Search for electromagnetic counterparts of gravitational wave sources with CALET

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Abstract

CALorimetric Electron Telescope (CALET) is observing high energy cosmic rays and gamma-rays on the International Space Station. CALET has been in normal operation since October 2015. The Calorimeter (CAL), which is the primary instrument of CALET, is collecting gamma-ray data in the 1 GeV ~ 10 TeV energy range. The CALET Gamma-ray Monitor (CGBM), which is a secondary instrument of CALET, is monitoring gamma-ray bursts (GRBs) with ~ 60 % duty cycles. At the end of October 2019, CGBM detected 173 GRBs. CGBM detects short GRBs, which are increased importance due to the discovery of GRB 170817A associating with GW170817. We searched for electromagnetic counterparts of 34 gravitational wave events, including one sub-threshold event in the LIGO & Virgo third observation run. As a result, we found no high energy gamma-rays in CAL data but significant excess in CGBM data around the trigger times of any gravitational waves.

Key words: GRBs, gamma-rays, electromagnetic counterparts of gravitational waves

1. Introduction

GRB 170817A, which is the first short GRB associating with the gravitational wave from the binary neutron star merger, was detected by Fermi-GBM and INTEGRAL SPI-ACS (Abbott et al. 2017a; Abbott et al. 2017b). The detection of GRB 170817A is proof of binary neutron stars merger can cause GRBs. Since GRB 170817A is the only GRB associating with the gravitational waves, further detections of short GRBs associating with gravitational wave are needed to understand the association between GRBs and gravitational waves.

The CALorimetric Electron Telescope (CALET) is a payload on the Japanese Experimental Module (JEM) on the International Space Station (ISS) (Torii et al. 2017). The main purpose of CALET is direct observation of high energy cosmic rays and gamma-rays (electrons: 1 GeV ~ 20 TeV, protons & nuclei: 10 GeV ~ 1 PeV, gamma-rays: 1 GeV ~ 10 TeV). CALET consists of two scientific instruments. One of them is Calorimeter (CAL), which is the main instrument of CALET. CAL consists of Charge detector (CHD), Imaging calorimeter (IMC), and Total absorption calorimeter (TASC). CALET Gamma-ray Burst Monitor (CGBM) is also mounted on CALET to enhance the capability of CALET for GRB observations. CGBM consists of two kinds of a scintillation detector, Hard X-ray Monitor (HXM), of which crystal is LaBr₃(Ce), and Soft Gamma-ray Monitor (SGM), of which crystal is B₄Ge₃O₁₂. Crystals of HXM and SGM are read out by PMTs for each. Two HXMs and one SGM are deployed on the CALET to cover the energy band from 7 keV to 20 MeV (Yamaoka et al. 2013). Although CAL and CGBM were in normal operation at the trigger times of GW 170817A & GRB 170817A, the position of GRB 170817A was outside of the CALET field of view (Abbott et al. 2017a; Abbott et al. 2017b; Adriani et al. 2018). In this paper, we summarize CALET observation for gravitational wave events in the LIGO/Virgo third observation run (O3 run).

2. CALET observation and analysis for GW events

CALET specification for gamma-rays is summarized in Table 1. While CGBM has no capability to determine the arrival direction of gamma-rays, CAL reconstructs...
shower tracks and determines the gamma-ray direction. The values shown in Table 1 are just typical values. Effective areas, energy resolutions, and angular resolution depend on energy, incident angle, tracking method, and tracking quality. The detail information about the CAL gamma-ray analysis and CGBM specification are available in Cannady et al. (2018) and Yamaoka et al. (2013), respectively.

CALET data are available from October 2015 to the present. For CAL analysis, we searched gamma-rays associating with gravitational wave events according to the method described in Adriani et al. (2018). We used observation data in the high energy trigger mode (HE mode) and the low energy gamma-ray mode (LEG mode) (Asaoka et al. 2018). The HE mode is the primary trigger mode and is always enabled to collect cosmic rays and gamma-rays above 10 GeV. The LEG mode is enabled at low geomagnetic latitude excepting South Atlantic Anomaly (SAA) and after the CGBM on-board trigger to collect low energy gamma-ray above 1 GeV. If gravitational wave events occurred in the HE mode or LEG mode, we searched gamma-ray events ± 60 s since the trigger times of the gravitational wave events in the energy range 10 GeV ∼ 100 GeV or 1 GeV ∼ 10 GeV, respectively. If there are overlaps between the LIGO&Virgo high probability region and CAL field of view at ± 60 s since the trigger times of the gravitational wave events, we calculated 90% upper limits of gamma-ray flux even if there are no gamma-ray events.

CGBM has been collecting monitor data with ∼ 60% duty cycle since October 2015. We turn off CGBM high voltages at the high latitude and around the SAA to protect PMTs. As of the end of October 2019, CGBM detected 173 GRBs. We measured T0 with SGM in the energy range from 40 keV ∼ 1000 keV. The T0 of 23 GRBs were shorter than 2 s. CGBM can observe short GRBs, which are plausible candidates of electromagnetic counterparts of gravitational wave events. CGBM is always collecting light curve data and spectral data every 1/8 s and 4 s for each. CGBM calculates signal-to-noise ratio (SNR) with the onboard trigger system every 0.25 s. Once SNR exceeds detection threshold, CGBM captures event data and CAL starts the LEG mode. Since no CGBM onboard trigger occurred around the trigger times of any gravitational wave events, we used light curve data for the signal search. The light curve data consists of the high gain data and low gain data. Both high gain and low gain data have four channels (from ch0 to ch3) for each. For the CGBM signal search, we calculated SNR using the light curve data. We used formula (1), which is used onboard trigger system, to calculate SNR.

\[
SNR = \frac{N_{\text{tot}} - N_{\text{BG}}}{\sqrt{N_{\text{BG}}}} \times \Delta t
\]  

,where \( \Delta t \) is integration time of foreground; \( \Delta t_{\text{BG}} \) is integration time of background; \( N_{\text{tot}} \) is integrated counts over \( \Delta t \); \( N_{\text{BG}} \) is integrated counts over \( \Delta t \). \( \Delta t_{\text{BG}} \) was taken from both sides of \( \Delta t \). However, \( \Delta t_{\text{BG}} \) was taken from the one side in the case of CGBM high voltages turning on or off within ±60 s of the event time. SNR was calculated every 1/8 s in 1440 conditions, which are a combination of detectors, gain, channels, \( \Delta t \), and \( \Delta t_{\text{BG}} \) summarized in Table 2. After the calculation of SNR, we searched for significant signals of which SNR exceed 7. The threshold of SNR = 7 is comparable with the detection threshold for the onboard trigger. Since the current CGBM background estimation is based on just integration of observed counts before and after \( \Delta t \), SNR is different from significance using a standard deviation of normal distribution.

The O3 run started on April 1, 2019. As of the end of September 2019, 33 gravitational wave events were reported to the GCN circular by the LIGO & Virgo Collaboration (LVC) during the O3 run.

For 18 out of 33 events, there were overlaps between the CAL fields of view and the LVC high probability region. However, we found no gamma-rays from the LVC high probability region. We estimated 90 % upper limits for the 17 events according to procedures described in Adriani et al. (2018). For another 15 events, there were no overlaps between the LVC high probability region and the CAL field of view. The remaining event occurred when we turned off the CALET high voltages for safety during the ISS special activity. The results of the CAL analysis is described in Mori et al. (2019).

For 19 out of 33 events, there were overlaps between the CGBM fields of view and the LVC high probability region. We searched for signals around the trigger times of gravitational wave events according to the method described above. As a result, there was no significant excess, of which SNR exceeds 7, within ±60 s, since the event times. The other 11 out of 33 events occurred when CGBM high voltages were off. For the remaining three, there were no overlaps between the LVC high probability region and the CAL field of view.

Fermi GBM-190816, which is a sub-threshold gravitational wave event & GRB, was reported (The LIGO Scientific Collaboration, the Virgo Collaboration, and the Fermi GBM team 2019). Although this event is sub-threshold, a gamma-ray signal was detected by Fermi-GBM. Figure 1 shows the CAL 90% upper limits map for gamma-ray in the energy range from 10 GeV to 100 GeV. The summed probability inside the CAL field of view is ∼25% within ±60 s, since the trigger time. We found no gamma-rays from the overlap region in CAL data. Figure 2 shows CGBM light curves around the trigger time of Fermi GBM-190816, and no significant signal can be seen in the CGBM light curves. The SNRs for all 1440
Table 1. CALET specification for gamma-rays

<table>
<thead>
<tr>
<th></th>
<th>HXM</th>
<th>SGM</th>
<th>CAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective area [cm(^2)]</td>
<td>30(^1)</td>
<td>68(^1)</td>
<td>400(^2)</td>
</tr>
<tr>
<td>Energy resolution [%]</td>
<td>8(^\pm)1</td>
<td>11(^\pm)1</td>
<td>∼3(^\pm)2</td>
</tr>
<tr>
<td>Energy range</td>
<td>7 keV∼1 MeV</td>
<td>40 keV∼20 MeV</td>
<td>1 GeV∼10 TeV</td>
</tr>
<tr>
<td>Filed of View [sr]</td>
<td>∼3</td>
<td>∼8</td>
<td>∼2</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>-</td>
<td>-</td>
<td>∼0.5°(^2)</td>
</tr>
</tbody>
</table>

1: For 200 keV gamma-rays. 2: For 10 GeV gamma-rays 3: For 511 keV gamma-rays.

Table 2. Conditions for SNR calculation

<table>
<thead>
<tr>
<th>Number of conditions</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>detector</td>
<td>HXM1, HXM2, SGM</td>
</tr>
<tr>
<td>gain</td>
<td>High, Low</td>
</tr>
<tr>
<td>channels</td>
<td>ch0, ch1, ch2, ch3, ch0-1, ch1-2, ch2-3, ch0-2, ch1-3, ch0-3</td>
</tr>
<tr>
<td>(\Delta t)</td>
<td>1/8 s, 1/4 s, 1/2 s, 1 s, 2 s, 4 s</td>
</tr>
<tr>
<td>(\Delta t_{BG})</td>
<td>8 s, 16 s, 32 s, 64 s</td>
</tr>
</tbody>
</table>

Fig. 1. CAL 90 % upper limit map for Fermi GBM-190816. A color bar shows 90 % upper limits for energy flux in the 10 GeV ∼ 100 GeV band. Green contours show the high probability region of the Fermi GBM-190816. A solid gray line and a cyan bold solid line are the trajectories of the center of the CAL field of view. The cyan bold solid line is for within ±60 s since the trigger time.

conditions at the trigger time was less than ∼4, which are comparable background fluctuations.

3. Conclusion and future works
The CALET has been operating since October 2015. We searched for electromagnetic counterparts for 34 gravitational wave events in the O3 run, including a sub-threshold event, in CALET data. We found no significant signals associating with gravitational wave events so far. We will continue to search for electromagnetic counterparts of gravitational waves and report CALET observation results to contribute coverage of the gamma-ray sky. We are working on the improvement of the CGBM signal search to take into account a more specific field of view analysis and actual background distribution.

References
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Fig. 2. CGBM Light curves for Fermi GBM-190816. The top three-panel show the summed rate light curve of HXM1 and HXM2. The bottom three-panel show to rate the light curve of SGM.

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