Discovery of the New X-Ray Transient MAXI J1807+132: A Candidate of a Neutron Star Low-mass X-Ray Binary

Megumi Shidatsu1, Yutaro Tachibana2, Taketoshi Yoshii2, Hitoshi Negoro3, Taiki Kawamuro4, Wataru Iwakiri1, Satoshi Nakahira1, Kazuo Makishima1, Yoshihiro Ueda5, Nobuyuki Kawaf6, Motoko Serino1, and Jamie Kennea1

1 MAXI team, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan; megumi.shidatsu@riken.jp
2 Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
3 Department of Physics, Nihon University, 1-8-14 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan
4 National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
5 Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto, Kyoto 606-8502, Japan
6 Department of Astronomy and Astrophysics, 0525 Davey Laboratory, Pennsylvania State University, University Park, PA 16802, USA

Received 2017 July 19; revised 2017 October 5; accepted 2017 October 9; published 2017 November 28

Abstract

We report on the detection and follow-up multi-wavelength observations of the new X-ray transient MAXI J1807+132 with the MAXI/GSC, Swift, and ground-based optical telescopes. The source was first recognized with the MAXI/GSC on 2017 March 13. About a week later, it reached maximum intensity (~10 mCrab in 2–10 keV), and then gradually faded in ~10 days by more than one order of magnitude. Time-averaged Swift/X-ray Telescope spectra in the decaying phase can be described by a blackbody with a relatively low temperature (0.1–0.5 keV), plus a hard power-law component with a photon index of ~2. These spectral properties are similar to those of neutron star low-mass X-ray binaries (LMXBs) in their dim periods. The blackbody temperature and the radius of the emission region varied in a complex manner as the source became dimmer. The source was detected in the optical wavelength on March 27–31 as well. The optical flux decreased monotonically as the X-ray flux decayed. The correlation between the X-ray and optical fluxes is found to be consistent with those of known neutron star LMXBs, supporting the idea that the source is likely to be a transient neutron star LMXB.

Key words: X-rays: binaries – X-rays: individual (MAXI J1807+132)

Supporting material: data behind figures

1. Introduction

Many X-ray point sources in the sky have significant variability on various timescales. In particular, transient low-mass X-ray binaries (LMXBs), involving accreting neutron stars or black holes, exhibit dramatic outbursts, changing their X-ray luminosity by orders of magnitude in relatively short periods (a few days to months; see, e.g., Done et al. 2007, for a review). Because their luminosity is mainly determined by the mass accretion rate, their transient nature makes them ideal objects to study the physics of accretion onto compact objects over a wide range of mass accretion rates.

The new transient MAXI J1807+132, located at an off-Galactic-plane region with a Galactic latitude of 15°5, was first noticed on 2017 March 13 (Negoro et al. 2017) by the nova-search system (Negoro et al. 2016) of the Monitor of All-sky X-ray Image (MAXI; Matsukawa et al. 2009), in an X-ray image provided by the MAXI/Gas Slit Camera (GSC; Mihara et al. 2011). The source position estimated with the MAXI/GSC turned out to be consistent with that of 2MASS J1807+132, which is listed in the MAXI/GSC transient source catalog (Kawamuro et al. 2016), based on an X-ray flaring event detected in 2011 May.

As shown in Figure 1, the source was detected in a seven-tile follow-up observation with the Swift/X-ray Telescope (XRT; Gehrels et al. 2005), and UltraViolet and Optical Telescope (UVOT; Roming et al. 2005), in the X-ray band and the optical to ultraviolet bands, respectively. Thus, the source position was determined accurately as \((\alpha^{2000}, \delta^{2000}) = (18^h08^m07^s549, +13^\circ15'05''40)\) and \((l, b) = (40^\circ123127, 15^\circ501653)\) with a 90% uncertainty of 0″16 (Kennea et al. 2017a, 2017b). The UVOT \(u\), \(b\), and \(v\)-band magnitudes were 17.4 ± 0.1 mag, 18.4 ± 0.2 mag, and >17.6 mag at that time (Kennea et al. 2017b), respectively. The source was also followed by ground-based optical telescopes (Armas Padilla et al. 2017b; Kong et al. 2017; Muñoz-Darias et al. 2017; Shields et al. 2017; Tachibana et al. 2017b).

These follow-up X-ray and optical observations have provided pieces of information to understand the nature of the object. The source showed significant flux variations in the optical band (Armas Padilla et al. 2017b; Kong et al. 2017; Shields et al. 2017; Tachibana et al. 2017b) as well as X-rays (Armas Padilla et al. 2017b; Kong et al. 2017; Negoro et al. 2017). Denisenko (2017) recognized the optical counterpart in an image taken about 35 years ago and suggested past activities of the source. The source was also detected optically in PanSTARRS-1 multi-epoch data, with a magnitude that was larger by 2–3 (i.e., ~10 times fainter in terms of the flux) than those obtained 35 years ago and in 2017 March (Denisenko 2017). LMXB-like characteristics were found through preliminary modeling of the XRT spectra (Shidatsu et al. 2017) and optical spectroscopy (Muñoz-Darias et al. 2017).

In this paper, we present the first results from the multi-wavelength monitoring of MAXI J1807+132 in 2017 March and April, with the MAXI/GSC, Swift, and ground-based optical telescopes, and discuss the nature of the source. Throughout the paper, errors represent the 90% confidence intervals of a single parameter with \(\Delta \chi^2 = 2.706\), unless otherwise stated.


2. X-Ray Observations and Results

2.1. Long-term Monitoring with MAXI

After the first detection on 2017 March 13, MAXI J1807+132 has been monitored with the MAXI/GSC. Figure 2 presents background-subtracted 2–4 keV and 4–10 keV light curves, created through the method of image fitting (Morii et al. 2016) to the MAXI/GSC event data version 1.8. The source intensity reached a maximum at around MJD 57827–MJD 57832 (2017 March 15–20), and then gradually decreased. The averaged 4–10 keV intensity was \( \approx 9 \) mCrab in that period, which is comparable with the peak intensity of the X-ray flaring event from 2MAXI J1807+132 recorded in Kawamuro et al. (2016).

2.2. Swift/XRT Spectral Analysis

A series of follow-up pointed observations of MAXI J1807+132 were carried out with Swift in the decaying phase. The net exposure was 0.5–2 ks in each observation. A log of these observations is given in Table 1, and the 0.3–10 keV XRT light curve is shown in Figure 2. We analyzed the XRT spectra taken during two weeks from the first Swift observation (March 26), using XSPEC version 12.9.1 m (Arnaud 1996). The light curve, spectra, and responses were downloaded via the online tools provided by the UK Swift Science Data Centre (Evans et al. 2009).\footnote{http://www.swift.ac.uk/user_objects/}

\[
c_{\nu} = \frac{n_{\nu}}{A_{\nu}} = \frac{1.0 \times 10^{21}}{10^{-21}} \approx 10^{21}
\]

The spectra taken on March 27 and 29, which have the best statistics among the present XRT data sets, were binned so that at least 30 counts are contained in each bin, and they were analyzed on the basis of the \( \chi^2 \) statistics. The other data, which have lower statistics, were grouped so that each bin has at least one count, and the Cash-statistics (Cash 1979) were adopted in the spectral analysis. The data taken on April 4 and 5 were omitted, because the source was not detected significantly. The data on April 6 and 7 were merged together to improve statistics; so were those on April 8 and 9. In the following analysis, the TBabs model is employed as the interstellar absorption model, with the table of solar abundances provided by Wilms et al. (2000).

As shown in Figure 3, we first analyzed the XRT spectra on March 27 and 31, which were obtained when the source intensity was relatively high and low, respectively. The spectrum on March 27 can be fit with an absorbed power-law model with a photon index of \( \Gamma = 2.4^{+0.2}_{-0.1} \), and a column density of \( N_H = (2.5 \pm 0.6) \times 10^{21} \text{ cm}^{-2} \), in agreement with the first report by Kennea et al. (2017a, 2017b). This model is fully acceptable (Figure 3(b)), with \( \chi^2/\text{dof} = 63/65 \). The resultant parameters are listed in Table 2. However, the estimated column density is somewhat higher than the total Galactic column, \( N_H = 1.0 \times 10^{21} \text{ cm}^{-2} \) derived using the tool \( \text{nh} \) in HEASOFT version 6.19, and that calculated from the optical spectrum of the source (\( N_H \approx 1.6 \times 10^{21} \text{ cm}^{-2} \); Muñoz-Darias et al. 2017). The fit quality became worse (\( \chi^2/\text{dof} = 84/66 \)), when \( N_H \) is fixed at \( 1.0 \times 10^{21} \text{ cm}^{-2} \) (Figure 3(c)).

As observed in Figure 3(a), the XRT spectrum changed significantly in shape from March 27 to 31. The March 31

![Figure 1](image1.png)

**Figure 1.** A 2–4 keV image (2'3 × 1'7) obtained in the MAXI/GSC observation from 2017 March 13 to April 1. The thick solid and dashed lines (black) indicate the error regions of MAXI J1807+132 determined by the MAXI/GSC in the 2–4 keV and 4–10 keV bands, respectively. The seven red circles represent the fields-of-view of MAXI J1807+132 determined by the Swift/XRT for individual pointings on March 26. The red cross point indicates the position of the source detected with Swift.

![Figure 2](image2.png)

**Figure 2.** MAXI/GSC light curves in 2–4 keV (top) and 4–10 keV (middle) with one-day time bins, and Swift/XRT light curve in 0.3–10 keV (bottom), with one observation per bin. The arrows represent upper limits. MJD 57825 corresponds to 2017 March 13. The data used to create this figure are available.

| Date       | Start Time (UT) | End Time (UT) | Net Exposure (ks) | XRT Mode |
|------------|-----------------|---------------|-------------------|----------|
| 2017 Mar 26| 08:44:23        | 10:26:52      | 0.22              | PC       |
| 2017 Mar 27| 07:01:39        | 09:50:56      | 1.94              | WT       |
| 2017 Mar 29| 05:08:51        | 07:10:38      | 1.99              | WT       |
| 2017 Mar 31| 08:13:39        | 11:12:56      | 2.05              | WT       |
| 2017 Apr 02| 14:18:11        | 14:29:56      | 0.69              | WT       |
| 2017 Apr 04| 11:06:57        | 11:07:02      | 0.005             | WT       |
| 2017 Apr 05| 15:36:52        | 15:52:53      | 0.95              | PC       |
| 2017 Apr 06| 06:08:03        | 06:16:52      | 0.51              | PC       |
| 2017 Apr 07| 21:38:20        | 21:54:53      | 0.98              | PC       |
| 2017 Apr 08| 21:29:20        | 21:44:53      | 0.91              | PC       |
| 2017 Apr 09| 16:56:20        | 17:12:53      | 0.99              | PC       |

**Table 1**

Log of Swift/XRT Observations

**Note.**

PC and WT indicate the Photon Counting mode and the Windowed Timing mode, respectively.

---

---
The spectrum appears to consist of a softer component dominant in <2 keV, and a harder power-law-like component with a photon index of <2 extending above 2 keV. Then, the spectral change from March 27 to 31 can be understood if the latter component decreased by an order of magnitude, with a relatively small change in the former. As a confirmation, we forced a single power-law model to the March 31 spectrum. The fit was formally acceptable (Table 2), but as shown in Figure 3(e), the data in >2 keV systematically exceeded the best-fit power-law model, which was required to have a very steep (Γ ≈ 3.2) slope. We hence regard the single power-law model as inappropriate, both on March 27 and 31.

Based on the above consideration, we next fitted the spectra with a model composed of a power-law component and a thermal emission component: a blackbody \textit{(bbodyrad in XSPEC terminology)} or a multi-color disk blackbody (diskbb Mitsuda et al. 1984). Here, \( N_H \) is assumed as \( 1 \times 10^{21} \text{ cm}^{-2} \). Then, the spectrum on March 27 has been well described by the model, with the reduced chi-squared values of \( \chi^2/\text{dof} = 60/64 \) and \( \chi^2/\text{dof} = 59/64 \) in the case of bbodyrad and diskbb, respectively. These values are almost the same as that obtained with a single power-law model in which \( N_H \) is left as a free parameter, while significantly smaller than that of the same model with \( N_H = 1 \times 10^{21} \text{ cm}^{-2} \). The XSPEC script \textit{simftest} shows a null-hypothesis probability of \( <10^{-6} \) in the latter case. Both models gave relatively small photon indices: \( \Gamma = 1.8 \pm 0.2 \) and \( 1.6^{+0.8}_{-0.8} \), with the bbodyrad and diskbb models, respectively.

The combination of the thermal and power-law components has successfully described the spectrum on March 31 as well. The reduced chi-squared values were slightly reduced from those of the single power-law model with \( N_H = 1 \times 10^{21} \text{ cm}^{-2} \) (\( \Delta \chi^2/\text{dof} < 11 \) for \( \Delta \Gamma = 2 \)), and the residual structure above \( \approx 2 \text{ keV} \) disappeared (Figure 3(g)). The probability that the improvement is only due to a random fluctuation is 0.004, according to \textit{simftest}. The temperature of the soft thermal component became lower by a factor of \( \approx 3 \), and the apparent linear size of its emission region became larger by a factor of \( 8-10 \) than those on March 27 (see Table 2).

The soft X-ray component is most likely optically thick thermal emission from the surface of a compact object (if it is not a black hole) or an accretion disk. The hard component, like in the present case, is often considered to originate via Comptonization of these thermal photons by a cloud of hot electrons (e.g., Done et al. 2007; Lin et al. 2007). Assuming that the observed hard tail is produced by Comptonization, we replaced the phenomenological power-law model with the \textit{compps} model (Poutanen & Svensson 1996).

The \textit{compps} model calculates a Comptonized spectrum when we specify the electron temperature \( kT_e \), the optical depth for scattering \( \tau \), the energy distribution of the seed photons, and the geometry of the Comptonization cloud (or corona). In the present study, following previous works (e.g., Sakurai et al. 2014), a spherical corona \( (\text{geom} = 4) \) was assumed (but see below for the cases of different geometries), with only thermal electrons. We first tested the case where the seed photons are provided by blackbody emission. The model is expressed as \( \text{TBabs*(compps+bbodyrad)} \), where the seed photon temperature \( kT_{\text{seed}} \) of the \textit{compps} component was linked to \( kT_{bb} \) of the bbodyrad component. Because the data did not allow us to simultaneously constrain \( \tau \) and \( kT_e \), we fixed \( kT_e \) at 20 and 100 keV, and left \( \tau \) as a free parameter. The other free parameters in this model are \( kT_{bb} \) and the normalizations of the bbodyrad and compps components. We ignored the reflection component from the disk.

This model, \( \text{TBabs*(compps+bbodyrad)} \), fitted the two spectra well, and yielded the best-fit parameters given in Table 2. Both spectra favored slightly smaller values of \( R_{bb} \) and \( \tau \), if we assume \( kT_e = 100 \text{ keV} \), compared with the case of \( kT_e = 20 \text{ keV} \).

We also tested the alternative possibility that the seed photons of Comptonization are provided by disk blackbody emission. Thus, the bbodyrad component in the \( \text{TBabs*(compps+bbodyrad)} \) model was replaced by diskbb, and the inner disk temperature \( kT_{\text{in}} \) of diskbb was set to be the same as \( kT_{\text{seed}} \) of compps \( (kT_{\text{seed}} = -kT_{\text{in}}, \text{in XSPEC terminology}) \). This \( \text{TBabs*(compps+diskbb)} \) model was also found to fit the two spectra well, yielding comparable reduced \( \chi^2 \) values to those of \( \text{TBabs*(compps+bbodyrad)} \).

Although we have assumed a spherical corona above, following previous works, we have confirmed that the choice of the coronal geometry does not affect the main conclusions from the \( \text{TBabs*(compps+bbodyrad)} \) and \( \text{TBabs*(compps+diskbb)} \) models. If a slab or cylindrical corona...
Table 2
Best-fit Parameters of Various Spectral Models for the Swift/XRT Data on March 27 and 31

| Parameter       | Unit   | $N_{\text{H}}$ | $\Gamma$ or $\tau$ | $N_{\text{f}}^d$ | $R_{\text{bb}}$ (comp)$^b$ | $kT_{\text{bb}}$ or $kT_{\text{m}}$ | $R_{\text{bb}}$ or $R_{\text{m}}^c$ | $F_{\alpha}^d$ | $\chi^2$/dof$^e$ |
|-----------------|--------|-----------------|--------------------|-----------------|------------------|--------------------------------|------------------|-----------------|-----------------|
| Model: TBAbs*powerlaw |        |                 |                    |                 |                  |                                |                  |                 |                 |
| Mar 27          |        | 2.5 ± 0.6       | 2.4$^{+0.7}_{-0.1}$| 12 ± 1          | ...              | ...                            | ...              | 5.7 $\times$ 10$^{-11}$ | 63/65           |
| Mar 27          |        | 1.0 (fixed)     | 2.07 ± 0.07        | 8.4 ± 0.4       | ...              | ...                            | ...              | 4.6 $\times$ 10$^{-11}$ | 84/66           |
| Mar 31          | <1.3   | 3.2$^{+1.9}_{-0.4}$| 0.7$^{+0.4}_{-0.1}$| ...              | ...              | ...                            | 3.9 $\times$ 10$^{-12}$ | 19/18           |
| Mar 31          | 1.0 (fixed) | 3.9 ± 0.5       | 1.0 ± 0.2          | ...              | ...              | 8.2 $\times$ 10$^{-12}$        | 21/19           |
| Model: TBAbs*(diskbb+powerlaw) |        |                 |                    |                 |                  |                                |                  |                 |                 |
| Mar 27          | 1.0 (fixed) | 1.6$^{+0.3}_{-0.1}$| 3 ± 2              | ...              | 0.50$^{+0.09}_{-0.06}$ | 1.8$^{+0.3}_{-0.2}$                 | 4.1 $\times$ 10$^{-11}$ | 60/64           |
| Mar 31          | 1.0 (fixed) | 1.4$^{+0.8}_{-0.1}$| 0.2$^{+0.3}_{-0.1}$| ...              | 0.15 ± 0.03      | 19$^{+17}_{-10}$                 | 7.8 $\times$ 10$^{-12}$ | 10/17           |
| Model: TBAbs*(bbodyrad+powerlaw) |        |                 |                    |                 |                  |                                |                  |                 |                 |
| Mar 27          | 1.0 (fixed) | 1.8 ± 0.2       | 5 ± 1              | ...              | 0.32$^{+0.06}_{-0.04}$ | 4.2$^{+1.8}_{-1.0}$                  | 4.1 $\times$ 10$^{-11}$ | 59/64           |
| Mar 31          | 1.0 (fixed) | 1.5 ± 0.1       | 0.2$^{+0.3}_{-0.1}$| ...              | 0.12 ± 0.02      | 32$^{+22}_{-12}$                 | 7.2 $\times$ 10$^{-12}$ | 10/17           |
| Model: TBAbs*(bbodyrad+compps(bbodyrad)) |        |                 |                    |                 |                  |                                |                  |                 |                 |
| Mar 27          | 1.0 (fixed) | 2.5$^{+0.5}_{-0.4}$| ...                | 18.1$^{+1}_{-1}$ | 0.22 ± 0.05      | <10                              | 3.7 $\times$ 10$^{-11}$ | 62/64           |
| Mar 27          | 1.0 (fixed) | 0.59$^{+0.08}_{-0.07}$| ...                | 12.9$^{+0.2}_{-0.1}$ | 0.26 ± 0.03      | <6                               | 3.8 $\times$ 10$^{-11}$ | 64/64           |
| Mar 31          | 1.0 (fixed) | 3.0$^{+1.0}_{-0.2}$| ...                | 7 ± 0.2         | 0.11 ± 0.02      | 32$^{+21}_{-12}$                 | 6.3 $\times$ 10$^{-12}$ | 10/17           |
| Mar 31          | 1.0 (fixed) | 1.5$^{+1.5}_{-1.3}$| ...                | 7 ± 0.2         | 0.12 ± 0.02      | 30$^{+29}_{-9}$                  | 6.4 $\times$ 10$^{-12}$ | 10/17           |
| Model: TBAbs*(diskbb+compps(diskbb)) |        |                 |                    |                 |                  |                                |                  |                 |                 |
| Mar 27          | 1.0 (fixed) | 3.0$^{+0.0}_{-0.0}$| ...                | 1.1$^{+0.1}_{-0.1}$ | 0.41$^{+0.07}_{-0.12}$ | <2.9                            | 3.9 $\times$ 10$^{-11}$ | 60/64           |
| Mar 27          | 1.0 (fixed) | 0.7$^{+0.3}_{-0.2}$| ...                | 1.2 ± 0.2       | 0.44$^{+0.07}_{-0.08}$ | <2.5                            | 4.0 $\times$ 10$^{-11}$ | 59/64           |
| Mar 31          | 1.0 (fixed) | 3.0$^{+0.0}_{-0.0}$| ...                | 2.0$^{+0.2}_{-0.1}$ | 0.14 ± 0.03      | 20$^{+12}_{-6.8}$                | 6.8 $\times$ 10$^{-12}$ | 11/17           |
| Mar 31          | 1.0 (fixed) | 2.0$^{+0.0}_{-0.0}$| ...                | 1.8$^{+0.1}_{-0.1}$ | 0.15 ± 0.03      | 17$^{+16}_{-8}$                  | 6.9 $\times$ 10$^{-12}$ | 10/17           |

Notes.

$^a$ Normalization of the power-law component, in units of $10^{-3}$ photons keV$^{-1}$ cm$^{-2}$.

$^b$ Radius of the emission region of the seed photons for Compton scattering, calculated from the photon flux of the compps component in 0.8–100 keV, by assuming a distance of 5 kpc and a spherical corona.

$^c$ The radius of emission region for the bbodyrad component, or the inner disk radius for the diskbb component. The distance and the inclination angle are assumed as 5 kpc and 0°, respectively.

$^d$ The unabsorbed X-ray flux in the 0.3–10 keV band.

$^e$ C-statistic/dof is instead presented for the March 31 results.

$^f$ $kT_{\alpha} = 20$ keV is assumed.

$^g$ The upper limit is pegged.

$^h$ $kT_{\alpha} = 100$ keV is assumed.

Figure 4. Time-averaged Swift/XRT spectra in the individual epochs on (a) March and (b) April, in the $\alpha F_{\alpha}$ form, with their best-fit TBAbs*(powerlaw +bbodyrad) models. The March 27 and 31 spectra in (a) are identical to those in Figure 3.
The pair of blue bars at the center of the image point MAXI

is assumed (i.e., geom = 1 or 2, respectively), \( \tau \) changes by a factor of \( \lesssim 2 \), but the other free parameters remain unchanged within their 90% error ranges. The chi-squared values were also found to depend little \( (\Delta \chi^2 \lesssim 1) \) on the assumed coronal geometries.

We next investigated the spectral variation over a longer period. Figure 4 presents the other XRT spectra, in addition to those of March 27 and 31, which were already analyzed. The spectral profile varied in a complex manner: the peak energy of the soft component shifted toward higher energies from March 31 to April 6–7 and then moved back to lower energies in April 8–9, even though the X-ray flux was comparable among these three epochs. These XRT spectra were also well reproduced individually by the \( \text{TBabs*(powerlaw+bbbodyrad)} \) model.

Figure 5 shows the best-fit parameters of these spectra in chronological order. It also shows the 3\( \sigma \) upper limits of the unabsorbed 0.3–10 keV flux on April 4 and 5, calculated by assuming the best-fit model on April 6. As suggested by the spectral shape changes, the variations of \( kT_{bb} \) and \( R_{bb} \) are rather complex and cannot be described as a simple function of the X-ray flux.

The spectra were also fit well with the \( \text{TBabs*(powerlaw+diskkbb)} \) model. The derived \( kT_a \) and \( R_{in} \) varied in a similar manner to \( kT_{bb} \) and \( R_{bb} \) of the \( \text{TBabs*(powerlaw+bbbodyrad)} \) model, respectively.

3. Optical Observations and Multi-wavelength Spectral Energy Distributions

Optical photometric observations of MAXI J1807+132 were performed with the \( g' \)-, \( R_c \)-, and \( I_c \)-band filters for four nights from 2017 March 27–30, with the \textit{Murikabushi} 105 cm telescope at the Ishigakijima Astronomical Observatory in Okinawa, Japan, and the MITSuME 50 cm telescope of Akeno Observatory in Yamanashi, Japan (for detailed information, see Tachibana et al. 2017a, and references therein). The target was observed for \( \sim 2 \) hr on each day, during which simultaneous three-band observations were repeated, with individual exposure times of 60 s. The raw data were preprocessed in a standard manner: subtraction of dark and bias, followed by flat fielding. The pixel coordinates were calibrated into celestial coordinates via WCSTools (Mink 1997). After these treatments, we combined all of the frames taken in a night in each band, and performed aperture photometry using IRAF tasks to estimate the magnitude of this object by comparing with six local reference stars. Figure 6 shows the stacked \( R_c \)-band image obtained with the \textit{Murikabushi} telescope on March 27, where MAXI J1807+132 and the six reference stars are indicated.

The apparent magnitudes in the individual nights are plotted in Figure 7, which clearly shows decay in all three bands, typically by \( \sim +0.4 \) mag per day. Previously, the source was much fainter, at least by \( \sim 3 \) mag, because multi-epoch Pan-STARRS observations gave an average \( r \)-band magnitude of 21.19 \( \pm 0.09 \) mag (Denisenko 2017), which is \( \sim 3 \) mag larger (i.e., the flux is \( \sim 16 \) times lower) than the \( R_c \)-band magnitude estimated on March 27. This suggests that the emission from the companion star contributes only less than \( \sim 6\% \) of the total optical flux on March 27.

Figure 8 shows the multi-wavelength spectral energy distribution (SED) on March 27, where the \textit{Swift}/XRT and UVOT data are plotted together with those from the \textit{Murikabushi} telescope. Here, we examine the optical flux...
the Comptonized corona and the disk, the fraction $f_{in}$ of the luminosity of the Comptonized component that is thermalized in the inner disk, the fraction $f_{out}$ of the bolometric flux that illuminates the outer disk, the radius $r_{in}$ of the Compton illuminated disk, the outer disk radius $R_{out}$, and the normalization, depending on the inner disk radius $R_{in}$ and the distance in the same manner as diskbb. Following previous works (Gierliński et al. 2008, 2009), we set $r_{in} = 1.1R_{in}$.

Considering the results of our XRT spectral analysis, we assumed $\Gamma = 2.0$, $kT_e = 100$ keV, $f_{in} = 0.1$, and left the other parameters free to vary. To account for the optical extinction, the reddened model with $E(B-V) = 0.13$ (which is converted to $N_H \sim 1 \times 10^{21}$ cm$^{-2}$ via the relation given in Predehl & Schmitt 1995) was multiplied to diskir.

As shown in Figure 8, the overall SED profile has been reasonably well reproduced by the diskir model with $kT_{in} \approx 0.4$ keV, $L_C/L_d \approx 2.3$, $R_{in} \approx 3$ km, $R_{out} \approx 1 \times 10^5$ R$_\odot$ $\approx 3 \times 10^3$ km (where the distance and inclination are assumed as 5 kpc and 0°, respectively), and $f_{out} \approx 3.7 \times 10^{-2}$. The estimated values of $kT_{in}$ and $R_{in}$ are comparable with those obtained from the XRT data alone using the diskbb + powerlaw model (Section 2.2).

4. Discussion

4.1. The Nature of MAXI J1807+132

We studied the behavior of the new X-ray transient MAXI J1807+132 using the multi-wavelength data of the MAXI/GSC, Swift, and optical telescopes. The source is likely to be identified with 2MAXIt J1807+132, which is listed in the first MAXI/GSC transient source catalog (Kawamuro et al. 2016) based on a long-term X-ray brightening event in 2011 May. Although Kawamuro et al. (2016) primarily aimed at a search for tidal disruption events (TDEs) by extragalactic supermassive black holes, the 2011 May episode of 2MAXIt J1807+132 was not categorized therein as a TDE. Below, we consider various interpretations of the nature of this object.

4.1.1. A Tidal Disruption Event?

Kawamuro et al. (2016) concluded that 2MAXIt J1807+132 is unlikely to be a TDE, because it has exhibited multiple enhancements (though with lower significances, at $\sim 3\sigma$ levels) from 2009 to 2013. Identifying the present source MAXI J1807+132 with 2MAXIt J1807+132, the TDE interpretation becomes even less likely, because the interval of the two strongest flaring events is much shorter than those predicted for TDEs (typically $\sim 10^4$ to $\sim 10^5$ years; e.g., Kawamuro et al. 2016).

To search for other brightening episodes of MAXI J1807+132, we analyzed the entire MAXI/GSC data of this sky region using the on-demand process system. Figure 9 shows the obtained light curve, from 2009 August to 2017 April. However, we detected no X-ray enhancements with a significance of $>3\sigma$, other than the flares in 2011 and 2017. As noticed in Figure 9, the present flaring event in 2017 is the brightest one in the last 7.5 years.

---

8 We have confirmed that the choice of the $R_{in}$ value does not strongly affect the estimation of $f_{in}$. The resultant $f_{out}$ value was kept unchanged within its 90% confidence range, in the case of $R_{in} = 1.1, 5$, and 10.

9 http://maxi.riken.jp/mxondem/
The Swift/XRT data allow us to further argue against the TDE interpretation of the present object. The XRT spectra of MAXI J1807+132 in 2017 March and April have been well described with a soft thermal component (blackbody or disk blackbody) visible below ~2 keV, and a hard tail with a photon index of ~2. The thermal component has a temperature higher than those of TDEs (typically ~0.1 keV; Esquej et al. 2008; Maksym et al. 2010). The hard X-ray tail is much stronger than those of non-jetted TDEs, although it could be compatible with the spectrum of the jetted TDE Swift J164449.3+573451 (Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011).

Typical TDEs, either with or without jets, are considered to decay with time as \( \propto t^{-5/3} \) (e.g., Rees 1988; Phinney 1989). In contrast, the X-ray emission of MAXI J1807+132 in the present flaring event decayed much more rapidly; fitting the XRT light curve (Figure 5(a)) with a power-law model, we obtained the best-fit decay curve as \( \propto t^{-6.1} \), where \( t \) is the time since 2017 March 13 when the source was first recognized with MAXI. This fast decay also shows that the source is unlikely to be a TDE.

4.1.2. A Galactic Magnetic Cataclysmic Variable (CV)?

Having excluded the TDE interpretation, we hereafter assume that the source is a binary system located in our galaxy. One of the most abundant subclasses of such binaries is accreting magnetic CVs (Polars and Intermediate Polars). Indeed, the X-ray flux observed on March 31, \( \sim 7 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), translates to a source luminosity of \( \sim 10^{34} \) erg s\(^{-1}\), if the source distance is assumed, e.g., to be 5 kpc. This luminosity is typical of magnetic CVs during their brightening episodes (e.g., Revnivtsev et al. 2008). An X-ray spectrum of a typical CV is composed of an optically thin thermal plasma emission produced in the accretion columns, and a blackbody emission from the polar cap region of the white dwarf. We found that the XRT spectra of MAXI J1807+132 above 1 keV can be fit with the optically thin plasma model mekal with a temperature of \( \gtrsim 5 \) keV, which is consistent with those of typical magnetic CVs. However, the soft thermal component of MAXI J1807+132 has a much higher temperature than the blackbody component in CVs (<0.1 keV). Therefore, the magnetic CV interpretation is unlikely.

4.1.3. A High Mass X-Ray Binary (HMXB)?

As MAXI J1807+132 is located at the relatively high Galactic latitude of 15°, the possibility of its being an HMXB would be low. If the companion star was an O- or B-type star located at ~8 kpc, with an absolute V-band magnitude of ~4 to 0 mag, we should have easily detected it with an apparent magnitude of 10–15 mag, even when the system was not active. In addition, during the present X-ray brightening, the optical flux of MAXI J1807+132 increased by an order of magnitude above the quiescence level. Such optical brightening should not take place in HMXBs even during increased mass accretion rates, because their optical fluxes are dominated by those from the mass-donating companions rather than from outer accretion disks. Finally, MAXI J1807+132 exhibited spectra that are considerably softer than those of high mass X-ray pulsars, which are roughly described by a power-law with a photon index of \( \lesssim 1 \) (Coburn et al. 2002). Therefore, MAXI J1807+132 cannot be an HMXB, regardless of the nature of the compact object involved.

4.1.4. A Transient BHXB?

The long-term spectral variation of MAXI J1807+132 throughout the present outburst is qualitatively similar to those seen in transient BHXBs. The spectrum became softer from March 26–29 to March 31 and harder again in April. Under the limited statistics of the XRT data, this behavior could be explained if we were witnessing a hard-to-soft and soft-to-hard transitions in these periods, respectively. Therefore, below we examine in more detail whether this interpretation is feasible or not.

If the source is a BHXB as assumed above, the prominent, low-temperature component seen on March 31 should be explained as disk emission in the soft state or an intermediate state (if in the hard state, the disk emission would not be as bright as in the March 31 spectrum). Indeed, similar temperatures and strengths of the soft component have been obtained in other BHXBs (e.g., Nakahira et al. 2014). However, if this were the case, MAXI J1807+132 should have an unusually large distance. Taking into account that the soft-to-hard transition of BHXBs normally occurs at a few % Eddington luminosity (Maccarone 2003), which corresponds to \( \sim 10^{37} \) (\( M_{\text{BH}}/10 M_{\odot} \)) erg s\(^{-1}\) (\( M_{\text{BH}} \) being the black hole mass), the March 31 flux as quoted above (\( \sim 7 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\)) implies a source distance as large as \( \sim 100 \) (\( M_{\text{BH}}/10 M_{\odot} \))\(^{1/2}\) kpc.

There is yet another piece of evidence against the BHXB interpretation. Applying the diskbb+powerlaw model to the March 27 spectrum, we obtained an unusually small inner disk radius, \( R_{\text{in}} \sim 1.5 \times 10^{12} \) cm (D/5 kpc) km. In order to identify it with the radius of the innermost circular orbit, we would have to assume an extreme inclination, e.g., \( i \gtrsim 85^\circ \), and a very light black hole (e.g., \( \sim 3 M_{\odot} \)) with a substantial spin.

Modeling the multi-wavelength SED on March 27 with the diskir model (Section 3) yielded an irradiation fraction of \( f_{\text{irr}} \approx 3.7 \times 10^{-2} \). This value is about several to ten times larger than those obtained from black hole X-ray binaries with X-ray luminosities of \( \gtrsim 10^{35} \) erg s\(^{-1}\) (e.g., Gierlinski et al. 2008, 2009; Chiang et al. 2010; Shidatsu et al. 2013; Nakahira et al. 2014, but see Rahoui et al. 2012). Even if no extinction is assumed (where the optical flux changes only by a factor of \( \approx 2 \)), the value of \( f_{\text{irr}} \) is reduced only by a factor of \( \lesssim 3 \) and is still somewhat larger than that of black hole X-ray
binaries. The situation worsens if we assume the stronger reddening, $E(B - V) = 0.28$, estimated via optical spectroscopy (Muñoz-Darias et al. 2017). Considering all of these results, we conclude that the source is unlikely to be a BHXB.

4.1.5. A Neutron Star LMXB?

A remaining possibility is that the source is a neutron star LMXB. The XRT spectra resemble those of neutron star LMXBs in their dim phases, with a luminosity below $\sim 10^{35}$ erg s$^{-1}$; at this luminosity range, they often exhibit a prominent soft thermal component with a power-law tail (Asai et al. 1996; Wijnands et al. 2001; Jonker et al. 2005; Chakrabarty et al. 2014; Sakurai et al. 2014), whereas such an apparent two-component feature is less significant when they are in the more luminous hard state (e.g., Barret 2001; Lin et al. 2007; Armas Padilla et al. 2017a). In particular, the properties of the XRT spectrum on 2017 March 27 are similar to those obtained in the two Suzuki observations of Aql X-1 in its dim phases (“Obs 5” and “Obs 6” in Sakurai et al. 2014), as noticed by comparing the compss results. If MAXI J1807+132 is a neutron star LMXB, and if the unabsorbed 0.8–100 keV luminosity on March 27 was between those in “Obs 5” and “Obs 6” of Aql X-1 ($5 \times 10^{35}$ erg s$^{-1}$ and $1 \times 10^{34}$ erg s$^{-1}$, respectively), the distance is calculated as $D \sim 1$–8 kpc.

A similar distance, $D = 5$ kpc, is derived from the relation between the luminosity versus the photon index for neutron star LMXBs (Wijnands et al. 2015), by using the photon index on March 27 ($\Gamma \approx 2.4$, when a single power-law model is applied) and the unabsorbed flux, $4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Assuming $D = 5$ kpc, the $3\sigma$ upper limit of the unabsorbed 0.3–10 keV flux on April 5, $8.8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, which is the lowest flux constraint in the XRT data sets, is converted to the Eddington ratio of $\sim 1.5 \times 10^{-5}$, for a neutron star with a mass of 1.4 $M_\odot$. This value is consistent with the minimum luminosity for neutron star LMXBs determined by Tomsick et al. (2005).

Such a low luminosity (below $10^{35}$ erg s$^{-1}$) would be favored to explain the high $L_{OPT}/L_X$ ratio, where $L_{OPT}$ and $L_X$ are the optical and X-ray luminosities, respectively, given a correlation of $L_{OPT} \propto L_X^\alpha$ with $\alpha \sim 0.5$ (van Paradijs & McClintock 1994; Russell et al. 2006, 2007). The X-ray flux of MAXI J1807+132 decreased by $\sim 2$ orders of magnitude from March 26 to early April. Similar rapid flux decay has been observed in other neutron star LMXBs, such as Aql X-1, 4U 1608$-$52, and MAXI J1421$-$613 (Campana et al. 1998; Asai et al. 2013; Serino et al. 2015), at luminosities below $10^{36}$ erg s$^{-1}$, where the propeller effect is considered to start operating and the centrifugal force prevents steady accretion onto the neutron star (Matsuoka & Asai 2013). These results provide additional support to our identification of MAXI J1807+132 as a neutron star LMXB in a dim phase.

4.2. Physical Interpretation of the X-Ray Spectra and Their Variations

Let us examine the X-ray properties of MAXI J1807+132, assuming that it is a dim neutron star LMXB. The soft X-ray component of such an object, at luminosities below $\sim 10^{35}$ erg s$^{-1}$, is generally considered to be thermal emission from the surface of the neutron star. The small radius of the blackbody emission region (a few km) can be naturally explained if only a part of the surface radiates X-rays. In fact, the blackbody radius of Aql X-1 was found to decrease from $\sim 10$ km at $\sim 1 \times 10^{36}$ erg s$^{-1}$ down to $\sim 3$ km at $\sim 1 \times 10^{34}$ erg s$^{-1}$ (Figure 6 of Sakurai et al. 2014), presumably because of the appearance of weak magnetic fields that limit the accretion flows to the magnetic poles. By contrast, the origin of the hard power-law tail is not yet fully understood. It allows several different interpretations, such as Comptonization of the blackbody emission in a hot accretion flow (Sakurai et al. 2014), bremsstrahlung from the hot flow itself (Chakrabarty et al. 2014), and the jet emission (Fender et al. 2003).

In Section 2.2, we applied the compss model to the XRT spectra on March 27 and 31, to examine the first interpretation in comparison with the Suzuki results of Aql X-1 (Sakurai et al. 2014), and found similarities between their best-fit parameters (see also Section 4.1.5).

The contribution by bremsstrahlung from the Comptonized corona was evaluated quantitatively by Ono et al. (2017), based on the observationally estimated accretion flow geometry in Aql X-1. When the source luminosity is $> 5 \times 10^{36}$ erg s$^{-1}$, they estimated the bremsstrahlung luminosity to be $L_{BB} \sim 1 \times 10^{34}$ erg s$^{-1}$. Then, assuming that MAXI J1807+132 has a typical luminosity of $2 \times 10^{35}$ erg s$^{-1}$ and that $L_{BB}$ decreases as the mass accretion rate gets lower, we conclude that $L_{BB}$ is likely to be still lower than the luminosity of the power-law tail.

We have detected significant variations in the temperature and the radius of the emission region of the blackbody component, which are not determined by the X-ray luminosity alone (see Figures 4 and 5). Similar peculiar behavior has been observed in other LMXBs, like Aql X-1 (Rutledge et al. 2002) and XTE J1709$-$267 (Jonker et al. 2005), at luminosities of $10^{33}$–$10^{35}$ erg s$^{-1}$. These variations were suggested to arise from residual accretion onto the polar cap region of the neutron star, in association with neutron star cooling (e.g., Cackett et al. 2010; Degenaar & Wijnands 2012). In the case of MAXI J1807+132, however, it is unclear whether the neutron star was at the stage of crustal cooling during the Swift observations, provided that the timescale of its flux decay was somewhat shorter than those in other neutron star LMXBs in quiescence (Homan et al. 2015).

The spectra of MAXI J1807+132 could be categorized into two types: (1) a flatter profile with a higher $kT_{BB}$ and a smaller $R_{BB}$ (e.g., the March 27 spectrum), and (2) a more complex profile in which the soft component, with a lower $kT_{BB}$ and a larger $R_{BB}$, and the hard tail are distinctive (e.g., the March 31 spectrum). This bimodality cannot be attributed to luminosity changes, considering that the spectrum switched a few times between the two types as the overall X-ray luminosity decayed almost monotonically.

One possible explanation of the observed variations between the two types would be to assume that the seed blackbody spectrum suffers strong color hardening, by a factor of $\kappa \sim 3$, in type-(1) spectra, whereas such an effect is small in type-(2) spectra so that the seed spectrum is close to a “bare” blackbody. In fact, Takahashi et al. (2009) observed spontaneous fluctuations in $\kappa$ in the LMXB 4U 1608$-$52 (even though the effect was only $\sim 20\%$ and was observed in the disk emission of the soft state). To examine this interpretation, we investigated the trend in the total photon flux of the soft thermal component, including both the direct and Compton-scattered components, assuming isotropic emission and conservation of the number of photons in Comptonization. In this analysis, the $\text{TRabs(bbodyrad+comps)}$ model was applied to the individual XRT spectra with $kT_{e} = 100$ keV. As shown in
Figure 10. Variation of the 0.01–100 keV photon flux of the soft thermal emission, calculated with the `tbabs*(bbodyrad+compss)` model. The abscissa is the same as in Figure 5.

Figure 10, the photon flux decreased rather monotonically. Thus, the observed variations could be described by a change in the color hardening factor (for some unspecified reasons) during a monotonic decrease in the mass accretion rate.

4.3. X-Ray and Optical Flux Correlation

The optical flux was reduced from March 27 to 31 by ~0.4 mag per day as the X-ray flux decreased. The optical decay can be expressed as $F_{\text{OPT}} \propto \exp(-t/\beta_{\text{OPT}})$, where $F_{\text{OPT}}$ represents the optical flux and $\beta_{\text{OPT}} \sim 2.7$ day. Fitting the XRT 0.3–10 keV light curve (Figure 5) in March 26–31 with an exponential function, $F_X \propto \exp(-(t/\beta_X))$, we obtain $\beta_X = 2.4 \pm 0.5$. From these two functions, the X-ray versus optical flux relation is derived as $F_{\text{OPT}} \propto F_X^{\alpha}$, where $\alpha \sim 0.7$–1.1. This $\alpha$ value is comparable with those obtained for other neutron star LMXBs in Russell et al. (2006, 2007).

We gratefully acknowledge the anonymous referee for constructive comments. M.S. acknowledges support by the Special Postdoctoral Researchers Program at RIKEN. This work is partly supported by a Grant-in-Aid for Young Scientists (B) 16K17672 (MS), for JSPS Fellows for young researchers (YT, TK), and for Scientific Research 17K05384 (YU) and 16K05301 (HN). This research has made use of MAXI data provided by RIKEN, JAXA, and the MAXI team and Swift data supplied by the UK Swift Science Data Centre at the University of Leicester. This work was partially carried out by the joint research program of the Institute for Cosmic Ray Research (ICRR), University of Tokyo.

Facilities: MAXI (GSC), Swift (XRT, UVOT).

Software: UK Swift Science Data Centre tools (Evans et al. 2009), HEASOFT, XSPEC (Arnaud 1996).

References

Armas Padilla, M., Ueda, Y., Horii, T., Shidatsu, M., & Muñoz-Darias, T. 2017a, MNRS, 467, 290
Armas Padilla, M., Wijnands, R., Degenaar, N., et al. 2017b, ATel, 10224, 1
Arnaud, K. A. 1996, in ASP Conf Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Asai, K., Dotani, T., Mitsuda, K., et al. 1996, PASJ, 48, 257
Asai, K., Matsuoka, M., Mihara, T., et al. 2013, ApJ, 773, 117
Barret, D. 2001, AdSpR, 28, 307
Bloom, J. S., Giannios, D., Metzger, B. D., et al. 2011, Sci, 333, 203
Burrows, D. N., Kennea, J. A., Ghisellini, G., et al. 2011, Nat, 476, 421
Cackett, E. M., Brown, E. F., Miller, J. M., & Wijnands, R. 2010, ApJ, 720, 1325
Campana, S., Stella, L., Mereghetti, S., et al. 1998, ApJL, 499, L65
Cash, W. 1979, ApJ, 248, 939
Chakrabarty, D., Tomskia, J. A., Grefenstette, B. W., et al. 2014, ApJ, 797, 92
Chiang, C. Y., Done, C., Still, M., & Godet, O. 2010, MNRS, 403, 1102
Coburn, W., Heindl, W. A., Rothschild, R. E., et al. 2002, ApJ, 580, 394
Degenaar, N., & Wijnands, R. 2012, MNRS, 422, 581
Denisenko, D. 2017, ATel, 10217, 1
Done, C., Gierliński, M., & Kubota, A. 2007, A&ARv, 15, 1
Esquej, P., Saxton, R. D., & Komsossa, S. 2008, A&A, 489, 543
Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, MNRS, 397, 1177
Fender, R. P., Gallo, E., & Jonker, P. G. 2003, MNRS, 343, L99
Gehrels, N., Chincarini, G., Giommi, P., et al. 2005, ApJ, 621, 558
Gierliński, M., Done, C., & Page, K. 2008, MNRS, 388, 755
Gierliński, M., Done, C., & Page, K. 2009, MNRS, 392, 1106
Homan, J., Fridriksson, J. K., Wijnands, R., et al. 2015, ApJ, 795, 131
Jonker, P. G., Galloway, D. K., McClintock, J. E., et al. 2005, MNRS, 354, 666
Kawamoto, T., Ueda, Y., Shidatsu, M., et al. 2016, PASJ, 68, 58
Kennea, J. A., Evans, P. A., Beardmore, A. P., et al. 2017a, ATel, 10215, 1
Kennea, J. A., Siegel, M. H., Evans, P. A., et al. 2017b, ATel, 10216, 1
Kong, A. K. H., Jin, R., Tseng, C.-H., & Lin, E.-T. 2017, ATel, 10245, 1
Levan, A. J., Tanvir, N. R., Cenko, S. B., et al. 2011, Sci, 333, 199
Lin, D., Remillard, R. A., & Homan, J. 2007, ApJ, 667, 1073
Maccarone, T. J. 2003, A&ARV, 409, 697
Maksym, W. P., Ulmer, M. P., & Eracleous, M. 2010, ApJ, 722, 1035
Matsuoka, M., Kawasaki, K., Ueno, S., et al. 2009, PASJ, 61, 999
Mihara, T., Nakajima, M., Sugizaki, M., et al. 2011, PASJ, 63, 623
Mink, D. J. 1997, in ASP Conf. Ser. 125, Astronomical Data Analysis Software and Systems VI, ed. G. H. Jacoby & H. E. Payne (San Francisco, CA: ASP), 249
Mitsuda, K., Inoue, H., Koyama, K., et al. 1984, PASJ, 36, 741
Mori, M., Yamaoka, H., Mihara, T., Matsuoka, M., & Kawai, N. 2016, PASJ, 68, 11
Muñoz-Darias, T., Jimenez-Ibarra, F., Mata Sanchez, D., et al. 2017, ATel, 10221, 1
Nakahira, S., Negoro, H., Shidatsu, M., et al. 2014, PASJ, 66, 84
Negoro, H., Kawamoto, T., Ueda, Y., et al. 2017, ATel, 10208, 1
Negoro, H., Kohama, S., Serino, M., et al. 2017, PASJ, 69, 23
Phinney, E. S. 1989, in IAU Symp. 136, The Center of the Galaxy: Proceedings of the 136th Symposium of the International Astronomical Union, ed. M. Morris (Dordrecht: Kluwer), 543
Poutanen, J., & Svensson, R. 1996, ApJ, 470, 249
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Rahoui, F., Coriat, M., Corbel, S., et al. 2012, MNRAS, 422, 2202
Rees, M. J. 1988, Natur, 333, 523
Revnivtsev, M., Sazonov, S., Krivonos, R., Ritter, H., & Sunyaev, R. 2008, ApJ, 489, 1121
Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, SSRv, 120, 95
Russell, D. M., Fender, R. P., Hynes, R. I., et al. 2006, MNRAS, 371, 1334
Russell, D. M., Fender, R. P., & Jonker, P. G. 2007, MNRAS, 379, 1108
Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., & Zavlin, V. E. 2002, ApJ, 577, 358
Sakurai, S., Torii, S., Noda, H., et al. 2014, PASJ, 66, 10
Serino, M., Shidatsu, M., Ueda, Y., et al. 2015, PASJ, 67, 30
Shidatsu, M., Tachibana, Y., Yoshii, T., et al. 2017, ATel, 10222, 1
Shidatsu, M., Ueda, Y., Nakahira, S., et al. 2013, ApJ, 779, 26
Shields, J., Stanek, K. Z., Kochanek, C. S., et al. 2017, ATel, 10227, 1
Tachibana, Y., Yoshii, T., Hanayama, H., & Kawai, N. 2017a, PASJ, 69, 63
Takahashi, H., Sakurai, S., & Makishima, K. 2009, ApJ, 738, 62
Tomsick, J. A., Gelino, D. M., & Kaaret, P. 2005, ApJ, 635, 1233
van Paradijs, J., & McClintock, J. E. 1994, A&A, 290, 133
Wijnands, R., Degenaar, N., Armas Padilla, M., et al. 2015, MNRAS, 454, 1371
Wijnands, R., Miller, J. M., Markwardt, C., et al. 2001, ApJL, 560, L159
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914