

Insight-HXMT Observations of the First Binary Neutron Star Merger GW170817 (Postprint)

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Abstract

Finding the electromagnetic (EM) counterpart of binary compact star merger, especially the binary neutron star (BNS) merger, is critically important for gravitational wave (GW) astronomy, cosmology and fundamental physics. On Aug. 17, 2017, Advanced LIGO and Fermi/GBM independently triggered the first BNS merger, GW170817, and its high energy EM counterpart, GRB 170817A, respectively, resulting in a global observation campaign covering gamma-ray, X-ray, UV, optical, IR, radio as well as neutrinos. The High Energy X-ray telescope (HE) onboard Insight-HXMT (Hard X-ray Modulation Telescope) is the unique high-energy gamma-ray telescope that monitored the entire GW localization area and especially the optical counterpart (SSS17a/AT2017gfo) with very large collection area ($\sim 1000 \text{ cm}^2$) and microsecond time resolution in 0.2-5

MeV. In addition, Insight-HXMT quickly implemented a Target of Opportunity (ToO) observation to scan the GW localization area for potential X-ray emission from the GW source. Although Insight-HXMT did not detect any significant high energy (0.2-5 MeV) radiation from GW170817, its observation helped to confirm the unexpected weak and soft nature of GRB 170817A. Meanwhile, Insight-HXMT/HE provides one of the most stringent constraints ($\sim 10^{-7}$ to 10^{-6} erg/cm²/s) for both GRB170817A and any other possible precursor or extended emissions in 0.2-5 MeV, which help us to better understand the properties of EM radiation from this BNS merger. Therefore the observation of Insight-HXMT constitutes an important chapter in the full context of multi-wavelength and multi-messenger observation of this historical GW event.

Full Text

Preamble

Insight-HXMT observations of the first binary neutron star merger GW170817

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Abstract

Finding the electromagnetic (EM) counterpart of binary compact star mergers, especially binary neutron star (BNS) mergers, is critically important for gravitational wave (GW) astronomy, cosmology, and fundamental physics. On August 17, 2017, Advanced LIGO and Fermi/GBM independently triggered the first BNS merger, GW170817, and its high-energy EM counterpart, GRB 170817A, respectively, resulting in a global observation campaign covering gamma-ray, X-ray, UV, optical, IR, radio, and neutrino wavelengths. The High Energy X-ray telescope (HE) onboard Insight-HXMT (Hard X-ray Modulation Telescope) is the unique high-energy gamma-ray telescope that monitored the entire GW localization area and especially the optical counterpart (SSS17a/AT2017gfo) with a very large collection area ($\sim 1000 \text{ cm}^2$) and microsecond time resolution in the 0.2-5 MeV energy band. In addition, Insight-HXMT quickly implemented a Target of Opportunity (ToO) observation to scan the GW localization area for potential X-ray emission from the GW source. Although Insight-HXMT did not detect any significant high-energy (0.2-5 MeV) radiation from GW170817, its observation helped to confirm the unexpected weak and soft nature of GRB 170817A. Meanwhile, Insight-HXMT/HE provides one of the most stringent constraints (~ 10 to $10^3 \text{ erg/cm}^2/\text{s}$) for both GRB170817A and any other possible precursor or extended emissions in the 0.2-5 MeV range, which helps us to better understand the properties of EM radiation from this BNS merger. Therefore, the observation of Insight-HXMT constitutes an important chapter in the full context of multi-wavelength and multi-messenger observation of this historic GW event.

Keywords: GW170817, BNS merger, gravitational wave electromagnetic counterpart

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1. Introduction

The first direct observation of gravitational waves (GW) from the binary black hole (BBH) merger GW150914 by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) heralded the era of GW astronomy

[1]. However, finding the electromagnetic (EM) counterpart of GW sources is critically important to independently confirm the physical event that produced the GW, to study the GW event in an astrophysical context, to independently measure the Hubble constant, and to investigate fundamental physics (e.g., mass of graviton, Lorentz invariance) [2-4]. Extensive EM follow-up observations have been implemented since the very first GW event GW150914 [5]. Although a possible EM counterpart candidate for GW150914 was reported by Fermi/GBM [6], other studies using the same GBM data [7, 8] and observations using INTEGRAL/SPI-ACS [9] rejected this candidate. In fact, BBH mergers are not expected to produce EM emission [10, 11], except under certain conditions [e.g., 12, 13]. Therefore, the primary targets for GW-EM joint detection are compact binary mergers involving a neutron star, either binary neutron star (BNS) or black hole-neutron star mergers, which is supported by extensive studies of short GRBs over decades [14].

The Hard X-ray Modulation Telescope (HXMT)¹, dubbed Insight-HXMT after its launch on June 15, 2017, was originally proposed in the 1990s based on the Direct Demodulation Method [15, 16]. As China's first X-ray astronomical satellite, it carries three main payloads [17]: the High Energy X-ray telescope (HE, 20-250 keV, 5100 cm²), the Medium Energy X-ray telescope (ME, 5-30 keV, 952 cm²), and the Low Energy X-ray telescope (LE, 1-15 keV, 384 cm²), as shown in Figure 1. The original primary scientific objectives of Insight-HXMT are: (1) to scan the Galactic Plane to reveal new transient sources and monitor known variable sources; (2) to observe X-ray binaries to study the dynamics and emission mechanisms in strong gravitational or magnetic fields [17].

Figure 1 (Left) Insight-HXMT is composed of HE, ME, and LE telescopes. Coordinates used in this paper are shown on the upper left. Incident angle theta is the angle between the line-of-sight to the source and the Z axis. Azimuthal angle phi equals 0° for the X axis and 90° for the Y axis. (Right) The design of the NaI/CsI detector. Slat collimators (not shown) are placed above the Be window.

HE normally operates in regular mode, in which NaI works in the energy range of about 20-250 keV while CsI operates in about 80-800 keV. In order to improve the spectroscopy capability for hard GRBs (i.e., $E_{\text{peak}} \sim \text{MeV}$), a dedicated working mode called GRB mode has been designed and implemented for HE. In this mode, the high voltage of the photomultiplier tube (PMT, the readout device for NaI/CsI scintillator) is reduced so that the measured energy range of CsI extends up to 0.2-3 MeV. Note that the above energy is the deposited energy in CsI caused by incident gamma-rays with energies from ~ 200 keV to tens of MeV, and most of these gamma-rays only deposit part of their energies in CsI.

Collimators placed in front of the detectors (Figure 1 [Figure 1: see original paper]) define the field of view, where CsI is used as an anticoincidence detector to reduce the background of the main detector NaI. However, downloading the individual photon data registered by CsI allows it to detect gamma-rays with

energies from ~ 200 keV up to tens of MeV that penetrate the spacecraft and payload structure and deposit energy in the CsI crystals.

Thanks to the innovative operation of the anticoincidence detectors of HE, the main scientific objectives of Insight-HXMT have been extended to monitor Gamma-Ray Bursts (GRBs) and GW EM counterparts, making Insight-HXMT one of the most important gamma-ray monitors in the gravitational wave astronomy era.

HE consists of 18 cylindrical NaI(Tl)/CsI(Na)² phoswich detectors, each with a diameter of 190 mm and thickness of 3.5 mm and 40 mm for NaI and CsI, respectively. The NaI/CsI phoswich detector is originally designed to measure hard X-rays in the 20–250 keV range incident from the nominal Field of View (FoV, $1.1^\circ \times 5.2^\circ$ and $5.2^\circ \times 5.2^\circ$) defined by slat collimators.

Figure 2 [Figure 2: see original paper] Simulated total effective area of HE's 18 CsI detectors for GRB detection in regular mode (Left) and GRB mode (Right). Each line represents the effective area for each theta angle averaged over azimuthal angle (phi angle from 0 to 360°).

Since the structure of the satellite is very complicated, the detector response to penetrated gamma-rays is quite difficult to compute. On-ground calibration of the response is impossible due to satellite constraints. Therefore, GEANT4 [18] has been utilized to simulate the response of the CsI detector. The simulated effective area as a function of incident energy at different angles for both regular and GRB modes is shown in Figure 2.

As shown in Figure 2, the effective area for typical incident geometry in both regular mode and GRB mode is ~ 1000 cm², meaning that HE is one of the largest GRB detectors in the hundreds of keV to tens of MeV range ever flown and that HE can detect GRBs in either mode. It also shows that HE is an omnidirectional detector for GRBs, thus the FoV for GRB observation is the entire sky not occulted by Earth.

Therefore, Insight-HXMT/HE could serve as an excellent wide-field monitor for high-energy transient sources, including GRBs and GW EM counterparts.

Since first light on June 21, 2017, HE has significantly detected 26 GRBs and published 20 GCN Circulars³ as of September 25, 2017. Examples of detected GRBs are shown in Figure 3 [Figure 3: see original paper]. GRB 170904A (Figure 3, left panel) is a typical bright burst, for which very high statistics were achieved by Insight-HXMT, allowing us to explore variability on the minimum timescale in the MeV energy band.

Figure 3 Light curves of GRB 170904A (Left) and GRB 170921C (Right) detected by Insight-HXMT/HE.

As shown in the right panel of Figure 3, GRB 170921C is a typical short hard burst that was triggered by HE with high significance (12). For comparison, Fermi/GBM only detected it as a sub-threshold event (total significance ~ 8),

while INTEGRAL/SPI-ACS did not trigger it and off-line analysis shows the detection significance is about ~ 4 .

These observational facts demonstrate the capability and advantage of Insight-HXMT/HE in detecting short hard GRBs, which are the expected high-energy EM counterparts of GW sources from binary mergers involving neutron stars (e.g., neutron star-neutron star or neutron star-black hole mergers).

2. GW170817 and Insight-HXMT Observations

On August 17, 2017, at 12:41:04.446 UTC, LIGO was triggered by the first neutron-star binary coalescence GW event (GW170817, [19]). About ~ 2 s later, a weak short GRB (GRB 170817A, [20, 21]) triggered Fermi/GBM independently at 2017-08-17T12:41:06.47 UTC (hereafter T0) [20]. The GBM localization is broadly consistent with the GW location given by the LIGO-Hanford detector [20].

Soon after, this GRB was confirmed by an offline data analysis of INTEGRAL/SPI-ACS [21]. IPN triangulation from the time delay between GBM and SPI-ACS further improved the location of GRB170817A, which is well consistent with the refined GW sky region (~ 30 deg², 90% CL) made by the Hanford-Livingston-Virgo detector network [19]. Coincidence in both temporal and spatial location between GW170817 and GRB170817A strongly supports that they are physically related [22].

Alerts of those observations were distributed quickly within the LVC EM follow-up community, resulting in a historic global observation campaign covering UHECR, gamma-ray, X-ray, UV, optical, IR, radio, and neutrinos [23]. These multi-wavelength and multi-messenger observations finally led to the first discovery of a BNS merger with gravitational waves and EM waves spanning from infrared to gamma-ray bands [23, and references therein].

Insight-HXMT is the unique gamma-ray telescope that monitored the entire GW localization area, especially the optical counterpart (SSS17a [24]), around the trigger time, with ~ 1000 cm² effective area and microsecond (s) temporal resolution at high energies (0.2–5 MeV). Not only did Insight-HXMT perform a prompt observation (section 2.1) of GW170817 and GRB170817A, it also quickly implemented a Target of Opportunity (ToO) observation to scan the GW localization area for potential X-ray counterpart emission (section 2.2), as well as a dedicated ToO observation of the Crab pulsar for calibration of the detector response (section 2.3).

Given the importance of its observation, results from Insight-HXMT have been included in the historic paper on GW170817 [23]. Here we report the detailed observation and data analysis of Insight-HXMT.

2.1 Prompt Observation

Insight-HXMT was conducting a pre-scheduled pointed observation of GRO J1008-57 when GW170817 occurred. HE monitored the entire localization region of Fermi/GBM, the complete LVC sky map, and the final GW source position (i.e., the optical counterpart SSS17a) without any Earth occultation at the trigger time (T0), as shown in Figure 4 [Figure 4: see original paper]. We note that shielding or occultation effects prevented many other X/gamma-ray telescopes from observing GW170817 and GRB170817A around the trigger time [23]. Indeed, Insight-HXMT had been monitoring the SSS17a sky area since the first light of HE ($\sim T0-50$ days), with interruptions only from Earth occultation of the source and automatic shut-off of HE when the satellite passed through the South Atlantic Anomaly (SAA) region. During the pointed observation of GRO J1008-57, Insight-HXMT observed SSS17a with constant incident geometry ($\theta=47.3^\circ$, $\phi=201.1^\circ$, with incident angle definitions shown in Figure 1 caption) from T0-1.15 days to T0+0.29 days.

As shown in the bottom panel of Figure 4, HE provided continuous coverage from T0-650 s to T0+450 s in the vicinity of the trigger time where a short GRB and its related emission episodes (i.e., precursor, extended emission) produced by the BNS merger are likely to occur. Within $T0\pm 5000$ s, the GW source was occulted by Earth from T0-2780 s to T0-650 s and from T0+2950 s to T0+5000 s, while HE was turned off due to SAA passage from T0+450 s to T0+1110 s.

Initial checks of the light curve revealed no counterpart of GRB170817A in the summed light curve of the 18 CsI detectors, which was reported as one of the earliest GCNs regarding GW170817 [25]. Here the summed light curves with different temporal resolutions (bin widths) and time intervals are shown in Figure 5 [Figure 5: see original paper]. The maximum time interval plotted in Figure 5 is T0-650 s to T0+450 s, during which Insight-HXMT provided the most valuable monitoring of any potential high-energy emission from the GW source.

As shown in the top panel of Figure 5, there is no significant excess around the GW merger time or GRB trigger time. We also performed a Monte Carlo simulation for GRB170817A with the incident angle of the GW position and the spectrum measured by GBM [20], and found that some CsI detectors are expected to receive more counts than others (see Figure 6). Therefore, we tried different selections and combinations of those CsI detectors in various energy ranges, but still found no excess. We also checked the light curve of NaI detectors and found no excess either.

The non-detection of GRB170817A in both CsI and NaI is consistent with the expected counts (Figure 6 [Figure 6: see original paper]) based on the GBM spectrum and the corrected detector response (see section 2.3). Thus we conclude that Insight-HXMT did not detect GRB170817A, suggesting that this burst is very weak in fluence and soft in spectrum, which is consistent with the GBM measurement [20].

Figure 4 (Top) The sky area monitored by HE for gamma-ray transients when GW170817 occurred. The entire area of Fermi/GBM localization, LVC location, and the optical counterpart SSS17a was not occulted by Earth. (Bottom) Evolution of the Earth angle of the GW source within $T_0 \pm 5000$ s. Earth angle $< 67.3^\circ$ means the source was occulted by Earth. Gray area indicates SAA passage when HE was turned off. Blue lines are time intervals when HE monitored the GW source (SSS17a).

Figure 5 Light curves of HE's 18 CsI detectors around GW170817 and GRB 170817A. From top to bottom the time ranges and bin widths are: $[T_0 - 2.5$ s, $T_0 + 1.5$ s] and 0.05 s; $[T_0 - 5$ s, $T_0 + 5$ s] and 0.2 s; $[T_0 - 50$ s, $T_0 + 50$ s] and 1 s; $[T_0 - 650$ s, $T_0 + 450$ s] and 5 s, respectively. No significant excess above background variation is found. The bump from $T_0 - 100$ s to $T_0 + 100$ s is caused by charged particles in orbit, as indicated by the bump in the same time interval in the ACD light curve (gray).

As shown in the bottom panel of Figure 5, a bump from $T_0 - 100$ s to $T_0 + 100$ s is evident. However, a similar bump is also seen in the same time interval in the plastic anticoincidence detectors (ACD), which are placed around the HE main detectors to reject charged particles and reduce the background of NaI/CsI [17]. Thus we conclude that this bump is caused by charged particles and has no relation to GW170817.

Searches with time bins of 20 ms, 50 ms, 0.2 s, and 1 s were also performed on the raw light curve, and no significant excess with signal-to-noise ratio (SNR) greater than 5 was revealed; the small bumps in the light curves are caused by charged particles in orbit, which are commonly seen in HE data.

Figure 6 Simulated count rate of the 18 CsI detectors for GRB170817A using the GBM spectrum [20], GW incident angles, and the corrected effective area (see section 2.3). In the 2 s duration of GRB170817A, the total count expected to be detected by HE is ~ 50 , which is well within the 1- σ statistical fluctuation (~ 120) of the background in Figure 5.

2.2 ToO Observation

Immediately after receiving the alerts for GW170817 and GRB170817A, we scheduled a ToO observation to scan the localization region, which was originally provided by GBM and later by the LIGO and Virgo collaboration (LVC) [23], aiming to find potential X-ray emission from the GW source.

The ToO was actually implemented from $T_0 + 6.9$ to $T_0 + 18.0$ hours. During this ToO, the nominal FoVs of ME and LE did not cover the SSS17a area because it was too close to the Sun and beyond the sun avoidance angle ($\sim 70^\circ$) of the telescope. Careful checking of the observation history reveals that some LE detectors with very large FoV ($\sim 50^\circ$) [17] temporarily covered the SSS17a area during the slew; however, those LE detectors were saturated due to the bright Earth.

2.3 Crab Calibration Observation

Since the response of the HE detector for GRB detection is very complicated and ground calibration was not achieved, Monte Carlo simulation should be validated or corrected based on in-flight calibration. Both the gamma-ray flux and spectrum of the Crab pulsar are stable, which could be used to calibrate the effective area of the HE CsI detector. We thus made a dedicated ToO observation with a total exposure time of 168 ks, for which the Crab was set at the same incident direction as GW170817.

The calibration using the Crab pulsar consists of the following steps: First, the arrival time of every event registered by CsI was converted to the Solar System Barycenter (SSB) and the phase was obtained using the ephemeris of the Crab pulsar. Then the pulse profile was folded as shown in Figure 7. Finally, the spectrum accumulated from phase 0.6 to 0.8 was taken as the background for the pulsed component. Considering the exposure time, the mean pulsed flux is about 1.24 ± 0.25 cnt/s.

Figure 7 [Figure 7: see original paper] Crab pulse profile accumulated in the calibration observation, normalized with maximum 1 and minimum 0. Phase 0 represents the position of the X-ray main peak observed by the HE NaI detector.

On the other hand, we calculated the expected mean count rate based on the spectrum of the pulsed component of the Crab pulsar and the simulated detector response for the incident geometry of GW170817. The spectrum of the pulsed component is from [26]. This calculation gives a mean rate of 2.58 cnt/s, thus the ratio between observation and simulation is 0.48 ± 0.1 (1). The same analysis was applied to the observation of Crab at a different incident angle ($\theta = 90.4^\circ$, $\phi = 302.2^\circ$); the observed mean count rate is 0.83 ± 0.14 cnt/s while the simulated rate is 1.95, resulting in a ratio of 0.43 ± 0.07 (1), which is very close to the ratio for the GW source. Therefore, we corrected the simulated effective area with a factor of 0.48 in the following analysis for the GW source.

3. Constraints on the High-Energy Radiation from GW170817

According to short GRB studies over decades, the most likely high-energy EM counterpart of a BNS merger is the short GRB and its afterglow [14], which has been confirmed by the observation of GW170817 [23]. In addition, short GRBs could be accompanied by other radiation components, such as precursors before the trigger [27] or extended emission after the main pulse of the GRB [28]. Although HE did not find any significant excess from GW170817 from T0-650 s to T0+450 s, Insight-HXMT/HE can place stringent constraints (upper limits) on the high-energy radiation from GW170817, including GRB170817A and other possible emission episodes.

We note that, among many operating gamma-ray telescopes, only four mon-

itored GW170817 during the trigger time (T0): Fermi/GBM, Konus-Wind, INTEGRAL/SPI-ACS, and Insight-HXMT/HE [23]. Out of those four telescopes, HE has the unique advantage of large effective area ($\sim 1000 \text{ cm}^2$) as well as microsecond time resolution in the high-energy band (0.2–5 MeV).

To calculate the upper limits, we use the corrected detector response (see section 2.3) as well as different spectral models (see Table 1) and timescales for the potential emission components. Three typical spectral models for short GRBs are used: Band function [29], Comptonized model (i.e., Power-Law with exponential cutoff), and simple Power-Law model. For each model, three sets of parameters are taken to represent soft, medium, and hard spectral hardness. Spectral parameters are summarized in Table 1.

Table 1 Spectral models used for the upper limit calculations.

Spectral model	alpha	beta	Epeak (keV)
Band_1	-1.0	-2.3	500
Band_2	-0.5	-2.3	1000
Band_3	0.0	-2.3	2000
Comp_1	-0.5	-	500
Comp_2	0.0	-	1000
Comp_3	0.5	-	2000
PL	-1.5	-	-

Since GRB170817A showed strong spectral evolution [20], we computed the upper limits for two time intervals for the main burst: $[-0.3 \text{ s}, 0]$ and $[0, 0.25 \text{ s}]$; all times are relative to the GBM trigger time (T0). For other potential emission episodes, timescales used to calculate upper limits are 0.1 s and 1 s for an assumed precursor before the trigger, and 1 s and 10 s for the assumed extended emission after the trigger. Detailed results of upper limits are shown in Figure 8 [Figure 8: see original paper] and summarized in Table 2. These tight upper limits down to $\sim 10 \text{ erg/cm}^2/\text{s}$ in the 0.2–5 MeV band on the high-energy radiation components including the prompt short GRB170817A and other possible precursor or extended emission will help us to better understand the properties of EM radiation from this double neutron star coalescence, as well as the physics of the relativistic jets of short GRBs.

Figure 8 Insight-HXMT upper limits (3) for GRB170817A, precursor, and extended emission with various timescales (width of the upper limit bar). Only results for three Comptonized models (see Table 1) are shown. See Table 2 for comprehensive upper limit results for all spectral models.

Table 2 Insight-HXMT upper limits (3) for different timescales and spectral models (see Table 1) for GRB170817A and other possible precursor and extended emission. T_start and T_end are the start and end times (relative to T0) of the assumed emission component used to calculate the upper limits.

Emission type	T_start (s)	T_end (s)	Band_1	Band_2	Band_3	Comp_1	Comp_2	Comp_3	BL
GRB170817A	0.3	0	1.4e-06	1.6e-06	2.3e-06	7.7e-07	8.9e-07	3.1e-07	1.9e-06
GRB170817A		0.25	2.2e-06	3.1e-06	1.1e-06	1.2e-06	4.3e-07	3.4e-06	3.6e-06
Precursor	-1.0	-0.9	4.8e-06	1.8e-06	2.0e-06	6.4e-07	1.3e-06	1.6e-06	2.3e-06
Precursor	-10.0	-9.0	1.2e-06	1.4e-06	2.1e-06	6.8e-07	7.9e-07	2.8e-07	3.0e-06
Extended	1.0	2.0	3.3e-06	4.4e-06	1.7e-06	1.8e-06	6.1e-07	2.2e-06	2.6e-06
Extended	10.0	20.0	3.6e-06	4.1e-06	1.7e-06	1.8e-06	6.1e-07	2.1e-06	2.3e-06

4. Summary and Conclusions

GW170817 is the first BNS merger discovered by LIGO and Virgo. Fortunately, its electromagnetic counterpart was successfully detected and identified in gamma-ray, optical, X-ray, and radio bands. Insight-HXMT/HE is one of only four gamma-ray telescopes that successfully monitored GW170817 during the trigger time, and HE possesses the largest effective area ($\sim 1000 \text{ cm}^2$) in the 0.2–5 MeV range and the highest time resolution (microsecond). Although HE did not detect GRB170817A, it helped to confirm the unexpected weak and soft nature of this short GRB. Meanwhile, these observations made by HE allowed us to derive one of the most stringent constraints on GRB170817A and other possible emission components related to the GW source, which is very important for characterizing the complete picture of this historic binary neutron star merger and its high-energy electromagnetic counterpart.

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Notes:

¹ <http://www.hxmt.org>

² Hereafter we use NaI and CsI for brevity.

³ https://gcn.gsfc.nasa.gov/gcn3_archive.html

IAU identification of AT2017gfo. Also named as DLT17ck.

The time delay between Insight-HXMT and Fermi/GBM is ~ 3.56 ms for GRB170817A, which is negligible in this analysis.

Note: Figure translations are in progress. See original paper for figures.

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