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Search for gamma-ray emission from electromagnetic counterparts of gravitational wave sources with the CALET calorimeter

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Introduction

The first detection of a gravitational wave event by advanced LIGO in 2015 prompted the search for and study of electromagnetic counterparts to gravitational wave events on a worldwide scale. If an electromagnetic signal is also observed, it would provide additional information that can give us significantly better constraints on the parameters (such as mass, orbit, spin) of the binary system.

The CALorimetric Electron Telescope (CALET) is a wide field-of-view instrument to study high-energy cosmic-rays onboard the International Space Station accumulating scientific data since October 2015. Gamma-rays in the energy range of 1 GeV to 10 TeV are monitored continuously with its 30 radiation-length deep calorimeter (CAL), with a field-of-view of about 2 sr and an angular resolution better than 0.4 degree above 10 GeV.

We have already reported an upper limit on the GW151226 event claimed by advanced LIGO [1]. In this paper, we describe the refined data analysis of CAL for the GW151226 event and the preliminary results on the third gravitational event, GW170104. Hard X-ray results from CALET Gamma-ray Burst Monitor will be presented separately.

Gravitational events

The first gravitational-wave detection by LIGO, dubbed GW150914, confirmed the existence not only of gravitational waves from astronomical objects but also of a binary black hole system with several tens of solar masses [2]. GW150914 is supposed to be the result of a merger of two black holes with initial masses of $36^{+5}_{-4}M_\odot$ and $29^{+4}_{-4}M_\odot$ at the luminosity distance of 410^{+160}_{-180}Mpc. The Fermi Gamma-ray Burst Monitor (GBM) reported a possible weak gamma-ray transient source above 50 keV at 0.4 s after the GW150914 trigger [3]. However, the upper limit provided by the INTEGRAL ACS instrument in a gamma-ray energy band similar to the Fermi-GBM energy band is not consistent with a possible gamma-ray counterpart of GW150914 suggested by the Fermi-GBM [4].

GW151226 (LIGO-Virgo trigger ID: G211117) is the second gravitational-wave candidate identified by both LIGO Hanford Observatory and LIGO Livingston Observatory with a high significance at 03:38:53.647 UT on 2015 December 26 [5]. The event is very likely a binary black hole merger with initial black hole masses of $14.2^{+8.3}_{-3.7}M_\odot$ and $7.5^{+2.3}_{-2.4}M_\odot$ and a final black hole mass of $20.8^{+6.1}_{-1.7}M_\odot$ [6]. The luminosity distance of the source is estimated as $\sim 440^{+180}_{-190}$Mpc. According to Racusin et al. [7], the flux upper limit of Fermi-GBM is from 4.5×10^{-7} to 9×10^{-7} erg cm^{-2}s^{-1} in the 10-1000 keV band. The Fermi-LAT flux upper limit using the first orbit data after the LIGO trigger is from 2.6×10^{-10} to 7.8×10^{-9} erg cm^{-2}s^{-1} in the 0.1-1 GeV band.

Recently the third candidate, GW170104 (LIGO-Virgo trigger ID: G268556), was identified similarly by the LIGO-Virgo collaboration at 10:11:58.6 UTC on 2017 January 2017 [8]. The inferred component black hole masses are $31.2^{+8.4}_{-6.0}M_\odot$ and $19.4^{+5.3}_{-5.9}M_\odot$. The luminosity distance of the source is estimated as 880^{+450}_{-390} Mpc, which corresponds to a redshift of $0.18^{+0.08}_{-0.07}$. Some electromagnetic counterpart searches at high energies were reported [9].

The CALorimetric Electron Telescope (CALET) mission [10], which was successfully launched and emplaced on the Japanese Experiment Module-Exposed Facility of the International Space Station (ISS) in 2015 August, was fully operational at the LIGO trigger times of GW151226 and GW170104. Here we report on search for electromagnetic counterparts of these events using the CALET data.

CALET/CAL analysis

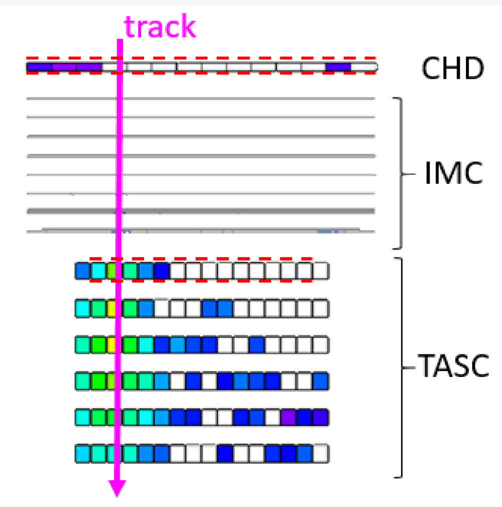

Fig.1 Schematic cross-sectional view of CAL with a sample event. We require that a track should cross the CHD (full area) and the TASC-top (with at least a 2 cm margin from the outer edge as shown by dashed lines).

The CALorimeter (CAL), the main instrument of CALET, consists of three main components: the CHarge Detector (CHD), the IMaging Calorimeter (IMC), and the Total AbSorption Calorimeter (TASC) (Fig. 1). CAL uses two gamma-ray trigger modes: a low-energy gamma-ray (LEG) mode with an energy threshold ~1 GeV used at low latitudes and following a CGBM burst trigger, and a high energy (HE) mode with a threshold ~10 GeV used in normal operation irrespective of geomagnetic latitude [17]. Around the trigger time of GW151226, between 03:30 and 03:43 UT, CAL was performing regular scientific data collection operating in LEG mode. In the case of GW170104, CAL was operating in the high energy trigger mode with an energy threshold of 10 GeV at the trigger time since ISS was orbiting in the high latitude region. In this paper we report on the analysis of the CAL data for these two events. First results on the analysis of GW151226 were already reported [1], and here we describe results with a refined analysis.

We apply a gamma-ray selection by tracking pair creation events in IMC [11, 12] for the flight data. The gamma-ray event selection used in this analysis is basically the same as the one described in ref.[11], although a stronger cut was applied by requiring three or more hits for track reconstruction. We require the tracks cross the CHD (full area) to the TASC-top (except for the 2 cm margin around the outside, see Fig. 1) so that reliable reconstruction of events is possible, and apply cuts to select electromagnetic showers. Finally we select gamma-ray candidates with no hits in CHD. According to the simulation study that has generated events around the instrument isotropically, we estimate that the highest gamma-ray efficiency is achieved around 10 GeV with an efficiency of 50% relative to a geometrical factor of 420 cm^2 sr, which is the 100% efficiency case, by applying the event selections described above. Analysis presented here is optimized to enlarge the field-of-view as wide as possible, so we use a different geometrical cut from the one used in ref. [12] which is optimized for point source analysis. Then we also have to reject gamma-ray candidates which come through the ISS structures (such as solar panels) to remove events generated by cosmic-ray interactions with these structures, which produce event clusters clearly visible in our field-of-view. We compare a distribution of gamma-ray events along the Galactic latitude summed over $|l| < 80^\circ$ with a diffuse model in Fig. 2 which shows a good agreement.

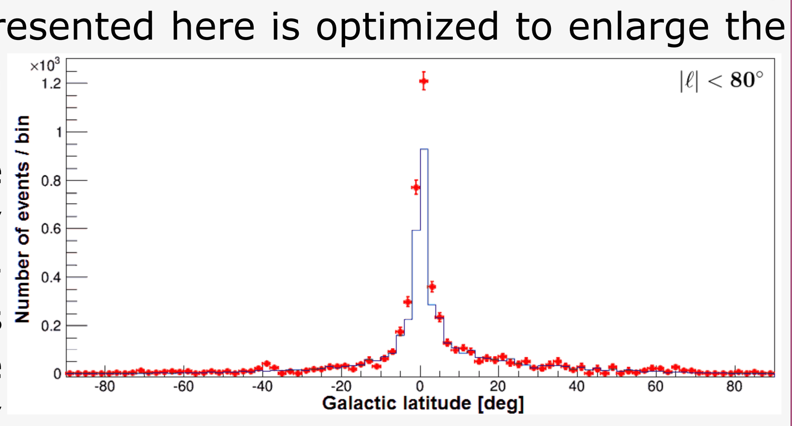

Fig.2 Galactic latitude distribution of gamma-ray candidates observed by CAL summed over the Galactic longitude range $|l|<80^\circ$ compared with an expectation based on the Galactic diffuse emission model [13].

Search for a counterpart of GW151226

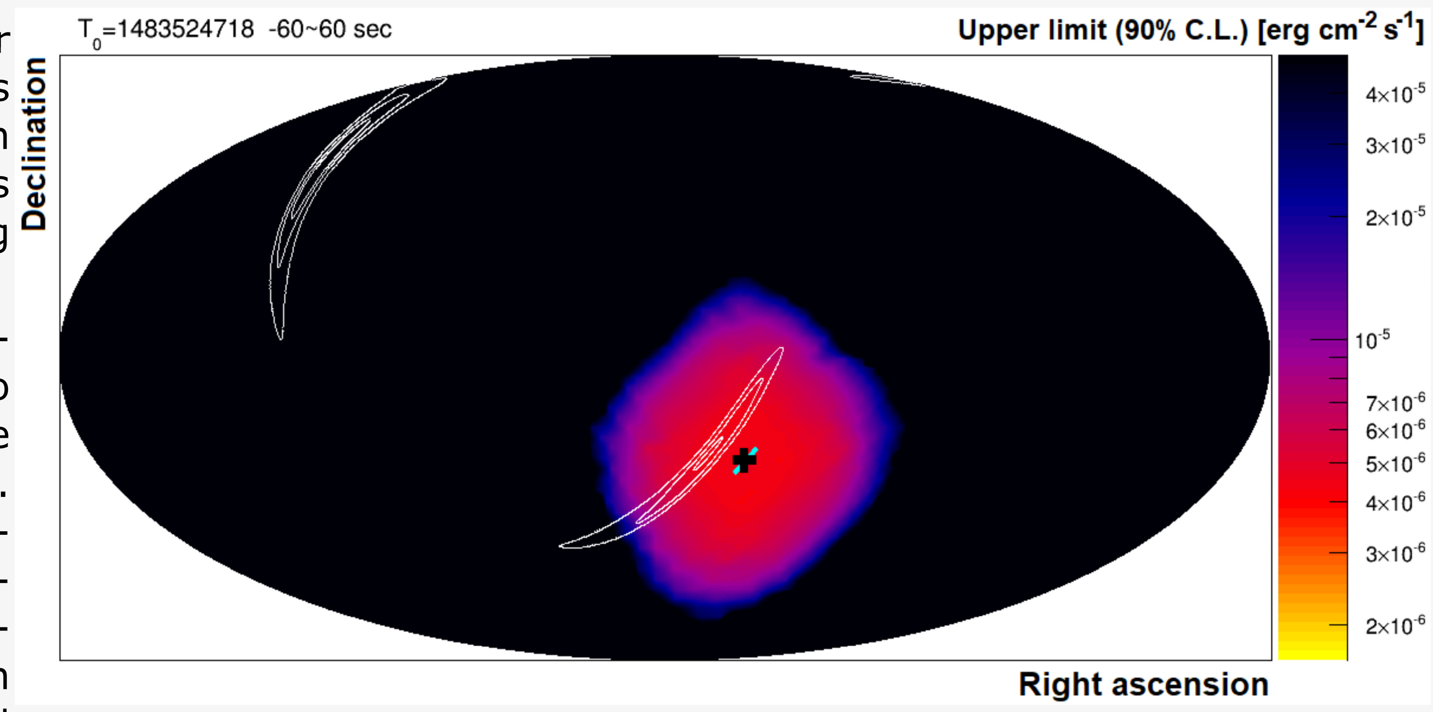

Fig.3 Upper limit (90% C.L.) on energy flux in the 1–10 GeV from GW151226 in the time window [T_0 -525 s, T_0 +211 s] shown in the equatorial coordinates. Thick cyan line shows the locus of the field-of-view center of CAL, and the plus symbol is that at T_0. White contours show the localization significance map of the gravitational wave signal reported by LIGO.

A search for gamma-ray events associated with GW151226 was carried out using the CAL data in the time interval from -525 to +211 s around the LIGO trigger (T_0). The CAL was operational in low-energy gamma-ray mode with an energy threshold of 1 GeV in this time period. We found no candidates in this time window. The upper limit of the CAL observation in this 736 s long period is estimated as follows. First, we calculated the effective area and the resultant exposure map in the time window for the 1–10 GeV band. At lower energies, the effective area gradually decreases below 10 GeV and reaches zero around 500 MeV. By estimating the number of expected number of background events in this time window by comparison of the observed data with a prediction by the Galactic diffuse model [13], we calculated an upper limit on energy flux. Fig. 3 shows the sky map of the flux upper limit at the 90% confidence level.

Search for a counterpart of GW170104

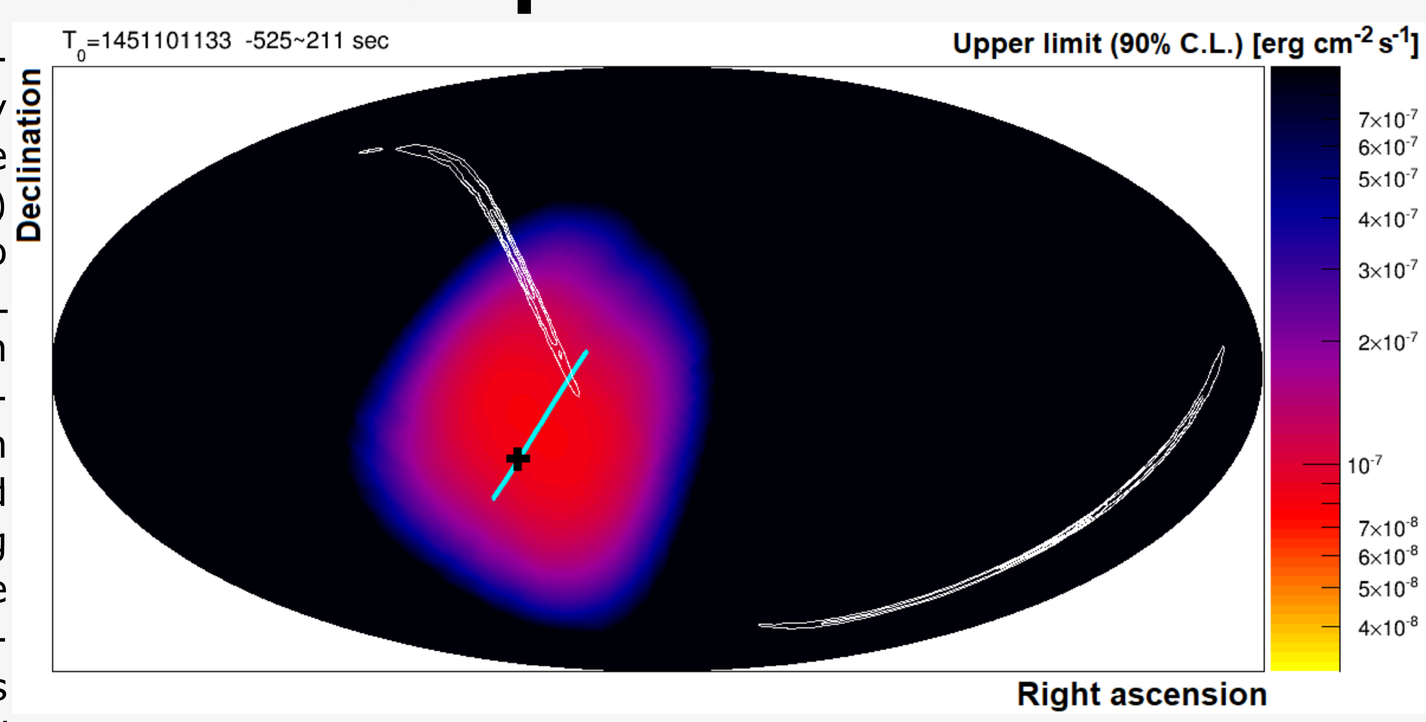

Fig.4 Upper limit (90% C.L.) on energy flux in the 10–100 GeV energy band from GW170104 in the time window [T_0 -60 s, T_0 +60 s] shown in the equatorial coordinates. Thick cyan line shows the locus of the field-of-view center of CAL, and the plus symbol is that at T_0. White contours show the localization significance map of the gravitational wave signal reported by LIGO.

For the time period in the vicinity of the trigger time of G268556 (T_0) corresponding to GW170104, CAL was operating in high energy trigger mode with an energy threshold of 10 GeV. Using CAL data, we have searched for gamma-ray events above 10 GeV from -60 s to +60 s from the GW trigger time and found no candidates. The number of background events in this time window is estimated as in the case of GW151226. Then we obtained an upper limit on the gamma-ray energy flux in the 10–100 GeV energy band for the sky region covering 30% of the summed LIGO probabilities as shown in Fig. 4.

Summary

Summary of CALET/CAL upper limits on energy flux and luminosity of GW151226 and GW170104 are tabulated in Table 1. These results, with other electromagnetic observations and follow-ups, can provide observational constraints for theoretical models for electromagnetic counterparts to black hole mergers. As long as the CALET mission continues, we will monitor gamma-ray emission from any kind of burst-like events at the sensitivity level as described here.

GW event	Energy range	Time window	Summed LIGO probabilities	Upper limit energy flux (90% C.L.) [erg cm^{-2}s^{-1}]	Upper limit Luminosity (90% C.L.) [erg s^{-1}]
GW151226	1-10 GeV	[T_0-525s, T_0+211s]	15%	1.5×10^{-7}	3.4×10^{48}
			25%	5.4×10^{-7}	13×10^{48}
		[T_0-60s, T_0+60s]	15%	1.6×10^{-6}	3.7×10^{49}
			20%	4.1×10^{-6}	9.5×10^{49}
		[T_0-1s, T_0+1s]	15%	1.0×10^{-4}	2.3×10^{51}
GW170104	10-100 GeV	[T_0-60s, T_0+60s]	30%	8.3×10^{-6}	7.7×10^{50}
		[T_0, T_0+1s]	30%	1.1×10^{-3}	1.0×10^{53}
		[T_0, T_0+10s]	30%	3.3×10^{-4}	3.1×10^{52}

Table 1. Summary of CALET/CAL upper limits (90% C.L.) on energy flux and luminosity of GW151226 and GW170104 in various time windows.

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