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Recent results with *Fermi* GBM

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Summary. — The *Fermi* Gamma-ray Burst Monitor (GBM) is an all-sky, hard X-ray/soft gamma-ray monitor, ideally suited to detect rare and unpredictable transient events. In the first eight years since the launch of *Fermi* in 2008 it has triggered on more than 5000 transients, including nearly 1900 gamma-ray bursts (GRBs), many solar flares, bursts from magnetars, and terrestrial gamma-ray flashes (TGFs). Dedicated offline searches over all or parts of the mission have yielded many bursts, non-impulsive steady or variable emission from numerous Galactic sources. *Fermi* GBM is also an excellent partner in the search for electromagnetic counterparts to gravitational-wave events detected by LIGO/Virgo. The paper will give an overview of recent GBM results and the EM follow-up of the recent LIGO O1 gravitational-wave events.

1. – Actual GBM catalogs

Recent published catalogs, making use of multiple years of GBM data, are showing the strong capabilities of GBM for transient source detection in triggered and offline search mode. The following sections are introducing the catalogs and presenting their major results shortly. For more details please see the reference to the original catalog papers.

1·1. *The third Fermi GBM GRB catalog: The first six years* [1]. – The intention of the GBM GRB catalogs is to provide information to the community on the most important observables of the GBM detected bursts. For each one, the location and main characteristics of the prompt emission, the duration, peak flux and fluence are derived. In addition to triggers on GRB events, GBM is triggering on other kinds of transient events. From 2008 July 12 to 2014 July 11, it triggered in total on 3350 transient events. Figure 1 shows the quarterly statistics over this period, highlighting different sources with

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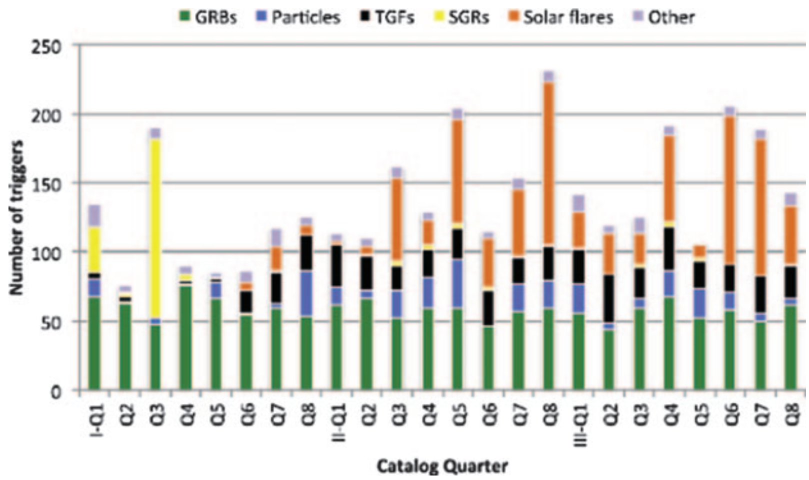

Fig. 1. – Quarterly trigger statistics over the first six years of the GBM mission. The different types of events triggering GBM are classified as shown at the top.

different colors. The total number of detected GRBs is 1404. From this number the six year average GRB rates can be derived, namely $0.662 \pm 0.018\,\text{day}^{-1}$ or 242 ± 7 year^{-1}. The GRB sky distribution in celestial coordinates is shown in fig. 2. There are 1176 long GRBs ($T_{90} > 2\,\text{s}$, black dots) and 228 short GRBs (blue asterisks). The isotropic distribution of long and short GRB arrival directions is evident. The distribution of GBM durations is consistent with the well-known bimodal distribution, with a fraction of short GRBs in the GBM sample of about 21%, which is not significantly different from that detected by BATSE, which is 24%.

1˙2. *The first GBM time-resolved spectral catalog* [2]. – The GBM time-resolved spectral catalog aims to obtain high-quality time-resolved spectral fits of gamma-ray bursts. It presents time-resolved spectral analysis with high temporal and spectral resolution of the brightest bursts observed by *Fermi* GBM in its first four years of mission. For the catalog 1491 spectra from 81 bursts were analyzed. Distributions of parameters, statistics of the parameter populations, parameter-parameter and parameter-uncertainty correlations, and their exact values are obtained and presented as main results in this catalog. Searching for the plausible blackbody emission components it was found that only three bursts (36 spectra in total) show evidence of a pure Planck function. It is observed that the peak energy and the averaged, time-resolved power-law index at low energy are slightly harder than the time-integrated values. It is recommended to use time-resolved spectroscopic results instead of time-integrated results when interpreting physics from the observed spectra.

1˙3. *The Fermi-GBM three-year X-ray burst catalog*[3]. – Although GBM excels in detecting the hard, bright extragalactic GRBs, its sensitivity above 8 keV and its all-sky view make it an excellent instrument for the detection of rare, short-lived Galactic transients. The results of a systematic search for transients using three years of GBM data are summarized in a catalog, containing analysis results for 1084 X-ray bursts [3]. Using spectral analysis, location, and spatial distributions 1084 events were classified into 752 thermonuclear X-ray bursts, 267 transient events from accretion flares and X-ray pulses,

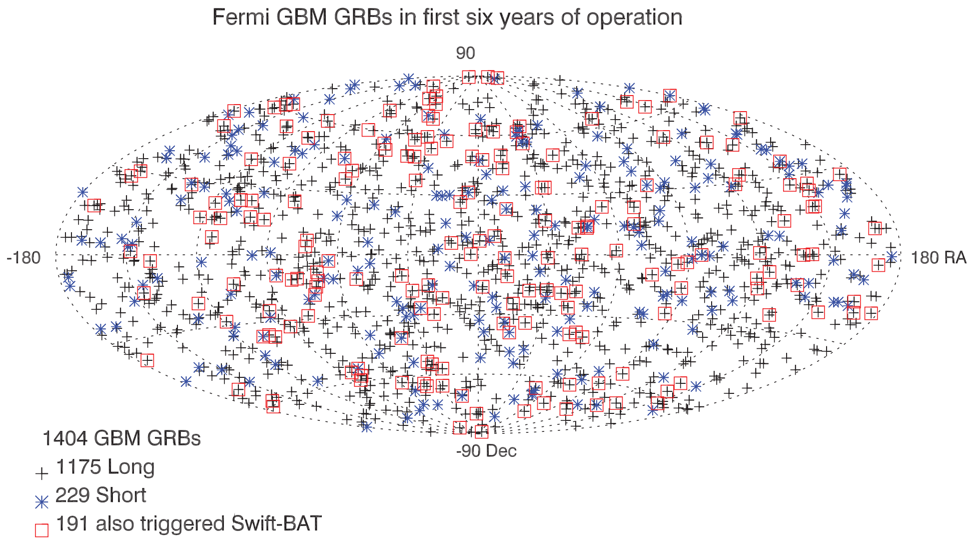

Fig. 2. – Sky distribution of GBM-triggered GRBs during the first six years in celestial coordinates. Crosses indicate long GRBs and asterisks indicate short GRBs. Also shown are the GBM GRBs simultaneously detected by Swift (red squares).

and 65 untriggered gamma-ray bursts. All thermonuclear bursts have peak blackbody temperatures broadly consistent with photospheric radius expansion (PRE) bursts. An average rate of 1.4 PRE bursts per day was found, integrated over all Galactic bursters within about 10 kpc.

1˙4. *The 2nd GBM TGF catalog.* – The second GBM TGF catalog is now online([1]). The catalog contains 4144 TGFs detected between 2008 July 11 and 2016 July 31. It is composed of TGFs bright enough to trigger on board as well as TGFs recovered in an offline search for weaker events ($> 80\%$). It should be noted that the on-board triggering algorithms evolved throughout the period covered by the catalog, and the offline search was first enabled by the availability of high temporal resolution data in 2010. The catalog also includes an associations table containing results for 1544 TGFs for which temporally-coincident radio signals of the World Wide Lightning Network (WWLLN) were found. These associations provide accurate localizations of the TGFs. Links to PDF maps of the WWLLN sferics are accesible in order to show the lightning and storm activity underneath the *Fermi* spacecraft at the times of TGFs.

1˙5. *The five-year Fermi GBM Magnetar Burst Catalog* [4]. – Since launch in 2008, *Fermi* GBM has detected many hundreds of bursts from magnetar sources. While the vast majority of these bursts have been attributed to several known magnetars, there is also a small sample of magnetar-like bursts of unknown origin. The *Fermi* GBM magnetar catalog [4] provides temporal and spectral analyses results of 440 magnetar bursts with high temporal and spectral resolution. This catalog covers the first five years of GBM magnetar observations, from 2008 July to 2013 June. It provides durations,

([1]) `https://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/`.

spectral parameters for various models, fluences, and peak fluxes for all the bursts, as well as a detailed temporal analysis for SGR J1550−5418 bursts. Finally, it is suggested that some of the bursts of unknown origin are associated with the newly discovered magnetar 3XMM J185246.6+0033.7.

2. – Search for electromagnetic counterparts to gravitational-wave events detected by LIGO/Virgo

With an instantaneous view of 70% of the sky, the *Fermi* GBM is an excellent partner in the search for electromagnetic counterparts to gravitational-wave (GW) events.

GBM observations at the time of the Laser Interferometer Gravitational Wave Observatory (LIGO) event GW150914 reveal the presence of a weak transient above 50 keV, 0.4 s after the GW event, with a false-alarm probability of 0.0022 (2.9σ) [5]. This weak transient lasting 1 s was not detected by any other instrument and does not appear to be connected with other previously known astrophysical, solar, terrestrial, or magnetospheric activity. Its localization is ill-constrained but consistent with the direction of GW150914. The duration and spectrum of the transient event are consistent with a weak short gamma-ray burst (GRB) arriving at a large angle to the direction in which *Fermi* was pointing where the GBM detector response is not optimal. If the GBM transient is associated with GW150914, then this electromagnetic signal from a stellar mass black hole binary merger is unexpected. The estimated luminosity in hard X-ray emission between 1 keV and 10 MeV is $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{1}. Future joint observations of GW events by LIGO/Virgo and *Fermi* GBM could reveal whether the reported weak transient is a plausible counterpart to GW150914 or a chance coincidence, and will further probe the connection between compact binary mergers and short GRBs.

Unfortunately, *Fermi* observations of LVT151012 and GW151226 [6] cannot conclusively resolve the unknown nature of the GBM candidate counterpart to GW150914. The partial GBM and LAT coverage of the LIGO localization regions at the time of trigger for both LVT151012 and GW151226 leaves open the possibility that similar EM counterparts occurred outside the GBM and LAT FoVs.

3. – GBM source monitoring programs

Fermi GBM is not a pointed or imaging instrument. But nevertheless it can be used as a monitor for known soures.

3˙1. *GBM Earth occultation observations.* – Within the GBM Earth occulation project, more than 200 sources are monitored continuously since the launch of *Fermi*(2). To determine fluxes for known sources, the change in the count rate observed in the NaI (or BGO) detectors could be measured when the source enters or exits Earth occultation. The measured counts in each energy channel are converted to fluxes using an assumed spectrum for each source. For these measurements the GBM CTIME data are used, with 0.256 s resolution and 8 energy channels covering 8 keV to 1 MeV. In principle this technique uses all 8 energy channels, but for most sources the majority of the signal is in the 12–25 keV and 25–50 keV bands. The most prominent result reported in 2011 is a $\sim$7% (70 mCrab) decline of the overall Crab Nebula flux, found by GBM in the 15–50 keV band using the Earth occultation technique [7].

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(2) `https://gammaray.nsstc.nasa.gov/gbm/science/earth_occ.html`.

3˙2. *GBM Pulsar Monitoring.* – The GBM team provides a web page with the time histories of accreting pulsars([3]). For each source plots are available, showing the history of pulse frequency and pulsed flux measured using the GBM NaI detectors. These measurements also use the CTIME data channels 1 (12–25 keV) and 2 (25–50 keV). The integration interval used varies from source to source, ranging from one to four days. For eclipsing systems each egress to ingress interval is divided into an integral number of equal parts, with no measurement made during the eclipse. The measured frequencies are barycentered. For sources where the binary orbit is known, the frequencies are corrected for the binary motion. The R.M.S. pulsed flux is given in the energy band in which the pulse search was made. This usually includes only the first and second harmonics.

4. – Other recent results: GBM observations of V404 Cygni

V404 Cygni was discovered in 1989 by the Ginga X-ray satellite during its only previously observed X-ray outburst and soon after confirmed as a black hole binary. On 2015 June 15, the GBM triggered on a new outburst of V404 Cygni. 13 days of GBM observations of this outburst were analyzed, including Earth occultation flux measurements and spectral and temporal analysis [8]. The Earth occultation fluxes reached 30 Crab with a detected emission to 100 keV and determined, via hardness ratios, that the source was in a hard state.

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