MAXI observes black-hole X-ray novae from the beginning to the end

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ABSTRACT

Galactic black-hole candidates newly discovered by MAXI are reviewed. 6 of 12 black hole candidates, MAXI J1659-152, J1543-564, J1836-194, J1305-704, J1910-057, and J1828-249, have been solely or independently discovered by MAXI since the beginning of the mission, August 2009. All these sources were automatically detected by the MAXI nova-alert system and the appearances were soon reported to the world, leading to successful followup observations not only by Swift but also by Suzaku and other observatories in multiwavelengths. These followup observations revealed the nature of the sources, e.g., black hole candidates, and peculiar properties in each source or binary system. For more than 100 days, MAXI continuously monitored the X-ray novae until fading away, down to fluxes of a few or several mCrab. During the outbursts MAXI also detected various state transitions, which were helpful to understand the cause of jet formation and to estimate the distance to the sources. Some noticeable features in known black hole candidates, for instance Cygnus X-1, revealed by MAXI observations are also described. It is demonstrated that the 6 MAXI X-ray novae can be classified into two types in terms of the long-term variations, and the cause of the faintness in X-ray flux of these sources is discussed.

KEY WORDS: stars: black holes | X-rays: individual (MAXI J1659-152, J1543-564, J1836-194, J1305-704, J1910-057, J1828-249, Cygnus X-1, GX 339-4, Swift J1753.5-0127)

1. Introduction

To date, about 70 black hole candidates (BHCs), or so-called black hole binaries, have been discovered in our galaxy since the first discovery of Cygnus X-1 in 1964 (Bower et al. 1965). About 20 of them are firm or reliable BHCs of which masses have been dynamically measured (e.g., Tanaka & Shibazaki 1996; McClintock & Remillard 2004), and the rest of them are also candidates because of their X-ray timing and spectral properties similar to those in the mass-confirmed BHCs.

One of the most characteristic properties of the BHCs is that most BHCs are transients. Only Cygnus X-1 and 4U 1957+115 are exceptionally persistent emission sources that exhibit bright X-ray emission for 50 years. Some sources, for instance GX 339-4, exhibit repeated renewed activities, but most BHCs appeared only once. We therefore have to find new BHCs to constantly study unsolved problems, for instance, the causes of state transitions, low and high frequency quasi-periodic oscillations (QPOs), jets and other observational phenomena.

MAXI, Monitor of All-sky X-ray Image is the first large X-ray mission mainly to find such transient X-ray sources (Matsuoka et al. 1999). It scans all the sky once or twice in every 92 minutes, and 75-80% data are downloaded in real-time to the ground. The MAXI nova alert system analyzes the data in real-time, and finds transient events such as X-ray/γ-ray bursts, stellar flares, X-ray novae and AGN flares (Negoro et al. 2010a). If a transient event is found, email alerts are sent to subscribers all over the world.

In the following sections, each BHC newly discovered by MAXI is shortly reviewed (§2), and it is demonstrated that the X-ray novae are classified into two types of outbursts in terms of the longterm flux variations (§4). Furthermore, in §3 some topics of known BHCs from MAXI observations are also described.

2. MAXI sources

Since the beginning of the MAXI mission, August 2009, 12 BHCs have been discovered. MAXI solely or independently discovered 6 of them (Fig. 1, 2), and Swift also discovered 5 BHCs, including Swift J1910.2-0546 (= MAXI J1910-057). RXTE and INTEGRAL also discovered XTE J1752-223 (Markwardt et al. 2009) and IGR 17177-3656 (Frankowski et al. 2011), respectively.

Those sources are regarded as BHCs from mainly X-ray properties, for instance, by showing typical hard and soft states, and neither pulsations nor X-ray bursts have been found. However, any masses of the sources have not been dynamically measured, yet. There are several
2.1. MAXI J1659-152/GRB 100925A
MAXI J1659-152 was first triggered with Swift/BAT, and initially reported as GRB 100925A (Mangano et al. 2010). The MAXI nova-alert system independently triggered the source showing a gradually increasing hard X-ray flux (Negoro et al. 2010b).

A number of followup observations mainly by RXTE and Swift revealed noticeable features of this source; type-B and C QPOs (Kalamkar et al. 2011; Muñoz-Darias et al. 2011; Yamaoka et al. 2012), and 2.4 hr periodic dips, a possible shortest orbital period in BHCs (Kennea et al. 2011a; Kuulkers et al. 2013).

The source is located at relatively high galactic latitude ($b \sim 16.5$ deg), but a companion star has not been identified and an M5 dwarf star is proposed (Kuulkers et al. 2013; also Kaur et al. 2012).

2.2. MAXI J1543-564
MAXI J1543-564 was discovered on the galactic edge by MAXI on 8 May 2011 (Negoro et al. 2011b). About 14 hours later, a Swift/XRT followup observation was carried out, and its precise location was obtained (Kennea et al. 2011b).

Type-C QPOs at 1–6 Hz were detected in RXTE observations (Altamirano et al. 2011; Stiele et al. 2012). One more unique feature in this source is its faintness through the outburst. The peak flux was only $\sim 77$ mCrab in the MAXI observations (Fig. 1), or 200-220 mCrab (unabsorbed) in a RXTE observation (Stiele et al. 2012) though the source exhibited state transitions (Stiele et al. 2012; Kennea et al. 2011c). This suggests the source distance to be 12-13 kpc (Stiele et al. 2012). An optical counter part is still unclear (e.g., Russell et al. 2011; Rau et al. 2011; Chakrabarty et al. 2011).

2.3. MAXI J1836-194
On 30 August 2011, the MAXI nova-alert system triggered MAXI J1836-194, and the source had also been de-
ected with Swift/BAT (Negoro et al. 2011c). A followup Swift/XRT observation provided its precise location and revealed an optical counterpart (not companion) (Kennea et al. 2011d). The source exhibited a “failed” transition to the soft state, and QPOs and a jet associated with the intermediate state were also detected. (Ferrigno et al. 2012; Russell et al. 2013).

A board iron line (like structure) in an energy spectrum was found in a Suzaku observation, and a model fit gave a spin parameter of $a = 0.88 \pm 0.03$. (Reis et al. 2012)

We also note that compact jets were often observed from the source (Miller-Jones et al. 2011; Pakull et al. 2011; Yan et al. 2012; Russell et al. 2013).

After half year later from the beginning of the outburst, the source was detected again in X-rays (Krimm et al. 2012a; Yang et al. 2012) and radio (Coriat et al. 2012). About this renewed activity, see Fig.1 and 3.

2.4. MAXI J1305-704
MAXI J1305-704 was found just beside ($\sim 1.4$ deg apart) a bright low-mass X-ray binary 4U 1254-690 on 9 April 2012 (Sato et al. 2012). The source was soon found to be a black hole binary from optical (Greiner et al. 2012) and X-ray followup observations with Swift/XRT (Greiner et al. 2012; Kennea et al. 2012a).

The source exhibited hard, intermediate, and soft states during the outburst (Suwa et al. 2012; Morihana et al. 2013).

The most interesting feature in this source is possible 1.5 hr periodic dips (Kennea et al. 2012b; also see Kulikers et al. 2012), ionized absorption (Miller et al. 2012; Shidatsu et al. 2013) or an eclipse (Kennea et al. 2012c). Suzaku 40 ks observations revealed two kinds of 9.7 hr periodic dips, which could be directly associated with the orbital period, and the deep and shallow dips could be understood by the absorbers, resulting from the accretion gas stream from the companion star, at the hotspot and at an inner circularization radius, respectively (Shidatsu et al. 2013).

2.5. MAXI J1910-057/Swift J1910.2-0546
MAXI J1910-057 was triggered by the MAXI nova-alert system on 31 May 2012 (Usui et al. 2012), but the detection with Swift/BAT was reported to ATel earlier (Krimm et al. 2012b). Consequently, the source is also known as Swift J1910.2-0546.

The outburst showed so-called FRED (fast rise and exponential decay) type long-term variations, and MAXI detected not only a reflare (secondary maximum) in $\sim 50$ days from the onset of the outburst but also 3rd and 4th! broad maxima in $\sim 120$ days and $200-220$ days, respectively (Fig.1, 3, Nakahira et al. 2014, hereafter N14).

Before the 3rd maximum, an optical intensity drop followed by an X-ray one was observed in Swift/XRT, UVOT and MAXI observations (Degenaar et al. 2014; N14), which could be understood as a consequence of disk cooling in an outer part of the accretion disk (N14).

During the outburst, the source underwent soft state transitions twice, which is also a quite unique feature in this outburst (N14), and probably associated optical longterm variations are also interesting (M. Yamauchi private comm.).

QPOs and a board iron-line spectrum were also observed in a 51 ks XMM-Newton observation (Reis et al. 2013), but a possibility of a retrograde spin black hole proposed is unlikely (N14).

2.6. MAXI J1828-249
MAXI J1828-249 was discovered with MAXI/GSC on 16 October 2013, apart from a bright low-mass X-ray binary GS 1826-238 by 1.2 deg (Nakahira et al. 2013). INTEGRAL also observed the source region at that time, and the position and a hard X-ray increase immediately reported (Filippova et al. 2013, 2014).

The source exhibited a hard-to-soft state transition at the beginning of the outburst (Kennea et al. 2013; Negoro et al. 2013). Radio emission was not observed in the soft state (Miller-Jones et al. 2013), but in the hard state (Corbel et al. 2014). These properties are typical signatures of BHCs.

MAXI J1828-249 was also a faint X-ray nova (Fig. 1) thought it showed the soft state (Fig. 1), suggesting the source is as far as MAXI J1543-564 (also see §4.1).

2.7. Comments on other newly discovered BHCs
A bright X-ray novae XTE J1752-223 (Markwardt et al. 2009) and Swift J1713.4-4219 (Krimm et al. 2009) were detected on 24 October 2009 and 11 November 2009, respectively, before the MAXI nova-alert system automatically triggered transient events ($\sim$ December 2009).

Swift J1357.2-0933 discovered on 28 January 2011 (Krimm et al. 2011; Padilla et al. 2013) and IGR J17177-3656 on 15 March 2011 (Frankowski et al. 2011; Paizis et al. 2011) were also faint in the MAXI/GSC energy band to be detected earlier even if the MAXI operation did not stop around 15 March 2011 because of a terrible earthquake.

For two near-galactic-center sources, Swift J1745.1-2624 discovered on 16 September 2012 (Cummins et al. 2012) and Swift J1753.7-2544 on 28 January 2013 (Cumming et al. 2013; Krimm et al. 2013a), it was difficult for MAXI to discover the sources avoiding severe contamination from nearby, very bright X-ray sources, GX 3+1 and GX 5-1 (e.g., Sakamoto et al. 2013).
Thus, except for the initial operation phase, MAXI has discovered almost all the BHCs, currently 6 of 12 BHCs, that it should detect.

3. Topics of other BHCs

3.1. Renewed activities

For 4.5 years, MAXI also detected and first reported a number of transient events, including renew activities from known BHCs: a giant outburst from GX 339-4 from January 2010 (Yamaoka et al. 2010), quasi-regular outbursts from H1743-322 (for time intervals getting longer and longer, see Shidatsu et al. 2012), a short outburst from SLX 1746-331 in January 2011 (Ozawa et al. 2011), outbursts followed by complex time variations from 4U 1630-472/Nor X-1 (Nakahira et al. 2011), and a dim and soft outburst from V4641 in January 2014 (Tachibana et al. 2014).

3.2. State transitions

The MAXI nova-alert system regularly produces false-color all-sky images using GSC data in 3 energy bands, which are often helpful to notice state transitions of BHCs (Negoro et al. 2010a). Cygnus X-1 underwent a hard-to-soft transition in July 2010 for the first time in 5 years (Negoro et al. 2011a), and a number of observations in multi-wavelengths were carried out. Cygnus X-1 in the soft state exhibits large flare-like short-term variations on timescales of hours or less, which are much different from other BHCs in the soft state (e.g., Negoro & MAXI team 2010). This was confirmed by power spectral densities on timescales of not only hours (Sugimoto et al. 2014) but also seconds (Suzuki et al. 2014) only using MAXI data.

Combined with Swift/XRT data, MAXI monitoring of Swift J1753.5-0127 revealed the nature of repeated short-term spectral softenings (Yoshikawa et al. 2014; also see Shaw et al. 2013 for a 420 day modulation).

4. Discussion

4.1. Faintness and distance

One of the most characteristic features in the MAXI BHCs is their faintness. No bright outbursts with $2 - 10(20)$ keV fluxes of more than 1 Crab, often observed in the Ginga and RXTE eras, have been observed. Only the 2-4 keV flux of J1910-057 exceeded 1 Crab slightly.

J1543-564, J1305-704 and J1828-249 showed soft state transitions, but their peak fluxes were only $\sim 100$ mCrab (Fig. 1), only $\sim 1/100$ of those of Ginga X-ray novae (see Fig. 3 in Tanaka & Shibazaki 1996). If the state transition is simply determined by an Eddington rate (e.g., Maccarone 2003), those sources must be 10 times further than the Ginga novae (§2.2), though low luminosity of J1305-704 was probably due to a high inclination angle (Shidatsu et al. 2013).

4.2. Two kinds of the outbursts

All the MAXI sources showed rapid increase in X-ray flux at the beginning of the outbursts. It took typically less than 10 days for the sources to reach the peak fluxes, while XTE J1752-223 (Nakahira et al. 2012) and GX 339-4 (Shidatsu et al. 2011) took as much as about 100 days.

4.2.1. fast rise and exponential decay, FRED

As shown in Fig. 3 and 4, however, there seems to be two kinds of long-term variations after the maximum in the MAXI sources. One is a classical, “fast rise and exponential decay, FRED (Chen et al. 1997)” type of
the outbursts: MAXI J1836-194, J1901-057, and J1828-249 (Fig. 3). Such outbursts were commonly observed in the Ginga era (Tanaka & Shibazaki 1996), but not so common in the RXTE era (e.g., McClintock & Remillard 2006). The FRED type of the outbursts is ideal for the study of the accretion disk because of a relatively simple mass-accretion decline rate.

The time profiles of J1836-194 and J1828-249 are very similar, but the spectral evolutions are different. J1828-249 showed the soft state transition rapidly (§2.6), but J1836-194 failed (§2.3). If the difference simply comes from the accretion rate, J1828-249 must be further than J1836-194 though both are at similar galactic latitudes ($b = -6.5$ deg and $b = -5.4$ deg, respectively).

It should be also noted that the decay time constants of these three BHCs are $\sim 25$ days, though the decay constants are influenced by spectral changes and depend on the term to fit. Similar decay time constants are obtained in A 0620-00 ($\sim 24$ days), GS 2000+251 ($\sim 30$ days), and GS 1124-684 ($\sim 30$ days) (see Tanaka & Shibazaki 1996, references therein) and others (Chen et al. 1997). The cause of the exponential decay has not been fully understood (Kato et al. 1998). The constancy of the decay constants in BHCs with various masses implies that the decay constant hardly depend on the mass.

### 4.2.2. fast rise and flat-top, FRFT

The other group of the outbursts is a "fast rise and flat-top, FRFT" type of the outbursts: MAXI J1659-152, J1543-564, and J1305-704 (Fig. 4). These sources showed flux plateaus lasting 30-60 days. Note that such morphology strongly depends on the energy band (we observe different components in different energy bands), and it should be done in the same energy band, or more precisely using bolometric luminosities. In that sense, careful attention should be paid to 6 types of classification using various satellite data by Chen et al. (1997).

Also note that in both the types of the outbursts, the flux changed by a factor of about two near the peak, resulting in multiple peaks\(^2\), which can be clearly seen when plotted in a linear scale, but ignored here because of little association with the state transitions.

The flux plateau implies a relatively constant accretion rate during it, which might result from Roche-lobe outflow rather than temporary gas accretion due to thermal instability of the accretion disk (Mineshige & Wheeler 1989). It is interesting to note that a longterm profile of J1659-152 stretching to the time-axis direction is similar to those of J1305-704 and J1543-564 (Fig. 4). This might simply reflect the size of the binary system. The shortest orbital period and an unobservable companion star in J1659-152 (§2.1) imply the system to be the most compact with a small size of the accretion disk and a small companion star, resulting in a small reservoir to provide accretion matter.

#### 4.2.3. small size of the system

The high galactic latitudes of the MAXI X-ray novae is another important feature. With non-detected companion stars, probably dwarf stars (Kuulkers et al. 2013 for J1659-152; Shidatsu et al. 2013 for J1305-704), these must be keys to understand the birth of these low-mass binaries at the high galactic attitudes.

All the outbursts in these BHCs last 150-300 days (Fig. 3, 4), while those in neutron star low-mass X-ray binaries (NS LMXBs) usually 40-120 days with some exceptions lasting more than 300 days, e.g., MAXI J0556-332 (Sugizaki et al. 2013). This difference may also come from the size of the binary system, supporting the above idea.

But a possibility due to relatively low ($\sim 1/10$) fluxes in NS LMXBs, say Eddington luminosities, and the detection limit cannot be excluded, and more qualitative discussion is necessary.

### 4.3. State Transitions

From an energy spectral point of views, there are also two types of outbursts. One is outbursts exhibiting an optically thick disk dominant state (soft state), and the other is ones staying in the intermediate state so long.

The soft states in GX 339-4 and Cyg X-1 might be good examples (Negoro & MAXI team 2010; c.f., Gierliński & Newton 2006). This and its relation with the morphological types in the longterm flux variations, FRED and FRFT, will be reported elsewhere.

## 5. Summary

To date, MAXI has discovered 6 of 12 BHCs, and complementarily worked with Swift and Suzaku to reveal the nature of the sources.

MAXI observed the sources from the beginning of the outbursts, when the hard-to-soft transition was often observed, to the end. Before the disappearing, MAXI detected the 3rd? and 4th broad maxima in J1836-194 and J1901-057, respectively. MAXI monitored these newly discovered and known BHCs, and detected the state transitions, leading a number of successful, prompt followup observations in multi-wavelengths.

The long-term behaviors of these sources can be classified into two types of the outbursts, 3 FREDs and 3 FRFTs. The cause is still unknown, but the similarity must be helpful to understand the accretion flow from the companion to the black hole through the accretion disk.

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