Overview

- Astrophysics at a GeV
  - Why we do it and some of the things we hope to find
- The Fermi Gamma-Ray Space Telescope
  - Working extremely well!
- Science Highlights from the First Six Months
  - 205 bright gamma-ray emitters
  - The Solar System
  - Our Galaxy
  - Beyond our Galaxy

Some Big Questions

- How and where does nature accelerate matter?
- What is matter like throughout the Universe?
- What characterizes our local environment?
- What about the distant Universe?
- How do Galaxies change over time?
- Are there variations in the physics we know?
The EGRET legacy

- Catalog of ~270 MeV-GeV gamma-ray sources
  - Blazars - bright, highly variable emission from the cores of galaxies
  - Pulsars - bright pulses from rotating neutron stars
  - Unidentifieds - many undetermined objects
  - The GeV excess - diffuse emission shows too many gamma rays at a GeV
  - GRBs - GeV emission detected from a few gamma-ray bursts, one burst over an hour after the trigger

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Fermi LAT Collaboration

- France
  - IN2P3, CEA/Seclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University [SLAC and HEPL/Physics]
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sanoma State University
  - Ohio State University
  - University of Washington

Principal Investigator:
Peter Michelson (Stanford University)

construction managed by Stanford Linear Accelerator Center (SLAC), Stanford University

Only a few short months ago...

GLAST with half of the fairing mounted, sitting on top of a Delta II Heavy rocket at launch complex 17-B in Cape Canaveral Air Force Base, FL June 2008
The satellite formerly known as GLAST

+ August 26, 2008
+ First Light
+ GLAST renamed in honor of Enrico Fermi
+ The Fermi Gamma-ray Space Telescope
+ Also fondly remembered as the day a few hundred web links broke...

The Fermi Observatory

Large Area Telescope (LAT)
- Large Field of View (>2.4 sr)
- Views entire sky every 3 hrs (every 2 orbits)
- Broad Energy Range (20 MeV - >300 GeV)

Gamma-ray Burst Monitor (GBM)
- Views entire unocculted sky
- NaI: 8 keV - 1 MeV
- BGO: 150 keV - 30 MeV

The Large Area Telescope

Anti-Coincidence Detector (ACD):
- Segmented (89 tiles)
- Self-veto @ high energy limited
- Efficiency 0.9997 (overall)

Tracker (TKR):
- Tungsten foils convert
- Silicon strip detectors (single sided, each layer rotated by 90 degrees)
- ~80 m² of silicon (total)
- ~106 electronics channels
- High-precision tracking, low dead time

Calorimeter (CAL):
- 1536 CsI crystals
- 8.5 radiation lengths
- Hodoscopic
- Shower profile reconstruction (leakage correction)
Candidate Gamma-ray Events – Flight Data

Green crosses → detected positions of the charged particles
Blue lines → reconstructed track trajectories
Yellow line → estimated direction of candidate gamma ray
Red crosses → detected energy depositions in the calorimeter

On-orbit Rates

- Overall trigger rate: ~few KHz
- Huge variations due to orbital effects
- Downlink rate: ~400-500 Hz
  - ~90% from gamma filter
  - ~20-30 Hz from diagnostic filter
  - ~5 Hz from heavy ion filter
- Photon-selected event rate (passing standard background rejection cuts): ~1 Hz

LAT Performance from Ground Simulations

- The LAT is a GeV, wide-field instrument
- Energy dependence of PSF: 60%
- 68% containment <0.5 deg above 1 GeV
- Energy dependence of effective area: Peaks above 1 GeV
- PSF dependence on inclination angle (10 GeV): Resolution maintained to >50 deg.
- Dependence of effective area on inclination angle (10 GeV): ~50% efficiency at 50 deg.

LAT Sensitivity with Time

From simulations: 5σ integral flux assuming a power law with index -2.0.

- Orbit poles are exposed every other orbit
- Long term scale asymmetry due to SAA passages
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Bright Source List

- Basic Info
  - http://fermi.gsfc.nasa.gov/ssc
  - Released February 9
  - Based on 3 months of data (Aug. - Oct.)
    - 2.8 million events
  - Detection significance, Location, Flux in two energy bands, Variability information
- Important Caveats
  - Incomplete (bright sources only)
  - Not flux-selected (>10σ)
  - Not uniform (sensitivity varies over sky)
  - Significance threshold favors
    - Hard spectra
    - High latitude (lower diffuse emission)

205 Preliminary LAT Bright Sources

- >50% associated with blazars
- 29 pulsars with gamma-ray pulsations
- Over 40 sources without clear associations
Source Associations

- Unassociated
- AGN
- Pulsar
- X-ray binary
- Globular cluster

### Solar System Gamma Rays

- Albedo gamma rays from cosmic rays impacting matter
- Earth
- Moon
- Sun
- Other planets, asteroids?
- Inverse-Compton (e.g. Moskalenko 2006, Orlando and Strong 2008)
  - Scattering of solar photons by Galactic cosmic-ray electrons
- Solar Flares (Solar Maximum in 2011)
  - Electrons and ions accelerated in solar magnetosphere
  - Generates particle cascades

### The GeV Solar System

The Earth

- Gamma rays from the Earth shown in instrument coordinates
- Time steps = 250 sec
- 2.8 hrs in total
- ~2 orbits

66 deg (~LAT FOV)
**The Sun and the Moon**

Detection of the quiet Sun in gamma rays!
Fluxes consistent with model expectations. Moon flux agrees with EGRET.

**The GeV Galaxy**

EGRET GeV excess

- Extra gammas at ~1 GeV in disagreement with models based on local cosmic rays
  - Spatial variation in cosmic ray spectra?
  - Unresolved sources?
  - Dark matter?
  - Instrument calibration issue?

LAT view of the local Galaxy

- EGRET GeV excess not confirmed by LAT for this part of the sky
  + Conventional diffuse model (local CR) in good agreement
  + LAT errors are systematic dominated and estimated ~10%
Rotation Powered Pulsars

- Electrons (positrons) accelerated to relativistic speeds, emit synchrotron radiation
-\ Radio emission along magnetic axis
- >1500 radio pulsars cataloged
- Rotational periods from msec to secs, increasing over time

Neutron star ~1.4 x Mass Sun

Gamma Ray Pulsars with CGRO

EGRET Pulsars confirmed

Gemina: P=237 ms
Vela: P=89.3 ms
Crab: P=33 ms

100s γ's per day
1 million over mission

Bright Gamma-ray Pulsars

Fermi Pulsar Detections
Pulsing Sky

Pulses shown at 1/10th true rate

Producing Gamma-ray Pulsations

Radio along the magnetic field axis
Gamma rays from the equator

Observer’s angle reveals different emission patterns:
- Radio only
- Radio + Gamma
- No radio or gamma
- Thermal only
- Gamma only

Discovery of Pulsar in CTA 1

\[ P = 316 \text{ ms} \]
\[ P_{\dot{\text{}}}= 3.6 \times 10^{-13} \]

Characteristic age \( \approx 10 \text{ kyr} \)

Flux \((>100\text{MeV}) \approx 3.8 \pm 0.2 \times 10^{-7} \text{ ph cm}^{-2} \text{s}^{-1} \)

Pulse undetected in radio/X-ray

LAT 95% error radius = 0.038 deg

Vela Pulsar Lightcurve

Time stamps accurate to 300 ns
Phase analysis accurate to \(-1\) us

Peak 1 (P1) stronger at low energy.  
Peak 2 (P2) stronger at higher energy.  
NEW: Peak 3 evolves with energy.  
( confirms EGRET )

Radio Rotational Phase

Consistent with simple exponential cutoff
Super-exponential rejected at 16.5σ
Excludes emission near neutron star surface

Blind-Search Pulsars at 6 Months

+ Search details
  + Known locations (EGRET/LAT, X-ray nebulae …)
  + Time differencing method (Atwood et al. 2006)
  + Robust to glitches
  + Minimum P=0.015 s
  + P, Pdot cover 95% ATNF catalog
+ 14 detected so far
  + 13 new ( radio quiet, e.g. CTA 1 )
+ Rough demographics
  + Age: 10 - 1800 kyr
  + Rotation Power: $10^{33}$ - $10^{36}$ erg/s

Still flux limited…

LAT Millisecond Pulsars

+ 7 detected (6 new in gamma rays)
+ PSR 0218+4232 confirmed (EGRET MSP)

Detecting high Edot/dt
Nearby - most within 1/2 kpc
Pulses are complex - work for theorists
Detection of Globular Star Cluster

47 Tucanae contains 23 radio ms pulsars

Fermi could be detecting combined emission from ms pulsars assuming average gamma-ray efficiency of ~10%.

- Search for pulsations from individual pulsars is ongoing

Consistent with Fermi PSF for point source

LS I +61 303 - a binary system

+ LSI +61 303
+ Massive Be star + compact object binary
+ 26.5 day orbital period

Orbital parameters:

- Apastron (phase 0.7)
- Periastron (phase 0.32)

Orbital period ~26.5 days

Strong GeV emission at periastron

TeV emission only detected at apastron

Cesares 2005

LS I +61 303 Periodicity

Orbital periodicity confirmed with gamma rays

26.5 ± 0.5 days

A Multi-TeV to GeV Connection?

+ Milagro Galactic Plane sources [Abdo et al. 2007]
  + Median energy ~20 TeV
  + 4 detections and 4 candidate sources in the Galactic Plane
  + 6 coincide with EGRET sources (includes Crab nebula and Geminga pulsar)
  + MGRO 1908+06, MGRO 2019+37*, MGRO 2031+41, and C4* overlap with new gamma-ray pulsars in the Bright Source List
  + Pulsations tend to cut off at a few GeV
  + Nebula emission formed by the pulsar particle outflow (PWN)?
GeV emission from beyond our Galaxy

What’s New?

+ 30% bright sources flagged as variable
  + The gamma-ray sky is dynamic!
+ About 30% overlap with EGRET
  + Expected due to weekly to yearly variability of AGN
+ Higher fraction of BL Lacs than EGRET
+ More distant AGN

3 Month Gamma-Ray Variability
**Fermi Gamma-Ray Bursts**

+ More than 115 GBM bursts since July
+ More than expected - GBM trigger has improved time sensitivity
+ 20 short GRBs
+ 4 bursts detected in LAT
  + Roughly consistent with expectations
  + GRB 080825C - the first one
    + >10 events above 100 MeV
  + GRB 080916C - the long one
  + GRB 081024B - the short one
    + detected >1 GeV photons
  + GRB 081215A - the transverse one
    + 86 deg from LAT on-axis - rate only, not imaged

**GRB 080916C - the long bright one**

+ 2nd GRB detected by the LAT
  + 1st since EGRET with imaged photons and energies > 1 GeV!
+ Brightest burst with a measured redshift
+ GROND measurement of redshift $z = 4.24$
+ Prompt emission
  + 1st GBM burst in fluence ($4.0 \times 10^{-4}$ erg/cm$^2$ in 50 – 300 keV) and in LAT FoV
  + >140 LAT events for spectral analysis (>100 MeV)
  + >3000 LAT events in first 100 seconds
+ Time-resolved spectroscopy over 6 decades in energy (10 keV to 10 GeV)
+ High-energy emission peaks at later times
+ High-energy emission observed up to 23 min after the trigger time

**Multiple detector light curve**

First 3 light curves are background subtracted
- The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV
- The first low-energy peak is not observed at LAT energies
- Spectroscopy needs LAT event selection (>100 MeV)
  - 5 intensities for time-resolved spectral analysis:
    - $2.0 \times 10^{-7}$ to $1.0 \times 10^{-6}$
  - 14 events above 1 GeV

**Spectroscopy of the main LAT peak**

- Consistent with band function from 10 keV to 10 GeV
- No evidence for any other component
- No evidence for any roll-off
How Relativistic is the Jet?

- High redshift and high fluence implies strongly collimated jet
- No spectral cut off ($z=4.35$)
- Bulk Lorentz factor $\Gamma \geq 600$ for second peak in light curve ($\geq 900$ for later timeslice of light curve)
- Also can set limit on Lorentz invariance violation
  - Highest $E$ photon $13.2 \text{ GeV} (1+z) = 70.6 \text{ GeV}$
  - Arrived $16.7$ sec after trigger
  - $M_{\text{QG}} > 1.50e18 \text{ GeV/c}^2 \sim 0.1 M_{\text{Planck}}$

Transients Unidentified and the Unexpected

LAT Transients in the Galactic Plane

- 2 ~day flares detected in the plane without obvious blazar counterpart
  - ATel #1771
    - Spatially coincident with 3EG J0903-3531
    - Variable EGRET source appearing in several viewing periods
    - 68% error radius 0.11 deg
    - No firm identification
  - ATel #1788
    - New GeV source, Fermi J0910-5041
    - 68% error radius 0.07 deg

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Summary

- The LAT is a powerful pulsar detector
- Already influencing pulsar models
- and a great flare monitor
  - Ideal for multiwavelength campaigns (always on!)
- Excellent performance for GRBs bright at >100 MeV
- The Bright Source List is similar in size to entire EGRET catalog (at only 3 months)
- The Gamma-Ray sky is dynamic
- Lots more *Fermi* science to come!

www.fermi.gsfc.nasa.gov
### Year 1 Science Operations Timeline

<table>
<thead>
<tr>
<th>Week</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Launch: June 11, 2008</td>
</tr>
<tr>
<td>6-12</td>
<td>spacecraft turnaround</td>
</tr>
<tr>
<td>13</td>
<td>LAT, GBM turn-on checkout</td>
</tr>
<tr>
<td>14</td>
<td>&quot;first light&quot; observatory tuning</td>
</tr>
<tr>
<td>15</td>
<td>&quot;first light&quot; survey starting</td>
</tr>
<tr>
<td>16</td>
<td>Initial tuning/calibrations</td>
</tr>
<tr>
<td>17</td>
<td>&quot;first light&quot; whole sky survey starting</td>
</tr>
<tr>
<td>18</td>
<td>Whole sky initial tuning/calibrations</td>
</tr>
<tr>
<td>19</td>
<td>Observatory turnaround</td>
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<tr>
<td>20</td>
<td>LAT, GBM turn-on checkout</td>
</tr>
<tr>
<td>21</td>
<td>LAT, GBM first light</td>
</tr>
<tr>
<td>22</td>
<td>LAT, GBM whole sky</td>
</tr>
<tr>
<td>23</td>
<td>LAT, GBM pointed + sky survey</td>
</tr>
<tr>
<td>24</td>
<td>LAT, GBM pointed + sky survey tuning</td>
</tr>
</tbody>
</table>

### LAT Background Model

Orbit-averaged background fluxes by component:

- **Green triangles**: protons
- **Magenta triangles**: helium
- **Red squares**: electrons
- **Light Blue circles**: positrons
- **Dark Blue triangles**: Earth albedo
- **Black squares**: Earth albedo

Low energy includes albedo and trapped electron/positron components.

Primary cosmic ray populations show effect of geomagnetic cutoff around a few GeV.

### Map of the South Atlantic Anomaly

- **South Atlantic Anomaly (SAA)**: region with a high density of trapped particles (mostly low energy protons)
- **No physics data taken (ACD HV turned off)**
- **TKR and CAL triggers counted to map the radiation intensity**
- **Conservative boundary defined pre-launch; new polygon now uploaded on the spacecraft (down time reduced from ~18% to ~15%)**

### Vela the Calibrator

- **Expected performance validated using the extremely bright Vela pulsar**
- **Confirm point spread function**
- **Higher energy requires more statistics and additional sources**
- **Additional validation using on and off pulse analysis**
- **Weekly trend monitoring of timing and reconstruction using bright pulsars**

68% containment radius measured using Vela (points) and simulated (line)
3 Month Skymap: Pulsars!

Source Associations in Inner Galaxy

Vela: Off-pulse Limit

PSR J2021+3651

- Pulse profile similar to Vela pulsar
  - $\Delta \phi = 0.468 \pm 0.002$
  - $\Delta \phi_{\text{radio}} = 0.182 \pm 0.004$
  - $P_1/P_2$ ratio decreases at higher energy

LAT Counts Map 300 MeV - 3 GeV
On pulse - Off pulse

<2.8% phase-average flux (95%)
J2021+3651 LAT Spectrum

\[ \frac{d\Phi}{dE} = kE^{-\Gamma} \exp\left(-E/E_0\right) \]

\[ \Gamma = 1.5 \pm 0.1 \]

\[ E_0 = 2.4 \pm 0.3 \pm 0.5 \text{ GeV} \]

Integral energy flux =

\[ 4.6 \pm 0.7 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \]

Simple exponential \( \Rightarrow \) Near-surface emission excluded

Large dispersion measure, but \(<9\) kpc favored, e.g., 4 kpc from X-ray thermal

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Galactic Transients

+ Monitored by the LAT team
  + Weekly shifts covered by an AGN and galactic advocate
+ Announced by ATels
  + E-mail notice, request for observations
  + 24 hr response time
  + LAT contact person for updates and to coordinate multiwavelength follow-up
+ Data release plan (1st year)
  + \( F (E>100 \text{ MeV}) > 2 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \)
  + Daily flux in two energy bands
  + Continues to flux \(< 2 \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1} \)

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Transient Flux and Spectra

**Historical**

EGRET avg flux (\(E>100\) MeV)

\(-0.16 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \)

EGRET peak flux

\(-0.32 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \) (Hartman et al. 1999)

**During flare (Oct 5-7)**

LAT flux \(-1 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \)

Index \(= 2.2 \pm 0.1\) (stat)

**During flare (Oct 15-16)**

Flux (\(E>100\) MeV)

\(-1 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \)

Index \(= 1.9 \pm 0.1\) (stat)
LS I +61 303 Variability

LAT flux Aug 4 - Dec 1 2008 (smoothed)

Orbit to orbit rate variations

TeV Added Value

+ GeV + TeV detections
  + Our pulsars are your PWNe?
  + Identifying LAT sources in the Galactic plane
  + TeV counterparts, localization, morphology
  + TeV spectra - discerning components
  + Gamma-ray Binaries
    + Periodicity and variability
    + Untangling progenitors and emission models
  + TeV non-detections of LAT sources
    + GeV populations with breaks/cutoffs?
    + LAT non-detections of TeV sources?
    + Does this become constraining at the 1 yr mark?
    + Note this is a longer term item...

Summary

+ Lots of exciting pulsar science
  + Exquisite light curves and spectra of bright pulsars
  + Gamma-ray only pulsars
  + Millisecond pulsars
  + Globular cluster
  + Nebula observations possible in off-pulse
  + Excellent and ongoing coverage of binary LS I +61 303 (5 orbits and counting)
  + Searching for additional binaries
  + Daily monitoring for transients in the Galactic plane
  + Increasingly interesting with time...

Supernova Remnants?

+ Too early to call...
  + Yes, there are sources in the bright source list that are near supernova remnants
  + But supernova remnants often coincide with pulsars
  + Cannot claim associations for SNR this early
  + At 1 year will have
    + Improved instrument response
    + Improved background models
    + More statistics above 10 GeV
    + Potential for studies of extended emission
Limits on Lorentz Invariance