disk temperature of ~0.5–1.2 keV. All of the obtained features support the source identification of a Galactic black-hole binary located in the Galactic bulge.

Key words: accretion, accretion disks — black hole physics — X-rays: binaries

1. Introduction

Galactic black-hole candidates in Binary systems (BHBs) occasionally exhibit an explosive X-ray brightening, referred to as “X-ray nova” or “outburst,” which is triggered by a sudden increase of in-flowing matter. A “typical” outburst light curve consists of a fast rise (a few days), followed by a longer (a few months) exponential decline (see Tanaka & Shibazaki 1996 for review). However, recent RXTE and MAXI surveys discovered a variety of outbursts with peculiar light-curve profiles (e.g., McClintock & Remillard 2006; Nakahira et al. 2010; Yamaoka et al. 2012).

During BHB outbursts, the luminosity can vary by a factor of \(10^4–10^5\), and also the spectrum will change (see McClintock & Remillard 2006 for review). These outbursts normally begin with the hard state. The hard-state spectrum is approximated by a single power-law with a photon index of \(\Gamma = 1.4–2.0\), up to the high-energy cutoff at \(\sim 100\text{ keV}\), and interpreted as a thermal Comptonization of soft photons by a hot and optically thin electron cloud (e.g., Takahashi et al. 2008; Makishima et al. 2008). During the initial brightening phase, they will exhibit the hard-to-soft state transition. The soft-state spectrum is represented by the combination of a thermal blackbody emission from an optically thick and geometrically thin accretion disk, a so-called standard disk (Shakura & Sunyaev 1973), with an inner-disk temperature of \(T_{in} \sim 1\text{ keV}\), and a power-law with \(\Gamma \sim 2–2.5\). In the course of the outburst decay phase, the source will return to the hard state again. The hysteresis in the X-ray intensity during the state transitions (Miyamoto et al. 1995) produces a q-shaped track in a hardness–intensity diagram (HID), a so-called q-curve (Homan & Belloni 2005). The “q-curve” can be used to identify a new X-ray source as a BHB.

A new X-ray transient, MAXI J1305–704, was first detected by MAXI (Monitor of All-sky X-ray Image: Matsuoka et al. 2009) GSC (Gas Slit Camera: Mihara et al. 2011; Sugizaki et al. 2011) in the direction to the outer Galactic bulge at \((l, b) = (304^\circ.2, -7^\circ.6)\) or (RA, Dec) = (196°.4, -70°.4). The source emergence was first noticed by the MAXI transient alert system (Negoro et al. 2012) at 2012 April 9 11:24:23 UT when the flux reached \(30\text{ mCrab}\) in the 4–10 keV band (Sato et al. 2012). Swift follow-up observations, which covered the entire MAXI/GSC error circle with five pointing observations, confirmed an uncatalogued bright X-ray source by both the X-Ray Telescope (XRT: Gehrels et al. 2005) and the UVOT (Roming et al. 2005), and then localized the position at (RA, Dec) = \((13^h06^m56.4^s, -70^\circ 27'04.9'\) with an uncertainty of 5° (Greiner et al. 2012; Kennea et al. 2012a). An optical follow-up observation found a new point source within the XRT error circle (Greiner et al. 2012). From the X-ray and optical spectra as well as their time variation, the source was proposed to be a BHB (Greiner et al. 2012;
Kennea et al. 2012a; Suwa et al. 2012). An observed X-ray dip or eclipse-like features (Kennea et al. 2012b, 2012c), and possible absorption-line signatures (Miller et al. 2012a, 2012b) suggest that our line of sight is located relatively edge-on of the accretion disk.

In this paper, we present results of MAXI/GSC observations of MAXI J1305−704, covering the entire outburst period from 2012 April to 2012 August, and discuss the identification and the nature based on the light curve and the spectral variation. In the following sections, all quoted errors are given at the 90% confidence limit.

2. Observation and Results

2.1. X-Ray Light Curves and Hardness Ratios

We performed GSC data analysis following the standard analysis procedure described in Sugizaki et al. (2011). Figure 1 shows the GSC image accumulating data taken from 2012 April 3 to July 17 in a region of 5′ from MAXI J1305−704. As can be seen in the image, a nearby bright X-ray source, 4U 1254−690, is located at a distance of 1′.4. To avoid any contamination from the source, we carefully selected the source and the background events. We first excluded data within 1′.6 from 4U 1254−690, and then collected source events from a circle of 1′.4 centered at the target position. To optimize the source-to-background event ratio, we adjusted these areas in each scan transit. Background events were then collected from the source-free region within 2′.5 from the MAXI J1305−704 position.

To obtain light curves, we calculated a photon flux corrected for an effective-area variation in each scan transit in each energy band. In the GSC data, we did not find any significant flux in a light curve above 10 keV in time bins from 1 d to 4 d. Figure 2 shows the obtained light curves in 2–4 keV and 4–10 keV, and that of the Swift/BAT in 15–50 keV obtained from the Swift/BAT transient-monitor archive1 provided by the Swift/BAT team. To clarify the spectral variation, we also give plots two hardness ratios of the 4–10 keV flux to the 2–4 keV flux (HR1) and the 15–50 keV to the 4–10 keV (HR2) in figure 2. We divided the entire outburst period into eight intervals, A, B, C, ... , and H, as illustrated in figure 2, to investigate any detailed flux and spectral variations in each outburst phase.

The light curve apparently shows different profiles among the three energy bands. In the initial brightening phase (period A), the onset is apparently earlier in the higher energy band. Both of the two hardness ratios, HR1 and HR2, then decreased during period A. This indicates that the hard-to-soft state transition occurred in the initial phase (Suwa et al. 2012). After the 2–4 keV flux peaked at MJD = 56030 (period B), the source stayed in an active phase with a flux above 30 mCrab for 60 d until MJD = 56030 (period B), the source remained at 0.3. The source activity then began to gradually decrease since MJD = 56110 (period G). During the outburst decay phase, the flux decline started earlier in the lower energy band, and then the two hardness ratios increased. This implies that the soft-to-hard state transition would occur.

The spectral changes are most apparent in the HR1. We thus utilize the HR1 value to discriminate the soft and the hard states, hereafter, and to set their boundary at HR1 = 0.5. This

Fig. 1. MAXI/GSC false-color image integrating data taken from 2012 April 3 to July 17 in 2–16 keV (Red: 2–4 keV, Green: 4–8 keV, and Blue: 8–16 keV). A white solid circle is the excluded region to avoid contamination of 4U 1254−690, and a green circle is a typical source-extract region with a radius of 1′.4. An annulus between the green dashed lines is for the background region.

Fig. 2. MAXI/GSC and Swift/BAT light curves of MAXI J1305−704 from MJD = 56000 (2012 March 14) to MJD = 56160 (2012 August 21) in three energy ranges of 2–4 keV, 4–10 keV (GSC), and 15–50 keV (BAT), and their hardness ratios. The data are binned per a day in MJD = 56000–56120, and per four days in MJD = 56120–56160. Vertical error bars represent the 1σ statistic uncertainty. The epoch of the Suzaku observation (Shidatsu et al. 2013) is also indicated.

1 http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/.
classifies periods A and G into the hard state, and the others into the soft state.

2.2. Hardness–Intensity Diagram (HID)

In figure 3, we plot a HID representing the relation between the 2–10 keV flux and HR1 during the outburst from MJD = 56022 to MJD = 56120. According to the photon count statistics of each outburst phase, data are binned by one-day intervals in periods A and B, and by 5-day intervals in periods C, D, E, F, and G. Due to the luminosity hysteresis in the state transitions in both the brightening and the decay phases, the HID exhibits a q-shaped track, which is a common feature in BHBs (Homan & Belloni 2005).

2.3. Spectral Analysis

The q-shaped HID track discussed in the previous subsection suggests that MAXI J1305–704 is possibly a BHB. We thus performed spectral analysis by fitting data with typical BHB emission models. We consider the validity of the assumed models and the source nature based on the obtained best-fit parameters.

GSC spectral data and their response files were obtained by using the MAXI on-demand data system \(^2\) (Nakahira 2012). The system implemented event data ver. 1.4 containing data taken by the GSC counters operated at both 1550 V and 1650 V. The total exposure reached 220.6 ks cm\(^{-2}\) with 1172 transits. Spectral data were binned so that each bin would contain at least \(\sim 30\) photons from the source region. All of spectral fits were carried out on XSPEC ver. 12.7.1. Figure 4 shows the obtained spectra in periods A, B, C, and D as examples.

We employed a single power-law model for the hard-state emission spectra, and a partly Comptonized multi-color-disk (MCD) model (Mitsuda et al. 1984; Makishima et al. 1986), represented by simpl*diskbb in XSPEC terminology, for the soft-state spectra. The simpl is an empirical Comptonization model that converts a given fraction, \(f_{sc}\), of incident photons into a power-law shape with a given photon index, \(\Gamma\) (Steiner et al. 2009). We fixed \(\Gamma\) of the simpl model at a typical BHB soft-state value, 2.2 (Ebisawa et al. 1994; Kolehmainen et al. 2011), and considered only the up-scattered component. Since the MCD dominates the GSC energy band, the data does not have sufficient statistics to determine \(\Gamma\) in the soft state. To take account of the interstellar absorption, a phabs model with the abundance of Anders and Grevesse (1989) was applied. We fixed the hydrogen column density, \(N_H\), at the Galactic H\(_1\) density, \(0.18 \times 10^{22}\) cm\(^{-2}\), in the source direction (Kalberla et al. 2005). Such a column density as the Galactic H\(_1\) only little affects the GSC energy band.

Table 1 summarizes the best-fit parameters obtained for the periods A to G. All of the fits were accepted within the 90% confidence limits. In figure 4, the folded/unfolded best-fit models and their data-to-model residuals are shown on each

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\(^2\) [http://maxi.riken.jp/mxondem/].
observed spectrum. In the hard state, the power-law photon index value is always $\sim 2.0$, which agrees with a typical value in the BHB hard states. In the BHB soft state, the inner disk radius is supposed to become constant when it reaches the innermost stable circular orbit. As can be seen in table 1, the MCD normalization parameter, $r_{\text{in}}/\cos i$, is almost consistent with each other in the three soft-state periods A, B, and C, and D, where the inner disk temperature, $T_{\text{in}}$, is also stable at $\sim 1$ keV. We thus fitted these soft-state spectra simultaneously with a common inner disk radius. The fit was acceptable; the obtained best-fit parameters are shown together in table 1. The $r_{\text{in}}/\cos i$ value then increased in periods E and F. This is considered to reflect the fact that the soft-to-hard state transition started gradually, as has been seen concerning the HID (figure 3).

3. Discussion

We analyzed the light curve and the spectral variation of the new X-ray transient, MAXI J1305–704, obtained from the MAXI/GSC all-sky survey data in the 2–20 keV band. We here consider the identification and the nature of the new object based on all of the obtained results.

The MAXI/GSC light curves and the hardness variations in figure 2 reveal the hard-to-soft state transition in the brightening phase and the soft-to-hard transition in the decay phase. The q-shaped HID track in figure 3 clarifies the luminosity hysteresis in the state transitions. These observed behaviors agree with the typical BHB feature (Homan & Belloni 2005). Gierlinski and Newton (2006) suggested that the initial hard-to-soft transitions of BHs are divided into two types: “bright/slow” type, which occurs at 30% of the Eddington luminosity, and takes more than 30 d, and “dark/fast” type, which occurs at less than 10% of the Eddington luminosity and takes less than 15 d. In the latter “dark/fast” type, the intermediate/very high state during the transition passes quickly. The observed transition on MAXI J1305–704, which had proceeded for $\lesssim 10$ d in the periods A + B, agree with the “dark/fast” type. The 2–20 keV X-ray spectra, represented by a simple power-law with $\Gamma = 2$ in the hard state and by a partly Comptonized MCD model with $T_{\text{in}} = 0.5$–1.2 keV and the scattering fraction $f_{\text{sc}} \gtrsim 0.2$ in the soft state, also agree with the typical BHBs (McClintock & Remillard 2006). However, similar behaviors have been observed in some transient neutron-star (NS) low-mass X-ray binaries (e.g., van der Klis 2006). Because of the limited photon statistics of the GSC data, a little difference in the X-ray spectra between the BH and the NS systems cannot be distinguished. Also, no confident evidence as a NS binary, such as a coherent pulsation and type-I X-ray bursts, has been detected. Therefore, we cannot conclude whether the object is either a BHB or a NS binary based on the MAXI/GSC data alone.

If MAXI J1305–704 is a BHB, the mass of the central accretor should be greater than the maximum NS mass, at least $2 M_\odot$. We consider the constraint on the mass $M$ and the source distance $d$ relation based on discussions in Yamaoka et al. (2012) and Nakahira et al. (2012). In the soft state, the inner radius of the accretion disk is supposed to reach that of the innermost stable circular orbit, $R_{\text{ISCO}}$, which is three-times the Schwartzschild radius, $6G/M^2$, if the central accretor has no spin and $<6G/M^2$ if it has a spin. By using the MCD model parameter, a realistic estimate of the innermost radius $r_{\text{in}}$ is represented by

$$R_{\text{in}} = \xi \kappa^2 r_{\text{in}} = 7.4^{+5.9}_{-4.3} \left( \frac{d}{10 \text{ kpc}} \right) (\cos i)^{-1/2} \text{ km}, \tag{1}$$

where $\xi = 0.41$ is a correction factor for the inner-boundary condition (Kubota et al. 1998), $\kappa = 1.7$ is the standard color hardening factor (Shimura & Takahara 1995), and the best-fit MCD model parameter for the periods B–D, $r_{\text{in}}/\cos i = 6.2^{+5.0}_{-3.6}$, are employed. Since MAXI J1305–704 shows an X-ray dip (Kennea et al. 2012c; Shidatsu et al. 2013), the disk inclination angle is expected to be $\lesssim 60^\circ$ (Frank et al. 1987). Assuming $R_{\text{in}} = 6G/M^2$ and $i = 75^\circ$, the mass $M$ is deduced to be

$$M = \frac{c^2 R_{\text{in}}}{6G} = 1.7^{+1.3}_{-1.0} \left( \frac{d}{10 \text{ kpc}} \right) (\cos i/\cos 75^\circ)^{-1/2} M_\odot. \tag{2}$$

| Period | MID | Exposure ($\text{ks}$) | $T_{\text{in}}$ ($\text{keV}$) | $r_{\text{in}}/\cos i$ (km) | $\Gamma$ | $f_{\text{sc}}$ | $F_{\text{sc}}$ ($10^{-14} \text{ erg cm}^{-2} \text{s}^{-1}$) | $F_{\text{bol}}$ ($10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$) | $\chi^2/d.o.f$ |
|--------|-----|-----------------------|-----------------------------|-----------------------------|-------|---------|-----------------|-----------------|----------------|
| A      | 56022.0–56028.0 | 20.0                   | 2.0$^{+0.8}_{-0.2}$          | 6.3$^{+0.5}_{-0.6}$          | 6.3   | —       | 30.0$^{+26}_{-26}$ |
| B      | 56028.0–56034.0 | 13.8                   | 9.6$^{+0.8}_{-0.2}$          | 2.2 (fix) 0.30$^{+0.14}_{-0.13}$ | 15.1$^{+1.2}_{-1.5}$ | 9.4   | 5.6   | 17.9$^{+28}_{-28}$ |
| C      | 56034.0–56042.0 | 17.7                   | 3.8$^{+0.8}_{-0.2}$          | 2.2 (fix) 0.00$^{+0.09}_{-0.07}$ | 7.9   | 0.0    | 7.9$^{+7.2}_{-7.2}$ |
| D      | 56042.0–56060.0 | 48.1                   | 8.2$^{+0.8}_{-0.2}$          | 2.2 (fix) 0.08$^{+0.04}_{-0.03}$ | 6.8   | 1.8    | 4.9$^{+14.4}_{-14.4}$ |
| E      | 56060.0–56090.0 | 62.5                   | 14.5$^{+0.8}_{-0.2}$         | 2.2 (fix) 0.10$^{+0.04}_{-0.03}$ | 7.4   | 1.8    | 4.3$^{+11.7}_{-11.7}$ |
| F      | 56090.0–56105.0 | 34.9                   | 37.5$^{+0.8}_{-0.2}$         | 2.2 (fix) 0.18$^{+0.05}_{-0.04}$ | 8.2   | 0.0    | 1.6$^{+20.9}_{-20.9}$ |
| G      | 56105.0–56120.0 | 23.6                   | 2.0$^{+0.4}_{-0.0}$          | 0.4$^{+0.3}_{-0.0}$          | 5.4   | 0.0    | 11.4$^{+10}_{-10}$ |

Table 1. Best-fit model parameters obtained from MAXI/GSC 2–20 keV spectra.
If the accretor has a spin, the mass could be larger than the equation above. Figure 5 illustrates the mass–distance relation in equation (2).

Based on past observations of X-ray outbursts from NS and BH binaries, Maccarone (2003) proposed that the soft-to-hard state transition in the outburst decay phase would presumably occur at the 1%–4% Eddington luminosity, \( L_{\text{edd}} = 1.25 \times 10^{38} M / M_\odot \text{ erg s}^{-1} \). The light curves (figure 2) and the HID (figure 3) indicate that the soft-to-hard transition occurred between periods F and G. If the best-fit spectral model of period F continues up to the cutoff at 100 keV, the bolometric flux at the transition \( F_{\text{trans}} \) is estimated to be \( (1.4^{+0.9}_{-0.3}) \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \). In figure 5, the expected mass–distance relations from \( 4\pi d^2 F_{\text{trans}} / L_{\text{edd}} = 1\% \) and 4% are drawn together.

Assuming \( R_{\text{in}} = R_{\text{ISCO}} \) in the soft state periods, \( i = 75^\circ \), as suggested by Shidatsu et al. (2013), and \( d \sim 10 \text{ kpc} \), the accretor mass is deduced to be \( \sim 2 M_\odot \) (figure 5). The estimated mass can be larger if the accretor has a spin. The source distance has not been determined. Instead, the absorption column density in the observed X-ray spectrum against the Galactic interstellar \( \text{H I} \) can be used as a distance estimate. Swift/XRT spectra obtained by multiple observations suggest that the absorption column density is approximately comparable to the Galactic \( \text{H I} \) density (e.g., Kennea et al. 2012a; Miller et al. 2012a; Shidatsu et al. 2013). Thus, we suggest that MAXI J1305–704 would be a non-rotating BHB located at a distance as far as the Galactic center in the Galactic bulge, or a rotating BHB at a smaller distance (Shidatsu et al. 2013).

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Fig. 5. Constraints on the mass–distance relation of MAXI J1305–704 from MAXI/GSC data. Relations expected from the assumptions of \( R_{\text{in}} = R_{\text{ISCO}} \) in the soft state and \( i = 60^\circ, 70^\circ, 75^\circ \), and of \( L_{\text{trans}} / L_{\text{edd}} = 1\% \). 4% are drawn with solid lines, and their limits within the statistical errors are in dashed lines. A possible mass–distance region from the assumptions of \( i \lesssim 75^\circ \) and 1% < \( L_{\text{trans}} / L_{\text{edd}} < 4% \) is shadowed.