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 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

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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"

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The EGRET Gamma-Ray Sky

- 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.

LAT Collaboration

- France
  - CERN/HEP, CEA/Dapbay
- Italy
  - INFN, LNAF
- Japan
  - University of Hokkaido
  - University of Tokyo
  - Institute of Technology
- Scandinavia
  - Stockholm University
- United States
  - Stanford University (SLAC and HHF, Physics)
  - University of California, Santa Cruz
  - Space Flight Center
  - Goddard Space Flight Center
  - University of California, Santa Cruz
  - University of Washington

PI: Peter Michelson (Stanford)

Construction: An international effort

Integration & Data System: US

ACD: US

Tracker: US, Italy, Japan
Colorimeter: 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 observations in response to bright GBM detected GRBs
- Calibrations (13 hours), Engineering (5 days)
- Very high uptime

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 + "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+106, PKS 1444-354
  - Flares from known gamma-ray blazars: 3C454.3, PKS 1510-080, 3C273, AO 0235+164, PKS 0258+512, 3C286, PKS 0837-441
  - Galactic plane transients: J0010-6341, 3EG J0803-3531, J1057-6027

http://fermisky.blogspot.com/

Multiwavelength Observations of LAT Transients in the Galactic Plane

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 Merger: 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: Jochem Greiner (MPE)

Since July 2008, GBM has detected over 260 GRB (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+2658); >10 TGFs and a solar flare.

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.
Limits on Lorentz Invariance Violation

- **Heuristic modification of the photon dispersion relation:**
  - $c' p' = E' (1 + \alpha(E_{EQG}))$, effective LV energy scale
  - For $E < E_{EQG}$: $c' p' = E' (1 + \alpha(E_{EQG}))^n$ for $n = 1$ or $2$ in current studies
  - $\alpha$ is just a constant (can disappear in $E_{EQG}$)
  - $\alpha < 0$: subluminal regime (high energy photons arrive later)
  - $\alpha > 0$: superluminal regime (high energy photons arrive earlier)

- **Simple case:** $n=1, \alpha < 0$:
  - 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 LV is $t-t_0 = \text{max}(0)$.
  - With a distance estimate, this results in a "conservative" lower limit on $E_{EQG}$.

- **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 ($56^\circ$)
  - White lines = $20^\circ$ (Earth avoidance angle) / $90^\circ$ above horizon
  - White points = LAT events (no cut on zenith angle)

- **GRB080916C**
  - High energy, ~1.2 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 GRB trigger):
    $$ M_{QG} > 1.50 \times 10^{-6} \text{ GeV/c}^2 $$

- **GRB080916C**
  - Highest energy, ~31 GeV photon detected 858 ms after onset of GBM emission
  - Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger):
    $$ M_{QG} > 1.42 \times 10^{-6} \text{ GeV/c}^2 (M_{	ext{Planck}}) $$
  - Rules out many $n=1$ scenarios

- **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

\[ P = 3.16 \text{ ms} \]
\[ P \text{ err.} = 3.6 \times 10^{-6} \]
\[ \text{Characteristic age} = 10 \text{ kyr} \]
\[ \text{flux (1000 GeV)} = 3.8 \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1} \]

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
- Consistent with Fermi PSF for point source
- Fermi likely to be detecting the combined emission from these ms pulsars assuming average γ-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)
- 3C454.3: Broken power-law

**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

Fermi-LAT electron observations

Update: Add the Low Energy Measurement

- Fermi-LAT electron observations
- Fermi sees more electrons at high energies than expected which suggests a local source, but what?

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

- Injection spectrum, e+e- production efficiency, PWN trapping

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/resources/newsletter/
    - General news
    - Multimwavelength
    - Data/software
- LAT data became public on Aug 25
  - http://fermi.gsfc.nasa.gov/ssc

Conclusions
- The LAT and GBM are both working well.
- First LAT 0.1-300 GeV catalog (currently being validated/checked) contains over 1000 new gamma-ray sources:
  - New classes of gamma-ray sources (millisecond 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 1806-20, SGR 1846-20 and SGR 1900+14), >10 TGFs and a solar flare.
- Science returns in solar system studies, Galactic astrophysics, extragalactic astrophysics, cosmic-ray physics and fundamental physics.
  - This 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...

CERN Beam Test Compared to Monte Carlo

Fitting the longitudinal shower profile event-by-event compensates for fluctuations in leakage
Limits on Lorentz Invariance Violation

• Heuristic modification of the photon dispersion relation:
  \[ c^2 p = E (1 + f(E/E_{QG})) \]
  \[ E_{QG} = \text{effective QG energy scale} \]
  \[ f \text{ is a linear, or quadratic function of } E \]

- For \( E < E_{QG} \):
  \[ c^2 p = E (1 + f(E/E_{QG})) \]
  \[ f \text{ is a constant (can disappear in } E_{QG} \)\]

- Highest energy, a 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
- The anti-coincidence shield wastes incoming charged particles
- The directions of the charged particles are recorded by particle tracking detectors, the measured tracks point back to the source

Tracker: angular resolution is determined by multiple scattering of low energy particles

Conversion foil resolution: high energy particles

Calorimeter: sufficient X, to contain shower, shower leakage correction

Anti-coincidence detector: Must have high efficiency for rejecting charged particles, but not gamma-rays

Occultation project

GBM - not just transients

GBM team have made non-GRB high level data/results available.
Fermi LAT Papers

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Another 23 papers are submitted, and many in preparation.

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)
  - Cited across a broad range of cosmic-ray, astronomy, particle physics (D0, BABAR)
- "Fermi Large Area Telescope Bright Gamma-Ray Source List" (07/2009)
- "Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C" (03/2009)
- "Bright Active Galactic Nuclei Source List from the First Three Months of the Fermi Large Area Telescope All-Sky Survey" (07/2009)
- "The Fermi Gamma-Ray Space Telescope Discovers the Pulsar in the Young Galactic Supernova Remnant CTA 1\" (11/2008)

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/

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 Januzzi
- Don Kniffen
- Henric Krawczynski
- Jamie Holder
- Wei Cui
- Scott Ransom
- Jim Ulvestad
- Alicia Soderberg

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

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

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 >10^9 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 (~140) 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
SED of the Isotropic diffuse emission (1 keV - 100 GeV)

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?