**Discovery of a new supergiant fast X-ray transient MAXI J0709–159 associated with the Be star LY CMa**

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**Abstract**

We report on the discovery of a new supergiant fast X-ray transient (SFXT), MAXI J0709–159, and its identification with LY CMa (also known as HD 54786). On 2022 January 25, a new flaring X-ray object named MAXI J0709–159, was detected by Monitor of All-sky X-ray Image (MAXI). Two flaring activities were observed in the two scans of ~3 hours apart, where the 2–10 keV flux reached $5 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. During the period, the source exhibited a large spectral change suggesting that the absorption column density $N_H$ increased from $10^{22}$ cm$^{-2}$ to $10^{23}$ cm$^{-2}$. NuSTAR follow-up observation on January 29 identified a new X-ray source with a flux of $6 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ at the position consistent with LY CMa, which has been identified as B supergiant as well as Be star, located at the 3 kpc distance. The observed X-
ray activity characterized by the short (∼ several hours) duration, the rapid (∼ a few seconds) variabilities accompanied with spectral changes, and the large luminosity swing (10^{32}–10^{37} erg s^{-1}) agree with those of SFXTs. On the other hand, optical spectroscopic observations of LY CMA revealed a broad Hα emission line, which may indicate the existence of a Be circumstellar disk. These obtained results suggest that the optical companion, LY CMA, certainly has a complex circumstellar medium including dense clumps.

**Key words:** stars:individul (LY CMA, HD 54786) — stars:Be — supergiant — stars:neutron — X-rays:binaries

### 1 Introduction

MAXI (Monitor of All-sky X-ray Image: Matsuoka et al. 2009) on the International Space Station (ISS) has been continuously scanning the almost entire sky every ISS orbital cycle (∼92 minutes) since the in-orbit operation started in 2009. It provides us a unique opportunity to discover new objects and study their transient behaviors. In fact, we have discovered 31 new X-ray objects including 14 black-hole binaries, 13 neutron-star binaries, and one white-dwarf binary, that appeared in our Galaxy and the Small Magellanic Cloud (e.g., Mihara et al. 2022). The data also enable us to study their variabilities in time scales from hours to over the 12 years. To uncover the nature of these new transient objects, prompt follow-up observations with large-area X-ray telescopes as well as multi-wavelength observations from both space and ground observatories are essential. The MAXI nova-alert system (Negoro et al. 2016) and prompt coordinated observations with Swift, NICER, NuSTAR satellites, have been working effectively for these transient studies such as an ignition of a classical nova, MAXI J0158−744 (Morii et al. 2013), a new Be X-ray binary pulsar, MAXI J0903−531 (Tsygankov et al. 2021), and a faint and short-duration back-hole binary candidate, MAXI J1848−015 (Pike et al. 2022).

On 2022 January 25, MAXI discovered a new X-ray transient with an instantaneous 4–10 keV flux of 270 mCrab (∼ 5 × 10^{-9} erg cm^{-2} s^{-1}), named MAXI J0709−159 (hereafter MAXI J0709), in the constellation Canis Majoris (Serino et al. 2022). The source was first detected during the scan transit at UT 10:42, but not detected in the next scan transit at UT 12:15. However, it was detected again in the next scan transit at UT 13:48 (Kobayashi et al. 2022). This means that the source exhibited a large intensity variation within the 3 hours. Three hours after the MAXI discovery, NICER (The Neutron star Interior Composition Explorer; Gendreau et al. 2012) started multiple pointing observations covering almost the entire region of the MAXI position error (circle of radius ∼ 0.2°). The new transient was successfully detected with the pointing observation carried out 6 minutes after the MAXI scan at UT 13:46. The NICER observations refined the source position with the error of 3′ and also revealed that the X-ray flux had declined by a factor of ∼ 10 from the MAXI observations (Iwakiri et al. 2022).

From 2022 January 19 to February 18, the Swift X-ray satellite (Gehrels et al. 2004) stopped the normal operation because the attitude control system was troubled1. Hence, we applied for the NuSTAR (Nuclear Spectroscopic Telescope Array; Harrison et al. 2013) ToO (Time of Opportunity) observation. The NuSTAR observation was carried out on 2022 January 29, 4 days after the discovery. The result revealed a new point source within the error circle of the MAXI J0709 position uncertainty. The position of the new source is consistent with LY CMA (also known as HD 54786), which has been identified as a Be star (Negoro et al. 2022; Nesci 2022). In Gaia Early Data Release 3, the distance is estimated to be D = 3.03^{+0.31}_{-0.27} kpc (Bailer-Jones et al. 2021)2. From optical follow-up observations and archival data analysis, Bhattacharyya et al. (2022) suggested that LY CMA would be an evolved Be star, rather than a main sequence star or a supergiant. A radio observation was carried out on 2022 January 31 with the MerrKAT radio telescope, but no significant emission was detected at 1.28 GHz and the 3-σ upper limit was estimated to be 57 μJy (Rhodes et al. 2022) Finally, the Swift ToO observation was carried out on 2022 February 23.

In this paper, we report the discovery of the new transient MAXI J0709 and results of the MAXI, NuSTAR, Swift, and eROSITA observations of the identified X-ray object. We also report an optical follow-up observation of the optical counterpart in the Chuo University. Based on the obtained results, we discuss the nature of the new X-ray object. In the following throughout the paper, errors represent 90% confidence limits of statistical uncertainties unless otherwise specified.

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1. https://swift.gsfc.nasa.gov/news/2022/safe_mode.html
2. https://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/352
2 MAXI observations and data analysis

MAXI Gas Slit Camera (GSC; Mihara et al. 2011; Sugizaki et al. 2011) consists of 12 identical camera units, namely GSC_0, ..., GSC_9, GSC_A, GSC_B. Utilizing the two wide ($160^\circ \times 3^\circ$) FOVs, GSC scans the whole sky every 92 minutes. We investigated X-ray activities of a new transient MAXI J0709 in time scales shorter than each scan transit ($\sim 40$ s) and longer than the scan cycle ($\sim 92$ minutes), using the GSC data. We here employed GSC event files of the process version 2.1, taken via the low-speed telemetry interface, and performed the data analysis using MAXI software included in HEASoft version 6.29 the calibration database (CALDB) version 20210504 released from JAXA data archive.

2.1 GSC light curve

We extracted GSC light curves of MAXI J0709 by fitting each GSC scan image with a model consisting of a point-spread function (PSF) for the target source and a uniform background (Morii et al. 2016). The source position was fixed at the position parameters refined by the NuSTAR observation (section 3.1). Figure 1 shows GSC 2–20 keV images taken by the GSC_4 and GSC_5 units, when MAXI J0709 was first detected on 2022 January 25 (MJD 59604). Within 10 days before and after the first detection, the source had been observed by either or both of these two GSC units.

Figure 2 shows the obtained 2–4 keV and 4–10 keV light curves from the 2 days before to the 5 days after the first detection. The data gap from MJD 59603.2 to 59604.3 corresponds to the period when the source position was shadowed by the frame structure in the GSC detector. After the data gap, there was no significant flux in the two scans. Then, the first X-ray activity was detected in the scan transit at UT 10:42 (MJD 59604.466, Scan-A).

The source count rates averaged over the scan transit were $0.19^{+0.03}_{-0.03}$ counts cm$^{-2}$ s$^{-1}$ (180 mCrab) in 2–4 keV and $0.35^{+0.04}_{-0.04}$ counts cm$^{-2}$ s$^{-1}$ (300 mCrab) in 4–10 keV. In the next scan transit at UT 12:15 (MJD 59604.510, Scan-B), there was no significant flux over the background with the $1\sigma$ upper limits of 0.005 counts cm$^{-2}$ s$^{-1}$ (5 mCrab) in 2–4 keV and 0.032 counts cm$^{-2}$ s$^{-1}$ (27 mCrab) in 4–10 keV. In the other next scan transit at UT 13:48 (MJD 59604.575, Scan-C), the source was detected again but only in the 4–10 keV band with $0.23^{+0.03}_{-0.03}$ counts cm$^{-2}$ s$^{-1}$ (200 mCrab). Those mean that the source intensity changed every scan transit by a factor of $\gtrsim 10$ and also the spectrum changed.

In the following scans after MJD 59604.639 (Scan-D), the source activity went down below the GSC sensitivity limit.

We then investigated the source variability within each scan transit of Scan-A and Scan-C, which include significant source photons. Figure 3 shows count rate variations during Scan-A and Scan-C, compared with the effective-area variations for the source position and the backgrounds estimated from the data in the adjacent source-free region. In Scan-A, the 2–20 keV count rate roughly traces the effective-area variation, indicating that the photon flux was approximately constant during the scan transit. However, at the middle of the transit, a dip-like structure lasting for $\sim 4$ s is clearly seen. We fitted the data around the dip with a constant-flux model, i.e. a normalized effective-area curve plus background. The result gives Cash statistic (C-stat; Cash 1979) = 7.5 for 3 degrees of freedom (d.o.f), meaning that the constant model is rejected with a confidence of $> 90\%$. In Scan-C, the 4–10 keV count rate shows a sharp peak at the center of the scan. We performed the model fit same as in Scan-A and obtained the similar result that the constant-flux model is rejected with a confidence of $> 95\%$. These results suggest the source has a rapid time variability on time scales of a few seconds or less.

We also investigated the past source activity from the beginning of the MAXI in-orbit operation in 2009 August. At the distance of 0.55 from the refined MAXI J0709 position, another X-ray source, 3MAXI J0708-155, was reported in the 7-year MAXI/GSC source catalog (Hori et al. 2018). There, the object is identified as the Blazar, PKS 0706-15. Although this nearby X-ray object can be distinguished from MAXI J0709 with the MAXI/GSC position accuracy ($\lesssim 0.2^\circ$), the PSFs of these two objects have an overlap, which causes the source confusion. We carefully estimate the amount of the possible confusion and confirmed that MAXI J0709 had not shown any significance ($> 4\sigma$) flaring activity until the present event.

2.2 X-ray spectra of two flaring events

Next, we analyzed GSC energy spectra in Scan-A and Scan-C in detail. Source spectra were extracted from a circular region within 1.5 from the source position. To avoid high background area near the edge of the detector in GSC_4 (figure 1), background spectra were extracted from the overlap region between an annulus of inner and outer radii of 2° and 7°, and a 14° × 3° rectangle along the scan direction, both centered at the source position. These source and background regions are illustrated in figure 1. We confirmed that background subtracted spectra were consistent between GSC_4 and GSC_5, and then added them into GSC_4+GSC_5 spectra.

3 https://www.darts.isas.ja.jp/astro/maxi/data.html
4 Also see the light curve in the MAXI homepage http://maxi.riken.jp/pubdata/v7lrkm/J0709-161/.
Fig. 1. GSC 2–20 keV images obtained by GSC_4 (left) and GSC_5 (right) units, within $10^{-7}$ of MAXI J0709 at the Scan-A (UT 10:39-10:46 on January 25). The image is smoothed with a Gaussian kernel of $\sigma = 2^\circ$. The source and background regions used in spectral analysis are shown by the solid and dashed lines, respectively.

Fig. 2. GSC light curves of MAXI J0709 in the 2–4 keV (black) and 4–10 keV (red) bands. Horizontal dashed lines represent the expected count rates for a 100 mCrab source, 0.106 counts cm$^{-2}$ s$^{-1}$ in 2–4 keV and 0.117 counts cm$^{-2}$ s$^{-1}$ in 4–10 keV. Vertical dotted lines represent the epoch of the NICER observation start (blue) and the NuSTAR observation period (green). The inset is a log-linear plot of the 0.7 d around the source onset, where Scan-A, B, C, D are annotated.
Figure 4 shows the obtained source-region spectra in Scan-A and Scan-C. As expected from the light curves in figure 2, the Scan-C spectrum has a lower-energy cutoff below 4 keV. We performed model fitting on XSPEC version 12.11.1 (Arnaud 1996) employing the C-statistic method. The energy response matrix for each data was calculated with mgsmfgen included in HEASoft. Also, spectral data were binned so that each bin contains at least one event. We first checked that background spectra were well represented by a two-powerlaw model. Then, we fitted source-region spectra including backgrounds and background spectra simultaneously to determine the source spectral model.

Firstly, we fitted each of Scan-A and Scan-C spectra with a power-law with an interstellar-medium (ISM) absorption. We hereafter employed the Tuebingen-Boulder ISM absorption model (TBabs) with the solar abundances provided by Wilms et al. (2000). Both fits to the Scan-A and Scan-C spectra were acceptable. Table 1 summarizes the best-fit model parameters. While the power-law photon indices, \( \Gamma = 2.3^{+0.7}_{-0.6} \) in Scan-A and \( 2.7^{+1.2}_{-1.0} \) in Scan-C, are consistent within the errors, the absorption column densities, \( N_H = 5.5^{+5.8}_{-4.8} \times 10^{22} \) cm\(^{-2}\) in Scan-A and \( 58^{+33}_{-30} \times 10^{22} \) cm\(^{-2}\) in Scan-C, are significantly different. The \( N_H \) value in Scan-A is larger than the Galactic H\( \text{I} \) density, \( 0.5 \times 10^{22} \) cm\(^{-2}\), in the source direction (HI4PI Collaboration et al. 2016). We then fitted the two spectra with a common \( \Gamma \) simultaneously. The fit was accepted similarly, and the best-fit \( \Gamma = 2.4^{+0.6}_{-0.5} \) was obtained. In this case, the absorption-corrected 2–10 keV fluxes are consistent between Scan-A and Scan-C at \( \sim 0.5 \times 10^{-8} \) erg cm\(^{-2}\) s\(^{-1}\).

We also fitted the two spectra with a blackbody model (bbbodyrad) with an interstellar absorption. The fits were acceptable in both Scan-A and Scan-C, as in the same way as the fits with a powerlaw model. The obtained model parameters are summarized in table 1. There, the blackbody model normalizations are given by a source radius \( R_{BB} \). \( N_H \) of Scan-A was constrained only by the upper limit (\( < 2.2 \times 10^{22} \) cm\(^{-2}\)). Although the blackbody temperatures, \( T_{BB} = 1.5^{+0.2}_{-0.1} \) keV in Scan-A and \( 2.4^{+0.8}_{-0.5} \) keV in Scan-C, were slightly different, we tried a simultaneous fit to the two spectra with a common \( T_{BB} \). The fit was still acceptable and the best-fit \( T_{BB} = 1.6^{+0.2}_{-0.1} \) keV was obtained.

### Table 1. Best-fit spectral parameters of MAXI J0709

| Model: TBabs*powerlaw | Scan-A | Scan-C |
|------------------------|--------|--------|
| \( N_H \) (10\(^22\) cm\(^{-2}\)) | 5.5\(^{+5.8}_{-4.8}\) | 58\(^{+33}_{-30}\) |
| \( \Gamma \) | 2.3\(^{+0.7}_{-0.6}\) | 2.7\(^{+1.2}_{-1.0}\) |
| \( F_{abs} \) | 0.48\(^{+0.08}_{-0.07}\) | 0.29\(^{+0.07}_{-0.06}\) |
| \( F_{unabs} \) | 0.7\(^{+0.04}_{-0.02}\) | 1.8\(^{+3.6}_{-1.1}\) |
| C-stat/d.o.f | 202/267 | 177/210 |

| Model: TBabs*bbbodyrad | Scan-A | Scan-C |
|------------------------|--------|--------|
| \( N_H \) (10\(^22\) cm\(^{-2}\)) | < 2.2 | 27\(^{+32}_{-21}\) |
| \( T_{BB} \) (keV) | 1.5\(^{+0.2}_{-0.1}\) | 2.4\(^{+0.8}_{-0.5}\) |
| \( R_{BB} \) (km) | 3.1\(^{+0.9}_{-0.7}\) | 1.8\(^{+1.5}_{-1.0}\) |
| \( F_{abs} \) | 0.50\(^{+0.09}_{-0.08}\) | 0.32\(^{+0.07}_{-0.06}\) |
| \( F_{unabs} \) | 0.50\(^{+0.09}_{-0.08}\) | 0.6\(^{+0.5}_{-0.2}\) |
| C-stat/d.o.f | 202/267 | 179/210 |

\( a \) Absorbed 2–10 keV flux in \( 10^{-8} \) erg cm\(^{-2}\) s\(^{-1}\)

\( b \) Unabsorbed 2–10 keV flux in \( 10^{-8} \) erg cm\(^{-2}\) s\(^{-1}\)

\( c \) Blackbody radius in km. Distance of 3 kpc assumed.

### 3 NuSTAR observation and data analysis

The NuSTAR observation of MAXI J0709 was carried out in 2022 January 29 UT 00:21–11:21 (OBSID:...
90801304002), with a net exposure of 18 ks. We performed data analysis using NuSTAR Data Analysis Software nustardas version 2.1.1 included in HEASoft version 6.29 and the CALDB version 20220215, following the NuSTAR Data Analysis Quick Start Guide\(^5\) and the NuSTAR Data Analysis Software Guide\(^6\). The unfiltered event files were first reprocessed by nupipeline. According to the recommendations given by the NuSTAR team, we screened high background-rate data taken during the South Atlantic Anomaly (SAA) passages by combining options SAAMODE=optimized and TENTACLE=yes with the default SAA calculation option (saacalc=3). The resultantly cleaned event files were used to obtain the image, light curve and time-averaged spectrum.

3.1 Localization and optical identification with NuSTAR image

We produced the NuSTAR images from the cleaned event files using nuproducts. In figure 5 (left panel), we show the NuSTAR 3–20 keV image. A significant point source was solely detected within the error circle (radius = 3\(') of the MAXI J0709 position determined by the NICER observation (Iwakiri et al. 2022). To determine the accurate source position, we performed image fit using sherpa included in the Chandra Interactive Analysis of Observation (ciao; version 4.14). To improve photon statistics, images of FPMA and FPMB are combined and binned by 2\times2 pixels. The obtained image in the 4\(' \times 4\(' region around the count peak was then fitted with a model consisting of a 2-dimensional (2-D) Gaussian function for the target point source and a flat surface for the background. There, we employed the Cash statistics. Because the ellipticity of the 2-D Gaussian was not significantly detected, the ellipticity parameter was fixed at 0 (circular). The best-fit model parameters are the source position ($\alpha, \delta$)(J2000) = ($7^h09^m37^s.1, -16^o05^m47^s$) with errors of 2\(', and the full width at half maximum (FWHM) of 16\('\pm3\(', where errors include only statistic uncertainties. The systematic error of the NuSTAR position accuracy is estimated at $\sim 20''$, which slightly depends on the source brightness (Lansbury et al. 2017).

Comparing the obtained NuSTAR image with the DSS (Original Digitized Sky Survey) optical image provided via the Skyview website\(^7\) in the same region (the right panel of figure 5), we identified a possible optical counterpart, LY CMa (also known as HD 54786), which is identified as a Be star (Chojuowski et al. 2015) with a spectral type of B1.5I(b), i.e. B supergiant (Houk & Smith-Moore 1988). By Gaia Early Data Release 3, its celestial position ($\alpha, \delta$)(J2000) = ($7^h09^m36^s.9791095248, -16^o05^m46.7801897476$), and distance $D = 3.03^{+0.31}_{-0.27}$ kpc are well determined (Gaia Collaboration et al. 2016; Gaia Collaboration et al. 2020; Bailer-Jones et al. 2021). The position is only 1\('8 from the NuSTAR best-fit parameters. The direction and distance suggest that the object locates

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\(^5\)https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_quickstart_guide.pdf

\(^6\)https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_sgguide.pdf

\(^7\)http://skyview.gsfc.nasa.gov
on the Perseus Arm, a major spiral arm of our Galaxy.

3.2 Light curve

We produced the NuSTAR light curves in 3 energy bands, 3–20 keV, 3–5 keV, and 5–20 keV, with nuproducts. Source data were extracted from a circular region with a radius of 30″ centered at the LY CMa position, and background data were extracted from another circle with a radius of 60″ in a source-free region. In this step, a barycentric time correction was applied to event files, assuming the source position of LY CMa. The data of FPMA and FPMB were combined with the tool lcmath. In figure 6 we plotted the obtained light curves in the 3 energy bands and the 5–20 keV to 3–5 keV hardness ratio, with 512 s bins. The 3–20 keV light curve shows flux variation by factor of $\lesssim 3$ on timescales of $\gtrsim 10^2$ s. The middle panel suggests that the variation is larger in the higher band (i.e., the source becomes harder with increasing flux), although it is not clear in the hardness-ratio variation.

3.3 Pulsation search

In order to search for coherent pulsations, we produced a power density spectrum (PDS) from the FPMA+FPMB data, which is shown in figure 7. We first barycenter corrected the time of arrival for each photon using the source position as determined using the automatic centroiding function in DS9 (Joye & Mandel 2003). We used JPL ephemeris DE-430 and NuSTAR clockfile v138. We extracted events with energy 3-20 keV using a source region with radius 30″. Next we used the Python package Stingray (Huppenkothen et al. 2019) to produce the Frequency Amplitude Difference-corrected PDS (Bachetti & Huppenkothen 2018), which corrects for timing effects due to deadtime. We specified a time resolution of $2^{-10}$ s and a light-curve segment size of 1024 s, resulting in 13 individual PDS, which we averaged to produce the PDS shown. The PDS has been rebinned logarithmically for clarity. We also calculated the $3\sigma$ detection level per logarithmic frequency bin using the formalism described in Leahy et al. (1983), which we show as a blue dashed line.

We did not detect any periodicity significantly, but we note that our timing analysis is severely limited due to a small number of photons ($<300$ total). As such we cannot rule out the presence of pulsations or other timing signatures.

3.4 Time-averaged spectrum

Figure 8 shows the time-averaged NuSTAR spectrum, which was extracted with nuproducts using the same source and background regions as in the light curve analysis (section 3.2). The FPMA and FPMB spectra were combined with the tool addspec to improve statistics, and binned so that each bin contains at least one count. We confirmed that the results did not change even if the data of FPMA and FPMB were analyzed separately.

We fitted the obtained spectrum with an absorbed power-law model (TBabs*powerlaw) on XSPEC employing W statistic. The results showed the fit statistic $W = 148$ for 184 d.o.f. and the best-fit $\Gamma = 1.7^{+0.5}_{-0.2}$. $N_H$ was constrained only by the upper limit, $<1.1 \times 10^{23}$ cm$^{-2}$, which is consistent with the result of the MAXI/GSC Scan-A spectrum (table 1 in section 2.2). From the best-fit model, the absorbed and absorption-corrected 2–10 keV fluxes were estimated to be $6 \pm 1 \times 10^{-13}$ and $6^{+3}_{-1} \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, respectively. These spectral parameters are consistent with those given by Bhattacharyya et al. (2022) which utilized the same NuSTAR data.

Although there is no emission-line feature in the NuSTAR spectrum, we tested the possibility of a narrow iron-K$\alpha$ emission line. We added a Gaussian function with a fixed centroid of 6.4 keV and a fixed width of 0 eV to the power-law model, and then fit it to the data. As the result, the 90 % upper limit on the iron-K$\alpha$ line flux was estimated to be $4 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$, which corresponds to the equivalent width (EW) of 0.6 keV.

4 Swift observation and upper limit

A ToO observation of the Neil Gehrels Swift Observatory (Gehrels et al. 2004) was carried out on 2022 February 23 (MJD 59634.62), 30 days after the discovery, with a total exposure time of 989 s. No X-ray source was detected with the 3$\sigma$ upper limit of 0.008 XRT counts s$^{-1}$ at the position of LM CMa. Assuming spectral parameters given in table 1, this provides an upper limit on the flux of $2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV) for the Scan-A parameters, and $1.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV) for the Scan-B parameters, where the flux is not corrected for absorption. These upper limits are consistent with the detected flux by NuSTAR.

5 eROSITA upper limits on the past activity

The Spectrum-Roentgen-Gamma (Spektr-RG, SRG) X-ray observatory (Sunyaev et al. 2021) has been performing an all-sky survey since 2019 December. The satellite carries
two kinds of X-ray telescopes, extended ROentogen Survey with an Imaging Telescope Array (eROSITA; Predehl et al. 2021), and Mikhail Pavlinsky Astronomical Roentgen Telescope (ART-XC; Pavlinsky et al. 2021), which cover 0.2–8 keV and 4–30 keV energy bands, respectively. The eROSITA all-sky survey (eRASS) has been carried out by consecutive scans of the entire sky, each of which is completed by six months. It currently archives the best sensitivity among all-sky X-ray surveys that have ever been performed.

The sky position of MAXI J0709 was covered by eROSITA in the past four eRASSs as listed in Table 2. All of eROSITA data are calibrated and cleaned using the pipeline version 946 of the eROSITA Science Analysis Software System (eSASS, Brunner et al. 2022). No significant X-ray emission at the position of LY CMa was detected in either the individual eRASS or the combined dataset. We estimated the 3-$\sigma$ upper limit of $4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in 2–10 keV band using all the eRASS data and assuming the typical power-law spectrum of $\Gamma = 2$ and the interstellar absorption corresponding to the Galactic H$\text{I}$ density $N_{\text{H}} = 0.5 \times 10^{22}$ cm$^{-2}$.

Fig. 5. (Left) NuSTAR/FPMA + FPMB 3–20 keV image around the source, where Gaussian smoothing is applied to the image with a radius of 2 pixels. The red cross and dashed circle indicate the best-fit position and the error (20$''$, including the systematic error) determined with NuSTAR, respectively. The NICER error circle (with a 3$'$ radius) is also shown with the green line. (Right) Optical image of the DSS Original Digitized Sky Survey. The NuSTAR source position and error are shown with the red cross and dashed circle.

Fig. 6. NuSTAR background-subtracted light curves in 3–20 keV (top), 3–5 keV (middle; black crosses) and 5–20 keV (middle; red open squares) with 512 s bins, and the hardness ratio between the latter two bands (bottom). The background level is 0.01–0.02 count s$^{-1}$ in the 3–20 keV during the observation. Vertical dashed lines represent the epochs of MAXI scans in figure 2.

Fig. 7. Power spectrum calculated using 3-20 keV NuSTAR FPMA and FPMB data, averaged over the entire observation period. The blue dashed line represents the 3$\sigma$ detection level of periodicity.
Fig. 8. (Top) Time-averaged NuSTAR/FPMA+FPMB background-subtracted, response-folded spectrum. The solid line represents the best-fit absorbed power-law model. (Bottom) Data-to-model ratio. Data in this figure were rebinned for visual clarity.

Table 2. eRASS observations on the MAXI J0709 position (upper limits).

| # | Start time       | End time       | $T_{\text{exp}}$ |
|---|------------------|----------------|------------------|
| 1 | 2020-04-17 09:34:14 | 2020-04-18 01:34:44 | 173              |
| 2 | 2020-10-20 08:25:17  | 2020-10-21 00:25:41 | 156              |
| 3 | 2021-04-18 02:34:27  | 2021-04-19 06:34:33 | 234              |
| 4 | 2021-10-20 13:25:24  | 2021-10-21 13:25:39 | 219              |

*a* eRASS survey number.  
*b* Exposure time (s).

6 Optical spectroscopy with SCAT

The Spectroscopic Chuo university Astronomical Telescope (SCAT) is a 355-mm diameter optical telescope equipped with an ATIK 460EX CCD camera and a Shelyak Alpy 600 spectrometer, located at the Chuo University Korakuen campus, Tokyo, Japan (Kawai et al. 2022). The spectral resolution is $R \sim 600$.

The SCAT observation of LY CMa was carried out on 2022 January 28 from UT 11:32 to 14:48 (approximately 3 days after the MAXI trigger) with a net exposure of 8610 s. The result showed a strong Hα emission line clearly. The FWHM of the Hα line was 19 Å, which is significantly larger than that of the Ne line in the calibration lamp (FWHM = 10 Å). Next, we estimated the line EW. To determine the continuum level, we fitted the observed spectrum excluding the Hα-line range with a linear function. Figure 9 shows the line profile normalized by the best-fit continuum model, where the Hα-line range was assumed to be from 6520 Å to 6605 Å. By integrating the profile, the EW was estimated to be $-23$ Å. It is consistent with the result of the Foligno Observatory low-resolution (R~50) spectrum taken on the same day (Nesci 2022). We repeated the EW calculation by shifting the assumed Hα-line range, and found that the obtained EW value has an uncertainty of $\sim 15\%$.

7 Discussion

7.1 Summary of MAXI J0709-159 activities with past and follow-up observations

We here summarize long-term activities of MAXI J0709 identified with the past and follow-up observations in the present analysis. Based on the results, we consider the nature of the new X-ray object in the next section.

The new transient MAXI J0709 was first discovered by the MAXI GSC all-sky survey on 2022 January 25. As seen in figure 2, significant X-rays were detected only in the two GSC scans, Scan-A (UT 10:42) and Scan-C (UT 14:48). In both scans, it showed flare-like time variabilities in a time scale of a few seconds (figure 3) and the 2–10 keV flux reached $5 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. At Scan-B (UT 12:15) and after the Scan-C (UT 15:21), the source has not been detected with the GSC sensitivity limit of 80 mCrab (1.5 $\times$ 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$ in 2–10 keV) per scan (Negoro et al. 2016). Therefore, the intensity swings between every adjacent scans from Scan-A to Scan-D exceed a factor of $\sim 5$.

The NICER and NuSTAR follow-up observations successfully identified the new transient with a new X-ray source, whose position is consistent LY CMa (figure 5). When the NICER observed it at 6 minutes after the MAXI Scan-C, the X-ray flux became about 10 mCrab (in 0.2-12 keV), which is $< 10^{-1}$ of that observed in Scan-C. When the NuSTAR identified the new object on January 29, 4
days after the MAXI detections, the X-ray flux became relatively stable at around $6 \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$. This means that the X-ray intensity decreased by a factor of $10^{-4}$ in the 3 days.

We investigated the past source activity using archival data. Until the first MAXI detection, the source had not been recognized in the MAXI GSC data for over 12 years. The upper limit on the average source flux is $5 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}$ (Hori et al. 2018). The object had not been recorded in any X-ray source catalog including ROSAT all-sky survey catalog (Boller et al. 2016). Also, eROSITA all-sky surveys which observed the MAXI J0709 position four times from 2020 to 2021, did not find significant X-ray source with the 3-$\sigma$ upper limit of $4 \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$ (section 5), which is lower than the flux observed by NuSTAR. This suggests that the source activity at the NuSTAR observation was still higher than that before the discovery.

In figure 10, the long-term activities after the discovery of MAXI J0709 are summarized. The X-ray intensity variation clearly reveals that the activity declined at $\sim 10^4 \text{ s}$ ($\approx 3$ hours). In the figure, the right-hand ordinate represents the luminosity calculated from the flux at the source distance of 3 kpc. The observed flux range of $10^{-13}$ – $10^{-8} \text{ erg cm}^{-2} \text{s}^{-1}$ corresponds to $10^{32}$ – $10^{37} \text{ erg s}^{-1}$ in the luminosity.

We also carried out an optical spectroscopic observation of the optical counterpart LY CMa on January 28, 3 days after the discovery, and then confirmed the H$\alpha$ emission line (section 6) as reported in Nesci (2022). The EW of the H$\alpha$ line was estimated to be $-23 \AA$ with an uncertainty of $\approx 15 \%$. Bhattacharyya et al. (2022) also performed optical follow-up observations and reported that the H$\alpha$ EW was $-17.6 \AA$ on February 2 and $-16.9 \AA$ on February 3. The results suggest that the EW might change in these 3 days.

7.2 Classification of the new X-ray object in high-mass X-ray binaries

As discussed in the previous section and summarized in figure 10, the observed X-ray activity of MAXI J0709 is characterized by the initial flaring phase of $\approx 3$ hours with a rapid ($\approx$ few seconds) variability reaching the peak luminosity $\approx 5 \times 10^{36} \text{ erg s}^{-1}$, and the following decay phase lasting for at least several days with a luminosity $\sim 10^{32}$ – $10^{33} \text{ erg s}^{-1}$ and a moderate variation. The rapid variability naturally lead us an idea of X-ray binaries embedding compact objects, neutron stars or black holes, where the transient behavior can be explained by the change in the mass accretion onto the compact object. In the present MAXI J0709 case, the mass-donating stellar companion is identified with LY CMa, which has a spectral type of B1.5I(b) (Houk & Smith-Moore 1988) and also the identification as Be star (Chojnowski et al. 2015). Hence, we consider the detail scenario to explain all the observed results in comparison with other high-mass X-ray binaries (HMXBs) that have been well studied.

The initial flaring behavior of the short duration ($\approx 3$ hours) and the rapid variability (in a time scale of a few seconds), agree well with the properties of Supergiant Fast X-ray Transients (SFXTs), a possible subclass of HMXBs that consist of OB supergiants and neutron stars showing sporadic short-duration ($\approx 3$ hours) outbursts (Sguera et al. 2006; Bozzo et al. 2015; Sidoli & Paizis 2018; review in Kretschmar et al. 2019). The observed luminosity range from $10^{32}$ to $10^{37} \text{ erg s}^{-1}$ agree with those from their quiescent value to the flaring peak. The X-ray spectra fitted with a power law of $\Gamma \approx 2$ in both MAXI and NuSTAR data are also typical as SFXTs which have power-law spectra with $\Gamma = 1 \pm 1$ (Pradhan et al. 2018).

During the initial flaring phase, the X-ray spectrum changed dramatically so that $N_H$ changed from $10^{22}$ to $10^{23} \text{ cm}^{-2}$ in ~3 hours (figure 4). The $N_H \gtrsim 10^{23} \text{ cm}^{-2}$ at the MAXI GSC Scan-C is significantly higher than the Galactic $H_2$ density $\approx 0.5 \times 10^{22} \text{ cm}^{-2}$, and also comparable to the highest among those of SFXTs that have ever been reported (Pradhan et al. 2018). So far, a similar spectral change has been observed in IGR J18410-0535, and it was explained by a scenario that the compact object (neutron star) just plunged into a dense clump in the circumstellar medium (Bozzo et al. 2011). The present result can be considered similarly.

Also, iron-K line was not significantly detected in either MAXI or NuSTAR spectrum. From the NuSTAR data, the upper limit on the equivalent width $EW_{FeK} < 0.6 \text{ keV}$ was estimated. In general, X-ray spectra of the SFXTs have lower $N_H$ and lower $EW_{FeK}$ than those of the classical supergiant HMXBs with persistent X-ray activities (Giménez-García et al. 2015; Pradhan et al. 2018). This implies that the SFXTs have more sparse and clumpy circumstellar medium than the classical supergiant HMXBs. The present results support the scenario.

To explain the short duration (several hours) and the extremely large dynamic range ($10^3$–$10^7$) from the quiescence to the peak in the SFXT outbursts, some mechanism to inhibit accretion such as magnetic and/or centrifugal barriers (Grebeniev & Sunyaev 2007; Bozzo et al. 2008) are required. If compact objects in SFXTs are magnetized neutron stars, observed X-ray variations may relate to the neutron star rotation. In fact, coherent pulsations were detected in several SFXTs. We performed the period search with the NuSTAR data, but could not find a significant pe-
Fig. 10. MAXI J0709 long-term X-ray activity since the first MAXI detection at UT 10:42 on 2022 January 25, obtained from the present analysis of the MAXI, NuSTAR, Swift, and eROSITA data and the NICER result reported by Iwakiri et al. (2022). Upper limits from the logarithmically-binned MAXI/GSC light curve are shown in gray arrows.

7.3 Is MAXI J0709-159 an evolved Be Fast X-ray Transient?

So far, we have discussed the nature of MAXI J0709 based on the X-ray results that agree well with the typical SFXTs. Meanwhile, the optical counterpart LY CMa is also identified as Be star (Chojnowski et al. 2015). In fact, optical follow-up observations confirmed the broad Hα line, which indicates the Be circumstellar disk (section 6). Bhattacharyya et al. (2022) proposed that LY CMa would be an evolved Be star located between main sequence stars and supergiants on the optical color-magnitude diagram. If it is so, MAXI J0709 should have an intermediate character between Be X-ray binaries (BeXBs) and supergiant X-ray binaries (sgXBs).

BeXBs usually cause outbursts lasting for several weeks (type-I) to a few months (type-II), according to the interaction between the neutron-star magnetosphere and the Be disk (e.g. Reig 2011; Sugizaki et al. 2017). The behavior is quite different from the present MAXI J0709 results. However, a few BeXBs, such as X Persei, are known to show short time-scale variabilities like flares (Delgado-Martí et al. 2001; Acuner et al. 2014). MAXI J0709 could be considered as its extreme case.

Recently, another new subclass of HMXBs involving supergiant B[e] (sgB[e]) stars as mass-donating companions, is getting a hot topic (e.g. Kraus 2019). The sgB[e] stars are thought to accompany dense, dusty disks. The two members of this subclass, CI Cam (Bartlett et al. 2019) and IGR J16318−4848 (Fortin et al. 2020), are known to exhibit extremely high ($\gtrsim 10^{24}$ cm$^{-2}$) and variable $N_H$ on their persistent X-ray activities. Although LY CMa is not definitely categorized into sgB[e], the thick and variable X-ray absorption feature in these two objects is quite similar with that observed in MAXI J0709 (section 2.2). This naturally induces an idea that some sgB[e] HMXBs may behave like SFXT. A candidate of such objects, namely sgB[e]FXTs, has been already reported (Sidoli et al. 2022). Further observations of LY CMa would give us useful hints about possible relations among these HMXB subclasses.

8 Conclusion

On 2022 January 25, MAXI discovered the new bright X-ray transient MAXI J0709-159 lasting for ~3 hours in the constellation Canis Majoris. Prompt follow-up observa-
tions with NICER and NuSTAR confirmed the new X-ray object and refined the source position with the 20″ accuracy. Then, the optical counterpart was identified with LY CMa, which has been identified as a B supergiant and also a Be star. Detail analysis of MAXI and NuSTAR data revealed the characteristic X-ray outburst represented by the short duration (∼3 hours), the rapid (∼a few seconds) variability accompanied with the spectral change, and large luminosity swing from the quiescence (onds) variability accompanied with the spectral change, and large luminosity swing from the quiescence (∼10^{32} erg s^{-1}) to the flare peak (∼10^{37} erg s^{-1}). These features agree well with the typical SFXTs. The spectral change during the short outburst period suggests that the N_H increased from 10^{22} to 10^{23} cm^{-2}, which can be explained by a scenario that the compact object (neutron star) just plunged into a dense clump in the circumstellar medium. Meanwhile, the optical spectroscopic observation of LY CMa reveals the broad Hα emission line suggesting the existence of the circumstellar Be disk. However, the observed X-ray behavior agrees with the SFXT, i.e. supergiant X-ray binaries rather than Be X-ray binaries. Thus, LY CMa is surrounded by complex circumstellar medium including dense clumps. These facts suggest that the object would be classified into the intermediate position between these HMXB subclasses, namely evolved Be Fast X-ray Transient.

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