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/ Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - JASJ/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
  - Sonoma 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
Lift Off!

June 24, 2008 - Instrument Activation Day
The project and instrument teams made it look easy to turn on a million channels on a $700 million mission in a single day.

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 0.56% (overall)

Tracker (TKR):
- Tungsten foils convert
- Silicon strip detectors (single sided, each layer rotated by 90 degrees)
- ~60 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:
- 68% containment <0.5 deg above 1 GeV
- Peaks above 1 GeV

Dependence of effective area on inclination angle (10 GeV):
- ~50% efficiency at 50 deg.

PSF dependence on inclination angle (10 GeV):
- Resolution maintained to >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 time 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)

The 3 Month Skymap

- E>200 MeV (>400 MeV thick detector)

205 Preliminary LAT Bright Sources

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

The GeV Solar System

Solar System Gamma Rays

- Albedo gamma rays from cosmic rays impacting matter
  - Earth
  - Moon
  - Sun
  - Other planets, asteroids?
- Inverse-Compton (e.g. Moskalenko Strong 2006)
  - 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 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.

RHESSI observes to ~20 MeV

<table>
<thead>
<tr>
<th>Simplex</th>
<th>PSF at 1 GeV</th>
<th>PSF at 10 GeV</th>
</tr>
</thead>
</table>

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 catalogued
- Rotational periods from msec to secs, increasing over time

Neutron star ~1.4 x Mass Sun

Gamma Ray Pulsars with CGRO

Radio
Optical
X-ray
Gamma Ray

CRAB
FERMI 300 MHz
Y. A.
S.F. 300 MHz
Fermi 331 MHz
Crab 331 MHz

D.I. Thompson (NASA / GSFC)

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

@ New pulsars discovered in a blind search
@ Millisecond radio pulsars
@ Young radio pulsars
@ Confirmed pulsars seen by Compton Observatory EGRET instrument
The Pulsing Sky

Pulses shown at 1/10th true rate

March 23, 2009

E. Hays

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

March 23, 2009

E. Hays

Discovery of Pulsar in CTA 1

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

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

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

Pulse undetected in radio/X-ray

LAT 95% error radius \( = 0.038 \text{ deg} \)

\textbf{Science Express} October 16
\textit{Abdo et al., 2008, Science}

Vela Pulsar Lightcurve

\textbf{Science Express} October 16
\textit{Abdo et al., 2008, Science}

\[ 100 \text{ MeV} \rightarrow 10 \text{ GeV} \]

Timestamps accurate to 300 ns

Phase analysis accurate to \( \pm 1 \text{ ns} \)

Vela Pulsar Energy Dependence

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

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/d^2
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

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LS I +61 303 - a binary system

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

Orbital parameters:
- Periastron (plane 0)
- Apostron (plane 0)

Strong GeV emission at periastron
TeV emission only detected at apostron

Cesares 2005

Army

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LS I +61 303 Periodicity

Orbital periodicity confirmed with gamma rays
26.5 ± 0.5 days

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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

3C 273 X-ray image

Active Galactic Nucleus

Relativistic Jet
Clouds of gas
Supermassive Black Hole
Accretion Disk
Dusty Torus

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 ($4.0 \times 10^{-4} \text{ erg/cm}^2$) 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
**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 lightcurve ($\geq 900$ for later timeslice of lightcurve)
- 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
  - $M_{QG} > 1.50 \times 10^{18} \text{ GeV/c}^2 \approx 0.1 \text{ M}_{\text{Planck}}$

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**Transients Unidentifieds and the Unexpected**

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**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
  - 86 firm identification
- ATel #1788
  - New GeV source, Fermi J0910-5041
  - 68% error radius 0.07 deg

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**LAT Transients in the Galactic Plane**

- Fermi LAT Detection of a New Gamma-ray Transient in the Galactic Plane: 2010-5041
  - Spatially coincident with 3EG J0903-3531
  - Variable EGRET source appearing in several viewing periods
  - 68% error radius 0.11 deg
  - 86 firm identification

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March 23, 2009
**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**

- **LAUNCH**: June 11, 2008
- **Spacecraft turn-on & checkout**
- **First light** (whole sky)
- **LAT, GBM turn-on & checkout**
- **First light** (whole sky)
- **Initial tuning/calibrations**
- **Pointed + sky survey**
- **Whole sky survey**
- **Science Operations** start
- **GBM and LAT GRB Alerts**
- **Continuous release of new photon data**
- **LAT Background Model**
- **Map of the South Atlantic Anomaly**
- **Vela the Calibrator**

**LAT Background Model**

- Orbit-averaged background fluxes by component
- 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!

Vela

PSR J2021+3651

PSR B1709-44

Source Associations in Inner Galaxy

Vela: Off-pulse Limit

LAT Counts Map 300 MeV - 3 GeV

On pulse

Off pulse

<2.8% phase-average flux (95%)

PSR J2021+3651

Pulse profile similar to Vela pulsar

$\Delta\phi_\gamma = 0.468 \pm 0.002$

$\Delta\phi_{\text{radio}} = 0.182 \pm 0.004$

$P_1/P_2$ ratio decreases at higher energy
J2021+3651 LAT Spectrum

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

+ $\Gamma = 1.5 \pm 0.1$
+ $E_0 = 2.4 \pm 0.3 \pm 0.5$ GeV
+ Integral energy flux =
  $4.6 \pm 0.7 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$

Simple exponential $\Rightarrow$ Near-surface emission excluded
Large dispersion measure, but $<9$ kpc favored, e.g. 4 kpc from X-ray thermal

LSI Count Map

Gamma-ray count map

Transient Flux and Spectra

Historical
EGRET avg flux ($E>100$ MeV)
- $0.16 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$
EGRET peak flux
- $0.32 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$
  (Hartman et al. 1999)

During flare (Oct 5-7)
LAT flux $\sim 1 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$
Index $= 2.2 \pm 0.1$ (stat)

During flare (Oct 15-16)
Flux ($E>100$ MeV)
- $1 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$
Index $= 1.9 \pm 0.1$ (stat)

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)
  + $F (E>100 \text{ MeV}) \geq 2 \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$
  + Daily flux in two energy bands
  + Continues to flux $< 2 \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$
### 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

### 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...

### LS I +61 303 Variability

LAT flux Aug 4 - Dec 1 2008 (smoothed)

Orbit to orbit rate variations

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Limits on Lorentz Invariance