A new view of the high energy gamma-ray sky with the Fermi Gamma-Ray Space Telescope

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see http://fermi.gsfc.nasa.gov and links therein

The EGRET Gamma-Ray Sky

Gamma-Ray Astrophysics

The Fermi energy range falls at the energetic end of this scale.
Very energetic photons require even more energetic particles to produce them — HE gamma-ray astrophysics does not probe quiet parts of the Universe.
High energy gamma-rays explore nature's accelerators — "Where the energetic things are" — natural connections to UHE cosmic-ray and neutrino astrophysics.

Fermi instruments

Large Area Telescope (LAT):
- 20 MeV ->300 GeV (including unexplored region 10-100 GeV)
- 2.4 sr FoV (sees entire sky every ~3hrs)

Gamma-ray Burst Monitor (GBM)
- 8 keV - 40 MeV
- views entire unocculted sky

Launched June 11, 2008!

A large leap in all key capabilities, transforming our knowledge of the gamma-ray universe. Great discovery potential.
Launch!

- Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT
- Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination.

The Fermi Large Area Telescope

**Overall LAT Design:**
- 46 array of detector towers
- 1500 MP 550K (collimator) 1.8 m × 1.6 m × 1.2 m
- Precision Stand Tracker (TXK)
  - 16 AT tracking planes 228 cm thick
  - High efficiency, Good position resolution (long, resolution at high energy)
  - 12 ± 0.03 X0, Beak end increase multiple scattering
  - 4 × 0.15 X0, back-end increase sensitivity
- Cal Calorimeter (CAL)
  - Array of 1500 Ca (11) crystals in 6 rings
  - Modulation × Cosmic ray rejection, Shower leakage correction
  - 0.5 X0, Shower max contained >100 GeV
- AntiCosmic Detector (ACD)
  - Segments of 110 plastic scintillator tiles
  - Minimum self bias

Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

LAT Collaboration

- PI: Peter Michelson (Stanford)
- 819 Scientific Members including 56 Affiliated Scientists, plus 68 Postdocs and 155 Students
- Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan, and Sweden
- Project managed at SLAC

The LAT Collaboration

- France
  - CNRS/INSU, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - KEK
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and IPAC, Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

Lat Construction: An international effort

**Integration & Data System: US**

**ACD: US**

Tracker: US, Italy, Japan

Calorimeter: US, France, Sweden
Operations and observing modes

- Almost all observations in survey mode: the LAT observes the entire sky every two orbits (~3 hours), each point on the sky receives ~30 mins exposure during this time.
- 25 ARR: 5 hour pointed mode observations in response to bright GBM detected GRBs
- Calibrations (13 hours), Engineering (5 days)

Monitoring the sky

- Automated Science Processing (ASP)
  - Transient detection: Uses source detection algorithm to find candidate point sources in data from each epoch (6hr, day, week)
  - Follow-up Source Characterization: Runs full likelihood analysis on list from source detection step in "Data Release Plan" (DRP) sources to produce fluxes and spectra
- Flare Advocates:
  - LAT scientists examine output from ASP pipeline and perform follow-up analyses, produce ATels, and propose ToOs

Active galaxies

- Power comes from material falling toward a supermassive black hole
- Some of this energy fuels a jet of high-energy particles that travel at nearly the speed of light
The flaring and variable sky

- >40 Astronomers telegrams
  - Discovery of new gamma-ray blazars PKS 1502+166, PKS 1444-354...
- Flares from known gamma-ray blazars: 3C454.3, PKS 1510-089, 3C273, AO 0235+164, PKS 0236-512, 3C386, PKS 0837-441
- Galactic plane transients: J0910-5041, J0903-3531, J1057-0627

Multiwavelength Observations of LAT Transients in the Galactic Plane

http://fermisky.blogspot.com/

Gamma-ray bursts come in at least three flavors

Collapsars: A rapidly spinning stellar core collapses and produces a supernova, along with relativistic jets that can produce long GRBs

Compact Mergers: Two neutron stars or a neutron star and a black hole, collide and merge, producing a jet that gives rise to a short GRB

Magnetars: Neutron stars in our Galaxy or nearby galaxies with extremely strong magnetic fields can give off powerful bursts that resemble short GRBs
Gamma-ray Burst Monitor

- USA (MSFC, UAH, LANL) and Germany (MPE)
- PI: Bill Paciesas (UAH)
- Co-PI: Jochen Greiner (MPE)

Since July 2008, GBM has detected over 260 GRBs (250/year c.f. 200/year predicted)
- Benefited from flexible onboard triggering algorithms
- Also has seen three SGRs (SGR 0501+4516, SGR 1806-20 and SGR 1815+09, 3TGFs, >10 TGFs and a solar flare.

GRB090510

- Z=0.9
- Emission of 37 GeV photon implies $\Gamma > 1220$ (implying that short bursts are at least as relativistic as long ones)
- Extended (in time) emission at higher energies
- High energy emission in LAT starts later than the lower energy in GBM.

Gamma-ray bursts

- 10 long and 2 short bursts detected by LAT at GeV energies
  - Both types of GRB show similar phenomenology at high energies
  - Swift XRT has detected X-ray afterglows from the 7 brightest LAT bursts resulting in the determination of the burst redshift/distance.

Testing Einstein's Theory of Special Relativity

- The Principle of Invariant Light Speed - Light in vacuum propagates with the speed $c$ (a fixed constant) in terms of any system of inertial coordinates, regardless of the state of motion of the light source.

- Consider a race between two photons traveling a very large distance at slightly different speeds. The slower photon will arrive later.
  - To do this we need
    - Distant object
    - Very bright
    - Well-defined start time

- To make it interesting, we want to make this test at the highest possible photon energies.
  - Some models of quantum gravity predict that space itself might be distorted by effects of quantum gravity.

- Testing Einstein's Theory of Special Relativity
Limits on Lorentz Invariance Violation

• Heuristic modification of the photon dispersion relation:
  \[ c' P' = E' (1 + \eta E' c' E' c') \]

- For $E/E'_c$: $c' P' = E' (1 + \eta E' c' E' c')^{1/2}$
- $\eta = 0$ or 2 in current studies
- $\eta$ is just a constant (can disappear in $E'_c$)
- $\eta = 0$: subluminal regime (high energy photons arrive later)
- $\eta = 2$: superluminal regime (high energy photons arrive earlier)

• Simple case: $\eta = 1$, $\alpha < 0$:
  - Consider a photon of energy $E$ observed at $t$.
  - If it belongs to the GRB, at the very least it has been emitted after the trigger $t_0$.
  - Thus the maximal time delay due to LIV is $t - t_0 = \eta t_0 - \alpha$.
  - With a distance estimate, this results in a "conservative" lower limit on $E_0$.
  - Independent of intrinsic time lags in GRBs.

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GRB090902B - Autonomous repoint

- LAT pointing in celestial coordinates from -120 s to 2000 s
  - Red cross = GRB 090902B
  - Dark region = occulted by Earth ($\alpha > 113^\circ$)
  - Blue line = LAT FoV ($\pm 66^\circ$)
  - White lines = 20° (Earth avoidance angle) / 59° above horizon
  - White points = LAT events (no cut on zenith angle)

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Limits on Lorentz Invariance Violation

• Lorentz Invariance:
  - GRB080916C
    - Highest energy, $13.2$ GeV photon, detected 16.5 sec after GBM trigger.
    - Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GBM trigger):
      \[ M_{\text{QG}} > 1.56 \times 10^{-16} \text{ GeV/c}^2 \]
  - GRB090510
    - Highest Energy, $\sim 31$ GeV photon detected 858 ms after onset of GBM emission
    \[ M_{\text{QG}} > 1.42 \times 10^{-17} \text{ GeV/c}^2 (>1.19 \text{ MeV/c}^2) \]
      - Rules out many $n=1$ scenarios.

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One year Fermi-LAT Sky

- Over 1000 new high-energy gamma-ray sources!
Pulsars

- Extremely dense stars, huge magnetic fields, rapidly rotating

New Populations of Pulsars

New Pulsar in CTA 1

Science Express October 16
Abdo et al., 2008, Science

P = 316 ms
Per = 5.6 x 10^6 yr
Characteristic age = 10 kyr
Flux (100 MeV) = 3.8 x 10^{-9} ph cm^{-2} s^{-1}

LAT 95% error radius = 0.038 deg
EGRET 95% error radius = 0.24 deg

Pulse undetected in radio-X-ray

Unidentified EGRET sources - many are pulsars!

Connection with Higher Energy Gammas

- Milagro (TeV) observations 14/34 Galactic BSL sources with 3 sigma Milagro excess.
- 9/14 are gamma-ray pulsars
- All 6 previously known Milagro sources now associated with Fermi Pulsars.

Abdo et al. 2009
**Fermi detection of 47 Tucanae**

- Global star cluster containing 23 known radio ms pulsars
- Fermi likely to be detecting the combined emission from these ms pulsars assuming average x-ray efficiency of ~10%.
- Search for pulsations from individual pulsars is ongoing.

**Extended Sources**

- LAT is resolving the MeV-GeV gamma-ray emission from extended sources.

**High Energy Gamma-ray spectra**

- LAT sensitivity and wide bandpass allows the measurement of many non-power-law spectra
- Phase averaged Vela Pulsar spectrum (power-law with exponential cutoff)

**LAT Energy Range**

- Joint fits between LAT (MeV-GeV) and IACTs (GeV-TeV)
- Peak sensitivity at a few GeV for typical spectra
Fermi-LAT capabilities for electrons

- 100% acceptance above 20 GeV (onboard filtering is disabled)
- Use ACD to veto against gamma-rays (≤2% contamination)
- Transverse shower-shape in TKR and Calorimeter to distinguish electromagnetic from hadron events

Update: Add the Low Energy Measurement

- Fermi-LAT electron observations

What if we randomly vary the pulsar parameters relevant for e+e- production?

Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results.
Want to know more?

- Fermi symposium
  - Washington DC, Nov 2-5
  - http://fermi.gsfc.nasa.gov/ssc/ressources/newsletter/
    - General news
    - Multiwavelength
    - Data/software
- LAT data became public on Aug 25
  - http://fermi.gsfc.nasa.gov/ssc

CERN Beam Test Compared to Monte Carlo

<table>
<thead>
<tr>
<th>Longitudinal Shower Profiles</th>
<th>Energy Resolution: Full Width @ 68% Cont.</th>
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<tbody>
<tr>
<td>Resolution integrated over all angles&lt;br&gt;(See figure for example)</td>
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Fitting the longitudinal shower profile event-by-event compensates for fluctuations in leakage

Conclusions

- The LAT and GBM are both working well
- First LAT 350 catalog (currently being validated/checking) contains over 1000 new gamma-ray sources!
  - New classes of gamma-ray sources (milli-second pulsars, gamma-ray binaries, globular clusters, starburst galaxies...)
  - Field of gamma-ray astrophysics is rapidly expanding
- GBM is detecting many kinds of MeV transients
  - >250 GRB/year, three SGRs (SGR 0418+5723, SGR 1806-20 and SGR 1818-12)
  - >10 TGFs and a solar flare.
- Science returns in solar system studies, Galactic astrophysics, extragalactic astrophysics, cosmic-ray physics and fundamental physics.
- The full data release was last month, software to assist with data analysis is also available.
  - http://fermi.gsfc.nasa.gov/ssc
- Lots more science to come...

LAT High Level data releases

The LAT team releases flux/spectra as a function of time for all sources in a pre-defined list — flaring sources during flares.

- Modified data release after Smooth:
  - Lowered flux threshold to release information on flaring sources by factor of 2.
  - Provided information continuously (not just during flares).
  - Started with 23 sources, now have >40
  - http://fermi.gsfc.nasa.gov/ssc
Limits on Lorentz Invariance Violation

- Heuristic modification of the photon dispersion relation:
  \[ c = \frac{E}{p}; \quad E = E_0 \left( 1 + \alpha \left( \frac{E}{E_0} \right)^n \right) \]
- \( \alpha \) is just a constant (can disappear in \( E_0 \)).
- \( E_0 = \text{effective UV energy scale} \)
- For \( E/E_0 \ll 1 \): \( E = E_0 (1 + \alpha) \)
- \( n = 1 \) or \( 2 \) in current studies

- Highest energy, 21 GeV photon, detected 859 msec after GBM trigger
- Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger):
  \[ M_{QG} > 1.2 \text{ M}_{\odot} \]

Pair Conversion Technique

- Photon converts to an e+e- pair in one of the conversion foils.
- The energy is measured in the calorimeter.
- Tracker: angular resolution is determined by multiple scattering (at low energies) 
  \( \Rightarrow \) thin conversion foils, position resolution (at high energies) 
  \( \Rightarrow \) few pitch detectors
- Conversion efficiency: \( \sim \) thin conversion foils, or many foils
- Calorimeter: \( \text{Enough } X_0 \text{ to contain showers, shower leakage correction.} \)
- Anti-coincidence detector: Must have high efficiency for rejecting charged particles, but not veto gamma-rays

Occultation project
Fermi LAT Papers

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<th>Journal</th>
<th>Published</th>
<th>Accepted</th>
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Another 21 papers are submitted, and many in preparation.

GLAST Science Support Center (GSSC)

- Supports guest investigator program
- Provides training workshops
- Provides data, software, documentation, workbooks to community
- Archives to HEASARC
- Joint software development with Instrument Teams, utilizing HEA standards
- Located at Goddard

see http://glast.gsfc.nasa.gov/ssc/ and help desk
http://glast.gsfc.nasa.gov/ssc/help/

Science impact by citation

- "Measurement of the Cosmic Ray e+e- Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope" (05/2009) ~150
  - Cited across a broad range - cosmic-ray, astronomy, particle physics (D6, BABAR)
- "Fermi/Large Area Telescope Bright Gamma-Ray Source List" (07/2009) ~60
- "Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C" (03/2009) ~60
- "Bright Active Galactic Nuclei Source List from the First Three Months of the Fermi Large Area Telescope All-Sky Survey" (07/2009) ~50
- "The Fermi Gamma-Ray Space Telescope Discovers the Pulsar in the Young Galactic Supernova Remnant CTA 1" (11/2008) ~30

Data Releases

- Beginning of science operations: GBM data + LAT high level data from start of science operations
- Feb 6, 2009: LAT bright source list, first LAT analysis software release
- Aug 25, 2009: low level LAT data, second LAT analysis software release

~400 queries in first day, many requesting the entire dataset.
- Made link to weekly all-sky file more obvious (no number of queries dropped)
Data analysis workshops

- The FSSC is holding a sequence of regional data analysis workshops
- First workshop on Oct 1 at GSFC
- 1-day, focus on hands-on activities
- ~25 participants
  - Larger group limits 1-on-1 interactions
- Future workshops
  - Venues chosen based on community feedback
  - May try internet conferencing analysis workshops

GLAST Users Committee Members

- Alan Marscher (Chair)
- Matthew Baring
- Pat Slane
- Buell Jannuzi
- Don Kniffen
- Henric Krawczynski
- Jamie Holder
- Wei Cui
- Scott Ransom
- Jim Ullvested
- Alicia Soderberg

- Neil Gehrels
- Ilana Harrus
- Julie McEnery
- Bill Paciesas
- Peter Michelson
- Steve Ritz
- Chris Shrade
- Dave Thompson
- Kathy Turner
- Lynn Cominsky

http://glast.gsfc.nasa.gov/ssc/resources/guc/

Components of the Gamma-ray sky

- Galactic diffuse
- Point sources
- Isotropic (extragalactic diffuse + residual backgrounds)

Extracting an extragalactic diffuse spectrum

- Start with a very clean data sample (more background rejection compared with the standard classes)
- Pixel-by-pixel max. likelihood fit of (b) 10^6 sky model components to LAT data:
  - Template γ-ray maps representing different Galactic foreground contributions in independent energy bins (200 MeV - 100 GeV)
  - Spectra of (>1400) point sources from LAT catalog are fitted simultaneously with diffuse components (weak source contribution included as a template map).
- Spectrum of isotropic component
  - Subtraction of residual background (derived from Monte Carlo prediction) from isotropic component
Some Questions Fermi is addressing

- How do super massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed?
- What are the jets made of?
- What are the mechanisms that produce Gamma-Ray Burst (GRB) explosions? What is the energy budget?
- What is the origin of the cosmic rays that pervade the galaxy?
- How does the Sun generate high-energy gamma-rays in flares?
- How has the amount of starlight in the Universe changed over cosmic time?
- What are the unidentified gamma-ray sources found by EGRET?
- What is the mysterious dark matter?