RXTE follow-up observations of new MAXI X-ray sources

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Abstract

The Monitor of All-sky X-ray Image (MAXI) is a highly sensitive X-ray all-sky monitor on the International Space Station with a 5 σ detection sensitivity of about 20 mCrab in one day. It has discovered three new X-ray binaries so far. To reveal the nature of these sources, we have carried out RXTE follow-up Target-of-Opportunity (ToO) observations approved in AO14 and AO15 programs. The sources have been identified as a black hole candidate (BHC) for MAXI J1659–152, an X-ray binary pulsar for MAXI J1409–619, and a low mass X-ray binary (LMXB) for MAXI J0556–332. In this paper, we will present the spectral and timing results from RXTE data.

Key words: accretion, accretion disks – stars: individual (MAXI J1659–152, MAXI J1409–619, MAXI J0556–332) – X-rays: stars

1. RXTE follow-up observations

Previous and current X-ray all-sky monitors have discovered bright unknown X-ray sources with a flux level of more than ∼20 mCrab. Most of these objects were low mass X-ray binaries (LMXBs) with a relatively high mass accretion rate. The RXTE/PCA Galactic bulge scan observation, which is one of the current best X-ray survey, has brought a discovery of many new sources including 4 millisecond pulsars with an excellent sensitivity (0.5 mCrab) (Markwardt et al. 2006). However, this monitoring performed twice a week is limited to the Galactic bulge. Hence, activities of fainter X-ray sources at outside of the bulge regions and sources with a short outburst duration within a few days must have been missed for a long time. In a lower flux range than ∼20 mCrab, we will be able to observe many other category sources: AGNs, active stars, cataclysmic variables and isolated neutron stars (SGRs and AXPs) as well as LMXBs and HMXBs. Furthermore, we will be able to monitor the whole globular cluster population of the Milky Way for transients, and will also see supergiant fast X-ray transients (*e.x.* Sidoli et al. 2009). It is strongly believed that there are many discovery space such as new categories of X-ray sources in this unexplored flux range.

The MAXI (Monitor of All-sky X-ray Image; Matsuoka et al. 2009) is a high sensitive all-sky monitor which consists of two kinds of instruments: position-sensitive proportional counters (GSC; Mihara et al. 2011) and X-ray CCD cameras (SSC; Tsunemi et al. 2010). It carries out an unbiased X-ray all-sky survey above 2 keV since the HEAO-1 A1 all-sky survey (Wood et al. 1984). Since the launch by the space shuttle Endeavor on July 16, 2009, the MAXI has been operated for about 1.5 years on the International Space Station (ISS). About 200 bright sources have been monitored by MAXI/GSC, and their light curves are now available at the MAXI web site (http://maxi.riken.jp/top). The current 5σ detection limit of MAXI/GSC is estimated at ∼15 mCrab in one day, ∼5–6 mCrab in one week, and ∼2-3 mCrab in one month (Sugizaki et al. 2011).

To identify the nature of faint X-ray sources discovered by MAXI, we have proposed RXTE Target-of-Opportunity (ToO) observations. They have been approved in the Guest Observer Program: AO14 (ObsID: 95358, Epoch: January 2010 to December 2010) and AO15 (ObsID: 96371, Epoch: January 2011 to December 2011). We can trigger this observation program up to five new sources with the 5–50 mCrab flux. The net exposure

Table 1. A list of new MAXI sources (up to February 2011).

Source name	J2000 Coordinates	Identification	Discovery date	Outburst dur.	peak flux
MAXI J1659–152	(254.76,–15.26)	black hole candidate	Sep. 25, 2010	∼65 days	∼300 mCrab
MAXI J1409–619	(212.61,–61.98)	X-ray binary pulsar	Oct. 17, 2010	∼100 days	∼40 mCrab
MAXI J0556–332	(89.19, –33.17)	low-mass X-ray binary	Jan. 11, 2011	>20 days	∼80 mCrab

for each source is 30 and 40 ksec for AO14 and AO15 respectively. RXTE ToO observations of three MAXI sources have been triggered till end of January 2011. Table 1 shows a list of new MAXI sources. Thanks to RXTE's spectral and timing capabilities, MAXI J1659–152, MAXI J1409–619, and MAXI J0556–332 were identified as a black hole candidate (BHC), an X-ray binary pulsar, and a low-mass X-ray binary (LMXB) respectively. In the next section, we will describe details of RXTE follow-up observations and preliminary results.

2. MAXI J1659-152

2.1. Discovery and Observations

MAXI J1659-152 was first discovered as GRB 100925A on September 25, 2010 (MJD 55464) by the Swift BAT (Mangaro et al. 2010). The GSC on-board MAXI independently detected this X-ray transient and localized it to (RA, Dec)=($16^{h}59^{m}10^{s}$, –15°16'05") with a 0.2 degree accuracy (Negoro et al. 2010). The MAXI/GSC data showed that, unlike normal GRBs, the X-ray flux rapidly increased following the discovery. RXTE follow-up observations revealed the source as a BHC from spectral and timing properties (Kalamkar et al. 2010). The XMM-Newton, RXTE, and Swift data revealed the presence of X-ray dips in their light curves with a period of 2.41 hours (Kuulkers et al. 2010, kuulkers et al. 2011, Belloni, Munoz-Darias, & Kuulkers 2010, Kennea et al. 2011). The amplitude modulation with this period was also confirmed by the optical data in the VSNET-team report (Kuroda et al. 2010). These results indicate that MAXI J1659–152 has the shortest orbital period among all the BHCs (the second shortest one is 3.2 hours for Swift J1753.5–0127 (Zurita et al. 2010)).

Following the Swift and MAXI discovery of MAXI J1659–152, we triggered our RXTE ToO observations. Follow-up observations started on September 28, 2010, and continued until November 8, 2010, when the source was not observable due to the Sun constraint of the satellite. These series of observations contain 65 pointed observations under the observation IDs 95358, 95108 and 95118. The net deadtime-corrected PCA exposure was 134.6 ksec, with an averaged exposure of about 2.1 ksec per pointed observation.

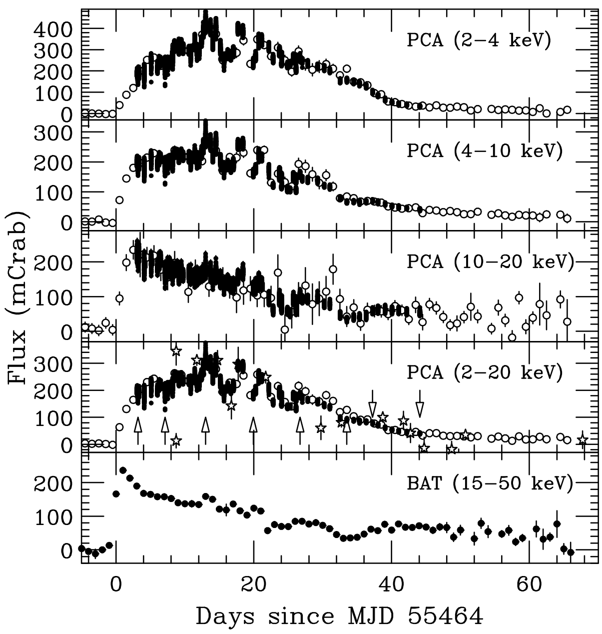

Fig. 1. RXTE/PCA light curves of MAXI J1659–152 during the 2010 outburst. The 2–4, 4–10, 10–20, and 2–20 keV ranges are shown in the upper four panels. The MAXI/GSC and RXTE/ASM data are superposed on the PCA data with open circles and open stars respectively. Swift/BAT data are also shown in the bottom panel for comparison.

2.2. RXTE Results

2.2.1. PCA Light Curve

The RXTE/PCA light curves with the four energy ranges (2–4, 4–10, 10–20, 2–20 keV) are shown in Figure 1. The data were normalized to the PCA counts for the Crab nebula. The MAXI/GSC, the RXTE/ASM, the Swift/BAT data were also normalized to the Crab and are shown for comparison. The flux measurements between PCA and GSC are consistent with each other. The soft band flux in the 2–10 keV range slowly rises with some variability, while the hard band flux rapidly rises within a few days and then slowly decreases. The approximate e-folding time is about 30 days at high energies. On October 15, 2010, the peak was about 300 mCrab in the 2–20 keV range, and the total outburst duration was about 65 days.

2.2.2. PCA Spectral Analysis

The multi-color disk model (Mitsuda et al. 1984) plus power law model has been used for spectral modeling of the BHC spectra. However, this model results in the problem that the hard power-law component diverges at low energies, which underestimates the disk normalization. Hence we used the Comptonization model, `simpl` (Steiner et al. 2009), in XSPEC for the hard component as a more accurate estimation for the disk parameters (i.e. `wabs*smedge*highecut*simpl`$\otimes$`diskbb`, where $\otimes$ means a convolution) because the power-law component of MAXI J1659–152 remained relatively strong throughout the outburst, The quality of the fitting was reasonable, giving an averaged χ^2 of 56.8 for 73 degrees of freedom. The time variation of the fitting parameters (innermost temperature $T_{\rm in}$, innermost radius[1] $r_{\rm in}$ for D=10 kpc and i=0°, photon index Γ, and e-folding energy $E_{\rm f}$, and the disk flux) is shown in Figure 2.

$T_{\rm in}$ increases from $\sim$0.5 to a peak of $\sim$0.8 keV (day 18), and then drops down to 0.5 keV in the decaying phase. During the initial and final phases, where the source is mainly in the hard state, the $r_{\rm in}$ shows some variations with large error bars. It never exceeds 1 keV, which has been observed in bright BHCs (e.g. GRO J1655–40, H 1743–322, and XTE J1550–564). The innermost radius is kept roughly constant; there is an initial drop from $\sim$50 km to $\sim$35 km, where it remains for most of the outburst. The photon index Γ smoothly varies from 1.6 to 2.4 and then back to 1.6. During a few observations in the initial phase, a high energy cutoff at 30–40 keV is required in the fits. This is a bit low compared with typical values of 100–200 keV in the hard state.

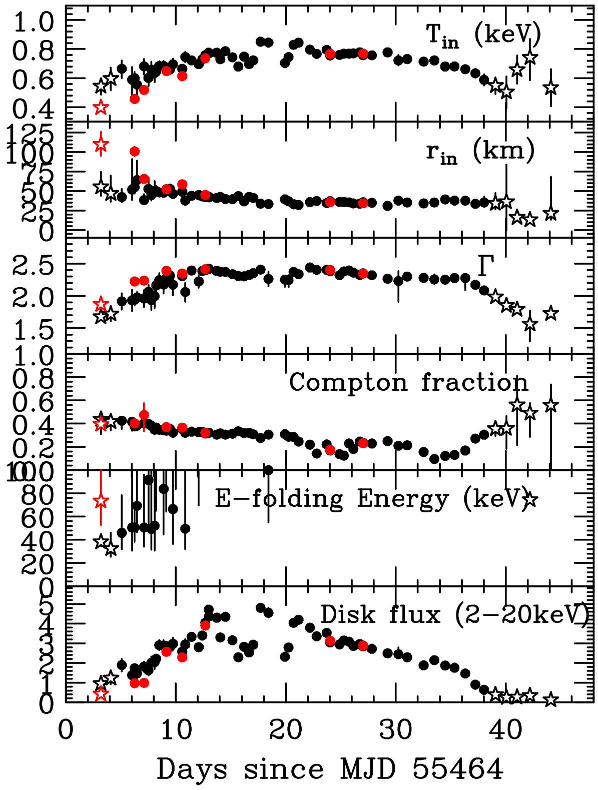

Fig. 2. Time evolution of spectral parameters obtained by `diskbb` plus `simpl` Comptonization model. The innermost temperature $T_{\rm in}$, innermost radius $r_{\rm in}$, Compton fraction, e-folding energy, and disk flux in the 2–20 keV range are shown from top to bottom.

2.2.3. Constraints on Mass of the Central Object

The constant innermost radii imply that the innermost radius of the disk reached the innermost stable circular orbit (ISCO). Using the averaged $r_{\rm in}$ value of 35.3 km for i=0° and D=10 kpc, and following the method described in Kubota et al. (1998), we can estimate the mass of the central object as follows:

$$R_{\rm in} = \xi\kappa^2 r_{\rm in} = 59.4 \left(\frac{D}{10{\rm kpc}}\right)\left(\frac{\cos i}{\cos 60^\circ}\right)^{-\frac{1}{2}} {\rm km}, \quad (1)$$

where ξ is 0.412 (Kubota et al. 1998) and $\kappa = \frac{T_{\rm col}}{T_{\rm eff}}$ is the spectral hardening factor (1.7; Shimura & Takahara 1995). Since we assume $R_{\rm in}$ to be $3R_{\rm S}$ ($R_{\rm S}$=$2GM/c^2$), the obtained black hole mass M is

$$M = \frac{c^2 R_{\rm in}}{6G} = 6.71 \left(\frac{D}{10{\rm kpc}}\right)\left(\frac{\cos i}{\cos 60^\circ}\right)^{-\frac{1}{2}} M_\odot. \quad (2)$$

In the case of a rapidly rotating Kerr black hole, the ISCO approaches much closer to the black hole to a minimum of $0.5R_{\rm S}$, depending on the spin parameter a. In the maximum rotating case ($a \approx$1), the BH mass estimate can be enlarged by a maximum factor of 6.

For the mass constraint, we need information for a distance D and an inclination angle i of MAXI J1659–152. We use estimates (D >5.3 kpc and i=60–75°) suggested by Kuulkers et al. (2010) and Kennea et al. (2011b). Furthermore, it is known that the thermal-to-hard transition will occur at 1–4 % of the Eddington luminosity ($L_{\rm E}$ = $1.25\times10^{38}\frac{M}{M_\odot}$ erg s^{-1}) in soft X-ray transients (Maccarone 2003). The observed flux from the hard state after the transition (MJD 55508, day 44.1) was 1.97×10^{-9} erg cm^{-2} s^{-1} in the 3–50 keV range. This was then converted to a bolometric flux of 4.50×10^{-9} erg cm^{-2} s^{-1}, assuming a high energy cutoff at 200 keV. Using these three constraints, we plotted the allowed BH mass range by changing the distance and inclination angle in Figure 3. The BH mass is constrained to 3.6–8.0 $M_\odot$ in the 5.3–8.6 kpc range.

[1] $r_{\rm in} = N_{\rm dbb}^{1/2}(D/10{\rm kpc})\cos i^{-1/2}$, where $N_{\rm dbb}$ is the normalization of the `diskbb` model, i is the inclination angle (face-on for i=0°), and D is the distance to the source.

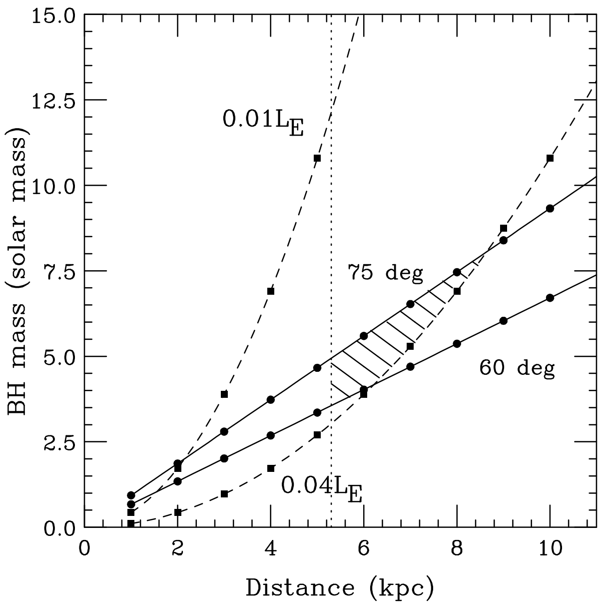

Fig. 3. The allowed range of the black hole mass for MAXI J1659–152, shown by the hatched region. The solid and dashed lines show constraints from the inclination angle of 60–75° and the transition luminosity to the hard state (1–4 % Eddington luminosity), respectively. The dotted line shows a lower limit using the distance 5.3 kpc.

3. MAXI J1409–619

3.1. Discovery and Observations

MAXI J1409–619 was first identified near the Galactic plane by the MAXI/GSC in its 7-day integrated image on October 17, 2010 (MJD 55486) (Yamaoka et al. 2010a). The source shows a sign of flaring behavior. It was not detected in the MAXI data archive before that day. The determined J2000 coordinates (RA, Dec) were $14^{h}09^{m}2^{s}.4$, $-61°57'00".0$ with a statistical error of about 0.2 degree. The position was marginally consistent with the RASS source 1RXS J141108.2-615601 which has been as a bright dMe star. Unfortunately, The source was outside of the MAXI/SSC field of view (FOV).

To confirm this X-ray transient, Swift ToO follow-up observations were performed at the Photon Counting mode on October 23, 2010 (Kennea et al. 2010a). An uncatalogued X-ray source was found within a Swift XRT FOV (23.6×23.6 arcmin). The best position was $14^{h}08^{m}02^{s}.56$, $-61°59'00".3$, which is 7.3 arc-minutes from MAXI/GSC best positions. After the Swift/XRT fine localization, we triggered RXTE ToO program. The source was highly variable in a time scale of ∼1000 seconds (Yamaoka et al. 2010b). Monitoring observations with Swift and RXTE continued till middle of November, 2010, but the source remained faint at around 5–10 mCrab in the 2–20 keV band.

At 15:35 on November 30, an X-ray brightening of MAXI J1409–619 triggered the Swift BAT. Swift automatically re-pointed to the source, and observed it in the active state (Kennea et al. 2010b). A clear pulsation at 503±10 sec was found from the Swift/XRT light curve, which makes the source an X-ray pulsar. Later, RXTE confirmed this X-ray pulsation at 506±1 sec (Yamamoto et al. 2010). The RXTE observations started on October 19, 2010, and lasted till February 10, 2011. The net PCA exposure was 120.7 ksec for 50 pointed observations (Observation ID: 95358, 95441, and 96410).

3.2. RXTE/PCA Results

3.2.1. PCA Light Curve and Pulse Profile

We compiled long-term light curves of MAXI J1409–619 taken by the four X-ray instruments: MAXI/GSC (2–20 keV), Swift/XRT (0.3–10 keV), Swift/BAT (15–50 keV) and RXTE/PCA (2–20 keV), and plotted in Figure 4. The source was initially in the low intensity level of about 20 mCrab for ∼40 days, and no clear pulsations were seen in the light curves. On November 28, 2010, it changes more active state with about 40 mCrab with clear pulsations at about 506 sec. Since then, the flux is gradually decaying with time, and returned to the quiescent level on February 10, 2011. The total outburst duration is estimated at about 100 days.

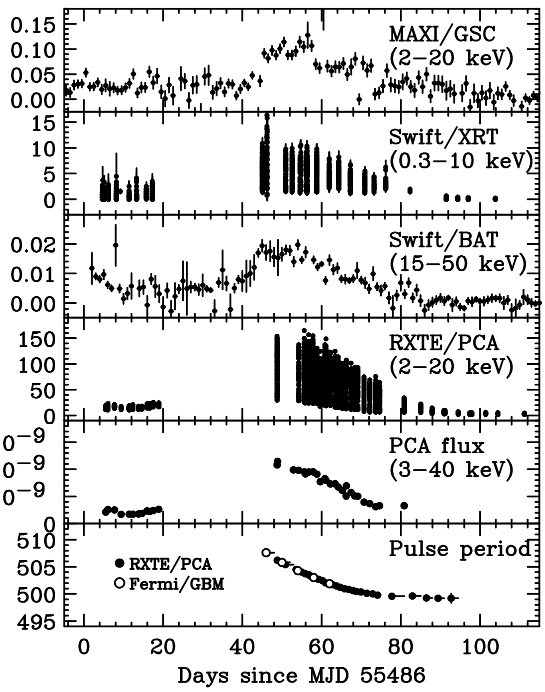

Fig. 4. X-ray light curves of MAXI J1409–619 observed with MAXI/GSC (2-20 keV), Swift/XRT (0.3–10 keV), Swift/BAT (15-50 keV), RXTE/PCA (2-20 keV). Time bins are one day for MAXI/GSC and Swift/BAT, while the Swift/XRT and RXTE/PCA data have 10 and 16 sec time resolutions, respectively. The lower two panel indicate the averaged PCA flux in the 3–40 keV range and the time variation of the pulse period.

The pulse shapes with the different energy ranges are shown in Figure 5. The pulse profile has clear double peaks in all the energy bands, and does not change very much with energy. The pulsed fraction was about 40 %.

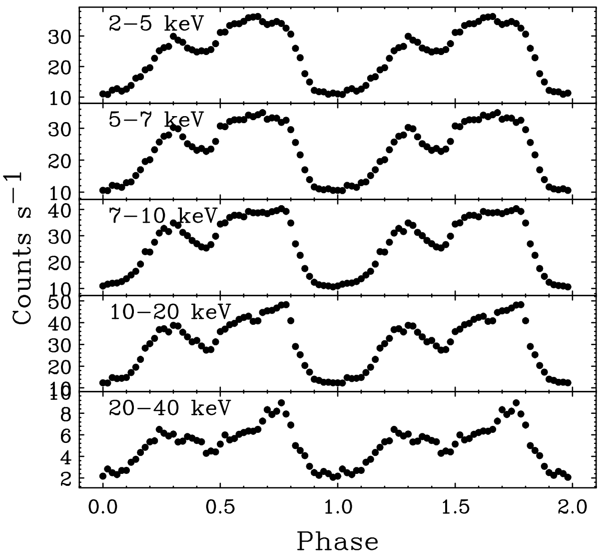

Fig. 5. Folded PCA pulse profile of MAXI J1409–619 in five energy ranges (2–5, 5–7, 7–10, 10–20, 20–40 keV from upper to lower).

3.2.2. Time Variation of Pulse Period

Using the barycenter-corrected light curves and event files, we determined the pulse period (P) with the epoch-folding technique. A typical PCA exposure of single pointing observation, less than a few ksec, is not so long compared with the pulse period of MAXI J1409–619, hence, we combined the data from a few continuous observasions. The χ^2 distribution around its maximum was fitted by a single Gaussian plus constant, and the 1 σ error for the pulse period is estimated as the Gaussian width at $\Delta\chi^2_\nu = 1.0$.

Thus, obtained time variation of the pulse period is shown in the bottom panel of Figure 4. The publicly available Fermi-GBM data are also shown for comparison. When the source just entered the active phase, the P was about 507 seconds. It is spinning up with time and approaches ~499 Hz before the quiescence. The time variation was fitted by third order polynomial function:

$$P(t) = P0 + \dot{P}(t - t_0) + \frac{1}{2}\ddot{P}(t - t_0)^2 + \frac{1}{6}\frac{d^3P}{dt^3}(t - t_0)^3 \quad (3)$$

The spin-down rate $\dot{P}$ was –4.46±0.07×10^{-6} s s^{-1} on MJD 55534.00. Using this equation, we derived the frequency derivative $\dot{\nu}$, and logarithmically plotted a correlation between the 3–50 keV luminosity in unit of 10^{37} erg s^{-1} (L_{3-50}) and the frequency derivative $\dot{\nu}$ in Figure 6. 14.5 kpc was assumed for the distance (Orlandini et al. 2010). A clear correlation was found, and can be explained by the best-fit model $\dot{\nu} = (3.60 \pm 0.35) \times 10^{-12} L_{3-50}^{0.87\pm0.07}$. The errors are quoted at statistical 90% level. This index is fully consistent with 6/7 as predicted by Ghosh & Lamb (1979), although we did not correct for the orbital modulation. Hence, we conclude that MAXI J1409–619 is the accretion driven X-ray pulsar.

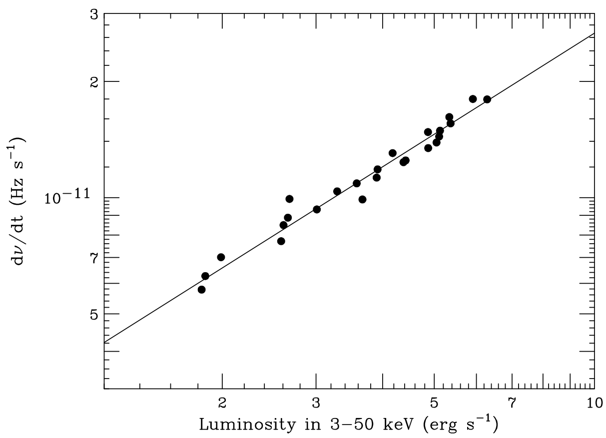

Fig. 6. Correlation between the 3–50 keV luminosity in unit of 10^{37} erg s^{-1} (L_{3-50}) and the frequency derivative ($\dot{\nu}$). The line indicates the best-fit model of $\dot{\nu} \propto L_{3-50}^{0.87}$.

4. MAXI J0556–332

4.1. Discovery and Observations

MAXI J0556–332 triggered the MAXI/GSC transient alert system (Negoro et al. 2011) on January 11, 2011 (Matsumura et al. 2011). The MAXI localized position was (RA, Dec)=($05^{\rm h}56^{\rm m}14^{\rm s}$, –33°12'36") with a systematic uncertainty of 0.2 degree. The source showed significant variability every GSC transit, and the maximum flux was 80 mCrab in the 4–10 keV range on January 11. This new X-ray source was confirmed by Swift/XRT, and finely localized to ($05^{\rm h}56^{\rm m}46^{\rm s}$.32, –33°10'28".2) with an estimated uncertainty of 1.7 arc-seconds (Kennea et al. 2011a). We trigger the RXTE follow-up observations of MAXI J0556–332 aiming at the Swift/XRT position, and the initial results were reported in Strohmayer & Smith (2011) and Strohmayer (2011).

4.2. PCA Light Curve and Energy Spectrum

Figure 7 shows the PCA light curves in the four energy ranges together with the MAXI/GSC till end of February, 2011. They show a significant variability in a time scale of ~days, and sometimes display an eclipse-like behavior (Strohmayer 2011). The energy spectrum has been gradually getting harder since discovery. The energy spectrum taken on January 26, 2011 is plotted in Figure 8. The spectrum can be well explained by disk blackbody plus blackbody plus iron-K line at 6.4 keV modified with Galactic absorption (χ^2/dof = 30.7/45). Obtained parameters are the innermost temperature 1.02±0.04 keV and the innermost radius 11.0±0.9 km for i=0 degree and D=10 kpc in the `diskbb` model, and the temperature 1.52±0.08 keV and the emission radius 2.72±0.53 km for D=10 kpc in the `bbodyrad` model. If we apply the disk blackbody plus power-law plus iron-K line, the fitting result gets worse (χ^2/dof = 52.5/45) and the photon index in the power-law would be very steep and unphysical giving a value of 3.66. This fact suggests that the energy spectrum is typical in LMXBs harboring not a black hole but a neutron star. It has been also suggested from radio (Coriat et al. 2011) and optical observations (Russel et al. 2011). Further RXTE monitoring observations are still in progress.

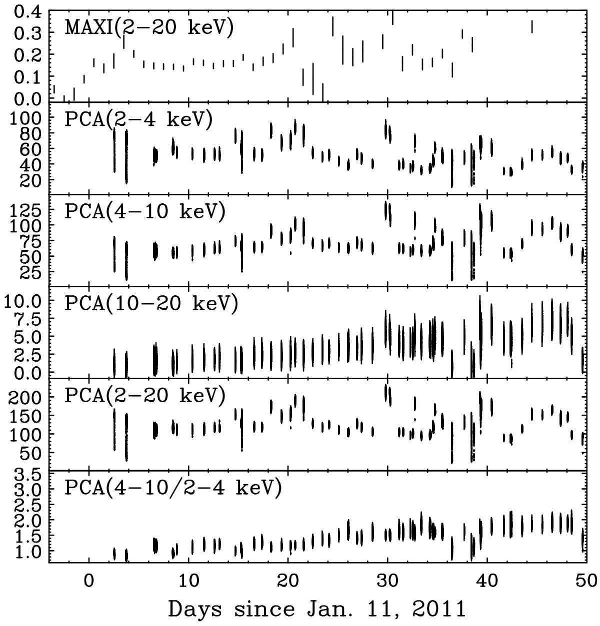

Fig. 7. MAXI/GSC and RXTE/PCA light curves of MAXI J0556–332 till February 2011. 2-20 keV flux for the MAXI/GSC, 2–4, 4–10, 10–20, 2–20 keV, and the hardness ratio between 2–4 and 4–10 keV for the RXTE/PCA are shown from top and bottom.

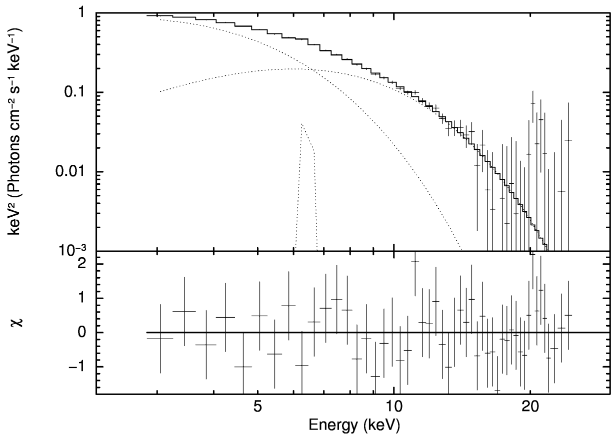

Fig. 8. PCA energy spectrum of MAXI J0556–332 taken on January, 2011. The spectrum can be fitted by disk blackbody plus blackbody, which is typical in LMXBs.

5. Summary

We have successfully carried out RXTE follow-up observations of new MAXI sources. The three Galactic x-ray sources: MAXI J1659–152, MAXI J1409–619, and MAXI J0556–332 were discovered by MAXI/GSC till February 2011, and identified as a black hole candidate, an X-ray binary pulsar, and a weakly magnetized neutron star binary, respectively. As the MAXI calibration and nova alert system are improved, we will expect further sources to be triggered in a future.

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