Spectral Evolution of a New X-Ray Transient MAXI J0556–332 Observed by MAXI, Swift, and RXTE

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1. Introduction

Galactic X-ray binaries distributed near the Galactic plane, exhibiting some of the brightest X-ray fluxes in the sky, have been well studied since the beginning of X-ray astronomy (e.g., Hayakawa 1981). Their X-ray emission is thought to occur when the gas from a companion (often late type) star accretes onto a compact star, a neutron star (NS) or a black hole (BH). They often show a large degree of X-ray flux variability and long periods of quiescence, only appearing in single (or sometimes recurring) periods of transient X-ray activity. Many attempts have been made to understand the behavior of these objects in a unified scheme, particularly by employing...
accretion-disk theory (Shakura & Sunyaev 1973).

So far, the standard-disk picture has successfully explained the X-ray emission from NS binaries with weak magnetic fields in their bright phase (Mitsuda et al. 1984; Makishima et al. 1986). Our next task is to understand their variations, particularly spectral state transitions that are often seen when these sources exhibit transient outbursts. Although RXTE, INTEGRAL, and Swift survey observations with wide sky coverages provided useful information, few studies have been made on the initial transitions. In particular, these studies on NS X-ray transients are limited because they are much fainter than BH X-ray novae.

Unbiased all-sky monitoring with Monitor of All X-ray Image (MAXI: Matsuoka et al. 2009) allows us to detect X-ray novae and transients, and to follow their intensity evolution from the beginning to the end. The MAXI mission started in 2009 August, and has already detected several X-ray transients and novae in their initial phase (e.g., Nakahira et al. 2010; Yamaoka et al. 2011; MAXI web site1). Asai et al. (2012) studied the initial rising behavior of outbursts from two transient NS low-mass X-ray binaries (LMXBs), Aql X-1 and 4U 1608–52, and then derived a relation between the initial hard-state duration and the hard-to-soft transition luminosity.

In the constellation Columba, a new X-ray transient, MAXI J0556–332, was discovered by the MAXI Gas Slit Camera (GSC: Mihara et al. 2011) at 9:21 (UT) on 2011 January 11 (Matsumura et al. 2011). Its position in Galactic coordinates, \((\alpha, \delta) = (238^\circ9', -25^\circ1'),\) is relatively away from the Galactic plane. A Swift (Gehrels et al. 2004) follow-up observation confirmed a bright uncatalogued X-ray source within the MAXI error circle, and localized the source position at J2000 coordinates of \((\alpha, \delta) = (89^\circ19'30", -33^\circ17'451") = (5^\circ56'46"32', -33^\circ10'28"2') with a positional uncertainty of \(1^\circ7\) (Kennea et al. 2011). The X-ray source agrees in position with an optical star with a \(B\)-magnitude of 19.4. RXTE Target-of-Opportunity (ToO) observations were also performed. The results revealed complex time variability, together with energy spectra that can be represented by the sum of a multi-color disk blackbody (diskBB in Xspec terminology) and a blackbody (BB) (Strohmayer & Smith 2011; Strohmayer 2011; Belloni et al. 2011). Based on color–color (CD) and hardness–intensity (HID) diagrams extracted from the RXTE data, Homan et al. (2011) suggested that the source is a transient neutron-star Z source. They estimated the source distance to be 20–35 kpc, better than the X-ray estimate of 20–35 kpc by Homan et al. (2011). Most of these results favor the collapsed component being a NS, although the BH scenario has not yet been completely ruled out.

This paper presents the X-ray behavior of MAXI J0556–332, including an initial transition and continuous long-term variations, observed by the MAXI/GSC. We also analyzed spectral variations using data taken by the Swift/X-Ray Telescope (XRT: Burrows et al. 2005) and the RXTE/Proportional Counter Array (PCA: Jahoda et al. 2006) on an approximately daily cadence. We describe the observations and the data reduction in section 2, and present the analysis results in section 3. In section 4, the origin of the X-ray emission and its evolution are discussed. All of the quoted errors are hereafter given at the 90% confidence limit, unless otherwise specified.

2. Observation and Data Reduction

2.1. MAXI/GSC

Every 92-minute orbital revolution, MAXI on the International Space Station (ISS) scans almost the whole sky with two kinds of X-ray cameras: the GSC working in the 2–30 keV energy band, and the Solid-state Slit Camera (SSC: Tsunemi et al. 2010; Tomida et al. 2011) in the 0.5–10 keV band. The new X-ray transient, MAXI J0556–332, first detected by the GSC on 2011 January 11, brightened to 80 mCrab in the 4–10 keV band within a day (Matsumura et al. 2011). The upper limit on the average 4–10 keV flux prior to the detection is 1.2 mCrab = \(1.5 \times 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) (Hiroi et al. 2011). The source was also detected by the SSC when the BH scenario was considered. The time coverage of the SSC was too limited to study spectral and flux changes. We therefore concentrate on the GSC data.

Reduction and analysis of the GSC data were carried out following the standard procedure described by Sugizaki et al. (2011). The source event data were extracted from a rectangular area of 3"6 along the detector anode wires and 3"0 in the scan direction centered at the source position; the latter corresponds to the point-spread function for each single scan transit of \(\sim 40\) s. The background was collected from data taken in the same anode area just before and after each scan transit.

1 (http://maxi.riken.jp/top/).
With the same analysis procedure, we processed the light curve of the Crab nebula for the same period, and then confirmed that calibration uncertainties in the standard light curves in the 2–4 keV, 4–10 keV, and 10–20 keV energy bands are at most 5% at the 1-σ level.

Figure 1 shows the obtained GSC light curve of MAXI J0556–332 in the 2–4 keV and 4–10 keV bands for the entire 1.5-year active period. These data represent the unfolded photon flux per 1-day time bin. In the 10–20 keV band, the GSC did not detect any significant flux above the 3-σ confidence limit, which is typically 0.015 photons cm\(^{-2}\) s\(^{-1}\) (45 mCrab).

### 2.2. Swift/XRT

Swift/XRT pointing observations of MAXI J0556–332 were performed over 112 epochs until 2011 November 22 utilizing the Windowed Timing (WT) mode and a typical exposure of 0.5–1 ks. Using the archival Swift/XRT data, we investigated the evolution of the 0.3–10 keV energy spectrum. The data reduction and analysis were performed using the Swift analysis software version 3.8, released as a part of HEASOFT 6.11 and CALDB (calibration database) files of version 20110915, provided via NASA/GSFC. Since the WT data are 1-dimensional, only spatial information in the CCD detector X (DETX) direction is available. The source events were collected from a 40 pixel wide region centered on the target position, and the backgrounds were collected from a region with the same width as the source region and 40-pixel away from the target along the DETX direction.

In a spectral model fitting, we used an XRT response matrix file, \texttt{xswxt0to2s6_20010101v014.rmf}, and ancillary response files built by \texttt{xrtmkarf}. A systematic error of 2% was implemented (Godet et al. 2009).

### 2.3. RXTE/PCA

From 2011 January 13 to 2011 December 29, MAXI J0556–332 was observed with RXTE/PCA on an almost daily basis with a typical exposure of 1–2 ks. The obtained data provide useful information in the energy range from 3 to 30 keV. We performed reduction of the PCA data with the standard RXTE analysis tools released as a part of HEASOFT 6.11 and the CALDB files of version 20111102 provided via NASA/GSFC. We used the PCA standard-2 data with a time resolution of 16-s for the spectral analysis, and the Good–Xenon data with a time resolution of 1-μs for the light-curve analysis. All of the data were screened with the standard selection criteria: the spacecraft pointing offset is smaller than 0.02, the Earth-limb elevation angle is larger than 10°, and the time since the last South Atlantic Anomaly passage is longer than 30 min. We used event data detected only on the top layer of the Proportional Counter Unit (PCU) #2, which is the best calibrated among all counter units. The background was estimated using the archived background model provided by the instrument team. The response matrix files were built with \texttt{pcarsp} for each pointing observation. A systematic error of 0.5% was applied.

### 3. Analysis and Results

#### 3.1. Long-Term Light Curve and Color Variations

In order to investigate long-term flux and hardness variations with a good statistical accuracy, we first extracted five-band X-ray light curves from the Swift/XRT (0.3–6 keV) and RXTE/PCA (2–20 keV) data. Figure 2 shows the results from 2011 January 13 (MJD = 55574) to 2011 December 29 (MJD = 55924), together with soft-color (3.6–5.6 keV/2.0–3.6 keV) and hard-color (8.5–18.4 keV/5.6–8.5 keV) variations. In order to enable direct comparisons among the different instruments, the observed count rates per 256-s time bin in each instrument were converted to the unfolded photon flux, assuming that the spectrum has a power-law with a photon index of 1 and a high-energy exponential cutoff at \(E_{\text{cut}} = 3\) keV, with an interstellar absorption of \(0.29 \times 10^{21}\) cm\(^{-2}\); these are based on the spectral analysis described in subsection 3.5. The Swift/XRT and RXTE/PCA data in the same energy band, taken within about one day, thus mostly agree with each other, which confirms the general consistency between the two instruments. The large flux discrepancy seen for a few data points close in time is indicative of flux changes between the pair of observations, which were not exactly simultaneous.

These light curves show complex energy-dependent variations, particularly during the initial ~50 days. In the lowest energy band (0.3–2 keV), the flux reached the maximum within a few days after the source emergence, and then decayed in about 50 days. In the highest energy band (8.5–18.4 keV), the flux in contrast increased gradually, reaching the maximum with a large short-time variability on about the 50th day. The contrast between the soft and hard flux evolutions are clearly reflected in the soft-color and hard-color variations, because both colors largely increased during the initial 50 days.

\footnote{[http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html]}. 

![Fig. 1. MAXI/GSC light curves of MAXI J0556–332 in 2–4 keV (top) and 4–10 keV (bottom). Each data point represents a daily average.](image-url)
Fig. 2. Light curves in 0.3–2.0 keV, 2.0–3.6 keV, 3.6–5.6 keV, 5.6–8.5 keV, and 8.5–18.4 keV energy bands obtained by the Swift/XRT (gray) and the RXTE/PCA. Black, red, green, blue, purple and cyan specify intervals A, B, C, D, E, and F respectively, as labeled in the second panel. Soft color (3.5–5.6 keV/2.0–3.6 keV) and hard color (8.5–18.4 keV/5.6–8.5 keV) of the RXTE/PCA data are shown in the bottom two panels. All panels utilize 256-s time bin. All of the vertical error bars represent the 1-$\sigma$ statistical uncertainty.
As shown in figure 2, we divided the entire observation period into six intervals (A, B, C, D, E, and F); they are characterized as follows. Int-A: initial (30 days) phase when the intensity below 2 keV was highest and the hardest-band intensity increased gradually. Int-B: brightest phase in the 5.6–8.5 keV and harder bands, with large variability in the whole band. Int-C: decaying phase where the large variability in the 5.6–8.5 keV and harder bands still remains. Int-D: intermediate phase where the average flux is lower than in the intervals just before and after. Int-E: re-brightening phase in the whole band with moderate variability. Int-F: low activity phase with a similar average flux to Int-D.

3.2. Color–Color and Hardness–Intensity Diagrams

To better grasp the spectral changes associated with the intensity variations, we plot several CDs in figure 3, representing the correlation between the two colors extracted from the RXTE/PCA data. There, data from the six intervals defined in figure 2 are shown separately. All of the six CDs apparently exhibit Z-like shapes, as often observed in bright NS LMXBs (e.g., van der Klis 2006). This strongly supports the source identification as a NS X-ray binary. These CDs are also classified into two groups. The Int-C behavior resembles that of Int-E, while Int-D resembles Int-F. This agrees with the report by Homan et al. (2011) on this source, that the CD track changed between 2011 February (MJD~55600) and 2011 September (MJD~55800). According to two subgroups of the Z-like CDs, represented by Cyg X-2 and Sco X-1 (e.g., Homan et al. 2010), the CDs of Int-A, B, C, and E are classified into the Cyg X-2 group, while those of Int-D and F are into the Sco X-1 group.

In figure 4, we plot the two colors against the intensity, to create two HIDs. There, the six intervals are specified with the same color scheme as in figure 3. As Homan et al. (2011) reported, the change of the HID tracks among the six intervals is also clearly seen.

3.3. Search for X-Ray Burst Activity

From multi-wavelength observations reported so far (section 1) and the results of the data analysis presented above, MAXI J0556–332 is considered most likely to be a NS X-ray binary. Transient NS X-ray binaries sometimes emit type-I X-ray bursts, characterized by a fast rise in a few seconds and an exponential decay in a few tens of seconds (e.g., Lewin et al. 1993). Therefore, we searched the entire RXTE/PCA light...
curves for type-I X-ray bursts using 1-s time bins. However, we did not find any burst-like event with a count-rate increase higher than 50 counts s\(^{-1}\) PCU\(^{-1}\) in the 2–20 keV band.

Even if the source is located at a distance of 35 kpc, which is the farthest limit estimated by Homan et al. (2011), we would have detected \(\sim 98\) counts s\(^{-1}\) with the RXTE/PCA from a typical X-ray burst, assuming a blackbody spectrum with a temperature of 2.1 keV and a luminosity as high as the Eddington luminosity of \(2 \times 10^{38}\) erg s\(^{-1}\), as seen in the typical type-I burst. Such a burst should have been observed with the RXTE/PCA.

### 3.4. Initial Transition Behavior

The initial emergent phase for about three days of MAXI J0556–332 was covered only by the MAXI/GSC all-sky survey. To clarify the source behavior, meanwhile, we extracted 2–4 keV and 4–10 keV lightcurves in a 12-hr time bin, and present them in figure 5. Like in figure 2, the GSC count rates were converted to the incident photon fluxes, to make the results approximately free from the instrumental responses. There, the Swift/XRT and the RXTE/PCA data are superposed, together with the hardness ratio and the 2–10 keV flux. The Swift/XRT and RXTE/PCA data points, each covering typically 0.5–2 ks (plotted with a bin width of 256 s), are significantly more scattered than the 12-hr averaged GSC data, presumably due to short-term (e.g., < 1 hr) variations. However, the hardness ratios are always consistent among the three missions. This implies that the spectral shape did not change largely on a time scale of a day or shorter, at least in the initial phase.

The MAXI/GSC hardness ratio clearly shows a step-like decrease at MJD = 55574.0 before the RXTE and Swift observations started. Therefore, the source is considered to have made a hard-to-soft transition at this epoch, when the flux was still rising rapidly. The flux then peaked at MJD = 55575.5 in the presumable soft state.

#### 3.5. X-ray Spectral Evolution

We carried out X-ray spectral analysis over the 0.5–30 keV broad band, by combining the Swift/XRT and RXTE/PCA data that were averaged over each observation (0.5–2 ks typically). Although these Swift and RXTE observations were not exactly simultaneous, any spectral change within one day is considered to be small, as already noted in subsection 3.1. We thus selected pairs of Swift and RXTE observations carried out within 12 hours, and performed their simultaneous fits. To avoid any possible inconsistency between the two instruments, we left the PCA versus XRT normalization, \(f_{PCA/XRT}\), free, and discarded those pairs of which the value of \(f_{PCA/XRT}\) deviated from the average (= 1.12) by more than 30%. The logs of the selected observations, totaling 72 pairs, are summarized in table 1. All spectral fittings were carried out using Xspec version 12.7.0, released as a part of HEASOFT 6.11.

Figure 6 shows the XRT and PCA spectra in their unfolded \(\nu f\nu\) form, from six typical observations, as indicated with arrows in the top panel of figure 7a. Including the six representatives, all of the obtained spectra were found to show a featureless continuum, without any significant emission or absorption features. We first attempted to fit them with a simple continuum model of either a power law (PL), a blackbody (BB), a broken power-law (bknpower), or a power law with a high-energy exponential cutoff (cutoffpl), all multiplied with photoelectric absorption (wabs, Morrison & McCammon 1983) with a free column density, \(N_H\). Then, 50 out of the 72 spectral pairs were reproduced by the wabs+cutoffpl model with reduced chi-squared (\(\chi^2_{\nu}\)) within the 99% confidence limits, while none of the other models were as successful on any data set. Figure 7a plots the time evolution of the best-fit wabs+cutoffpl model parameters, together with the absorption-corrected 0.1–100 keV fluxes. Thus, the photon index, \(\Gamma\), was in the range of 0.4–1 throughout, while the cutoff energy, \(E_{\text{cut}}\), changed from \(\sim 1.5\) keV to \(\sim 5\) keV. The flux decreased from \(4 \times 10^{-9}\) to \(5 \times 10^{-10}\) erg cm\(^{-2}\) s\(^{-1}\) over 10 months, in agreement with the light curve (figure 2). The best-fit parameters for the spectra in figure 6 are summarized in table 2.

The spectrum, represented by a cutoff power-law with \(\Gamma = 0.4–1\) and \(E_{\text{cut}} = 1.5–5\) keV, roughly agrees with those of typical bright NS-LMXBs. The cutoff energy could
Table 1. List of Swift/XRT and RXTE/PCA observation pairs used in the simultaneous spectal fits.

| MJD  | Obs ID   | Swift/XRT         | Exp [s] | RXTE/PCA        | Exp [s] |
|------|----------|-------------------|---------|-----------------|---------|
| 55574* | 00031914001 | 01/13 10:51 11:14 | 1413 | 96371-01-02-00 | 01/13 12:32 13:22 | 2912 |
| 55575 | 00031914000 | 01/14 06:10 06:31 | 1277 | 96371-01-01-00 | 01/14 16:44 19:06 | 5872 |
| 55578 | 00031914002 | 01/17 14:23 14:42 | 1125 | 96371-01-03-00 | 01/17 12:13 19:24 | 15872 |
| 55580 | 00031914007 | 01/19 16:09 16:24 | 891 | 96371-01-04-01 | 01/19 19:35 20:00 | 864 |
| 55582 | 00031914009 | 01/21 10:10 10:33 | 1375 | 96371-01-05-00 | 01/21 08:52 09:17 | 1456 |
| 55584* | 00031914102 | 02/12 18:15 18:39 | 146 | 96371-01-05-01 | 02/12 13:02 13:51 | 2800 |
| 55584 | 00031914101 | 02/23 05:30 05:54 | 1480 | 96371-01-05-02 | 02/23 14:27 14:57 | 1616 |
| 55587 | 00031914104 | 02/26 15:13 15:37 | 1442 | 96371-01-05-05 | 02/26 08:06 08:48 | 2352 |
| 55589 | 00031914105 | 02/27 04:03 04:19 | 955 | 96371-01-05-06 | 02/27 13:56 14:36 | 2224 |

* Energy spectra are shown in figure 6 and the best-fit parameters are summarized table 2.
† Date and time are in UT (Universal Time).
represent the temperature of blackbody radiation from a neutron-star surface (e.g., Mitsuda et al. 1984, 1989). We thus attempted a canonical two-component model for bright NS-LMXBs, consisting of a multi-color-disk blackbody (diskBB) in Xspec terminology and a blackbody (BB) (Mitsuda et al. 1984). However, as shown in figure 7a (fifth panel) and table 2, the best-fit \( \chi^2 \) values of the wabs*(diskBB+BB) fits were no better than those with the wabs*cutoffpl. The residuals revealed excess features at both low and high energies, which can be considered as a signature of a Comptonization process. Following Lin, Remillard, and Homan (2007, 2009b), we hence tried to add a broken power-law function approximating the Comptonized component to the canonical two-component model, but the model wabs*(diskBB+BB+bknpower) did not improve the fit significantly.

We then examined more rigorously the Comptonization emission process, employing a thermally Comptonized continuum model, nthcomp in Xspec terminology (Zdziarski et al. 1996; Zycki et al. 1999). It describes Comptonized emission arising when thermal seed photons with a BB or a diskBB spectrum are up-scattered by hot thermal electrons with a temperature of \( kT_e \). This model uses an asymptotic power-law photon index, \( \Gamma \), which is related with \( kT_e \), and the scattering optical depth, \( \tau \), as

\[
\Gamma = \left[ \frac{9}{4} + \frac{kT_e}{m_e c^2} \frac{1}{\tau} \left( 1 + \frac{\tau}{3} \right) \right]^{-\frac{1}{2}} - \frac{1}{2}
\]

(Sunyaev & Titarchuk 1980).

The nthcomp model alone, with seed photons of neither BB nor diskBB, was able to fit the observed spectra, even if the \( N_H \) was left free. The residuals showed a large discrepancy in the soft X-ray band below 2 keV. Adding another soft thermal component, of which the spectral shape is the same as that of the seed photons, did not improve the fit. However, when the temperature of the soft component was allowed to be free, and hence different from the seed-photon temperature, the Comptonization plus soft-component model became acceptable. Therefore, the seed photons for Comptonization and the additional soft component must be of different origin.

When the additional soft component was represented by a BB model, the fit always made the absorption column density \( N_H < 0.1 \times 10^{21} \) cm\(^{-2} \). This upper limit is significantly lower than the Galactic H I density of \( 0.29 \times 10^{21} \) cm\(^{-2} \) in the source direction (Kalberla et al. 2005). This would contradict the high Galactic latitude (\( |b| = 25^\circ \)) and the suggested large distance, which place MAXI J0556–332 well outside the Galactic disk. On the other hand, an alternative model employing a diskBB for the soft component always gave the best-fit \( N_H \) that is larger than the Galactic H I. Therefore, we hereafter use the diskBB model for the soft component.

Then, how about the seed-photon spectrum? If the optical depth of the Comptonizing medium is high enough (\( \tau \gg 1 \)), whether the seed photon spectrum follows a BB or a diskBB model causes little difference in the emergent spectrum, and therefore are difficult to distinguish. Hence, we assume that the seed photons have a BB spectrum. In subsection 4.2, we discuss the validity of this model based on the obtained best-fit parameters.

Using the wabs*(diskBB+nthcomp) model with a BB seed-photon source, we fitted all of the spectrum pairs, and obtained successful fits, as exemplified in figure 6.
Table 2. Best-fit model parameters of six sample epochs obtained by Swift/XRT and RXTE/PCA combined spectral analysis.*

| Parameter          | Obs#1 | Obs#2 | Obs#3 | Obs#4 | Obs#5 | Obs#6 |
|--------------------|-------|-------|-------|-------|-------|-------|
| $N_H$ [10^{22} cm^{-2}] | 0.63+0.06 | 0.63+0.06 | 0.63+0.06 | 0.65+0.10 | 0.34+0.12 | 0.39+0.12 |
| $\Gamma$            | 0.93+0.03 | 0.88+0.03 | 0.91+0.04 | 0.81+0.04 | 0.54+0.05 | 0.85+0.09 |
| $E_{cut}$ [keV]      | 1.56+0.02 | 2.19+0.01 | 3.03+0.06 | 3.51+0.08 | 3.23+0.09 | 4.52+0.16 |
| $f_{PCA/XRT}$       | 0.89+0.01 | 1.06+0.01 | 1.11+0.02 | 1.07+0.02 | 1.12+0.02 | 1.02+0.02 |
| $F_{PL}$ (d.o.f.)   | 4.01    | 2.91    | 2.10    | 1.74    | 1.30    | 0.98   |
| $\chi^2_r$ (d.o.f.) | 1.32(426) | 1.26(389) | 1.17(316) | 1.04(309) | 0.94(251) | 1.10(187) |

| Parameter          | Obs#1 | Obs#2 | Obs#3 | Obs#4 | Obs#5 | Obs#6 |
|--------------------|-------|-------|-------|-------|-------|-------|
| $N_H$ [10^{22} cm^{-2}] | 0.54+0.04 | 0.28+0.05 | 0.23+0.06 | 0.24+0.06 | 0.24+0.07 | 0.00+0.00 |
| $kT_{in}$ [keV]     | 0.96+0.02 | 0.80+0.02 | 0.99+0.03 | 1.30+0.05 | 1.69+0.10 | 1.37+0.06 |
| $R_{BB}$ [km]       | 13.9+0.05 | 14.9+0.04 | 7.9+0.04 | 4.4+0.03 | 2.5+0.02 | 2.7+0.02 |
| $f_{BB}$ [keV]      | 1.32+0.01 | 1.25+0.02 | 1.61+0.03 | 2.03+0.06 | 2.49+0.02 | 2.25+0.07 |
| $R_{BB,10kpc}$ [km] | 5.7+0.6 | 5.5+0.6 | 3.0+0.2 | 1.7+0.2 | 0.8+0.3 | 1.2+0.1 |
| $f_{PCA/x}$         | 0.89+0.01 | 1.07+0.01 | 1.11+0.02 | 1.05+0.02 | 1.11+0.02 | 1.01+0.02 |
| $F_{diskBB}$        | 3.54    | 1.87    | 1.30    | 1.16    | 1.05    | 0.57   |
| $F_{BB}$            | 0.44    | 0.79    | 0.63    | 0.51    | 0.26    | 0.37   |
| $\chi^2_r$ (d.o.f.) | 1.25(425) | 1.54(388) | 1.46(315) | 1.15(308) | 0.90(250) | 1.31(186) |

| Parameter          | Obs#1 | Obs#2 | Obs#3 | Obs#4 | Obs#5 | Obs#6 |
|--------------------|-------|-------|-------|-------|-------|-------|
| $N_H$ [10^{22} cm^{-2}] | 0.00+0.00 | 0.00+0.00 | 0.00+0.00 | 0.00+0.00 | 0.00+0.00 | 0.00+0.00 |
| $kT_{BB}$ [keV]     | 2.99+0.03 | 2.51+0.02 | 2.26+0.07 | 2.17+0.08 | 2.17+0.08 | 1.98+0.07 |
| $R_{BB}$ [km]       | 0.58+0.03 | 0.60+0.04 | 0.64+0.02 | 0.67+0.05 | 0.73+0.09 | 0.67+0.09 |
| $\tau$              | 8.7+1.0  | 10.3+1.0 | 10.3+1.0 | 9.8+0.8 | 9.7+1.4 | 10.5+1.0 |
| $R_{seed}$ [km]     | 44+2.0  | 32+2.0  | 24+2.0  | 21+2.0 | 16+2.0 | 15+2.0 |
| $f_{PCA/XRT}$       | 0.88+0.01 | 1.03+0.01 | 1.09+0.02 | 1.04+0.02 | 1.10+0.02 | 1.00+0.02 |
| $F_{BB}$            | 1.16    | 1.14    | 0.66    | 0.38    | 0.24    | 0.20   |
| $F_{nthcomp}$       | 2.92    | 1.85    | 1.48    | 1.40    | 1.14    | 0.81   |
| $\chi^2_r$ (d.o.f.) | 1.19(423) | 1.14(386) | 1.10(313) | 1.00(306) | 0.89(248) | 1.02(184) |

| Parameter          | Obs#1 | Obs#2 | Obs#3 | Obs#4 | Obs#5 | Obs#6 |
|--------------------|-------|-------|-------|-------|-------|-------|
| $N_H$ [10^{22} cm^{-2}] | 0.93+0.15 | 0.79+0.11 | 0.76+0.16 | 0.85+0.23 | 0.55+0.24 | 0.89+0.35 |
| $kT_{in}$ [keV]     | 0.34+0.03 | 0.42+0.03 | 0.44+0.05 | 0.40+0.07 | 0.50+0.08 | 0.37+0.05 |
| $R_{BB}$ [km]       | 1.41+0.07 | 1.72+0.13 | 2.14+0.15 | 2.51+0.19 | 2.76+0.24 | 2.87+0.20 |
| $kT_{seed}$ [keV]   | 0.54+0.02 | 0.67+0.04 | 0.70+0.05 | 0.69+0.04 | 0.82+0.07 | 0.71+0.06 |
| $\tau$              | 1.00+0.02 | 9.1+0.07 | 9.8+0.06 | 9.7+0.06 | 8.5+1.0 | 10.0+0.7 |
| $R_{seed}$ [km]     | 51+2.0  | 25+2.0  | 20+2.0  | 20+2.0 | 13+2.0 | 14+2.0 |
| $f_{PCA/XRT}$       | 0.88+0.01 | 1.03+0.01 | 1.10+0.02 | 1.05+0.02 | 1.10+0.02 | 1.00+0.02 |
| $F_{diskBB}$        | 1.32    | 1.25    | 0.70    | 0.41    | 0.26    | 0.23   |
| $F_{nthcomp}$       | 3.02    | 1.71    | 1.40    | 1.38    | 1.09    | 0.81   |
| $\chi^2_r$ (d.o.f.) | 1.12(423) | 1.09(386) | 1.10(313) | 1.00(306) | 0.88(248) | 1.01(184) |

* (i) All errors represent the 90% confidence limits of statistical uncertainty for a single parameter of interest. (ii) $R_{BB}$ is a BB-model parameter representing the source radius if the source distance is 10 kpc. (iii) $R_{BB,c}$ is a diskBB-model parameter related to the inner radius of the accretion disk, $R_{in}$, and the disk inclination, $i$, in the assumed 10 kpc source distance. (iv) $R_{seed}$ is the radius of blackbody seed photons in the thermally Comptonized continuum model (nthcomp) in the assumed 10 kpc source distance. (v) $F_{CPL}$, $F_{BB}$, $F_{BBH}$, and $F_{nthcomp}$ represent absorption-corrected fluxes of each continuum model of cutoffpl, BB, diskbb, and nthcomp, respectively, in units of 10^{-9} erg cm^{-2} s^{-1} in the 0.1–100 keV band.
Fig. 7. Evolution of the best-fit spectral parameters, jointly determined with the Swift/XRT and the RXTE/PCA data. (a) Results from the empirical $\text{wabs} \times \text{cutoffpl}$ fits. From top to bottom, the absorbing column density, the cutoff energy, the power-law index, the absorption-corrected model flux, the $\chi^2$ values, and the degree of freedom. In the fifth panel, the fit goodness with an alternative $\text{wabs} \times (\text{diskBB+BB})$ is shown by a (red) cross. (b) Case with more physical $\text{wabs} \times (\text{diskBB+nthcomp})$ fits. In the third panel, $R_{\text{seed}}$ and $R_{\text{in}} \sqrt{\cos i}$ were calculated at the assumed source distance of 10 kpc.

Then, assuming that the Comptonization process conserves the photon number in the original BB radiation, we estimated the radius of the BB seed-photon sphere, $R_{\text{seed}}$, according to the formula

$$F_{\text{nthcomp}}(T_{\text{seed}}, R_{\text{seed}}, d) \quad \text{(photons cm}^{-2} \text{s}^{-1})$$

$$= \int f_{\text{BB}}(E, T_{\text{seed}}, R_{\text{seed}}, d) dE$$

$$= 20.1 \left( \frac{k T_{\text{seed}}}{1 \text{ keV}} \right)^3 \left( \frac{R_{\text{seed}}}{1 \text{ km}} \right)^2 \left( \frac{d}{10 \text{ kpc}} \right)^{-2},$$

(2)
where \( F_{\text{nthcomp}}(T_{\text{seed}}, R_{\text{seed}}, d) \) is the incident photon flux calculated from the best-fit model parameters in Xspec, \( T_{\text{seed}} \) is the seed-photon BB temperature, \( d \) is the source distance, and \( f_{\text{BB}}(E, T_{\text{seed}}, R_{\text{seed}}, d) \) is the photon-flux spectrum of BB emission. Including the values of \( R_{\text{seed}} \), the best-fit model parameters from the six representative spectra are given in table 2.

Figure 7b shows temporal variations of the best-fit parameters, including \( \tau \) and \( R_{\text{seed}} \) derived using equations (1) and (2), respectively, and the unabsorbed fluxes of the diskBB and nthcomp components. The values of \( R_{\text{seed}} \) and the diskBB-model parameter, \( R_{\text{in}} \sqrt{\cos i} \), related to the disk inner radius, \( R_{\text{in}} \), and the inclination, \( i \), are calculated assuming \( d = 10 \text{kpc} \). The actual radii are proportional to the source distance.

4. Discussion

MAXI J0556–332 is a new X-ray transient that appeared on 2011 January 11. Using the MAXI/GSC, Swift/XRT, and RXTE/PCA data, we studied the intensity and spectral evolution of this source over the entire active period for more than one year.

4.1. Source Identification from X-Ray Spectrum

The wide-band (0.5–30 keV) X-ray spectra obtained by the Swift/XRT and XTE/PCA are featureless, and can be approximated by a cutoff power-law with \( \Gamma \approx 0.4–1 \) and \( E_{\text{cut}} \approx 1.5–5 \text{keV} \). They are better fitted with a two-component model that consists of a multi-color-disk blackbody and a thermmally Comptonized blackbody. This spectral model has been often used to describe X-ray emission from LMXBs containing a weakly magnetized NS (e.g., Gierliński & Done 2002; Sakurai et al. 2012) or a BH candidate (e.g., Done et al. 2004).

NS LMXBs have been classified mainly into “Z-type” and “atoll-type” sources according to their CD-track shapes (Hasinger & van der Klis 1989; van der Klis 2006). The former objects are persistently as bright as \( L_{\text{EDD}} \), and sometimes show rapid flux variations of up to a factor of \( \approx 5 \). The latter are fainter than the former, and often appear as transients or recurrences. The luminosity of atoll sources varies over a large range from \( \sim 10^{-3} \) to \( \sim 0.2 \) times \( L_{\text{EDD}} \), accompanied by spectral state changes. The higher-energy cutoff of 1.5–5 keV of MAXI J0556–332, represented by \( E_{\text{cut}} \) in the wabs*(diskBB+nthcomp) model, agrees well with those of the Z sources, such as Cyg X-2 (Di Salvo et al. 2002), Sco X-1 (D‘Afi et al. 2007), GX 5–1 (Sriram et al. 2011), GX 17+2 (Farinelli et al. 2005), and GX 349+2 (Di Salvo et al. 2001), whose luminosities are always \( > 0.5 L_{\text{EDD}} \). The \( E_{\text{cut}} \) values of atoll sources are also below 5 keV in the soft state with the luminosity being higher than 0.1 \( L_{\text{EDD}} \), while they tend to increase up to \( > 15 \text{keV} \) in the hard state with the luminosity being on the order of 0.01 \( L_{\text{EDD}} \); the latter examples include Aql X-1 (Lin et al. 2007; Sakurai et al. 2012), 4U 0614+09 (Singh & Apparao 1994), 4U 1608–52 (Gierliński & Done 2002; Lin et al. 2007; Takahashi et al. 2011), 4U 1705–44 (Barret & Olive 2002; Lin et al. 2010), and 4U 1728–34 (Tarana et al. 2011). Therefore, if the source is a NS LMXB, the X-ray luminosity should be higher than \( 0.1 L_{\text{EDD}} = 1.8 \times 10^{37} \text{erg s}^{-1} \) in the observed period. The absorption-corrected model flux, which changed from \( 4 \times 10^{-9} \) to \( 5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \), constrains the source distance to be \( d > 17 \text{kpc} \), in agreement with the estimate of \( d = 20–35 \text{kpc} \) by Homan et al. (2011), deduced from the luminosity at a CD-track transition.

Galactic BH X-ray binaries have been observed mostly in either of the two major spectral states, the low/hard or the high/soft state. These spectra are represented by a combination of thermal emission from the accretion disk and a Comptonized harder component (although detailed model parameters differ significantly between the two states). The obtained \( E_{\text{cut}} \) of 1.5–5 keV seems to be too high as the temperature for the accretion disk in BH binaries, which is typically below 1 keV, and is also too low for the cutoff energy of the Comptonized component, which is usually higher than 50 keV (e.g., McClintock & Remillard 2006). However, the peculiar Galactic BH binary, GRS 1915+105, sometimes shows in the bright phases, such a spectrum as represented by diskBB with \( kT_{\text{in}} \approx 2 \text{keV} \) (Done et al. 2004). Therefore, the possibility of a BH X-ray binary cannot be completely ruled out from the spectral parameters alone. As has been seen in the CDs and HIDs (subsection 3.2), the spectral time evolution, to be explored below, gives us other helpful information to identify the source nature.

4.2. Emission Geometry in NS-LMXB Scenario

According to the widely accepted picture of NS-LMXBs (e.g., Mitsuda et al. 1984, 1989), the two continuum components in the wabs*(diskBB+nthcomp) model are interpreted as a thermal emission from the accretion disk (diskBB), and blackbody emission from the NS surface (the boundary layer), modified through Comptonization by surrounding hot electrons (nthcomp). In figure 7b, the time evolution of the parameters of these physical components are plotted.

In order for the diskBB model to be physical, its inner disk radius has to be larger than the NS radius, \( \sim 10 \text{km} \). We may derive a realistic estimate of the inner disk radius, \( r_{\text{in}} \), from the model parameter \( R_{\text{in}} \sqrt{\cos i} \) as

\[
 r_{\text{in}} = \xi \kappa^2 R_{\text{in}} = 1.2 \left( \frac{\xi}{0.41} \right) \left( \frac{\kappa}{1.7} \right)^2 \left( \frac{d_{10}}{\sqrt{\cos i}} \right) \cdot R_{\text{in}} \sqrt{\cos i}. \tag{3}
\]

where \( \xi = 0.41 \) is a correction factor for the inner boundary condition (Kubota et al. 1998; Makishima et al. 2000), \( \kappa = 1.7 \) is the standard color hardening factor (Shimura & Takahara 1995), and \( d_{10} \) is the source distance in units of 10 kpc. Here, we adopted the same canonical \( \xi \) and \( \kappa \) values as for the accretion disk around a black hole. We find that \( r_{\text{in}} \) changed from \( \sim 80 \) (\( d_{10}/\sqrt{\cos i} \)) km to \( \sim 20 \) (\( d_{10}/\sqrt{\cos i} \)) km across the observations.

If the source distance is \( > 17 \text{kpc} \), as estimated in subsection 4.1, the condition of \( r_{\text{in}} \) > 10 km is always satisfied. The best-fit parameters also satisfy the expected relations of \( R_{\text{seed}} < r_{\text{in}} \) and \( kT_{\text{seed}} > kT_{\text{in}} \). Thus, the derived model parameters are reasonable, even though the range of \( kT_{\text{in}} \approx 0.3–0.6 \text{keV} \) seems to be slightly lower than the typical values, as obtained in Cyg X-2 (Di Salvo et al. 2002),...
4.4. State Transition in Color–Color Diagram

State transitions are considered to reflect changes of the physical condition in the emission region including the NS surface (or the boundary layer) and the accretion disk, mainly in response to changes in the luminosity. On the basis of the Z source features seen in the CD/HID tracks extracted from the RXTE/PCA data, Homan et al. (2011) reported that MAXI J0556–322 is the third transient Z source after XTE J1701–462 (Homan et al. 2010) and IGR J17480–2446 (Altamirano et al. 2010). They also reported on a source transition between the two types of Z source tracks, from Cyg-like to Sco-like substates. This kind of transition has been observed previously only from XTE J1701–462, which exhibited all three kinds of CD/HID tracks (Cyg-like Z, Sco-like Z, and atoll) during the decay phase of its outburst in 2006–2007 (Homan et al. 2010). Actually, in figure 3 and figure 4, we confirm that these tracks can be classified into either Cyg-like Z (int-A, B, C, and E) or Sco-like Z (int-D and F). These CDs and HIDs resemble those of XTE J1701–462 in the 2006–2007 outburst (Homan et al. 2007).

The other two transient Z sources, XTE J1701–462 and IGR J17480–2446, showed type-I X-ray bursts (Lin et al. 2009a; Chakraborty & Bhattacharyya 2011). However, we did not find any burst-like events.

4.5. Distance Estimate and Source Location

Homan et al. (2011) estimated the distance of MAXI J0556–322 to be 20–35 kpc, assuming that the transition between the Cyg-like and the Sco-like substates occurred at the same luminosity as that in XTE J1701–462, whose distance is estimated to be 8.8 kpc from the luminosity of its type-I X-ray bursts (Lin et al. 2009a). In the energy-sorted light curves given in figure 2, the substate transition occurred when the 2.0–3.6 keV PCA count rate crossed ~14 counts s$^{-1}$. For a comparison, XTE J1701–462 exhibited the transition at a PCA count rate of ~80 counts s$^{-1}$ in 2.0–2.9 keV, or 121 counts s$^{-1}$ in the 2.0–3.6 keV. Assuming that the two sources make the transition at the same intrinsic luminosity, MAXI J0556–322 is then estimated to be 2.9-times farther, located at $d \sim 26$ kpc; this reconfirms the estimate by Homan et al. (2011). This estimate and the Galactic coordinates of $(l, b) = (238^\circ.9, -25^\circ.2)$ indicate its location of 11 kpc below the Galactic plane and 31 kpc away from the Galactic center. This places the source on the outskirts of the Galactic halo, where the population of LMXBs is rather small (Grimm et al. 2002).

Assuming $d = 26$ kpc, the observed maximum flux of $4.3 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ in the initial phase can be converted to the absorption-corrected luminosity of $3.5 \times 10^{38}$ erg s$^{-1}$. This is
twice as high as the Eddington limit for the typical 1.4 $M_\odot$ NS, and agrees with the maximum luminosity in some bright NS LMXBs, such as Sco X-1 (D’Aì et al. 2007).

4.6. Initial Transition

The MAXI/GSC light curve in figure 5 reveals a hard-to-soft state transition that occurred on the fourth day from the brightening onset, at the middle of the initial brightening phase. As can be seen in other transient NS LMXBs (Asai et al. 2012) as well as BH LMXBs (Gierliński & Newton 2006), this transition may be interpreted as the initial formation of an optically-thick accretion disk. The observed X-ray flux just before the transition was $1.0 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band.

By comparing the Swift/BAT and the MAXI/GSC data, Asai et al. (2012) investigated the outburst rising behavior in the two transient NS binaries, Aql X-1 and 4U 1608–52, and revealed that the initial hard-to-soft state transition of these sources occur at a 2–15 keV luminosity of $0.5 \times 10^{36} - 2 \times 10^{37}$ erg s$^{-1}$. If the distance to MAXI J0556–322 is $> 17$ kpc, as estimated above, the initial hard-to-soft transition is inferred to have occurred at a luminosity of $> 3.5 \times 10^{37}$ erg s$^{-1}$. This is significantly higher than that in Aql X-1 and 4U 1608–52. Further discussion on this point requires a more detailed consideration of the inclination angle, and possible differences in magnetic-field strengths.

5. Conclusion

Throughout the active period, which lasted for more than one year, the 0.5–30 keV X-ray spectra of the new X-ray transient, MAXI J0556–322, obtained by the Swift/XRT and RXTE/PCA were successfully represented by a two-component model, consisting of an optically thick thermal emission from an accretion disk with an inner-disk temperature of $kT_\text{in} \approx 0.3$–0.4 keV, and a Comptonized emission of thermal seed photons of $kT_{\text{seed}} \approx 0.6$–0.8 keV by hot electrons with $kT_e \approx 1.5$–3 keV. The obtained model parameters are consistent with those of NS LMXBs when their luminosity is higher than $\sim 0.1 L_{\text{Edd}}$. This, together with the source behavior on CDs, constrains the source distance to be $> 17$ kpc, most likely 26 kpc, and places the source on outskirts of the Galactic halo. The long-term spectral variations can be understood by the evolution of the accretion disk and the emission region on the NS. The MAXI/GSC light curve revealed a hard-to-soft transition in the middle of the initial brightening phase. The transition luminosity would be significantly higher than those observed in other typical transient NS LMXBs.

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