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

Astroparticle Science at a GeV
(in one slide!)

- Shocks
- Jets
- Winds
- Matter
- Magnetic Fields
- Radiation Fields

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
  - 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
  - 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.

GLAST Mission Operation Control at GSFC

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)
- Silicon strip detectors (single sided, each layer rotated by 30 degrees)
- ~80 m² of silicon (total)
- >106 electronics channels
- High precision tracking, low dead time

Tracker (TKR):
- Tungsten foils convert
- Silicon strip detectors
- 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
Energy dependence of effective area: 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)

205 Preliminary LAT Bright Sources

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

The 3 Month Skymap

- E>200 MeV (>400 MeV thick detector)
Solar System Gamma Rays

- Albedo gamma rays from cosmic rays impacting matter
- Earth
- Moon
- Sun
- Other planets, asteroids?
- Inverse-Compton \((e.g., \text{Moskalenko 2006, Orlando and Strong 2008})\)
  - 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

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

~ 66 deg (~LAT FOV)
Detection of the quiet Sun in gamma rays!
Fluxes consistent with model expectations. Moon flux agrees with EGRET.

RHESSI observes to ~20 MeV

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?

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

D.J. Thompson (NASA / GSFC)

EGRET Pulsars confirmed

Gemini: 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
The Pulsing Sky

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

Vela Pulsar Lightcurve

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

1420 Hz radio map

LAT 95% error radius = 0.038 deg

P = 316 ms
Flux = 3.6 x 10^{-11}
Characteristic age = 10 kyr
Flux (>100MeV) = 3.8 ± 0.2 x 10^{-7}
ph cm^{-2} s^{-1}

Pulse undetected in radio/X-ray

Timestamps accurate to 300 ns
Phase analysis accurate to ~1 us
Vela Pulsar Energy Dependence

Peak 1 (P1) stronger at low energy. Peak 2 (P2) stronger at higher energy.

Consistent with simple exponential cutoff

Super-exponential rejected at 16.5σ

Excludes emission near neutron star surface

NEW: Peak 3 evolves with energy

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: \(10^{32} - 10^{36}\) 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

March 23, 2009

LS I +61 303 - a binary system

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

Orbital parameters:
Apogee (perihelion) 26.5 days

Strong GeV emission at periastron
TeV emission only detected at apastron

Cesares 2005

March 23, 2009

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)?

March 23, 2009
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} \text{ erg/cm}^2 \text{ in } 50-300 \text{ keV})
  + >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

- 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 intervals for time-resolved spectral analysis
    - -2.6 to -1.7, -1.6 to 0.5, -0.3
  - 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 cutoff
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 (z=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 $16.7 \text{ sec after trigger}$
  + $M_{\text{QG}} > 1.50e18 \text{ GeV/c}^2 \sim 0.1 M_{\text{Planck}}$

Transients
Unidentifieds
and the Unexpected

Transients in the Galactic Plane

+ 2 ~day flares detected in the plane without obvious blazar counterpart
  + ATel #1771
    + Spatially coincident with 3EG J0953-3531
    + 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

LAT Transients in the Galactic Plane
Transient Light Curves

- Daily rate (exposure corrected, relative to background)

3EG J0904-3531

J0910-5041

Transient Multiwavelength Search

- X-ray sources are weak
- One thermal source
- No hints in radio

- Marginally variable
- Archival radio and AT20G source (Sadler et al ATel #1843)

Summary

- The LAT is a powerful pulsed 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

Back up slides...
**Year 1 Science Operations Timeline**

- **Launch**: June 11, 2008
- **60 days**
- **LAT, GBM turn-on checkouts** (first light)
- **Whole sky survey** (nearly 90% energy, extraordinary TIDs)
- **Initial tuning/calibrations**
  - **Pointed + sky survey**
- **Release Flaring and Monitored Source Info**
- **LAT and GBM GRB Alerts**
- **Continuous release of new photon data**
- **LAT 6-month high-confidence source release, GSSC science tools advance release**
- **GI Cycle 2 Proposals**
- **LAT Year 1 photon data release PLUS LAT Year 1 Catalog and Diffuse Model**
- **Fermi Science Symposium (Nov)**

**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 ~15% 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**: Off-pulse Limit
  - LAT Counts Map 300 MeV - 3 GeV
  - On pulse
  - Off pulse
  - <2.8% phase-average flux (95%)

- **Source Associations in Inner Galaxy**
  - Preliminary

- **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
J2021+3651 LAT Spectrum

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

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

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

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)

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}
**LS I +61 303 Variability**

**TeV Added Value**

- **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