X-ray upper limits of GW151226 with MAXI

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Abstract

The error region of the gravitational-wave (GW) event GW151226 was observed with Monitor of All-sky X-ray Image (MAXI). MAXI was operated at the time of GW151226, and continuously observed to 4 minutes after the event. MAXI covered about 84% of the 90 percent error region of the GW event during the first 92 minutes or bit after the event. No significant X-ray transient was detected in the GW error region. A typical 3-σ GSC upper limit for a scan is $1.2 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ in the 2–20 keV. The auto-detection (MAXI nova-search) systems detected a short excess event with a low significance (2.85σ) from 5257 s to 5260 s after the GW trigger. Finally, we discuss the sensitivity of MAXI to long X-ray emissions of short gamma-ray bursts, which are expected to accompany GW events.

Key words: gravitational waves — methods: observational — X-rays: general

1 Introduction

The second detection of the gravitational wave (GW) event was made by LIGO (Laser Interferometer Gravitational-Wave Observatory) on 2015 December 26, 03:38:53.647 UT, and named GW151226 (Abbott et al. 2016a). The event was a merger masses of two black holes (BHs), of which the masses are estimated as $14.2_{-3.7}^{+8.3}$ and $7.5_{-2.3}^{+2.0} M_\odot$. A luminosity distance of $440_{-190}^{+180} \text{Mpc}$ was derived by the waveform analysis. An important aspect of this event is that it added another example of a merger of BHs with the total mass of $> 20 M_\odot$ after the first detection of GW150914 (Abbott et al. 2016c).

These GW detection motivated theoretical studies of electromagnetic (EM) radiations from BH mergers (Yamazaki et al. 2016; Loeb 2016; Perna et al. 2016; Kimura et al. 2017). Merger events are possible sources of short gamma-ray bursts (SGRBs; Nakar 2007; Nakamura et al. 2014), which emit gamma-rays and X-rays for a few – several hundred seconds. There are models which predict that these emissions arise from relativistic jets or outflows. EM counterparts can provide essential information of sources such as host galaxies and populations of nearby stars. Searches of an X-ray counterpart of this GW event were carried out by the Fermi/GBM (Racusin et al. 2016), the CALET Gamma-ray Burst Monitor (Adriani et al. 2016), Swift (Evans et al. 2016), XMM-Newton (Racusin et al. 2016), and Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009). No X-ray counterpart was reported for this GW event by any of them, which was similar to the result of GW150914 (Abbott et al. 2016b).

MAXI is an instrument for X-ray monitor from the International Space Station (ISS). It scans most of the sky every orbits (~ 92min) of the ISS with a narrow and long field of view. MAXI searched for an X-ray counterpart of GW150914,
and reported upper limits (Serino et al. 2016; Kawai et al. 2017). In this paper we present detailed results of the MAXI follow-up of GW151226, following a quick report of MAXI non-detection by Negoro et al. (2015).

2 Instrumentation

MAXI on ISS has two instruments: the GSC (Gas Slit Camera; Mihara et al. 2011) and the SSC (Solid-state Slit Camera; Tomida et al. 2011). The field of views (FOVs) of GSC is about 2% of the whole sky. The GSC is not operating in the regions with high particle-background, including the South Atlantic Anomaly and regions with the latitude higher than ~40 degrees, and in the vicinity of the sun (~5 degrees). Although the operating duty ratio is about 40%, the GSC covers about 85% of the whole sky in a scan (Sugizaki et al. 2011). Because the SSC is operated in the night time to avoid the sun light, its operating efficiency becomes considerably low. The SSC duty ratio and sky coverage is about 25-30% and 30% respectively.

A nominal GSC camera can detect transient events with the 2–20 keV flux of ~2 ×10^{-9} erg cm^{-2} s^{-1} (e.g. Serino et al. 2014a; Negoro et al. 2016) in a scan transit. Seven out of the 12 GSC cameras were functioning at the time of GW151226. However, one GSC camera (GSC_0) has a gas leak and lost the stopping power in the high energy band (Mihara et al. 2014). In addition, two GSC cameras (GSC_3 and GSC_6) are working with a half effective area due to the loss of a carbon anode wire, and suffer high background because of loss of the veto cells at the bottom of the counters. Since GSC_0 and GSC_6 observe the same sky region and GSC_0 has better sensitivity (even though the high energy efficiency is less), we did not use the data of GSC_6.

3 Observations

3.1 the observation and coverage of GSC and SSC

The GSC was operated at the time of GW event (t_0 = 2015-12-26T03:38:53.648 UT). The FOVs of the GSC at the time is indicated as white (yellow in the color version) lines in figure 2. Because the instantaneous FOVs of GSC is only 2% of the whole sky, it covered, at the time of the event, 1% of the 90 percent error region of the GW location. Figure 1 shows only the part that GSC covered the GW error region. There is no excess along the line of t_0 or in the GW error region, which means no obvious X-ray counterpart of short timescale around the time of the GW event.

We calculated the coverage of the 90 percent region of both initial BAYESTAR (LIGO Scientific Collaboration & Virgo 2015) and refined LAInference (LIGO Scientific Collaboration & Virgo 2016) GW skymaps. Table 1 gives the GSC-covered fraction of the GW error regions, for three representative time intervals.

Figures 2, 3, and 4 show the all sky X-ray images obtained by the working 6 GSC cameras in the first orbit (92 min), in 1 day and in 10 days, respectively. In producing these GSC images, we did not use the “right” half of the GSC_0 and GSC_3, whose observing regions were covered by normal cameras. As can be seen from these images, the GSC observed about 85% and 99% of the GW error regions in the first orbit and in 1 d, respectively. At ten days after the GW event, the GSC covered the whole of the GW error regions.

On the other hand, scarcely any part of the GW error regions were observed by SSC. Figure 5 shows the all sky X-ray image obtained by SSC. Only 16.5% of the 90 percent region of BAYESTAR map was covered. The observation coverage of SSC is also shown in table 1. Moreover, the effective exposure of SSC observation was low. It was 168 cm^2 s at most and lower than 50 cm^2 s in the 55% of the covered 90 percent region for 10 day observation. 3r upper limit of SSC in 1-5 keV is about 0.25 photons cm^{-2} s^{-1} for the effective exposure of 168 cm^2 s.

3.2 Event search by the nova-alert system

If a GW source emit a significant amount of X-rays, the MAXI nova-alert system (Negoro et al. 2016) may find the emission as a transient X-ray source. However, the MAXI nova-alert system was not triggered in any GW error regions for 1 day since the
Fig. 2. An X-ray image observed by GSC from $t_0-100$ s to $t_0+92$ minutes. The GW 90% probability contours of the LALInference and the BAYESTAR are shown in solid and dashed lines, respectively. The white (yellow in the color version) regions are the FOV of GSC at the GW event. The unit of gray-scale is counts per pixel of HEALPix. The image is in the equatorial coordinates. (Color online)

Fig. 3. Same as figure 2 but from $t_0$ to $t_0+1$ day.

Fig. 4. Same as figure 2 but from $t_0$ to $t_0+10$ days.
GW trigger time, meaning that there was no significant variability with a typically more than $3\sigma$ level. The nova-alert system consists of two nova-search systems to find time variability of the sky, and a following alert system to promptly evaluate statistical significance of the variability.

In figure 6, we plot locations of events which triggered one of the two nova-search systems (one with a relatively higher event threshold). The diamonds represent short-term events that triggered from $t_0 - 100$ s to $t_0 + 92$ min in any of integrated-time bins (1 s, 3 s, 10 s, 30 s, and 1-orbit ($\simeq 92$ min)). The squares show long-term events that triggered from $t_0 + 1$ orbit to $t_0 + 4$ orbits (in 4 orbits bin), and from $t_0 + 4$ orbits to $t_0 + 1$ d (1 d bin). The black, red, green, and blue colors of the marks (see electric version) represent the triggered energy bands; which are at energies of 3–10 keV, 2–4 keV, 4–10 keV, and 10–20 keV, respectively. Chance probabilities to be triggered by background fluctuations, i.e., the trigger criteria, are $\leq 10^{-3}$ to $10^{-4}$. Except for triggers by bright known source activities as shown in figure 6, the system detected 106 short-term triggers in 29 of 49152 sky pixel regions, divided by the HEALPix library (Górski et al. 2005), and 230 long-term triggers in 105 regions. Most these events are thought to be statistical noise because of the relatively low criteria.

A series of 15 events at the position denoted by 'A' in figure 6, however, just fall in the GW error region. At this position, the $3$–$10$ keV and $4$–$10$ keV count rates exceeded the trigger thresholds of the nova-search system, from $t_0 + 5257$ s to $t_0 + 5260$ s (in the first scan transit at the region after the GW trigger). This is true for time bins of 10 s, 30 s and 1-orbit. But, none of the detection criteria of the alert system had not been satisfied (for the detection criteria, see Negoro et al. (2016) in more detail).

As shown later, the count-rate excess at 'A' is only $2.85\sigma$. However, the source image shows a point-source-like structure. By assuming a constant source intensity, we obtained the source position at (R.A., Dec) = (19.913 deg, $-14.480$ deg) = (01$^h$19$^m$39$^s$, $-14^\circ$28'48") (J2000), and the statistical 90% C.L. elliptical error region has the long and short radii of $0.49$ and $0.46$, respectively. The roll angle of the long axis from the north direction is $174.50$ counterclockwise. There is an additional systematic uncertainty of $0.1$ for the above position (90% containment radius). Figure 7 shows a 4–10 keV light curve in the 1-scan bin at this position. The source flux averaged over a scan is $5.1^{+2.1}_{-1.8} \times 10^{-2}$ counts cm$^{-2}$ s$^{-1}$ at the maximum,$^1$ corresponding to approximately $43 \pm 16$ mCrab for a Crab-like spectrum source.

### 3.3 upper limits of the flux

We evaluate the upper limits of the X-ray flux associated with GW151226 by the following procedure. As shown in figure 8, we first selected 26 points representing the observed region. Then we counted the photons in the circular regions with the radii of 2$^\circ$, which is large enough to cover the point spread function. The $1\sigma$ fluctuation of the background is taken as $\sqrt{n}$, where $n$ is the observed counts within the circular region. Next, we calculated the effective exposure $a$, which has the dimension of area.

$^1$ The unit of the source flux is counts cm$^{-2}$ s$^{-1}$ instead of photons cm$^{-2}$ s$^{-1}$, because the image fitting procedure simply provides the count flux and its errors, and we do not apply any corrections for them. The discrepancy between count and photon fluxes comes from the detection efficiency of the GSC cameras, which is more than 80% in 4–10 keV energy range.
Fig. 6. Event positions having triggered a nova-search system of short-term events and long-term events. The black, red, green, and blue colors of the marks represent the triggered energy bands. A position with a label 'A' is the only position in the GW error region (see text for details). The image is the 2–20 keV 1 d GSC image, and the LALInference contour is shown and the BAYESTAR one is omitted. (Color online)

Fig. 7. A 4–10 keV GSC light curve at the position A shown in figure 6. The data were obtained in each scan transit using the image fitting method of Morii et al. (2016).

Fig. 8. The points used to calculate the GSC signal upper limits. The points are selected uniformly within the GW 90% probability contours. The grayscale is the same as figure 2.

4 Discussion

X-ray counterparts of GW events would be detected as short gamma-ray bursts (SGRBs; Nakar 2007; Nakamura et al. 2014). Therefore we compare the flux upper limits in the previous section to expected X-ray fluxes of SGRBs.

First, we compare the upper limits of one scan with a typical flux of an extended emission (Norris & Bonnell 2006), which is long (~ 100 s) X-ray emission after the short hard pulse of a SGRB. The 3σ GSC upper limits of a scan for GW151226 range from 0.11 to 0.45 photons cm$^{-2}$ s$^{-1}$ in 2–20 keV. If we assume a power-law spectrum with a photon index of 2.0, which is typical of extended emissions of SGRBs (Kaneko et al. 2015), the corresponding energy fluxes are $9 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ in 2–20 keV. The observed peak fluxes of extended emissions range from $10^{-8}$ to $5 \times 10^{-6}$ ergs cm$^{-2}$ s$^{-1}$ in 15–350 keV (Kaneko et al. 2015), corresponding to the fluxes of $2 \times 10^{-9}$ to $10^{-5}$ ergs cm$^{-2}$ s$^{-1}$ in 2–20 keV, when the photon index is 2.0. Therefore MAXI/GSC is sensitive to extended emissions with a typical flux.

Next, we consider the case of a short pulse. If the X-ray emission lasts only for 1 sec, the result changes as follows. We need $\sim 10$ photon counts for a 3σ detection of a source. If a GSC camera detects 10 photons in a second and the effective area toward the source is 1 cm$^2$ in 2–20 keV$^2$ at that time (equiv-
alient to the photon flux of 10 photons cm\(^{-2}\) s\(^{-1}\), it corresponds to the energy flux of \(1 \times 10^{-7}\) ergs cm\(^{-2}\) s\(^{-1}\). Here we assume a power-law spectrum with a photon index of 1.0, which is typical of short pulses of SGRBs (Kaneko et al. 2015). In the same way, in order to detect a burst with a duration of 0.1 sec, the 2–20 keV flux should be more than \(1 \times 10^{-6}\) ergs cm\(^{-2}\) s\(^{-1}\). The observed peak fluxes of initial spikes range from \(5 \times 10^{-8}\) to \(10^{-7}\) ergs cm\(^{-2}\) s\(^{-1}\) (Bostanci et al. 2013; Kaneko et al. 2015), corresponding to the flux of \(3 \times 10^{-8}\) to \(5 \times 10^{-6}\) ergs cm\(^{-2}\) s\(^{-1}\) in 2–20 keV, and thus not all of them can be detected by MAXI/GSC.

The distance to the source of GW151226 was estimated as \(440^{+180}_{-150}\) Mpc (Abbott et al. 2016a). On the other hand D’Avanzo et al. (2014) reported the average redshift of SGRB is 0.85, which is \(\sim\) ten times as far as GW151226. The lowest redshift in the samples of D’Avanzo et al. (2014) and Kaneko et al. (2015) are 0.122 and 0.125, respectively, and they are comparable to GW151226. The fact suggests that MAXI/GSC will be able to detect emissions from GW events, especially extended emissions, if the GW events are at the distance of GW151226 or nearer and they are accompanied by SGRBs.

Finally we note that MAXI is capable of detecting bright hard GRBs even out of the field of view (FOV). These GRBs penetrated the shields and the collimators of GSC and deposit the energy in the detectors. Although the processes of the energy deposit, the effective area, and the detection efficiency of these events are different from those of in-FOV events, the detection limits of out-of-FOV events are similar by chance to those of in-FOV events. For example, MAXI detected three out-of-FOV events, GRB 120816B, GRB 140219A (Serino et al. 2014b), and GRB 160625B, whose peak fluxes range from \(10^{-5}\) to \(10^{-3}\) erg cm\(^{-2}\) s\(^{-1}\) in 20 keV–10 MeV (Golenetskii et al. 2012; Golenetskii et al. 2014; Svinkin et al. 2016) and corresponding energy fluxes in 2–20 keV range from \(10^{-7}\) to

| Table 2. observation coverage of the GW maps. |
|---------------------------------------------|
| pt*                                      |
|   RA, Dec†                                |
| cam²                                      |
|    cnt³                                    |
|   exp²                                    |
|    U.L.‡                                  |
|---------------------------------------------|
| a 191.25, 4.93 4 26 87 0.17                |
| b 196.87, -9.44 — — 0 — 4.5 481 1012 0.06 |
| c 202.50, -14.32 4.5 51 155 0.14           |
| d 202.50, -24.46 4.5 49 164 0.13           |
| e 208.12, -29.83 4.5 39 145 0.13           |
| f 213.75, -35.50 — — 0 — 4.5 663 2004 0.04 |
| g 219.37, -41.61 — — 0 — 4.5 532 1542 0.04 |
| h 225.00, -47.95 — — 0 — 5 268 404 0.12   |
| i 232.46, -54.15 — — 0 — 2 141 332 0.11   |
| j 242.89, -60.25 2 27 96 0.16              |
| k 258.49, -66.26 2 39 126 0.15             |
| l 303.75, -66.44 2 29 142 0.11             |
| m 16.87, -19.31 4.5 47 171 0.12            |
| n 22.50, -4.63 4.5 36 152 0.12             |
| o 33.75, 4.93 4 19 91 0.14                 |
| p 33.75, 14.63 4 25 88 0.17                |
| q 39.37, 19.63 4 31 83 0.20                |
| r 45.00, 24.79 4 27 76 0.20                |
| s 50.62, 30.17 4 39 68 0.27                |
| t 56.25, 35.87 3 70 64 0.39                |
| u 61.94, 42.01 3 89 70 0.40                |
| v 70.83, 48.34 3 136 77 0.45               |
| w 82.70, 54.53 0 67 151 0.16               |
| x 97.30, 54.53 0 69 172 0.14               |
| y 112.38, 54.53 0 122 179 0.18             |
| z 127.46, 54.53 0, 122 179 0.18            |

* point ID shown in figure 8
† position of the point in J2000 coordinates
‡ ID of the cameras which observed the point. Camera number in parenthesis was not used
§ observed counts in a circular region of 2 degree radius
# 3σ upper limit in 2–20 keV in the unit of cm\(^{-2}\) s\(^{-1}\)

The duration where the effective area > 1 cm\(^2\) contains about 70% and 85% of the duration of a scan transit for the observation of single camera and two cameras, respectively.
The observed duration of short hard GRB 120816B by MAXI was about 0.8 s, which was consistent with the result of Golenetskii et al. (2012). If short hard GRBs are really associated with some of GW events, MAXI/GSC may detect emissions of them. Although MAXI cannot determine the position of such out-of-FOV GRBs, the position may be determined with the triangulation method using the arrival time of the GRB.

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3 The $E_{peak}$ of SGRB is about 1 MeV. It makes the flux difference between two energy bands by a factor of $10^{-3}$.