Fermi GBM as a Transient Monitor

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Outline

• GBM Instrument
• Brief transients (milliseconds to minutes)
  – On-board triggers and ground searches
  – Science of EM counterparts to GWs
  – GBM X-ray burst detections
• Long transients & variable sources (hours to years)
  – Earth occultation and accreting pulsar monitoring
  – Observational results
• Conclusions/Future work
Fermi Gamma-ray Burst Monitor (GBM)

- GBM detectors are scintillating crystals with attached photomultipliers
- NaI: 8 – 1000 keV
- BGO: 200 keV – 40 MeV

Meegan et al 2009, Apj, 702, 791
Fermi GBM provides gamma-ray context observations in the Multi-Messenger Era:

- 87% uptime (off due to SAA),
- Views 69% of sky (Earth blockage),
- Views a particular point on the sky 60% of the time, on average.
Localization is performed by comparing the relative observed rates from the GRB in each detector to the expected rates on a 1 degree grid.

This requires an assumption of the spectrum, and the sky grid limits to a statistical minimum uncertainty of 1 degree radius.
GBM Detector / Instrument Response

- GRB Photon Spectrum
- Instrument Response
- Instrument Background
- Observed Data

GRB Flux (keV · cm$^{-2}$ · s$^{-1}$)
GBM Data

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Time Resolution</th>
<th>Energy Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIGDAT</td>
<td>1024/256/64 ms</td>
<td>8 channels</td>
</tr>
<tr>
<td>CTIME</td>
<td>256/64 ms</td>
<td>8 channels</td>
</tr>
<tr>
<td>CSPEC</td>
<td>4096/1024 ms</td>
<td>128 channels</td>
</tr>
<tr>
<td>TTE</td>
<td>2 s</td>
<td>128 channels</td>
</tr>
<tr>
<td>CTTE (New!)</td>
<td>2 s</td>
<td>8 channels</td>
</tr>
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</table>

- TRIGDAT: used primarily for localization & quick look (triggers only)
- CTIME: temporal analysis
- CSPEC: spectral analysis
- Initially TTE was available ~30s pre-trigger - ~300 s post-trigger
- Continuous TTE (CTTE) implemented on November 26, 2012
Brief Transients
(milliseconds to minutes)
GBM On-Board Triggering

• GBM triggers when 2 or more detectors exceed background by $n$ sigma over timescale $t$ in energy band $e$.

• 70 algorithms operating simultaneously.
  – $4.5 \leq n \leq 7.5$
  – $16 \text{ ms} \leq t \leq 8.096 \text{ s}$
  – $e =$ one of $25 - 50 \text{ keV}$, $50 - 300 \text{ keV}$, $100 - 300 \text{ keV}$, $> 300 \text{ keV}$

⇒ What does GBM trigger on?
GBM Triggers (2008-2017)

2051 GRBs

748 TGFs

270 SGR bursts

1126 Solar Flares

446 Other, 883 particles
GBM Triggered GRBs

- 13% Also seen by Swift
- 6% Also seen with LAT

52% in LAT FoV
48% Outside LAT FoV
Short and Long GRBs

Each year GBM sees:
~200 long GRBs
~40 short GRBs
Swift: ~9 short GRBs/yr

84% of GBM GRBs are long (>2s)
16% are short

GBM is the most prolific detector of short GRBs!
Short GRB / CBC Association

Jet–ISM Shock (Afterglow)
- Optical (hours–days)
- Radio (weeks–years)

GRB
(t ~ 0.1–1 s)

θ_{obs}

Θ_{j}

Ejecta–ISM Shock
Radio (years)

Kilonova
Optical (t ~ 1 day)

Merger Ejecta
Tidal Tail & Disk Wind

v ~ 0.1–0.3 c

BH

Metzger and Berger, 2011
Short GRB / CBC Association

**GW**
- In-spiral confirms CBC progenitor model
- Information about binary system parameters
- Precise merger time
- Standard candle $\rightarrow$ luminosity distance

**EM**
- EM energetics
- X-ray or optical afterglow gives precise location
- Breaks degeneracy in binary parameter estimation
- Host galaxy/redshift
- Local environment information
- With many: jet opening angle
Joint Sub-threshold Searches

The GBM and LIGO teams have been working together to develop automated pipelines to search for sub-threshold signals.

In all cases, the presence of a signal in GBM or LIGO, can raise the significance of the signal being real in the other instrument.

A confident gamma-ray signal enables detecting a fainter gravitational wave signal, increasing the GW detection distance limit, in turn increasing the event rate by a factor of the distance cubed.

<table>
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<tr>
<th>Ideal Scenario</th>
<th>Bright GBM</th>
<th>Bright LIGO</th>
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<tbody>
<tr>
<td>GW150914 Scenario</td>
<td>Sub-threshold GBM</td>
<td>Bright LIGO</td>
</tr>
<tr>
<td>Typical more distant short GRB</td>
<td>Bright GBM</td>
<td>Sub-threshold LIGO</td>
</tr>
<tr>
<td>Both Sources Faint</td>
<td>Sub-threshold GBM</td>
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GBM Ground Searches

• Un-targeted search
  – Looks for signals too faint to trigger on-board
  – Needs no input from other instruments

• Targeted search
  – Seeded with a time and optional sky map
  – Inputs generally from LIGO, neutrino detections, etc.

• X-ray Burst search
  – Manual search, resulting from data cleaning for pulsar monitoring
Un-targeted Search (1)

- [https://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html](https://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html)
- Developed to search for faint short GRBs
- Uses CTTE data, 2μs time resolution, 128 energy channels
- 18 timescales: 64 ms to 32s
  - On-board: 16 ms to 8.096 s
- Time series are made 4 times, offset in phase
- 5 energy ranges (optimized on triggered sGRBs)
- Fit a background using cubic splines and filter out bad background fits
- Fast, efficient, runs on hourly CTTE data as it arrives
Un-targeted Search (2)

- Test for statistically significant excesses in two NaI detectors:
  - Require $\geq 2.5\sigma$ in the best NaI detector & $\geq 1.25\sigma$ in the second best NaI detector,
  - Require Poisson probability $\leq 1E^{-6}$, including trials factor for Nbins in one day,
  - Other trials factors not included.
- Require the detector pair be valid for a distant point source.
Un-Targeted Search Results

318 short, hard candidates (known triggers omitted) in 46 months. ~80 per year, twice the rate of GBM triggered sGRBs.
Verification 1/2

Positive candidates (blue) versus Negative deviations (red)

Current threshold: 1E-6
Un-Targeted Search Verification

- ~1/4 have signals in more than 2 GBM detectors.
- Swift GRB 140606A: not a GBM trigger, easily detected at $P = 1 \times 10^{-20}$.
- INTEGRAL Anti-Coincidence Shield (ACS):
  - ~1/3 of spectrally-hard candidates are detected by the ACS
  - GBM triggered sGRBs: ~50% detected with the ACS.

A very average candidate: signal in only two detectors & $P=2 \times 10^{-7}$.

Not detected in INTEGRAL ACS
Targeted Search of GBM data to GW events

- Developed during LIGO S6 observing run (Blackburn et al. 2015, Goldstein et al. 2016)

• Coherent search over all 14 GBM detectors (NaI and BGO)
  ➢ seeded with time & (optionally) sky location of any LIGO/Virgo candidate event
  ➢ over user-specified time window (±30 s)
  ➢ estimate of background rate by polynomial to local data outside the foreground interval

❖ For each template spectrum (soft, medium & hard) and sky location
  ➢ Each model spectrum is folded through the detector response to determine detector counts
  ➢ Detector counts for each energy channel are weighted according to the modeled rate
  ➢ and inverse noise variance due to background
  ➢ Weighted counts from all NaI and BGO detectors are summed to obtain a signal-to-noise optimized light curve for that model
  ➢ Each model is assigned a likelihood by the targeted search based on the foreground counts

❖ Candidates are ranked by a Bayesian likelihood statistic

❖ Will reveal short-duration candidates between 0.256 s to 8.192 s (CTIME)
Targeted search around GW150914:

- Initial 60s (± 30s) search window (selected a priori)
- 2 candidates
  - Soft transient: $T_{GW} + 11$ s, 2s long: Gal.Cent. region
  - Hard transient: $T_{GW} + 0.4$ s, 1s long: GW150914-GBM

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We report on a sub-threshold targeted followup of LIGO candidate event G184098 in Fermi-GBM survey data for bursts between 0.256s and 8s in duration, and covering a range of GRB spectral models. Although there was no on-board GBM trigger at the time of the event, Fermi-GBM was exposed to a large fraction of the LIGO sky position and thus we searched offline data for untriggered events. The GBM FOV is blocked by the Earth which occults 67 degrees from (RA, DEC) = (355.14, -21.23). Thus GBM observation is able to cover about 87.8% of the cWB sky posterior, and 91.5% of the LIF posterior. We scanned several minutes of GBM live-time centered on the GW event time using a pipeline developed specifically for following-up LIGO-Virgo events in GBM archival data during the LIGO-Virgo S6/VSR3 run [1].

The search identified a possible transient beginning at 150914 09:50:45.8, about 0.4s after the reported LIGO burst trigger time of 09:50:45.39, and it lasted for about 1 second. The intrinsic time resolution for this search was 0.256s. Of the three GRB model spectra tested in the search, the event was best matched to the one corresponding to the hardest spectrum. Using GBM...
GW150914-GBM

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$\rightarrow$ 0.2% probability of occurring by chance (2.9σ)

**False Alarm Probability Calculation:**

- False Alarm Rate (FAR) = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

$$P = 2 \times 4.79 \times 10^{-4} \text{ Hz} \times 0.4 \text{ s} \times (1 + \ln(30 \text{ s} / 0.256 \text{ s})) = 0.0022$$

**Model-dependent count rates:**

Raw count rates weighted & summed to max signal-to-noise for a modeled source

**Raw count rates:**

Sum of all GBM detectors: 12 x NaI + 2 x BGO
NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV
Characteristics of GW150914-GBM

- Unusual detector pattern:
  - Nearly equal count rates in all NaI detectors
  - Localization: source direction **underneath** the spacecraft, 163° to the spacecraft pointing direction

<table>
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<th>NaIs:</th>
<th>50 – 980 keV</th>
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<tr>
<td>BGOs:</td>
<td>420 keV – 4.7 MeV</td>
</tr>
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\[ \text{SNR: } 6\sigma \]

\[ \text{\( \sigma \) deviation from a background fit} \]
Characteristics of GW150914-GBM

• Unusual detector pattern: nearly equal count rates in all NaI detectors
  – Localization: source direction **underneath** the spacecraft, 163° to the spacecraft pointing direction
  – If association with GW150914 was true: shrink LIGO localization by 2/3
Characteristics of GW150914-GBM

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  nearly equal count rates in all NaI detectors
  – Localization: source direction **underneath** the spacecraft, 163° to the spacecraft pointing direction
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• Energy spectrum:
  – Peaking in BGO energy range
  – Best fit **simple PL** with index $-1.4$ (average for sGRBs), Fluence $2.4 \times 10^{-7}$ erg cm$^{-2}$ (weaker than average for sGRBs)
Association with GW150914?

- Evidence for:
  - 3 sigma False Alarm Probability
  - GBM signal localized to a region consistent with the LIGO sky map
  - Cannot be attributed to other known astrophysical, solar, terrestrial or magnetospheric activity

- Evidence against:
  - Low significance
  - Lack of corroboration by other experiments
  - Nature of the LIGO event is a BH-BH merger

<table>
<thead>
<tr>
<th></th>
<th>Duration</th>
<th>Localization</th>
<th>Energy Spectrum</th>
<th>Lightcurve Shape</th>
<th>Fermi Orbit Position</th>
<th>Origin?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning (TGFs/TEBs)</td>
<td>No</td>
<td>No</td>
<td>?</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Galactic Sources</td>
<td>?</td>
<td>No</td>
<td>No</td>
<td>?</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>Solar Activity</td>
<td>?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>Magnetospheric</td>
<td>No</td>
<td>?</td>
<td>?</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Short GRB</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The most likely explanation is a short GRB...
GBM Observations of GW Events

**GW 150914**
(Abbott et al. 2016a)
- BH+BH Merger
- 36 & 29 M☉
- 410 Mpc

**LVT 151012**
(Abbott et al. 2016a)
- Candidate BH+BH
- 23 & 13 M☉
- 1100 Mpc

**GW 151226**
(Abbott et al. 2016b)
- BH+BH Merger
- 14 & 7.5 M☉
- 440 Mpc

- **GW150914-GBM**, a 2.9σ event consistent with a short GRB
  - Not predicted by theoretical models
- **No gamma-ray detections for LVT151012 or GW151226** – not constraining
  - 32% and 17% of LIGO localization region blocked by Earth for GBM
  - Backgrounds were 18% and 3% higher in GBM
  - Distance for LVT151012 was 3x larger
  - If gamma-ray emission is in a jet, only 15-30% would be pointed toward Earth
- **Need more events before we can say more!**
Type 1 X-ray Burst

Neutron star accreting matter from a low mass companion at low mass accretion rate.

- Three types
  - Normal
    - 10-100 s
    - H, He
    - $L \sim 10^{39} - 10^{40}$ erg/s
  - Long
    - 10-30 Minutes
    - He
    - $L \sim 10^{41}$ erg/s
  - Super
    - Hours – Days
    - C
    - $L \sim 10^{42}$ erg/s

$\dot{M} \sim 2\%$ Eddington
GBM X-ray Burst Search

Visual Inspection of CTIME Data

12 NaI detectors
12-25 keV
8 second bins

Initiated March 12, 2010
Identification Process

4U 0614+09

Location

Spectral
What does GBM see?

4U 0614+09

Photospheric Radius Expansion (PRE) Touchdown

Kuulkers et al. 2010

GBM
Three Year X-ray Burst Catalog

https://gammaray.nsstc.nasa.gov/gbm/science/xrb.html


752 Thermonuclear XRBs
267 Transient Events from accretion flares
65 Untriggered GRBs

GBM is sensitive to photospheric radius expansion (PRE) bursts

1.4 PRE bursts per day within 10 kpc
Associations for Low $M_{\text{dot}}$ Accretors

Locations are poor. Must use MAXI rates to determine if potential source is active. Automatic checking.
Long Transients  
(hours to years)
Accretion Powered Pulsar Monitoring

- **Blind search**
  - For unknown sources and unmonitored transients
- **Dedicated search**
  - Search around known frequencies
  - Currently monitoring 39 systems (36 detected)
- **GBM Advantage**
  - Typically > 40,000 s of on-source time per day!

Roche lobe overflow

Wind accretion

Accretion from a Be star’s circumstellar disk
EXO 2030+375 ($P_s=42 \text{ s}, P_{\text{orb}}=46 \text{ d}$)

- Discovered during a giant outburst in 1985 with EXOSAT; Second giant outburst in 2006 (RXTE)
- Transitioned to spin down in 1995 and again in 2016
- Abruptly shifted in outburst orbital phase in 1995 accompanied by a drop in outburst flux; again in 2016
- Detected outburst at nearly every periastron passage since 1991, unlike most Be X-ray binaries
- Correlated peak flux and orbital phase of outburst peak – delay of accretion from Be disk onto NS accretion disk?
GBM Discovers rare torque reversal in Be X-ray binary EXO 2030+375
EXO 2030+375 Long Term Behavior

Graphs showing the behavior of EXO 2030+375 over time, with markers for BATSE, RXTE, GBM, Swift/BAT, and Giant Outburst events.
Orbit Determination – Flux based torque model

Torque Model

\[ \dot{\nu} \propto B^{2/7} F^{6/7} \]

\( \dot{\nu} = \text{frequency derivative} \)
\( B = \text{Magnetic Field} \)
\( F = \text{X-ray Flux} \)

GX 304-1

\( P_{\text{orb}} = 131.69 \)
\( T_{\text{pi/2}} = 2455815.8 \)
\( a_x \sin i = 930 \)
\( e = 0.325 \)
\( \text{Long. of periastron} = 85.8 \)
Orbit Determination

Polynomial Torque model

$P_{\text{orb}} = 131.84$
$T_{\pi/2} = 2455697.9$
$a_x \sin i = 930$
$e = 0.446$
Long. of periastron = 52.3
Earth Ocultation with GBM

‘Occultation steps’ occur in the detector count rates as sources rise above and set below the Earth’s horizon...

GBM Observations of V404 Cyg

• $10 \, M_\odot$ black hole only 2.4 kpc away
• Last X-ray outburst observed with Ginga in 1989
• Two confirmed optical outbursts in 1938 and 1956
• 169 GBM triggers over 13 days starting June 15, 2013
• 73 distinct flaring episodes
• Reached 30 crab with emission up to 300 keV
• GBM observed the entire outburst. It can be analyzed using both triggered data and Earth occultation
Comparing V404 Cyg to GX 339-4

V404 Cyg is predominately in the Low/Hard State

V404 Cyg - Fermi 2015
Long-term Hard X-ray Variations in the Crab Nebula
Searches for multi-messenger counterparts using Earth occultation

• Using the Earth occultation technique, we search for new sources by measuring fluxes for source positions covering the LIGO arc or for the neutrino detection position. This is a search for extended (time) emission.
• We performed these searches for GW150914 (Connaughton et al. 2016), GW151226, and LVT151012 (Racusin et al. 2016) using ± 1 day, 1 month, and 1 year if data were available.
• We have performed similar searches for neutrinos
• To date we have not detected any new sources in these searches
Summary

- GBM detects a broad range of transients, on timescales from milliseconds (TGFs) to years (X-ray binaries and Crab Nebula variations).
- GBM is especially well suited to detecting short GRBs due to its wide field of view, high duty cycle, and broad energy range.
- GBM is the most prolific detector of short GRBs available and we are eagerly awaiting detections of gravitational waves from NS-NS mergers!
- In the meantime, there is plenty of science to do with GBM data.