Low-Mass X-Ray Binary MAXI J1421−613 observed by MAXI GSC and Swift XRT

Motoko Serino, Megumi Shidatsu, Yoshihiro Ueda, Masaru Matsuoka, Hideo Negoro, Kazutaka Yamaoka, Jamie A. Kennea, Kosuke Fukushima, Takahiro Nagayama

1 MAXI team, Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
2 Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan
3 ISS Science Project Office, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan
4 Department of Physics, Nikon University, 1-8-14 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan
5 Department of Particle Physics and Astronomy, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
6 Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
7 Department of Astronomy and Astrophysics, 0525 Davey Laboratory, Pennsylvania State University, University Park, PA 16802, USA
8 Department of Physics and Astronomy, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan

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Abstract

Monitor of All sky X-ray Image (MAXI) discovered a new outburst of an X-ray transient source named MAXI J1421−613. Because of the detection of three X-ray bursts from the source, it was identified as a neutron star low-mass X-ray binary. The results of data analyses of the MAXI GSC and the Swift XRT follow-up observations suggest that the spectral hardness remained unchanged during the first two weeks of the outburst. All the XRT spectra in the 0.5–10 keV band can be well explained by thermal Comptonization of multi-color disk blackbody emission. The photon index of the Comptonized component is ≈ 2, which is typical of low-mass X-ray binaries in the low/hard state. Since X-ray bursts have a maximum peak luminosity, it is possible to estimate the (maximum) distance from its observed peak flux. The peak flux of the second X-ray burst, which was observed by the GSC, is about 5 photons cm$^{-2}$ s$^{-1}$. By assuming a blackbody spectrum of 2.5 keV, the maximum distance to the source is estimated as 7 kpc. The position of this source is contained by the large error regions of two bright X-ray sources detected with Orbiting Solar Observatory-7 (OSO-7) in 1970s. Besides this, no past activities at the XRT position are reported in the literature. If MAXI J1421−613 is the same source as (one of) them, the outburst observed with MAXI may have occurred after the quiescence of 30–40 years.

Key words: methods: data analysis — X-rays: bursts — X-rays: individual (MAXI J1421−613)

1. Introduction

Thermonuclear (type I) X-ray bursts are one of the key phenomena in understanding previously unknown X-ray sources. The cause of a sudden energy release is nuclear burning of accreted H/He fuel on the neutron star (Lewin et al. 1993). Once an X-ray burst is detected, we know that the source must be a neutron star binary with a low-mass companion. Moreover, the existence of the characteristic luminosity of type I X-ray bursts with photospheric radius-expansion (PRE) is useful to determine the limit of the distance to these sources. The luminosity of those bursts are thought to have reached the Eddington luminosity, while recent studies of PRE bursts have shown the variation of peak luminosity of ~ 10% (Ebisuzaki et al. 1984; Kuulkers et al. 2003; Galloway et al. 2008).

The MAXI Nova-Alert System (Negoro et al. 2010) triggered on a source at 01:13:07 UT on 2014 January 9. The position of the source was calculated as R.A. = 215.413 deg, Dec = −61.345 deg and reported to the Astronomer’s Telegram as MAXI J1421−613 (Morooka et al. 2014). At 19:35 on the same day, Swift performed a Target of Opportunity observation, tiling the MAXI GSC error ellipse with 7 pointings, to confirm the detection. In the Swift X-ray Telescope (XRT; Burrows et al. 2005) data, there was an X-ray point source, in two out of the seven tiles (Kennea et al. 2014a). Figure 1 shows the image of MAXI J1421−613 observed by Swift XRT with the GSC error ellipse. The position was determined by Swift XRT, utilizing UVOT to correct for astrometric errors (Evans et al. 2009) as R.A., Dec(J2000) = 215.40838 deg, −61.60693 deg (Kennea et al. 2014a). Utilizing 6ks of Photon Counting (PC) mode data taken between January 14 and 20, Kennea et al. (2014b) revised the position to R.A., Dec(J2000) = 215.40504 deg, −61.60700 deg. The error radius for this revised position is 1.5 arcsec (90% confidence). It was also reported that the BAT Transient Monitor (Krimm et al. 2013) did not detect the
source, suggesting that the source had a soft spectrum. Although the flux in the BAT energy band was low at that point, there may be an excess in the BAT light curve around January 14\footnote{http://swift.gsfc.nasa.gov/results/transients/weak/MAXIJ1421-613/}. A radio counterpart of this source was detected by the Australia Telescope Compact Array (ATCA) (Coriat et al. 2014a; Coriat et al. 2014b). The final position obtained by ATCA is R.A., Dec (J2000) = 14°21′37″2, −61°36′25″4 with uncertainties of 0.3 arcsec in both RA and Dec.

At least three type I X-ray bursts were detected from the source. The first one was detected at 19:05 UT on January 10 by JEM-X on-board INTEGRAL (Bozzo et al. 2014), the second one at 03:16 UT on January 16 by MAXI GSC, and the third one at 08:40 UT on January 18 by Swift BAT and XRT (Baumgartner et al. 2014). The detection of the X-ray bursts reveals that the source is a low-mass X-ray binary containing a neutron star.

In this paper, we analyze the data of MAXI J1421−613 observed with MAXI GSC and Swift XRT. Section 2.1 presents the light curves and the results of spectral analyses covering the whole outburst period. We also report an upper flux limit obtained by a Suzaku observation. In section 2.2, we focus on the X-ray bursts. The results of follow-up observations in near-infrared are presented in section 2.3. In section 3.1, we discuss the distance to the source and constrain the spectral type of the companion star. The origin for an rapid decay observed at the end of the outburst is discussed in section 3.2. Finally, in section 3.3, we discuss possible past activities of MAXI J1421−613, using X-ray source catalogs in the literature.

2. Observations and Data Analyses

2.1. Light curve and spectra of the outburst

MAXI J1421−613 has been monitored by MAXI (Matsuoka et al. 2009) throughout the outburst. In addition, Swift XRT carried out pointed observations approximately every other day. We used these data sets to investigate the overall profile of the outburst.

The upper three panels (a, b, c) of figure 2 show the GSC light curves of MAXI J1421−613 that are publicly available \footnote{http://maxi.riken.jp/top/index.php?cid=1&jname=J1421-616}. The time bin size of the light curves are 6 h. The brightening of the source started around January 7 and the flux increased almost linearly toward the peak on January 10. The peak photon flux in the 2–20 keV energy band was about 0.25 photons cm$^{-2}$ s$^{-1}$. Assuming the spectral model derived from the XRT observations ($n$thComp of disk blackbody with $T_{in}$ = 1.0 keV, $\Gamma$ = 2.1, $kT_e$ = 20 keV, with a photoelectric absorption of $N_H$ = 4.8 × 10$^{22}$ cm$^{-2}$; see below), we estimated the flux to be 2.6 × 10$^{-9}$ ergs cm$^{-2}$ s$^{-1}$ in the same energy band. Then the flux decreased and went back to the background level on January 21. The three arrows in the top panel indicate the time of the X-ray bursts from the source. The GSC data point at the second arrow contains the emission of the X-ray burst. The fourth panel (d) shows the hardness ratio between the 4–10 keV and 2–4 keV bands, which is binned up to 24 h.

A series of monitoring observations (Target ID = 33098) by Swift XRT started on January 11. There were eleven observation segments until the last observation on February 4. Two of them (seg. 9 and 10) were performed with the PC mode and the rest were with the WT mode. An X-ray burst occurred during seg. 5, which triggered Swift BAT (Baumgartner et al. 2014). The automated follow-up observation with the PC mode started immediately after the burst. We also analyzed the data obtained by this follow-up observation (designate as seg. 5+ in this paper). At the time of seg. 7, the source had already become faint and the poor photon statistics did not allow us to perform spectral fitting. We thus used seven observations (seg. 1–6 and 5+) for the spectral analysis. For seg. 5, we excluded the data of the last 40 s of the observation, when the X-ray burst occurred.

We extracted spectra from event data of each observation using XSELECT, and analyzed them with XSPEC. First, we tried three simple models; power law with high energy exponential cutoff model ($Cutoffpl$), power-law model ($Powerlaw$), and blackbody model ($Bbody$). All of them are multiplied by the photo-electric absorption model ($Wabs$, Morrison & McCammon 1983). We jointly fit the data of the seven observations with a common absorption column density. The chi-squared (and the degree of freedom) of the fitting with $Cutoffpl$, $Powerlaw$, and $Bbody$ models are 1392.32 (1402), 1527.32 (1409), and 1591.70 (1409), respectively. Therefore, $Cutoffpl$ model is the most favored model to describe the spectral shape of this source. If we link the photon indices of the $Cutoffpl$ model among all the segments, we still have an acceptable fit (the chi-squared is 1464.92 for 1408 degrees of freedom). In this case, the photon index is 0.6 ± 0.3 and the cutoff energy is $\sim$ 3 keV for all the segments. Although the errors on the photon indices are large, the result is consistent.
with the supposition that the hardness (or spectral shape) did not change significantly throughout the outburst.

It is suggested that a hard-to-soft spectral transition occurs at 1–4% of the Eddington luminosity (Maccarone 2003; Asai et al. 2012). If the X-ray burst observed by the GSC reached the Eddington luminosity (see section 3.1), the flux of 4% of that becomes $\sim 3 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$. The observed flux was lower than this value throughout the outburst, unlike other transient neutron star low-mass X-ray binaries with spectral state transitions observed by MAXI (Asai et al. 2012; Sugizaki et al. 2013). Therefore, it is reasonable to interpret that MAXI J1421–613 remained in the hard state during the outburst.

Then, we tried some typical spectral models for the hard state. A typical spectrum of the hard state consists of a soft thermal component, which is described as blackbody or multi-color disk blackbody ($\text{diskbb}$ Mitsuda et al. 1984), and a hard Comptonized component ($\text{nthComp}$ Raichur et al. 1984; Sakurai et al. 2012; Mori et al. 2012). First, we tried thermally Comptonized continuum model ($\text{nthComp}$, Zdziarski et al. 1996) + $\text{diskbb}$ with $\text{wabs}$. However, the parameters were not well constrained, perhaps due to the poor statistics or the low flux of the soft component. Then, we simplified the model as $\text{nthComp}$ with $\text{wabs}$. Here we selected the disk blackbody model as the seed photons. Because the energy band is limited (0.5–10 keV), we were not able to determine the electron temperature $T_e$ from the spectral fit. Thus, we fixed $T_e$ to 20 keV. In addition, we fixed the column density of this fit to $4.8 \times 10^{22}$ cm$^{-2}$, which was derived from the spectral fit of the third X-ray burst (see section 2.2), since the column density of X-ray burst spectra is not affected much by the uncertainty in the shape of the continuum.

Figure 3 shows the samples of the spectra of the seg. 1 (black) and 5+ (gray) observations fitted by $\text{nthComp}$ with $\text{wabs}$ model. The spectral parameters are shown in figure 2. The panel (e), (f), and (g) of figure 2 show the asymptotic power-law indices $\Gamma$, the temperature ($kT_{\text{in}}$) of the seed photons, and the flux in the 0.5–10 keV band, respectively. Although some parameters are not well constrained, the decay trend of the best fit fluxes agrees with the MAXI GSC light curve. The index $\Gamma$ distributes around 2, which is consistent with the interpretation of the hard state.

We requested a Suzaku observation of MAXI J1421–613. The observation started at 12:20:40 UT on 2014 January 31, and the exposure was about 49 ks. The clock mode of the X-ray Imaging Spectrometer (XIS) was normal and no window and burst options were applied. The source was not significantly detected, however. We calculated an upper flux limit, using the XIS0 data of both 3x3 and 5x5 editing modes. We extracted the events from the central 2.5 arcmin region. The total observed count for the 48.4 ks exposure was 1030 counts in the 0.5–10 keV band. The background region of the same size was taken to the South of the source region.

Fig. 2. The light curves (a, b, c) and the hardness ratio (d) observed by the GSC, and the spectral parameters of MAXI J1421–613 derived by fitting the XRT data (e, f, g). The error bars on the GSC light curves and the hardness ratio are at 1σ. The arrows in the top panel indicate the time of the X-ray bursts. The lower panels show the spectral parameters of the fit with $\text{nthComp}$ model. The numbers in the panel (f) represent the seg. numbers. The asymptotic power-law indices $\Gamma$, the seed photon temperature, and the observed fluxes are shown in panel (e), (f), and (g), respectively. The bottom panel (g) shows the flux in the 0.5–10 keV band. If $\Gamma$ is linked over the segments, we obtained the parameters shown with circles. The best-fit value (and its error region) of linked $\Gamma$ is shown with the solid (and dashed) horizontal lines. Otherwise, the obtained parameters are plotted with the triangles. The errors on these spectral parameters are at the 90% confidence level.

\footnote{We also tried $T_e$ of 40 keV but the result did not change significantly.}
and the observed count for the same exposure and energy band was 1084 counts. Therefore, the 3σ error on the observed count is 138 counts and the corresponding count rate is 0.0028 counts s$^{-1}$. Assuming the spectral parameters of the last XRT observation, (nthComp of disk blackbody with $kT_{\text{in}} = 0.37$ keV, $\Gamma = 2.1$, $kT_{\text{e}} = 20$ keV, with a photoelectric absorption of $N_H = 4.8 \times 10^{22}$ cm$^{-2}$), we obtained the 3σ upper limit of $1.2 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–10 keV). This limit is consistent with the upper limit of the Chandra observation reported by Chakrabarty et al. (2014).

2.2. Light curves and spectra of the X-ray bursts

In order to understand the nature of the X-ray bursts, we analyzed the GSC and XRT data taken at the time of the bursts. Figure 4 shows the effective area corrected light curves of the GSC transit at the X-ray burst. The burst occurred in the first half of the transit and lasted about 36 seconds. Although the statistics are not sufficient, there is a hint of spectral evolution. At the time around $-25$ s in figure 4, the photon flux in the 2–4 keV band decrease, while that of in the 10–20 keV band increase, suggesting an increase of the temperature.

The third X-ray burst was detected during the pointed observation of the XRT. The top panel of figure 5 shows the XRT light curve in the 0.5–10 keV band. We performed time-resolved spectral analyses of the burst. Since the count rate is larger than 100 counts s$^{-1}$, the first and second parts may be affected by pile-up$^4$. Hence, we exclude photons in the central 2 pixels of the image for these intervals.

We fitted the spectra of seven time intervals, using the blackbody model with a photoelectric absorption. We performed a joint spectral analysis with a common absorption column density, which resulted in $(4.8^{+1.8}_{-1.1}) \times 10^{22}$ cm$^{-2}$. The results of the spectral analyses are shown in the same figure. We find that the temperature decreases as the flux decreases, which is typical of the decay part of X-ray bursts.

2.3. Follow-up observations in near-infrared

Near-infrared photometric observations in the $J$ (1.25 μm), $H$ (1.63 μm), and $K_S$ (2.14 μm) bands were carried out with the SIRIUS camera (Nagayama et al. 2003) on the 1.4 m telescope of Infrared Survey Facility (IRSF) in South African Astronomical Observatory (SAAO) on

$^4$ XRT User’s Guide (http://swift.gsfc.nasa.gov/analysis/xrt_swguide_v1.2.pdf)
2014 January 16, 17, 20, 21, 22, and 24. The exposure in each night was 300 sec (after combining 15 dithered frames with a 20-sec exposure), and the typical seeing in the J band was ≃1.5′′ in full width at half maximum. The standard data reduction (bias correction, dark subtraction, flat fielding, sky subtraction, and combining dithered images) was performed through the IRSF pipeline software “sirius09” on the IRAF (Image Reduction and Analysis Facilities; Tody 1986) package.

The counterpart of MAXI J1421–613 in any band was not detected at any night within the 90% error circle (1.7′′) of the Swift XRT position (Kennea et al. 2014a). The upper limits of MAXI J1421–613 magnitudes were estimated from 3 standard deviations (3σ) of the averaged background counts in nearby source-free regions. Here, to obtain the tightest constraints, all the images are co-added by using “pyIRSF”, a python package of the IRSF data reduction, after excluding those of January 20, which are out of focus, and those of January 22, where the signal-to-noise ratios are twice worse than in the other data. The conversion from the counts to magnitudes was based on the comparison of stellar photometry around the source position with the magnitudes of 2MASS all-sky catalog (Skrutskie et al. 2006). The apparent magnitudes were >18.9 mag, >18.2 mag, and >16.9 mag in the $J$, $H$, $K_S$ bands, respectively.

3. Discussions

3.1. X-ray bursts and distance to the source

We calculate the bolometric peak flux of the two X-ray bursts observed by the GSC and the XRT. The peak photon flux of the second X-ray burst, observed by the GSC, is about 5 photons cm$^{-2}$ s$^{-1}$ in the 2–20 keV band. By assuming the blackbody spectrum of 2.5 keV, the bolometric peak flux is calculated to be $7 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$.

For the third X-ray burst observed by the XRT (figure 5), the peak flux (the first time interval) is $1.5 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–10 keV band. The (unabsorbed) bolometric flux based on the best fit model is $3.2 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$.

Assuming the empirical maximum luminosity of X-ray bursts, $3.8 \times 10^{38}$ ergs s$^{-1}$ (for helium burning, Kuulkers et al. 2003), and using the peak burst flux of $7 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, we estimate the maximum distance to the source as 7 kpc.

By using this distance, together with the hydrogen column density, upper limits of absolute magnitudes of the near-infrared counterpart can be calculated. To derive the limits conservatively, we calculate the extinction in each band from the 90% upper limit of the averaged hydrogen column density ($N_{H} = 6.1 \times 10^{22}$ cm$^{-2}$) obtained from the X-ray spectra during the third X-ray burst (see Section 2.2), using the $N_{H}$ versus reddening ($E(B-V)$) relation in Bohlin et al. (1978) and the extinction curve in Cardelli et al. (1989) for $R_V(= A_V/E(B-V)) = 3.1$.

The resultant 3σ upper limits of the extinction-corrected absolute magnitudes are $-4.51$ mag ($J$ band), $-2.24$ mag ($H$ band), and $-1.05$ mag ($K_S$ band). These constraints suggest that the companion of the MAXI J1421–613 should be fainter than B3 star, if it is a main sequence star (Wainscoat et al. 1992). This is consistent with the identification of MAXI J1421–613 with a low-mass X-ray binary, which can exhibit type-I X-ray bursts.

3.2. The decay of the outburst

The flux limit derived from the Suzaku observation ($<1.2 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–10 keV band at 3σ) is lower than an extrapolation of the flux observed by the XRT (§2.1). Compared with the observed flux of $5.1 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–10 keV) on January 20, the flux of the source had decayed by more than two orders of magnitude in $\sim 10$ days. This decay rate is much faster than the observed decay curve of the flux measured with the XRT (figure 2). Such rapid decay has been observed from other neutron star low-mass X-ray binaries. For example, in the 1997 February–March outburst of Aquila X-1, the luminosity decreased from $\sim 10^{36}$ to $\sim 10^{33}$ ergs s$^{-1}$ in 10 days (Campana et al. 1998). This decay is interpreted as the onset of the propeller effect (Asai et al. 2013). In the case of MAXI J1421–613, the propeller effect is a possible cause for the sudden decrease of the source flux.

3.3. Cataloged X-ray Sources at the Position of MAXI J1421–613

At the revised position determined by the Swift XRT, there are no previously cataloged X-ray sources whose position errors are less than 1 arcmin. We find, however, that two X-ray sources reported in the literature contain the XRT position of MAXI J1421–613 in their large error regions.

The first one is an (anonymous) X-ray source reported by Wheaton et al. (1975) (hereafter W75), which was detected with OSO-7 between 1971 and 1972. The position is R.A., Dec (equinox 1972.0) = 14\degree15′59″, $-62′$2′′ with an uncertainty of $\sim 3$ deg (Markert et al. 1977). The other cataloged source is MXB 1418–61 (or MXB 1418–61 in SIMBAD; Wenger et al. 2000), which was also detected with OSO-7 between 1971 and 1974 (Markert et al. 1975; Markert et al. 1977). The position and its error of MX 1418–61 was reported as R.A., Dec (B1950) = 14\degree18′55″.5 ± 1″8, $-61′′4$ ± 0″2. The XRT position is apart from the center of the error box by $\sim 4.6$ arcmin but is within the error box. This source might be the same one (or a part of) the object reported by W75.

Since the late ’70s, there were several X-ray satellites that were able to monitor bright X-ray sources by covering a wide area of the sky, such as Hakucho (‘79–’85), Ginga (’87–’91), and RXTE (’95–2012). Although they discovered many X-ray transients including X-ray bursters, none of the cataloged X-ray sources is consistent the position

5. Although the identifier is “MXB”, the original reference of this source is not “X-ray bursters and the X-ray sources of the galactic bulge” (Lewin & Joss 1981) and no X-ray bursts are reported from this source in the literature.
of MAXI J1421–613. If MAXI J1421–613 exhibited X-ray bursts, they could have been well detected with these observatories. The ROSAT All Sky Survey detected no X-ray source at the XRT position (Voges et al. 1999; Voges et al. 2000), either. These facts imply that the source had been in the quiescent state for more than 30 years. Hence, if MAXI J1421–613 is identical with MX 1418–61 (and/or the object reported in W75), the outburst of MAXI J1421–613 may have occurred after the quiescence of 30–40 years.

4. Conclusion

MAXI GSC triggered on a new outburst of the X-ray source MAXI J1421–613 and Swift XRT located its position with an accuracy of 1.5 arcsec (90% confidence). There were three X-ray bursts during the outburst, which showed the source to be a low-mass X-ray binary containing a neutron star. All seven spectra of the XRT in the 0.5–10 keV band can be well explained by thermal Comptonization of multi-color disk blackbody emission. These results may suggest that the spectral state of this source remained the hard state. This behavior is consistent with the relation between the luminosity and the spectral transition. The fast decay at the end of outburst can be explained as the onset of the propeller effect.

The X-ray burst observed by the GSC was brighter than that observed by the XRT. Using the peak flux of the burst, we estimated an upper-limit of the distance to the source as 7 kpc. Assuming the distance and the hydrogen column density determined by the analysis of the X-ray burst, the upper limits for the absolute magnitudes are -4.51, -2.24, and -1.05 mag for J, H, and Ks band, respectively. It means the companion should be fainter than B3 star, and it is consistent with the identification of MAXI J1421–613 with a low-mass X-ray binary.

The position of MAXI J1421–613 is consistent with MX 1418–61 and the object reported in W75, both detected by OSO-7 in 1970s, within their very large positional errors (~0.4–3 deg). Besides this, no past activities at the XRT position are reported in the literature. If MAXI J1421–613 is the same source as (one of) them, the outburst observed with MAXI may have occurred after the quiescence of 30–40 years.

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