X-ray upper limits of GW150914 with MAXI

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Received ; Accepted

Abstract
We searched for X-ray candidates of the gravitational wave (GW) event GW150914 with Monitor of All-sky X-ray Image (MAXI). MAXI observed the error region of the GW event GW150914 from 4 minutes after the event and covered about 90% of the error region in 25 minutes. No significant time variations on timescales of 1 s to 4 days were found in the GW error region. The 3σ upper limits for the X-ray emission associated with the GW event in 2–20 keV were $9.5 \times 10^{-10}$, $2.3 \times 10^{-10}$, and $0.8 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ for the time scale of $\sim 1000$ s, 1 day, and 10 days, respectively. If GW events are associated with short GRBs like GRB 050709, MAXI will be able to detect X-ray emissions from the source.

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

1 Introduction

The first detection of the gravitational wave (GW) has been made by LIGO on September 14, 2015, as known as GW150914 (Abbott et al. 2016a). The strain waveform indicates merger of two black holes (BHs) with masses of 29 and 36 $M_\odot$. It is the first test of the general relativity in the strong field. It is also the first test of the theory for propagation of the gravitational wave in the space. A rough distance of $\sim 400$ Mpc was derived by the waveform analysis with a rather large uncertainty. Another important aspect of this event is the first solid evidence for existence of BHs with intermediate masses $\sim 30 M_\odot$, and the resulting BH with $60 M_\odot$. Reliable dynamical mass measurements of BHs have been made only for the stellar mass BHs in the Milky Way galaxy and the Large Magellanic Cloud, and the super-massive BHs that lie at centres of galaxies including the Milky Way. The stellar mass BHs whose masses are smaller than a few tens of $M_\odot$ are known to be produced by collapse of massive stars at the end of their lives. However, origin of supermassive BHs in nuclei of galaxies is not yet clear. They may be produced by hierarchical mergers of many BHs, or by accretion of gas to the single BH. In either case the massive BHs at high redshifts indicates that there need to be more massive BH as the seed. Kinugawa et al. (2014) suggested that BHs of $\sim 30 M_\odot$ are naturally produced by collapse of pop-III stars at their endpoints, and that binaries of such BHs are the most common sources of gravitational waves. GW150914 is naturally explained in this scenario, and may imply that the remnants of the Universe’s first stars may be found in the neighbourhood of the Milky Way. In order to confirm or test these theories on the birth and evolution of massive BHs, the distance and the environment of the BHs mergers are essential. The poor localization of GW does not allow us to associate the source to any known class of objects such as galaxies, or to know its relative position to its host galaxy.

In order for that we need precise location that is only achievable with electromagnetic (EM) waves. EM counterparts of gravitational wave event have been discussed quite extensively for the case of merger of double neutron star (NS) binary, or NS-BH binaries, where the ejected NS material are supposed to produce EM emission through nuclear decay of r-process elements.
Accretion on to the newly formed BH (Nakar & Piran 2011; Piran et al. 2013), or interaction of Blandford-Znajek jet from the rotating BH (Nakamura et al. 2014).

Not so much discussion was made for BH pairs, but some mechanism have been suggested for possible production of EM emission. For example, Nakamura et al. (2016) suggests a mechanism in which the merged BH could accrete from the interstellar medium to emerge as an EM counterpart.

The possible gamma-ray detection (Connaughton et al. 2016) resembling a weak short gamma-ray burst have prompted theoretical ideas for EM emission. It may not be at all impossible for BH mergers to produce EM emission, if the environment is suitable.

In this paper we present the MAXI follow-up of GW150914. MAXI (Monitor of All-sky X-ray Image; Matsuoka et al. 2009) is an X-ray all-sky monitor on the International Space Station (ISS). It scans most of the sky in every orbit (~92 min) of the ISS with its narrow and long field of view. Most of the error region of GW150914 was covered by MAXI following the event, and placed upper limits on the X-ray emission from the GW event on various time scales.

2 Instrumentation

MAXI has two instruments: GSC (2–20 keV; Mihara et al. 2011) and SSC (1–7 keV; Tomida et al. 2011). The instant field of views (FOVs) of GSC and SSC are about 2% and 1% of the whole sky. The FOVs scan the whole sky once in 92 minutes. Currently 6 out of 12 GSC cameras are functioning (Mihara et al. 2014). GSC are not operating in the regions with high particle-background, which are South Atlantic Anomaly and higher latitude than ~40 degrees. The functioning time is about 40%. GSC is turned off in the vicinity of the sun (~5 degrees). Still, GSC can cover about 85% of the whole sky in 92 minutes (Sugizaki et al. 2011). Because SSC is operated in the night time to avoid the sun light, its operating efficiency becomes considerably low. The SSC functioning time and sky coverage in 92 minutes are about 25-30% and 30%, respectively.

MAXI/GSC is capable to detect transient events with the limit of ~2 × 10−9 erg cm−2 s−1 in the 2–20 keV band (e.g. Serino et al. 2014; Negoro et al. 2016) in a scan transit.

3 Observations

3.1 time and area of the observation

MAXI observes a point of the sky every ~92 minutes. The first GSC observation of the GW150914 region carried out from t₀ (=2015/09/14 09:50:45 UTC) + 4 min to t₀ + 25 min (the first scan, hereafter). Figure 1 shows the sky map of the observed area by GSC during the first scan. Figure 2 shows the observed area and scan time of GSC from t₀ + 4 min to t₀ + 74 min (the first orbit). Probability maps of the GW source position were calculated by various algorithms: Coherent Wave Burst (cWB; Klimenko et al. 2016), LALInference (LALInf; Veitch et al. 2015), LALInference Burst (LIB; Lynch et al. 2015), and BAYESTAR (bay py; Singer & Price 2016). The region with high significance are observed mainly by GSC2, GSC4, and GSC5.

The SSC observation did not started until t₀+48 min, since the ISS entered the day-earth region from t₀-12 min to t₀+44 min, and also South Atlantic Anomaly from t₀+35 min to t₀+46 min. Figure 3 shows the all-sky image obtained by two SSC cameras in 1 day.

3.2 coverage

We calculated the coverage of the 90 percentile region of each GW skymap by the following procedure. First, we calculated the HEALPix map1 of the region which is observed by each GSC camera during the first scan (figure 1). If the center of a pixel is in the field of view of the camera during the time, we regard the pixel as an observed one. Since the pixel size is smaller than the GSC point spread function, it is reasonable. Then we add the maps of all cameras.

Next, we listed the pixel number in the 90 percentile region of each HEALPix map of GW. Then examined in the MAXI map whether the pixels were observed or not. As a result, we obtained the observation coverage within the first scan for each GW map (table 1).

We also show all-sky X-ray images obtained by working 6 GSC cameras from t₀ + 4 min to t₀ + 74 min (in 1.5 hours; figure 4), and in 4 days (figure 5). In producing these GSC images, we did not use GSC4 data of the region where the GSC4 had also observed. This was because the background rate in GSC4 was high due to the loss of the anti-coincident

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1 the pixel size of this GSC map is ~1 deg × 1 deg
the nova-search system.

In figure 6, we plot locations of triggered events in one of two nova-search systems (a system with relatively high event thresholds) for the first 4 days around the error regions. The diamonds represent short-term events that triggered in 1.5 hours in 1 s, 3 s, 10 s, 30 s, and 1 orbit (∼92 min) integrated-time bins. The squares show long-term events triggered from t0 + 1 orbit to t0 + 4 orbits (in 4 orbits bin), from t0 + 4 orbits to t0 + 1 day (1 d bin) and from t0 + 1 day to t0 + 4 days (4 d bin). The colors, black, red, green, and blue, of the marks represent energy bands triggered, corresponding to the 3–10 keV, 2–4 keV, 4–10 keV, and 10–20 keV energy band, respectively. Different mark sizes for different energy band data are to avoid overwriting, and does not show any significance. Chance probabilities to trigger, i.e., the trigger criteria, are ≤10−3 to 10−4.

The circles show detected events, related with the triggered events for 4 days, which meet detected criteria as statistically significant events in the alert system (Negoro et al. 2016). As described previously, no event was detected in any of the 90% probability regions. Bright catalogued sources, such as Cen X-3 and Vela X-1, and their neighborhoods often triggered the system, but are masked in the alert system.

 Triggered events without circles are not statistically significant (usually at least 3σ levels), but are candidates of variable events. An event A at (α, δ) = (132.43, 6.73) in the cWB error regions is noticeable because it first triggered at 09:57:42 (t0 + 417 s) in 30-s and 1-orbit time bins. The 4–10 keV flux at the region in the scan transit at 09:57 was 0.035±0.018 counts cm−2 s−1, and we could not confirm any point-source like excess for this event in GSC images.

An event B at (α, δ) = (150.44, −10.55) near the LALInf 90% probability region and in the LIB one triggered the system from 11:37:36 (∼t0 + 107 min) from 13:10:19 (∼t0 + 200 min) in the 4 orbits bin. These events, however, are due to the noise caused by the reduction of high voltage of the counters and not astronomical events.

### 3.4 upper limits of the flux

We evaluated the upper limits of the flux by the following procedure. First, we selected 10 points representing the observed region and counted the photons in the circular regions with the radii of 1.5 deg, which is the typical size of the PSF. The 1-sigma fluctuation of the background is defined as √n, where n is observed count in the circular region. Next, we calculated the effective exposure a, which has the dimension of area × time, of each of the 10 points. Then we regarded f ≡ 3√n/a as 3-sigma upper limit of the flux at the point. The averages of 3-sigma upper limits of the points for the observations of a scan is 0.12 ± 0.02 c s−1 cm−2 (in 2–20 keV), which corresponds to the energy flux of (9.5 ± 1.8) × 10−10 erg s−1 cm−2.
Fig. 3. A single pixel event X-ray image observed by SSC from $t_0 + 48$ min to $t_0 + 1$ day. The GW 90% probability contours with the same colors in figure 2 were also shown.

Fig. 4. An X-ray image observed by GSC from $t_0 + 4$ min to $t_0 + 74$ min. GW contours are same as figure 3.

Fig. 5. An X-ray image observed by GSC from $t_0 + 4$ min to $t_0 + 1$ day. GW contours are same as figure 3.
The upper limits for the one day and ten days observations in the same energy band are of a scan $0.029 \pm 0.004 \text{ c s}^{-1} \text{ cm}^{-2}$ $[(2.3 \pm 0.4) \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}]$ and of a scan $0.010 \pm 0.001 \text{ c s}^{-1} \text{ cm}^{-2}$ $[(8.2 \pm 1.0) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}]$, respectively.

4 discussion

The upper limits on the X-ray flux on three different time scales can be summarized in table 2. The upper limits for the energy radiated in X-ray over the measurement time scale are also shown, and compared with the energy radiated in gravitational wave. These can be treated as upper limits for the extended X-ray afterglow of the GW event. For example, we estimate that the energy radiated in X-ray afterglow over 1000 seconds is less than $3.5 \times 10^{-6}$ of the total energy released in the BH merger. Since GW150914 is a BH binary merger, strong X-ray emission is not naturally expected. In that respect, our upper limits do not constrain the theory or information on the environment. On the other hand, possible detection of a weak short gamma-ray transient similar to a short GRB by Fermi GBM was reported (Connaughton et al. 2016). The future observation of LIGO with improved sensitivity is expected to detect gravitational waves from mergers of double NSs or BH-NS binaries are expected. For these systems, significant fraction of NS matter is expected to be ejected. Theories predicts various ways of generating electromagnetic radiation from these events resulting from the radiative decays of r-process nuclei (kilonova) and free neutrons, or the relativistic jet powered by the central engine such as accreting BH or rotating magnetic compact objects through the Blandford-Znajek process. In particular, the latter is considered as the promising origin of short gamma-ray bursts, that emits intense gamma-ray radiation followed by extended X-ray emission.

It is interesting to compare the MAXI sensitivity to the X-ray flux expected from the possible gamma-ray transient recorded by Fermi GBM. Using the photon power-law index $-1.4$ and fluence between 10 and 1000 keV of $2.4 \times 10^{-7} \text{ erg cm}^{-2}$ reported for this event, we estimate the 2–20 keV fluence of $\sim 2 \times 10^{-8} \text{ erg cm}^{-2}$. If the event were captured at the middle of the scan transit, it would produce a significant detection with $\sim 10$ counts in a MAXI GSC camera in less than a second, which is more than an order of magnitude higher than the background of GSC (Sugizaki et al. 2011) for that duration. In general, however, MAXI has only a small chance for detecting prompt emission coincident with the gravitational wave, because the instantaneous sky coverage of MAXI is only 2% of the entire sky. We need to wait for more GW events to be detected for such a luck.

It is also instructive to see how the present MAXI upper limits for GW150914 are compared with a possible future detection of a short GRB coincident with GW detection. In Fig. 7 we plot the MAXI upper limits for the X-ray flux as a function of the time since the GW150914 trigger. The three points are naturally aligned on a straight line on a logarithmic plot following a $\propto t^{-1/2}$ relation expected for the background-limited sensitiv-
We can also compare the MAXI sensitivity with the X-ray flux of GRB 050709, a short GRB. We choose this short GRB for comparison, since it is the only short GRB for which the prompt burst phase has been observed in the energy band common with MAXI/GSC. No other GRB missions like Swift and Fermi have comparable sensitivity in the X-ray band below 10 keV. The XMM on HETE-2 observed the prompt short-hard pulse with duration $\sim 0.3$ s and the extended soft X-ray emission that lasted $> 100$ s in the 2–25 keV X-ray band (Villasenor et al. 2005). Its X-ray afterglow was detected by Chandra, which lead to Hubble detection of optical afterglow and identification of the host galaxy at $z \approx 0.16$ with the precise localization (Fox et al. 2005). We plot its X-ray fluxes in the short hard pulse, the extended X-ray emission, and the afterglow with open symbols in Fig. 7. These fluxes are scaled to the source distance of 100 Mpc, the expected range for double NS merger with LIGO O2 (Abbott et al. 2016b). It is immediately clear that the prompt X-ray emission, both short pulse and extended emission, of GRB 050709 is far brighter than the detection threshold of MAXI/GSC even at its original redshift, not to mention the case scaled to the LIGO O2 range. Here after we discuss the possibility for detecting the X-ray emission if a short GRB is associated with the NS merger event in the LIGO O2 run. Despite this high flux, the chance for detecting short pulse is expected to be very low because of the narrow collimation of short GRBs emission (Fong et al. 2015) and MAXI’s small instantaneous sky coverage. While there is strong evidence for the short pulse originating in a relativistic jet with small opening angle, the nature and origin of the soft extended emission remains a mystery. If the collimation of the soft X-ray extended emission is weak, as in the model proposed by Nakamura et al. (2014), the chance for MAXI detection may not be negligible. The MAXI sky coverage may be still a problem, since the duration of soft extended emission is much shorter than the scan interval of MAXI of 92 minutes, the ISS orbital period. However, if the soft extended emission is connected to the late afterglow as indicated by a dashed line in Fig. 7, its flux stays above the MAXI threshold for more than 3000 s, a major fraction of the scan interval, suggesting a higher probability for detection.

In summary, MAXI set an upper limit for the X-ray emission associated with the gravitational wave event GW150914 on the timescales of one orbit ($\sim 1000$ s), day, and 10 days following the GW trigger. In the future GW observing runs, MAXI has the possibility to constrain the model for electromagnetic radiation and association of GW events with short GRBs.

### Acknowledgments

This research has made use of the MAXI data provided by RIKEN, JAXA and the MAXI team. This research was supported by JSPS KAKENHI Grant Number 24740186.

### References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016a, Physical Review Letters, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016b, Living Reviews in Relativity, 19
Connaughton, V., Burns, E., Goldstein, A., et al. 2016, ApJL, 826, L6
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ, 815, 102
Fox, D. B., Frail, D. A., Price, P. A., et al. 2005, Nature, 437, 845
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ, 815, 102

### Table 2. Upper limits for the X-ray flux and radiated energy obtained by MAXI/GSC.

| Timescale  | Flux (2–20 keV) | Luminosity * | Radiated Energy | $E_X / E_{GW}$ |
|------------|----------------|--------------|----------------|----------------|
| 1 orbit    | $< 9.5 \times 10^{-10}$ | $< 1.9 \times 10^{46}$ | $< 1.9 \times 10^{49}$ | $< 3.5 \times 10^{-6}$ |
| 1 day      | $8.6 \times 10^{4}$   | $< 2.3 \times 10^{-10}$ | $4.6 \times 10^{45}$ | $7.4 \times 10^{-5}$ |
| 10 days    | $8.6 \times 10^{5}$   | $< 0.8 \times 10^{-10}$ | $1.6 \times 10^{45}$ | $2.6 \times 10^{-4}$ |

* Distance of 410 Mpc assumed.