# *Fermi* Solar Flare Observations

*Submitted in response to NASA Solicitation NNH08ZDA001N-FERMI*
*Fermi Guest Investigator - Cycle 2*
*(Phase 1)*

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## Abstract (800 characters maximum)

We propose a 3-year effort to ensure realization of the unique scientific potential of *Fermi* solar-flare observations. We will make the GBM and LAT flare data and our IDL analysis tools readily accessible to the solar community. We will analyze X- and gamma-ray flares, and cross-calibrate GBM with *RHESSI* and other solar instruments. From these measurements we will obtain information on flare-accelerated electrons and ions that can be compared with SEPs. We will expand the pion-decay model used in LAT analysis to include non-isotropic production. We propose autonomous solar pointing to optimize the study of long-duration gamma-ray flares with LAT. We will encourage the international solar physics community to carry out joint scientific analysis of *Fermi* data.

# *Fermi* Solar Flare Observations

## 1. Summary

This three-year effort is designed to ensure the full realization of the unique scientific potential of *Fermi* solar-flare observations. We propose the following four distinct tasks to achieve this goal:

1. Provide the scientific community with *Fermi* solar flare data products, rapid access to GBM and LAT solar data, and Solar Software (SSW) tools for joint spectral and time series analysis. We will encourage the joint analysis of *Fermi* solar observations with data from other instruments observing at the same time in similar energy ranges and at other wavelengths.
2. Analyze GBM X-ray flares. This effort will include the cross-calibration of the GBM detectors with *RHESSI* and other solar instruments. We propose to determine the total energy in nonthermal electrons, analyze the subsecond structure of the hard X-ray time histories, and evaluate the relation between hard X-ray spectral evolution and the occurrence of Solar Energetic Particle (SEP) events at the Earth.
3. Analyze gamma-ray events seen above 300 keV with GBM, and those detected above 20 MeV with LAT. This will include, (a) gamma-ray spectroscopic studies to obtain information on the ambient medium, accelerated ions and electrons, and their relation to SEP events, and (b) improved theoretical modeling of the production of pion-decay gamma rays and the determination of neutron sensitivity for use in the analysis of LAT observations up to tens of GeV.
4. Support autonomous *Fermi* solar pointing to maximize LAT exposure to long-duration gamma-ray flares.

The analysis of the *Fermi* solar observations will be greatly enhanced by incorporating data from other instruments observing at the same time in similar energy ranges and at other wavelengths. We are providing specific software tools to access and jointly analyze data from *RHESSI*, *INTEGRAL*, and *CORONAS*, but all data available through the Virtual Solar Observatory (VSO) will be accessible for inclusion in the analysis.

This proposal is relevant to NASA's Strategic Heliophysics Science Area - Understand the Sun and its effects on Earth and the solar system. It addresses the Science Question - How and why does the Sun vary?

## 2. Scientific Motivation

Based on almost 300 years of history since the Maunder Minimum ended in 1715, we can be confident that solar activity will increase during the three years of the proposed effort as Solar Cycle 24 begins. Predictions made by a NOAA panel in 2008 suggest that solar activity will be lower than the recent average and will peak in 2012. However, even taking the lower bound of these predictions, in the three years of the proposed effort, we can expect to detect thousands of GBM events above its threshold energy, tens of events above 300 keV, and several gamma-ray events detectable with LAT.

The rarity and importance of the LAT events means that we must be well prepared to observe them with the highest possible exposure in the next three years. This requires autonomous repointing of the spacecraft towards the Sun when such an event occurs because high energy emission can extend for hours. Historically, these intense high-energy solar flares often occur during the rising phase of a solar cycle. For example, the intense activity in 1997 November, just one year after solar minimum, culminated in the November 6 gamma-ray flare and its associated ground-level particle event.

GBM and LAT together provide the capability for observing solar flare X- and gamma-rays from ~8 keV to hundreds of GeV. GBM covers the energy range from ~8 keV to ~40 MeV. Its NaI detectors have sensitivity similar to *RHESSI*'s up to ~1 MeV while the BGO detectors are significantly more sensitive, with the photopeak effective area comparable to the Gamma-Ray Spectrometer on the Solar Maximum Mission, but with somewhat worse energy resolution. LAT covers the energy range from 20 MeV to several hundred GeV. Its peak effective area of 9000 $cm^2$

is much greater than EGRET's on CGRO. All of these high-energy measurements will complement those made by *RHESSI*, *INTEGRAL*, and *CORONAS*, and they will provide the high-energy context for solar observations made by other observatories in space (e.g. STEREO, Hinode, SOHO, ACE, SDO) and on the ground.

X-ray flare emissions include a thermal component sometimes extending to 30 keV or higher from plasma at temperatures of 10 – 20 MK or higher. Bremsstrahlung from nonthermal electrons dominates at higher X-ray energies. Above ~300 keV, gamma-ray line and continuum emission from accelerated ions becomes important. Above ~50 MeV, the emission is expected to be dominated by pion-decay radiation with a spectrum extending to several GeV that closely reflects that of the flare-accelerated protons and alpha particles. The accurate measurement of these X-ray and gamma-ray emissions provides critical information needed to understand electron and ion acceleration in solar flares to the highest energies. Share and Murphy (2007) discuss the major solar science objectives that *Fermi* can achieve through these observations.

The relative intensities of the gamma-ray line and continuum emissions provide information on the composition and spectra of accelerated ions and electrons and the composition and conditions in the ambient atmosphere where the ions interact. A major *Fermi* solar objective is to compare the flare-accelerated particle population revealed by the gamma-ray observations with the in-situ space particle measurements. This is important in understanding the origin of potentially dangerous SEP events.

## 3. Proposed Research

### 3.1 Enabling Access to *Fermi* Solar Data

Under our currently funded *Fermi* GI program entitled "Facilitating the Joint Analysis of GLAST Solar Flare Observations," we are developing software to make GBM and LAT data readily analyzable by the international solar physics community. For this purpose, we are using our existing IDL display and analysis tools that build on our experience with our CGRO/BATSE GI program and that have been developed during the seven years of the *RHESSI* mission. We expect that augmentation of these tools, all available through SSW, will be completed by July 2009 to accommodate GBM and LAT data. At that time, any user will be able to carry out detailed temporal and spectral analysis of *Fermi* solar flare data with minimal instrument-specific knowledge. Furthermore, contemporaneous observations of the same flares, including those made by *RHESSI* and *CORONAS*, will be available for joint analysis using the same familiar software tools.

Functions commonly used for solar flare X-ray and gamma-ray spectral analysis are already incorporated in OSPEX, our spectral analysis package specifically designed for solar X-ray and gamma-ray data. These include the thermal X-ray line and continuum spectra from CHIANTI, and multiple power-law electron and photon spectra. , We propose to add templates for the gamma-ray lines between ~300 keV and 10 MeV depending on the spectrum of the accelerated ions. In addition, we will add other gamma-ray functions to accommodate the full LAT energy range. These will incorporate new results as they become available from the theoretical modeling of the pion-decay emission extending to several GeV discussed in section 3.3.2.

Examples of the basic capabilities of our software tools are shown in Figs. 1 and 2, where time histories and spectra are plotted from different instruments for a GOES C-class flare. The disagreement between the GBM and *RHESSI* spectra evident in Fig. 2 already reveals a problem with either one or the other response matrix or both.

Based on this software development, we will generate the following products and capabilities for *Fermi*'s first year of operations and for the duration of the proposed three-year program:

- An on-line flare list with the usual flare parameters similar to the *RHESSI* flare list found at http://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt
- Quicklook plots of GBM light curves for each orbit available on line through a Web browser similar to the *RHESSI* browser at http://sprg.ssl.berkeley.edu/~tohban/browser/?show=grth+qlpcr

- Event files containing GBM and LAT solar flare data and the appropriate detector response matrices for both GBM triggered and untriggered events.

### 3.2 GBM X-ray Flares

A major objective of this proposal is to use GBM flare data to complement *RHESSI* observations. Fig. 2 shows the need for cross-calibration especially at the lowest energies where the attenuation is highest. This issue will be pursued by comparisons with separate spectra from each of *RHESSI*'s nine germanium detectors.

Below 20 keV, comparisons will also be made with coincident spectra measured with the Solar Photometer in X-rays (SPHINX) on the recently launched Russian *CORONAS* mission. SPHINX covers the energy range from 1 – 20 keV with better than 1 keV FWHM resolution. Three collimated silicon PIN detectors with widely different areas are used to mitigate pulse pile-up. We will conduct a detailed comparison of *RHESSI*, SPHINX, and GBM spectra for a wide variety of solar flares with the objective of greatly improving the accuracy of the GBM response matrices in this low energy range.

We will also make spectral comparisons of *RHESSI* and GBM observations for larger flares as they occur. These will be especially valuable when either instrument suffers from significant pulse pile-up or particle contamination. We will also examine the spectral evolution during these flares for evidence of the "soft-hard-harder" characteristic identified by Kiplinger et al. (1995) as a predictor of SEP events.

A major objective of our analysis of the X-ray flare data is to determine the total energy in non-thermal electrons above ~20 keV. This information is critical because of the large fraction of the total flare energy that these electrons carry. It complements the information on accelerated ions determined from *Fermi*'s gamma-ray measurements and, indeed, is required for any comprehensive analysis of flare observations made by the many other instruments operating during the upcoming period of high solar activity. If *RHESSI* operations cease, GBM will be one of the most sensitive instruments capable of making the required X-ray measurements to provide this critical information on the energetically important flare-accelerated electrons, their spectrum and time histories.

Another objective of our proposed effort is to utilize GBM's subsecond time resolution capability to carry out X-ray timing analysis versus energy similar to that reported by Aschwanden et al. (1996) using BATSE observations. This has the potential to locate the electron acceleration site for comparison with the location of coronal hard X-ray sources sometimes seen in *RHESSI* images.

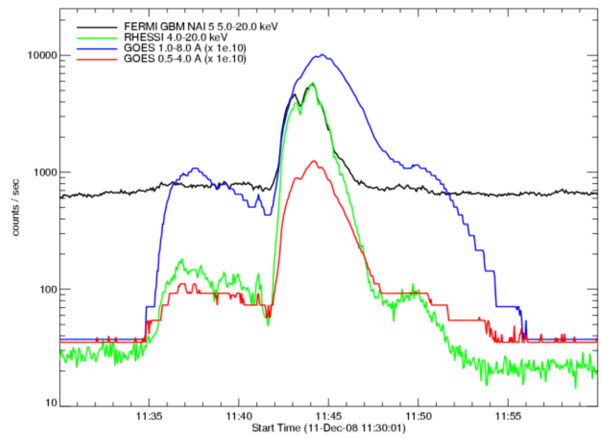


**Fig. 1.** GBM, *RHESSI*, and GOES light curves for a C-class solar flare on 11 Dec. 2008.

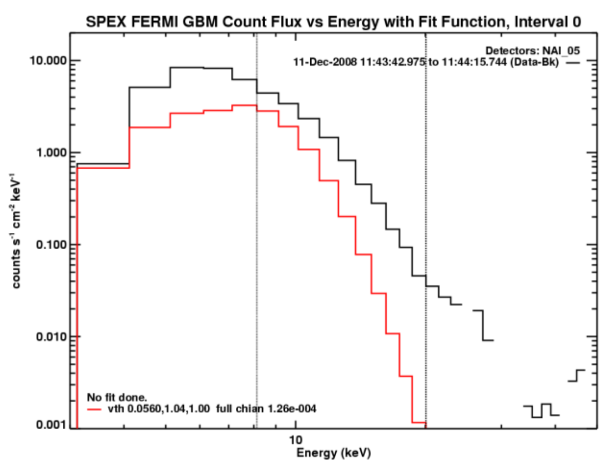


**Fig. 2.** GBM X-ray count-rate spectrum (upper, black) at the peak of the same flare shown in Fig. 1. Also shown for comparison is the best fit thermal spectrum to the *RHESSI* data (lower, red) for one of its nine germanium detectors folded through the GBM instrument response matrix.

### 3.3 Gamma-ray Flares

#### 3.3.1 Gamma-Ray Spectroscopic Studies

New nuclear spectroscopic models have recently been developed (Murphy et al. 2009) for gamma-ray spectra that for GBM observations have been combined into two templates: a 'direct component' from protons and α-particles interacting with ambient solar material, and an 'inverse component' from accelerated heavy ions interacting with ambient H and He. These two templates plus a third from α-α fusion have been calculated for different accelerated and ambient elemental abundances, accelerated particle spectra, accelerated α/p ratios, and flare heliocentric angles. These templates will be used in OSPEX to fit spectra from both the NaI and BGO detectors in the same way as it has been done with the flare spectrum from SMM shown in Fig. 3, providing information on ambient abundances and accelerated particle spectra and compositions.

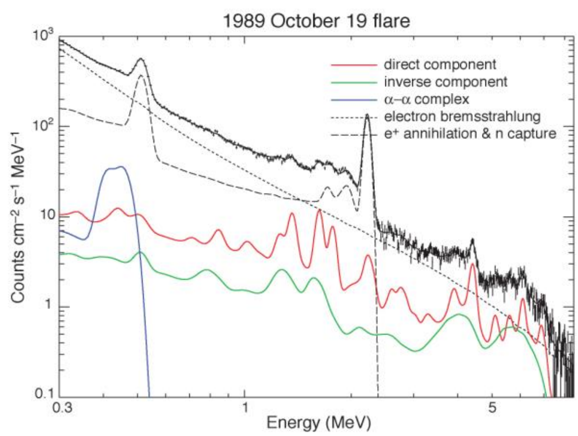


**Fig. 3**. Fit to a strong flare observed by SMM showing the different components.

The best fit to the electron bremsstrahlung component of the flare spectrum is a sum of two power laws, with one containing an exponential rollover above a few MeV. This suggests a break in the electron spectrum >10 MeV. The ability to fit GBM spectra to 40 MeV will enable confirmation of this rollover. Furthermore, LAT spectral measurements at higher energies will permit any pion contribution to be separated from the high-energy continuum. The fits to the combined GBM and LAT spectra thus provide information on the populations of accelerated ions (>1 MeV) and electrons (>20 keV) in closed loops. The characteristics of these populations can be compared with those in SEPs to determine if they have a common origin.

#### 3.3.2 Improved Pion-Decay Theory and LAT Neutron Sensitivity

With LAT's high sensitivity to >100 MeV gamma rays, it is important to update code that calculates the gamma-ray spectrum from the different products of pion decay since these are expected to dominate at such energies. The products include gamma-rays from neutral pions, bremsstrahlung from positrons and electrons produced by charged pions, and radiation from the in-flight annihilation of positrons produced by positively-charged pions. The calculations are currently performed only for isotropic energetic ions. We propose to extend our isotropic calculations of pion-decay spectra by calculating spectra from ion beams as a function of observation angle. We will develop code to combine these spectra and obtain pion-decay emission spectra for any ion angular distribution viewed from any direction.

Neutrons are produced by the same interactions producing the gamma rays. The presence of these neutrons at the Sun is revealed by the strong capture line at 2.2 MeV, shown in Figure 3. Neutrons that escape the Sun may be directly detectable by LAT, providing additional information on the spectrum and directionality of accelerated ions. We therefore propose to continue a study of the LAT sensitivity to neutrons >30 MeV described by F. Longo at the first GLAST Symposium.

### 3.4 Autonomous Solar Pointing to Study Long-Duration Gamma-Ray Flares

The observation of long-duration (>~1 hour) gamma-ray flares (Chupp and Ryan 2009) is a key objective for *Fermi*. Kanbach et al. (1993) showed that pion-decay emission from the 1991 June 11 flare observed with CGRO/EGRET continued for 8 hours after the impulsive phase. Observations of other flares suggest that this high-energy component may be different from lower-energy impulsively accelerated ions. It is possible that this long-duration component is related to large SEP events produced when particles are accelerated by shocks associated with coronal mass ejections. With its exceptional sensitivity and positional capability of <1 arcmin. above 500 MeV, LAT can observe events of shock origin and determine if the center of the emission is cospatial with or separate from X-ray foot-points produced by particles on closed loops. In addition, the angular distribution of interacting ions from a receding shock could be quite different from that of ions interacting within a flare loop, and this will be reflected in the shape of the pion-decay emission spectrum.

Studies of these long-duration flares require increased LAT solar exposure in order to monitor emission from onset through ~5 hours of its decay. Regular Sky Survey mode rocks the pointing of the spacecraft on alternate orbits so that the Sun would possibly be poorly viewed at times, risking missing important portions of these flares. We therefore propose an onboard Autonomous Repoint Recommendation (ARR) mode for solar flares similar to that used for gamma-ray bursts. We suggest the following onboard requirements for conducting a solar pointing: (1) ground command enabling solar ARRs when high-energy solar flares are likely (e.g. X-Class flare probability >30%); (2) GBM triggers on gamma-ray signal; (3) the event is detected above 5 MeV in the BGO detector(s), and (4) the on-board location is <10° from the Sun. The algorithm will be optimized based on experience with BATSE on CGRO. These criteria would be implemented in the GBM flight software.

## 4. Schedule and Management

### Year 1 of proposed effort

- Process first year of GBM data creating products detailed in section 3.1.
- Modify analysis codes and refine the GBM detector response matrices based on GBM, *RHESSI*, and SPHINX cross-calibrations.
- Add new nuclear-line and existing pion decay gamma-ray templates into OSPEX.
- Verify the LAT analysis tools using both simulated flare data and flight data and modify OSPEX codes as required.
- Commence theoretical pion-decay and LAT neutron sensitivity studies.
- Analyze high-energy solar flares as they occur to obtain information on accelerated electrons and ions.
- Finalize plan and algorithm for autonomous solar pointing in response to GBM trigger.

### Years 2 and 3

- Continue to provide the GBM and LAT solar data products.
- Continue to refine software and response matrices.
- Analyze high-energy solar flares and publish results.
- Import new anisotropic pion-decay gamma-ray templates into OSPEX.
- Implement revised ARR criteria in the GBM flight software and support planning to enable solar ARR mode during periods of high solar activity.

**PI Brian Dennis** (0.1 FTE) will coordinate the proposed effort and interface with the *Fermi* program and the Solar System Science Team. He will actively participate in the scientific analysis of the GBM hard X-ray data and coordinate analysis of solar flare observations from other missions such as *RHESSI* and the newly launched *CORONAS* Photon satellite with the SPHINX X-ray data provided through an agreement with its PI, Janusz Sylwester in Wroclaw, Poland.

### Funded CoIs

**Michael Briggs** (0.1 FTE) will provide the necessary GBM flight software needed for solar flare re-pointing of the *Fermi* spacecraft for the proposed investigation. He will lead the deconvolution of GBM spectral data on solar flares.

**Jerry Fishman** (0.1 FTE) will provide all relevant information concerning aspects of GBM calibrations and background spectra, pulse pile-up and deadtime corrections at high count rates needed for analyzing GBM solar flare data.

**Ron Murphy** (0.1 FTE) will develop code for producing pion-decay gamma-rays from an anisotropic distribution of ions.

**Richard Schwartz** (0.1 FTE) will provide the software expertise that fully integrates the use of GBM and LAT data within the SSW framework. He will incorporate the nuclear-line and pion-decay functions into OSPEX. The direction of his effort shifts to building instrumental and scientific expertise into the analysis tools as the data sets grow in complexity and solar activity increases.

**Gerald Share** (0.1 FTE) will optimize the techniques and analyze the high-energy emissions from flares to provide information on accelerated particle spectra and composition that will be compared to SEPs measured in space and on the ground.

**Kim Tolbert** (0.1 FTE) will incorporate the *Fermi*, *INTEGRAL*, and *CORONAS* data and analysis routines into OSPEX and SHOW_SYNOP, preserving the flexibility of the dual command line / GUI interface that she developed for the analysis of *RHESSI* data. She will write software to create the GBM flare list, database of GBM flare data files and response matrices, and quicklook plots.

**Unfunded Collaborators**

**Charles Dermer** will work with Ron Murphy to update the pion production code.

**Francesco Longo** will be the liaison CoI with the LAT instrument team. He and his graduate student will analyze gamma-ray data and perform calculations of the LAT sensitivity to neutrons.

**Andreas von Kienlin** and **Roland Diehl** will facilitate access to the *INTEGRAL* solar gamma-ray data, and, as members of the GBM team, will participate in the GBM solar flare data analysis.

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