FERMI GBM CAPABILITIES FOR MULTI-MESSENGER TIME-DOMAIN ASTRONOMY

V. Connaughton^{1,2}, V. Pelassa¹, M.S. Briggs^{1,2}, P. Jenke¹, E. Troja³,
J.E. McEnery³ and L. Blackburn³

Abstract. Owing to its wide sky coverage and broad energy range, the *Fermi* Gamma-ray Burst Monitor (GBM) is an excellent observer of the transient hard X-ray sky. GBM detects about 240 triggered Gamma-Ray Bursts (GRBs) per year, including over 30 which also trigger the *Swift* Burst Alert Telescope (BAT). The number of GRBs seen in common with *Swift* is smaller than expected from the overlap in sky coverage because GBM is not as sensitive as the BAT and the GBM GRB population is thus skewed to the brighter, closer bursts. This population includes about 45 short GRBs per year, giving GBM an excellent opportunity to observe the electromagnetic counterpart to any gravitational wave candidate resulting from the merger of compact binary members. The same characteristics make GBM an ideal partner for neutrino searches from nearby GRBs, and for the elusive Very-High Energy (VHE) counterparts to GRBs. With the deployment of the next-generation gravitational-wave detectors (Advanced LIGO/VIRGO) and VHE experiments (CTA and HAWC) potentially within the lifetime of the *Fermi* Gamma-ray Space Telescope, the prospects for breakthrough observations are good.

1 Introduction

The Gamma-ray Burst Monitor (GBM) on-board the *Fermi* Gamma-ray Space Telescope covers the entire unocculted sky using 12 thin (1.27 cm) Sodium Iodide (NaI) detectors with different orientations placed around the spacecraft and covering an energy range from 8 keV to 1 MeV, and two bismuth germanate (BGO) scintillators placed on opposite sides of the spacecraft with energy coverage from 200 keV to 40 MeV (Meegan *et al.* 2009). In four years of operation,

¹ CSPAR, University of Alabama in Huntsville, AL 35805, USA

² Department of Physics, University of Alabama in Huntsville, AL 35805, USA

³ NASA GSFC, USA

Fermi has opened a new window to the world of Gamma-Ray Burst (GRB) spectroscopy. Observations by the GBM between 8 keV and 40 MeV and the Large Area Telescope (LAT, Atwood *et al.* 2009) from 100 MeV to tens of GeV have provided a high-energy view over an unprecedentedly long energy baseline. Follow-up observations of LAT-detected GRBs have revealed the distance to 10 GRBs. Typically the *Swift* X-Ray Telescope (XRT) observes the LAT error circle in one or a small number of pointings beginning from 11 to 48 hours after the GBM trigger, after ground-processing of the LAT data. This is followed by optical observations of any fading XRT afterglow candidates. In three LAT-detected GRBs, the latency was much smaller because the GRB also triggered the *Swift* BAT, and in two LAT-detected GRBs the LAT position was accurate enough to permit optical follow-up without the intermediate stage of the *Swift* XRT pointing. The impact of GBM on afterglow observations has been less dramatic owing to the limitations of the uncollimated GBM detectors, which provide good spectral coverage but no imaging localization capabilities. GRB 090902B was observed by ROTSE (Pandey *et al.* 2010) an hour after the GBM trigger, with ROTSE tiling the GBM prompt emission error circle. A source was detected by ROTSE at the position of the burst hours before a better localization was obtained using LAT prompt and *Swift* afterglow data, providing the earliest measurement of the GRB afterglow. The MASTER wide-angle robotic telescope regularly observes GBM error boxes looking for prompt optical emission, but has not found any candidates down to between 8th and 12th magnitude (Tyurina *et al.* 2009). In general, the small fields-of-view of the most sensitive follow-up telescopes have prevented regular afterglow observations of the degrees-scale error circles resulting from GBM localizations and GRB 090902B is the only GBM GRB for which an optical counterpart was detected without localization by an imaging instrument or the InterPlanetary Network.

2 GBM localization of GRBs

Source localization is achieved using the relative rates recorded in the 12 NaI detectors to estimate the most likely arrival direction given the angular and spectral response of the detectors. In addition to background rates which average above 1000 counts/sec over the *Fermi* orbit and vary by a factor of about 2 depending on geomagnetic latitude, the recorded rates from the source of gamma rays contain three elements: direct flux from the source, flux scattered in the spacecraft, and flux scattered from the atmosphere. The contributions from each of these components depend on the observing geometry as well as the spectrum of gamma rays from the source. We construct our response to a particular GRB by adding two model terms, the direct response which depends only on the source-spacecraft geometry, and the atmospheric response which depends on the source-spacecraft-Earth geometry. We compare the observed rates to the expected rates from a GRB coming from each position on the 1° resolution sky grid with one of three typical input GRB spectra - soft, medium and hard - selecting the position and spectral shape that minimize χ^2 . Using a sample of 200 reference GRB positions

from instruments with good localizing capabilities such as the *Swift* BAT, *Fermi* LAT, INTEGRAL, MAXI, SuperAGILE, and the InterPlanetary Network (IPN), we estimate that in addition to the statistical uncertainty associated with this process, there is a 3° systematic uncertainty (1σ) that applies to most GRBs, with about 10% of GBM-detected GRBs having a much larger systematic effect extending beyond 10° (Connaughton *et al.*, in prep.).

Because of on-board computing limitations, the locations produced by the Flight Software (FSW) use a coarser 5° grid, a single spectral shape, and assume the Earth is directly beneath the spacecraft. The ground automated (GA) locations and the final human-in-the-loop (HiTL) locations use the full-resolution grid and Earth-*Fermi* geometry, but the GA location sees only a snippet of source and background data provided by the FSW, whereas the HiTL location requires a longer data downlink and interaction by the burst advocate on duty to select both a good background and an optimized source interval. All three location types are distributed as notices to the GRB Coordinates Network (GCN). Both the FSW and GA notices arrive within seconds of data receipt, or about 30 s following the trigger, and the HiTL notice can arrive as soon as 20–30 minutes up to several hours after the trigger. A HiTL notice is not sent if another instrument has detected the GRB and provided a more precise location, but the FSW and GA notices appear automatically.

3 Who should follow up GBM-detected GRBs?

3.1 TeV community

After 20 years of looking for Very High Energy (VHE) photons from GRBs, beginning in the BATSE era with the Whipple 10-m telescope (Connaughton *et al.* 1997), the field is still without a VHE GRB counterpart or even a meaningful upper limit. A photon with energy E_1 will interact with a photon of energy E_2 to produce an electron-positron pair if $E_1 E_2 * (1 - \cos \theta) > 2(m_e c^2)^2$, where θ is the angle between the two photons, m_e the rest-mass of an electron and c the speed of light. This results in the attenuation of gamma-ray signals above a few tens GeV owing to the presence of intervening Extragalactic Background Light (EBL) photons, and limits the visible horizon so that the higher the energy of a photon, the closer the source must be in order to detect it, with the exact horizon depending on the model assumed for EBL as a function of energy and redshift. Observations of photons above 10 GeV from GRB 080916C by the LAT from a redshift of 4.4, without noticeable attenuation, excluded some proposed EBL models (Abdo *et al.* 2009) but the remaining viable models predict that detections above a few hundred GeV will be possible only within redshift unity. VHE observations of GRBs are also difficult because the duty cycle of the Imaging Atmospheric Cherenkov Telescope (IACT) is low (10–13%) owing to the need for dark, moonless nights, and the slew time to reach a GRB is typically tens of seconds to over a minute. With an energy threshold of 400 GeV, the pioneering IACT, the Whipple 10-m, had a very limited source horizon owing to EBL absorption. The lower energy threshold (100 GeV) of the current-generation IACT arrays such as VERITAS means

that more GRBs lie within the detectable VHE horizon compared to the Whipple era. The most recent results from VERITAS (Acciari *et al.* 2011) show that VHE observations have occurred within the duration of the prompt emission, but not for GRBs known to be within the VERITAS EBL horizon. The next-generation IACT, the Cherenkov Telescope Array (CTA) will be much more sensitive, with three telescope types including the Large Size Telescope (LST) which will have an energy threshold of tens GeV, bringing all but the most distant GRBs within the detection horizon of CTA. The field-of-view of the LST will be $3.5 - 4^\circ$ so that a tiling strategy for following GBM GRBs will be adopted. Estimates of the annual detection rate of GBM GRBs by CTA, taking into account this tiling necessity, the average slew rate of the telescope, and the average spectral and duration properties and distance distribution of GBM-detected GRBs, are a few tenths of a GRB per year, comparable to the expected overlap with the *Swift*-detected GRB sample (Gillmore *et al.* 2013). With broad sky coverage and high duty cycle, the High Altitude Water Cherenkov (HAWC) will be sensitive to bright nearby GRBs without slewing, but with lower sensitivity than CTA. Annual detection rates have yet to be published.

3.2 Neutrino experiments

Neutrinos are expected through the delta resonance from $p\gamma$ interactions in the fireball, and subsequent decay of the delta resonance pion into leptons and neutrinos. For bright GRBs with Lorentz factors of around 100, this flux should be detectable with IceCube (Dermer & Atoyan 2006). A lack of neutrino detection constrains (i) how much energy is in protons relative to electrons in the fireball or (ii) how low the Bulk Lorentz factor of the fireball can be. The lack of neutrino detection by IceCube from a set of over 200 GRBs (a mixture of *Fermi* and *Swift* GRBs) (Abbasi *et al.* 2012) constrains the parameter space in at least one of these directions: either the fireball has such a high bulk Lorentz factor (greater than 400) that the true energy of the protons at the source is too low for the $p\gamma$ interaction, or the amount of energy in protons is much less than 1/10 the energy in electrons. For an individual GRB, the detectability of its neutrino signal depends on (i) the observed gamma-ray fluence of the GRB - the neutrino flux scales with the gamma-ray flux (ii) the Lorentz factor of the GRB - lower is better. Given that GBM is a prolific detector of bright GRBs, it is an ideal partner for neutrino searches from individual bursts in the IC59-or-beyond configurations of IceCube.

3.3 Next-generation gravitational wave experiments

Neutron Star - Neutron Star (NS-NS) and Neutron Star - Black Hole (NS-BH) mergers are believed to be likely sources of detectable gravitational waves. They are also the preferred model for short GRBs (SGRB). Searches for GW signals from 154 GRBs using past science runs from LIGO and VIRGO were not fruitful (Abadie *et al.* 2012), but LIGO was sensitive to SGRBs only within 33 Mpc from NS-NS, 70 Mpc from NS-BH systems, closer than any SGRBs with measured redshift. The expected signal from long GRBs is uncertain. The Advanced

Fig. 1. SGRB rate as a function of redshift for *Fermi* and *Swift*. ALIGO horizons for NS-NS and NS-BH mergers are shown as black vertical lines (Pelassa *et al.* 2012).

configurations of both LIGO and VIRGO will have horizons of $z = 0.11$ (445 Mpc) and 0.22 (927 Mpc) for NS-NS and NS-BH mergers, respectively (Abadie *et al.* 2010). Estimates of annual SGRB detection within these horizons are shown in Figure 1 (Pelassa *et al.* 2012). The SGRBs with known redshift in the *Swift*-detected population are assumed to form part of the same population as those with unknown redshift so that the number of SGRBs detected by *Swift* per year, N_{Swift} , as a function of redshift is presented as the number of SGRBs with measured redshift in each bin divided by the fraction of SGRBs with known redshift. The same assumption about the underlying redshift distribution of GBM-detected SGRBs yields the number of SGRBs per year seen by GBM, N_{GBM} , as a function of redshift. Given that $N_{GBM}/N_{Swift} = 4.5$ we show the expected SGRB detection for GBM as a function of redshift by multiplying the *Swift* SGRB distribution by this factor. Bromberg *et al.* (2012) suggest that because of the greater sensitivity of *Swift* to short collapsar events relative to GBM, the *Swift* SGRB sample may be contaminated by collapsar events and one can be confident that *Swift* SGRBs are merger events only in the sub-sample of SGRBs lasting less than 0.6 s. For this reason, N_{GBM}/N_{Swift} may be larger for merger SGRBs and the number of merger events seen by GBM within the ALIGO horizon could also be larger than suggested by Figure 1. ALIGO localization of detected GW events can produce large non-contiguous sky regions covering up to 100 sq degrees, so that in addition to providing the electromagnetic counterpart to a GW candidate, the moderate localization capability (10 sq degrees) of GBM is useful in eliminating some of these regions for follow-up by X-ray or optical instruments. In the absence of a convincing GW event, GBM can also provide useful seed sky positions for sub-threshold offline ALIGO searches.

4 The future

Even with no improvement in localization capabilities over the *Fermi* mission, GBM is an ideal partner for neutrino and GW searches, particularly in the era

of ALIGO/VIRGO and the deployment of new IceCube configurations with more strings. A modest improvement would really help the case for CTA, removing the need to tile the error box, and thus increasing the joint GBM-CTA GRB detection rate from a few tenths to 1 per year. Efforts to improve GBM GRB localization include: (i) characterization of systematic errors to either identify GRBs with low systematic uncertainties or refine the localization based on GRB or geometrical properties that might lead to a large but measurable systematic effect (ii) moving to a real-time GA location that uses more data and is not limited by statistics (iii) improving our detector response database by identifying its deficiencies through our study of localization errors and (iv) reducing the statistical uncertainty of GBM locations through finer grid resolution, gradient searches within the existing grid, or other algorithmic techniques.

References

- Abadie, J., Abbott, B.P., Abbott, R., *et al.*, 2010, *Class. Quant. Grav.*, 27, 173001
- Abadie, J., Abbott, B.P., Abbott, R., *et al.*, 2012, *ApJ*, 760, 12
- Abbasi, R., Abdou, Y., Abu-Zayyad, T., *et al.*, 2012, *Nature*, 484, 351
- Acciari, V., Aliu, E., Arlen, T., *et al.*, 2011, *ApJ*, 743, 62A
- Atwood, W.B., Abdo, A.A., Ackermann, M., *et al.*, 2009, *ApJ*, 697, 1071
- Abdo, A., Ackermann, M., Arimoto, M., *et al.*, 2009, *Science*, 323, 1688
- Bromberg, O., Nakar, E., Piran, T., & Sari, R., 2012 [[arXiv:1210.0068](#)]
- Connaughton, V., Akerlof, C.W., Barthelmy, S., *et al.*, 1997, *ApJ*, 479, 859
- Dermer, C.D., & Atoyan, A., 2006, *New J. Phys.*, 8, 122
- Gilmore, R., Bouvier, A., Connaughton, V., *et al.*, 2013, to appear in *Exp. Astron.*
- Greiner, J., Clemens, C., Kruehler, T., *et al.*, 2009, *A&A*, 498, 89
- Meegan, C., Lichti, G., Bhat, P.N., *et al.*, 2009, *ApJ*, 702, 791
- Pandey, S., Swenson, C.A., Perley, D.A., *et al.*, 2010, *ApJ*, 714, 799
- Pelassa, V., Connaughton, V., Troja, E., *et al.*, 2012, *eConf Fermi Symposium 2012*
- Tyurina, N., Lipunov, V., Kornilov, V., *et al.*, 2009 [[arXiv:0907.1036](#)]