Discovery of the massive black hole transient MAXI J1348–630

Mayu Tominaga, Satoshi Nakahira, Megumi Shidatsu, Motoki Oeda, Ken Ebisawa, and Yasuharu Sugawara

1Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210, Japan
2Department of Physics, Ehime University, 2-5, Bunkyocho, Matsuyama, Ehime 790-8577, Japan
3Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

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ABSTRACT

We report the first half-year monitoring of the new Galactic black hole candidate MAXI J1348–630, discovered on 2019 January 26 with the Gas Slit Camera (GSC) on-board MAXI. During the monitoring period, the source exhibited two peaks, where the first peak flux (at $T=14$ day from the discovery of $T=0$) was $\sim 4$ Crab (2-20 keV) and the second one (at $T=132$ day) was $\sim 10\%$ of that. The source exhibited distinct spectral transitions between the high/soft state and the low/hard state and an apparent “q”-shape curve on the hardness–intensity diagram, both of which are well-known characteristics of the black hole binaries. Compared to other bright black hole transients, MAXI J1348–630 is characterized by its rather low disk-temperature ($\sim 0.75$ keV at the maximum) and high peak flux in the high/soft state. The low peak-temperature leads to a large innermost radius that is identified as the innermost stable circular orbit (ISCO) around the black hole. The black hole mass is estimated from the ISCO as $\sim 16 \, (D/5 \, \text{kpc}) \, M_\odot$, where $D$ is a distance to the source, assuming the face-on geometry of the accretion disk and a non-spinning black hole. The black hole is considered even more massive if the disk is inclined or the black hole is spinning. The source is in the direction of the Galactic Scutum-Centaurus arm at $\sim 4$–8 kpc, of which distance is consistent with the observed hydrogen column density. These inferred mass and distance values go with an empirical relationship between the peak luminosity ($L_{\text{peak}}$) and the Eddington luminosity ($L_{\text{Edd}}$), as $L_{\text{peak}}/L_{\text{Edd}}=0.2$–0.4. We suggest that MAXI J1348–630 may host the most massive black hole among the known black hole binaries in our Galaxy.

Keywords: X-rays: individual (MAXI J1348–630) — X-rays: binaries — accretion, accretion disks — black hole physics

1. INTRODUCTION

Black hole binaries (BHBs), those consisting of a stellar mass black hole and a star, show two distinct X-ray spectral states; the “low/hard” state and the “high/soft” state. The low/hard state is observed when mass accretion rate is relatively low. When the accretion rate becomes higher than a certain threshold, the disk switches its nature from the optically-thin/geometrically-thick state to the optically-thick/geometry-thin state. One of the most efficient ways to discover BHBs is to continuously monitor the entire sky in X-rays, because most BHBs are transients and exhibit unpredictable X-ray outbursts. The Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009), which is attached to the ISS and surveying $\sim 85\%$ of the sky every $\sim 92$ minutes (corresponding to the ISS orbital period, where each strip of the sky is exposed for a duration of 40–100 sec), is one of the most ideal instruments for that purpose. In fact, since 2009, MAXI discovered 13 new BHB transients. In this letter, we report the discovery of MAXI J1348–630 on January 26 2019, by MAXI/GSC and the results of continuous
monitoring of the source till 2019 Aug 3 (176 days after the discovery).

2. OBSERVATION

MAXI J1348–630 was first discovered by MAXI at 03:16 UT on 2019 Jan 26 (MJD 58509, T=0; hereafter, T is defined as MJD-58509) with the X-ray flux 47±8 mCrab (4–10 keV) (Yatabe et al. 2019) and subsequently observed with other X-ray telescopes, Swift (Kennea & Negoro 2019), INTEGRAL (Lepingwell et al. 2019) and NICER (Sanna et al. 2019).

Optical counterpart was detected by iTelescope.Net T31 0.51-m telescope in Siding Spring, Australia (Denisenko et al. 2019), Swift/UVOT instrument (Kennea & Negoro 2019) and Las Cumbres Observatory (LCO) network 2- m and 1-m telescopes (Russell et al. 2019a). The radio counterpart was detected by Australia Telescope Compact Array (ATCA)(Russell et al. 2019b) with a flat spectrum consistent with a compact jet.

3. RESULTS

We analyzed the long term data of MAXI J1348–630 using the MAXI/GSC on-demand web interface 1. Figure 1 shows the X-ray light curve of MAXI J1348–630 in 2–6 keV and 6–20 keV, and the hardness ratio between these energy bands, as well as the light curve in 15–50 keV obtained with Swift/BAT 2. Because the Crew Dragon Spacecraft, which was launched by SpaceX, was located in the line of sight during T=36–41, we do not use the data during this period.

After the discovery on 2019 January 26 (MJD 58509, T=0), the hard band (6–20 keV) flux rapidly increased and reached the peak on T=8. The source spectra showed a distinct hard-to-soft transition between T=8 and T=21. The source was initially in the hard state, where the hardness ratio was almost constant at around 0.5 until the hard-band peak (T=8). After that, the source flux in the high energy band rapidly declined until T ~ 21, then slowly decreased throughout the following 70 days. On the other hand, the source flux in 2–6 keV further increased after the high energy band peak (T=8), then reached its peak on Feb 9 (T=14) at the flux ~1.1×10^{-7} erg cm^{-2}s^{-1} (2-20keV). The whole energy band flux observed with MAXI/GSC declined steadily during T=21–91 with holding the almost constant hardness ratio at around 0.05. Approaching the end of the first outburst (T=91–95), the source went back to the hard state with the hardness ratio ~0.5. After T=95, the source gradually faded, and finally reached under the detection limit of MAXI/GSC at T=104.

On 2019 May 31 (MJD 58634, T=126), the source brightened again and reached the peak flux ~1.0×10^{-8} erg cm^{-2}s^{-1} (2–20 keV) on T=132, which is about 10 % of the first peak, followed by steady decline of the flux. The hardness ratio during the re-brightening phase was almost constant at 0.5, thus the source was obviously in the hard state throughout the second outburst. After T=175, the source flux was below the detection limit again.

The hardness-intensity diagram (HID) in Figure 2 shows a clear “q”-curve (e.g. Nakahira et al. 2019). According to time-history of the hardness ratio, we classified the entire observation period into the three spectral states; T=0–8 and 107–191 as the low/hard state; T=8–21 and 91–106 as the transition state; T=21–91 as the high/soft state.

Both the distinct spectral transitions and the “q”-shaped HID are common properties of BHBs (e.g. Homan & Belloni 2005), so we applied a standard BHB spectral model. We used xspec version 12.10.0c for spectral model fitting. Daily MAXI/GSC data do not have enough photon statistics for model fitting, so we accumulated several days of data for each spectral fitting. For the high/soft state, we adopt the optically thick Multi-Color Disk-blackbody model diskbb (Mitsuda et al. 1984) and inverse-Compton scattering model simpl (Steiner et al. 2009). We applied the Tsubingen-Boulder interstellar medium model tbabs and the solar abundance table given by Wilms et al. (2000). We fixed the neutral hydrogen column density at N_H = 6 × 10^{21} cm^{-2} (Sanna et al. 2019). The model is described as tbabs + simpl * diskbb where the free parameters are scattering fraction (F_{esc}) of simpl, innermost temperature (T_{in}) and normalization (N_{disk}) of diskbb. The photon index (\Gamma) is assumed to be constant at the canonical value \Gamma=2.5 since the hard-tail in the high/soft state is so weak and the index is hardly constrained (e.g. McClintock & Remillard 2009). For the low/hard state, the model is described as tbabs + powerlaw where the free parameters are photon index (\Gamma) and normalization of powerlaw. During the transition states, we applied the same model as the high/soft state, but \Gamma was treated as a free parameter. After the spectral fittings, we estimate the realistic innermost disk radius R_{in} as follows: Definition of the diskbb normalization N_{disk} is such that

\[ N_{\text{disk}} = \left( \frac{R_{\text{in}}}{D/10 \text{kpc}} \right)^2 \cos i \]  

(1)

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1 http://maxi.riken.jp/mxondem (last accessed on 2020-02-12)

2 https://swift.gsfc.nasa.gov/results/transients/
Figure 1. The MAXI/GSC 2–6 keV and 6–20 keV light curves, hardness ratio between 6–20 keV and 2–6 keV band, and the 15–50 keV Swift/BAT light curve, from top to bottom. Grey points indicate individual scans and colored points are adaptively binned data. The difference in color represents the initial outburst (red) and the re-brightening (blue). Black dashed lines show the following key dates; $T=8$ (hard band peak), $T=14$ (soft band peak), $T=21$ (end of the hard-soft transition), $T=91$ (start of soft-hard transition), $T=95$ (end of the soft-hard transition), $T=104$ (disappearance), $T=126$ (reappearance), $T=132$ (peak after reappearance), and $T=175$ (second disappearance).

Figure 2. Hardness Intensity Diagram (HID) between the hardness ratio (6–20 keV/2–6 keV) vs. 2–20 keV intensity. The grey points and the color points connected by line are produced in the same manner as in Figure 1.

where $D$ is the source distance, $i$ is the disk inclination, and $r_{in}$ is an apparent disk radius. We estimate the realistic inner radius $R_{in}$ as

$$R_{in} = \xi \kappa^2 r_{in}$$

where $\xi=0.41$ is a correction factor for the inner boundary condition (Kubota et al. 1998), $\kappa=1.7$ is the color hardening factor (Shimura & Takahara 1995). Figure 3 shows a time-history of the spectral fitting parameters, where $R_{in}$ is calculated assuming $D=5$ kpc and $i=0$.

Here, we point out that the maximum disk temperature is as low as $T_{in} \approx 0.75$ keV even at the high/soft state luminosity peak ($T=14$). This is remarkably lower compared to other luminous black hole transients, where the maximum disk temperature almost always exceeds $\approx 1$ keV. The low disk temperature and the high luminosity lead to the large innermost radius because the disk luminosity is proportional to $R_{in}^2 T_{in}^4$. The large innermost radius suggests that MAXI J1348–630 harbors a relatively massive black hole compared to other black hole binaries (see the following discussion).
4. DISCUSSION

We discuss nature of the new X-ray transient MAXI J1348–630 from the data analysis results above. The source has indicated clear spectral transitions (Figure 1) and a q-shaped track on the HID (Figure 2), both of which are well-known characteristics of BHBs. Furthermore, we successfully fitted energy spectra in all the three spectral states assuming typical models for different spectral states of BHBs (Figure 3). These facts strongly suggest that MAXI J1348–630 is a new black hole binary.

In particular, innermost radius of the accretion disk ($R_{\text{in}}$) is nearly constant during the high/soft state while the 2–20 keV flux and the disk temperature were significantly variable (Figure 3). This is a remarkable property in the high/soft state BHBs, such that the constant radius is believed to be the Innermost Stable Circular Orbit around the black hole (ISCO; e.g., Tanaka 1989; Ebisawa et al. 1993; Steiner et al. 2010), which is determined by only black hole mass and spin. In the case of non-rotating black holes, ISCO is equal to three times the Schwarzschild radius. Thus, from the average innermost radius of the disk, $R_{\text{in}} \approx 142 \pm 17 (D/5 \text{ kpc})(\cos i)^{-1/2}$ km, the black hole mass is estimated as

$$M_{\text{BH}} = \frac{c^2 R_{\text{in}}}{6G} \approx 16 \pm 2 \left(\frac{D}{5 \text{ kpc}}\right)(\cos i)^{-1/2} M_{\odot}. \quad (3)$$

This distance-mass relationship is indicated in Figure 4 for $i = 0^\circ$ and $60^\circ$.

In addition, BHBs often show similar luminosity dependence of the spectral states. For instance, in the current case of MAXI J1348–630, the flux at the soft-to-hard transition ($T=91$) is $\sim 10\%$ of the peak flux in the high/soft state ($T=14$); this value is consistent with those of other BHBs discovered by MAXI, such as MAXI J1820+070 ($\sim 12\%$; Shidatsu et al. 2019) and...
Figure 4. Observational constrains on the distance-mass diagram. Two solid colored lines represent Equation 3 when $i = 0^\circ$ (blue) and $60^\circ$ (cyan). The dashed lines with the same colors denote the error region due to systematic error. The pink curves give the empirical relation that the peak luminosity in the high/soft state is $0.2–0.4 \ L_{\text{Edd}}$. The pink-hatched region represents the plausible mass and distance range. The vertical lines on $d = 4–8 \ \text{kpc}$ indicate distance range to the Scutum-Centaurus arm in our line of sight.

MAXI J1910-057 ($\sim 10–15\%$; Nakahira et al. 2014). Furthermore, the soft-to-hard transition typically occurs at $1–4\%$ of the Eddington luminosity ($L_{\text{Edd}}$: Maccarone 2003). Namely, the high/soft state peak luminosity is presumably between 0.1 to 0.4 $L_{\text{Edd}}$. In fact, McClintock & Remillard (2009) found that the peak luminosity in the high/soft state corresponds to 0.2–0.4 $L_{\text{Edd}}$ for the established black hole binaries with known masses and distances, GRS1915+105, GRO J1655–40 and XTE J1550–564. Assuming the same peak luminosity for MAXI J1348–630 ($0.2–0.4 \ L_{\text{Edd}}$), we may put another constrain to the mass-distance relation. The pink curves in Figure 4 give the distance-mass relationships for $L_{\text{peak}}/L_{\text{Edd}} = 0.2$ and 0.4, where we took the peak flux on $T = 14$ and $L_{\text{Edd}} = 1.3 \times 10^{39} (M/M_{\odot}) \ \text{erg s}^{-1}$.

Next, we try to estimate distance to the source. The galactic coordinate of the source is ($l, b$) = (309.3, $-1.1$), which is tangential to the Galactic Scutum-Centaurus arm. If MAXI J1348–630 locates in the Scutum-Centaurus arm, the distance is estimated as $4–8 \ \text{kpc}$ (e.g., Xu et al. 2018). The neutral hydrogen column density $N_{H} = 6 \times 10^{21} \ \text{cm}^{2}$ determined by NICER observations (Sanna et al. 2019) does not contradict with these distances, assuming $\lesssim 0.5 \ \text{H cm}^{-3}$ and little circum-stellar absorption.

From these arguments, we may constrain the likely black hole mass and distance range as the pink-hatched area in Figure 4, where we assumed the face-on disk geometry. Note that the mass is greater than $\sim 16 \ M_{\odot}$ at $\sim 6 \ \text{kpc}$, so this is possibly the most massive black hole among the known black holes in our Galaxy, exceeding that of GRS 1915+105 ($\sim 12 \ M_{\odot}$; Reid et al. 2014). If the black hole is spinning (=ISCO becomes smaller for the same mass) or the disk is inclined, the black hole mass will become still larger. Existence of such massive black holes has been confirmed via gravitational wave detection due to black hole merger (e.g., Abbott et al. 2019). However, they have never been observed as X-ray binaries. Follow-up optical/infrared spectroscopic observations are strongly encouraged to constrain the black hole mass of MAXI J1348–630 more precisely from dynamical motion measurement.

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