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

Fermi Gamma-ray Burst Monitor (GBM)

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.
GBM Localization Method

• 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

[Diagrams and graphs depicting GRB photon spectrum, instrument response, instrument background, and observed data]
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>
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<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>
</tbody>
</table>

- TRIGDAT: used primarily for localization & quick look (triggers only)
- CTIME: temporal analysis
- CPSEC: 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.
  – $4.5 \leq n \leq 7.5$
  – $16 \text{ ms} \leq t \leq 8.096 \text{ s}$
  – $e = \text{one of } 25 - 50 \text{ keV}, 50 - 300 \text{ keV}, 100 - 300 \text{ keV}, > 300 \text{ keV}$

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

- 2051 GRBs
- 748 TGFs
- 270 SGR bursts
- 1126 Solar Flares
- 446 Other, 883 particles

Fermi GBM Trigger History

<table>
<thead>
<tr>
<th>Quarter</th>
<th>GRBs</th>
<th>Particles</th>
<th>TGFs</th>
<th>SGRs</th>
<th>Solar Flares</th>
<th>Other</th>
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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

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

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

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

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

![GBM and LIGO Waveforms](image)
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

Probability distribution, short events
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.

6.1σ

A very average candidate: signal in only two detectors & \( P=2\times10^{-7} \).

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)
GW150914-GBM

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

Raw count rates:
Sum of all GBM detectors: $12 \times$ NaI + $2 \times$ BGO
NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV

Model-dependent count rates:
Raw count rates weighted & summed to max signal-to-noise for a modeled source
GW150914-GBM

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

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

False Alarm Probability Calculation:

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

Raw count rates: Sum of all GBM detectors: 12 x NaI + 2 x BGO
NaI: 50–980 keV / BGO: 420 keV – 4.7 MeV

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

**Nals:**
50 – 980 keV

**BGOs:**
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
  - If association with GW150914 was true: shrink LIGO localization by 2/3
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

- 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 magnetostronic 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>Origin</th>
<th>Duration</th>
<th>Localization</th>
<th>Energy Spectrum</th>
<th>Lightcurve Shape</th>
<th>Fermi Orbit Position</th>
<th>Origin?</th>
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<tr>
<td>Lightning (TGFs/TEBs)</td>
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<td>Short GRB</td>
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<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
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</table>

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

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

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

**GW 151226**
(Abbot 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 ∼ 10^{39} – 10^{40} \text{ erg/s}
  – Long
    • 10-30 Minutes
    • He
    • L ∼ 10^{41} \text{ erg/s}
  – Super
    • Hours – Days
    • C
    • L ∼ 10^{42} \text{ erg/s}

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

Visual Inspection of CTIME Data

12 NaI detectors
12-25 keV
8 second bins

4U 0614+09

Initiated March 12, 2010
Identification Process

Location

4U 0614+09

Spectral
What does GBM see?
Three Year X-ray Burst Catalog

[Image with GRB waveforms]

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

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

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
Orbit Determination – Flux based torque model

Torque Model

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

\( B = \) Magnetic Field

\( F = \) X-ray Flux

\( \dot{\nu} = \) frequency derivative

**GX 304-1**

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

\[ P_{\text{orb}} = 131.84 \]
\[ T_{\pi/2} = 2455697.9 \]
\[ a \times \sin i = 930 \]
\[ e = 0.446 \]

Long. of periastron = 52.3
Earth Occultation 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.