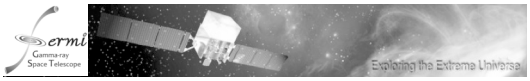
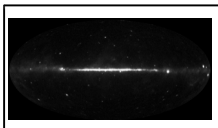




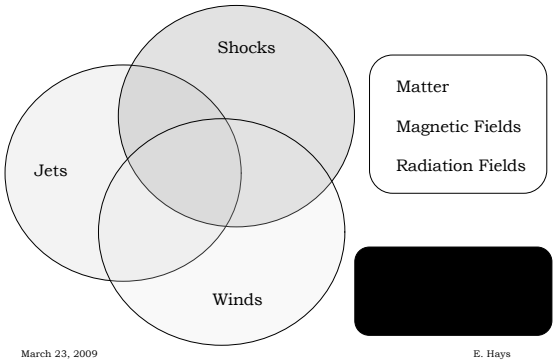
Fermi at Six Months

Elizabeth Hays
NASA/GSFC

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!)



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

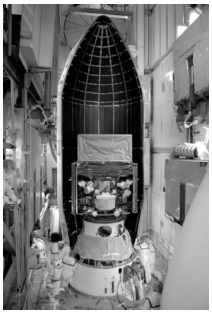
- France
  - IN2P3, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University 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*



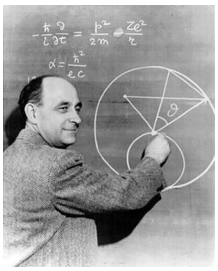
Lift Off !

GLAST Mission Operation Control at GSFC

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

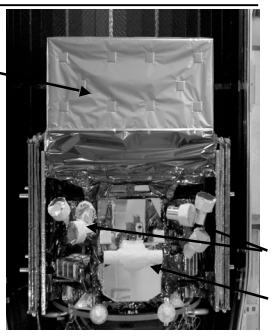
- August 26, 2008
  - First Light
  - GLAST renamed in honor of Enrico Fermi
    - The *Fermi* Gamma-ray Space Telescope
  - *Also fondly remembered as the day a few hundred web links broke…*



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

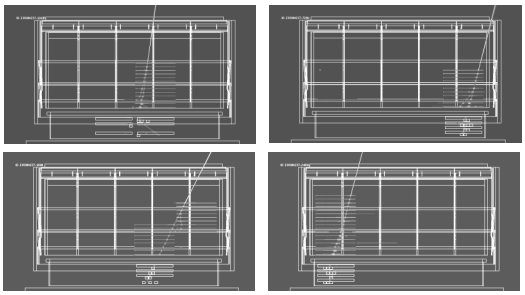
The Large Area Telescope

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

Tracker (TKR):
- Tungsten foils convert
- Silicon strip detectors (single sided, each layer rotated by 90 degrees)
- ~80 m² of silicon (total)
- ~10^6 electronics channels
- High precision tracking, low dead time

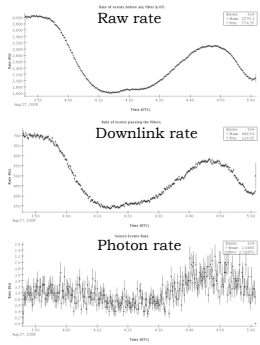
Calorimeter (CAL):
- 1536 CsI crystals
- 8.5 radiation lengths
- Hodoscopic
- Shower profile reconstruction (leakage correction)

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

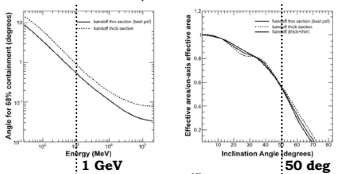


- Overall trigger rate: ~few KHz
  - Huge variations due to orbital effects
- Downlink rate: ~400-500 Hz
  - ~90% from gamma filter
  - ~20-30 Hz from diagnostic filter
  - ~5 Hz from heavy ion filter
- Photon-selected event rate (passing standard background rejection cuts): ~1 Hz

LAT Performance from Ground Simulations

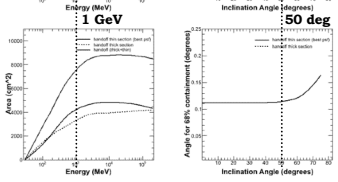
The LAT is a GeV, wide-field instrument

Energy dependence of PSF. 68% containment <0.5 deg above 1 GeV



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

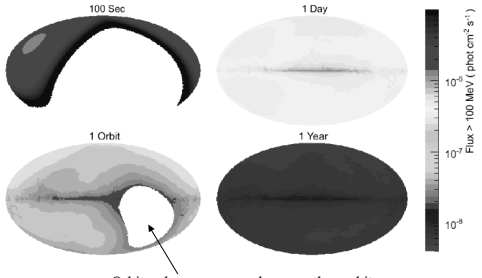
Energy dependence of effective area. Peaks above 1 GeV



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

Overview

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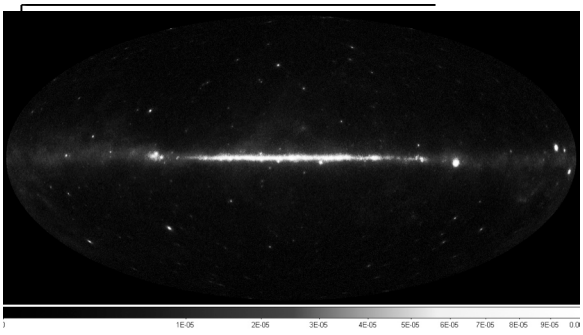
The 3 Month Skymap



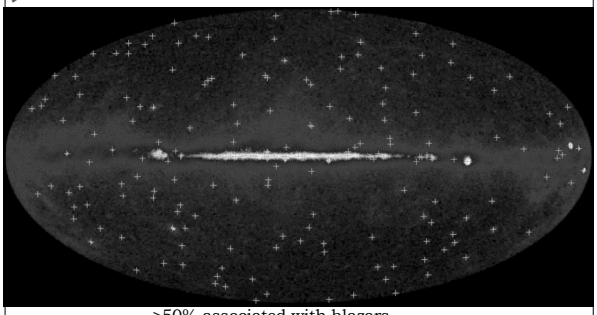
E>200 MeV (>400 MeV *thick detector)*

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)

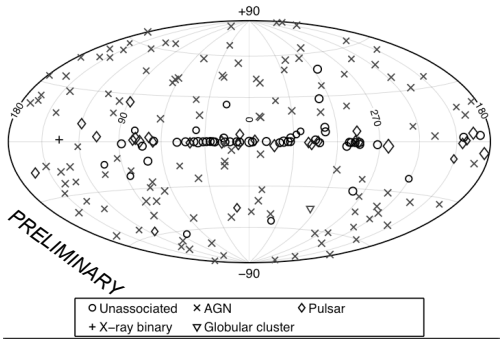
Google Fermi FSSC

205 Preliminary LAT Bright Sources



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

Source Associations

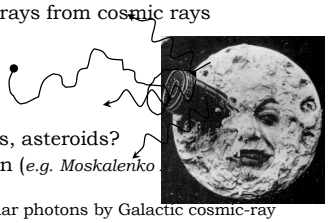


March 23, 2009 E. Hays

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 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



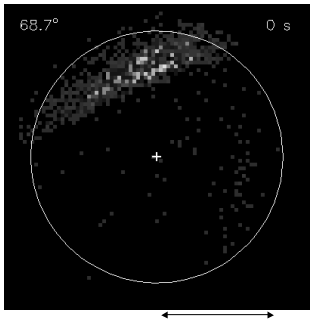
March 23, 2009 E. Hays

The Earth

Gamma rays from the Earth shown in instrument coordinates

Time steps = 250 sec

2.8 hrs in total
~ 2 orbits



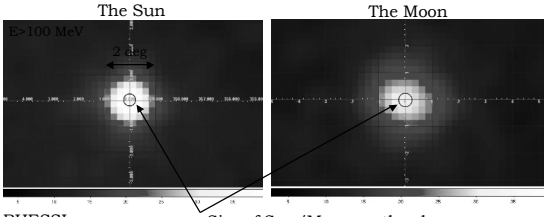
66 deg (~LAT FOV)

March 23, 2009 E. Hays

The Sun and the Moon

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

The Sun | The Moon



RHESSI observes to ~20 MeV

Size of Sun/Moon on the sky

PSF at 1 GeV

PSF at 10 GeV

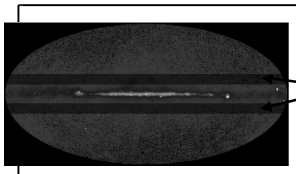
The GeV Galaxy

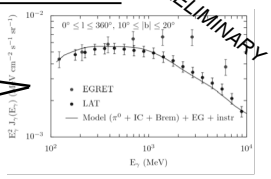
EGRET GeV excess

- 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

PRELIMINARY

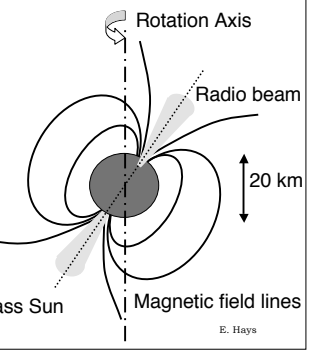




- EGRET GeV excess not confirmed by LAT for this part of the sky
- Conventional diffuse model (local CR) in good agreement
- LAT errors are systematic dominated and estimated ~10%

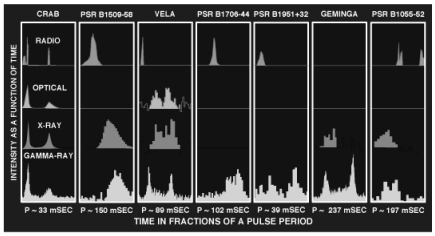
Rotation Powered Pulsars

- 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



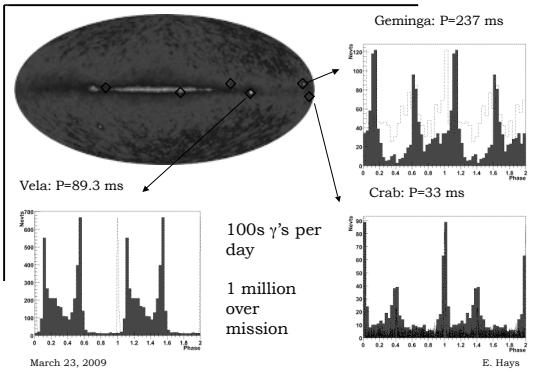
Gamma Ray Pulsars with CGRO

Radio
Optical
X-ray
Gamma Ray



D.J. Thompson (NASA / GSFC)

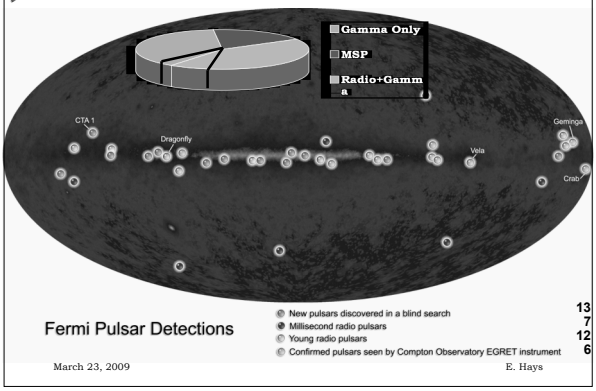
EGRET Pulsars confirmed



100s γ's per day

1 million over mission

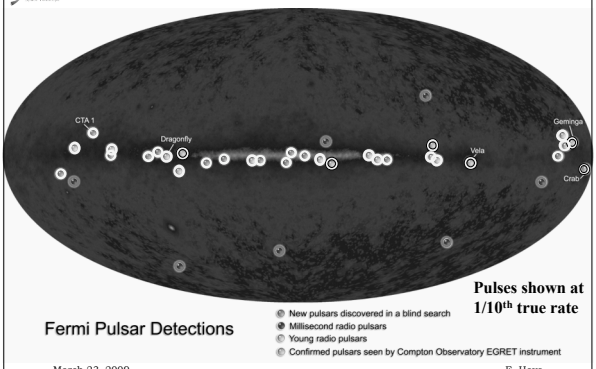
Bright Gamma-ray Pulsars



Fermi Pulsar Detections

New pulsars discovered in a blind search	13
Millisecond radio pulsars	7
Young radio pulsars	12
Confirmed pulsars seen by Compton Observatory EGRET instrument	6

The Pulsing Sky



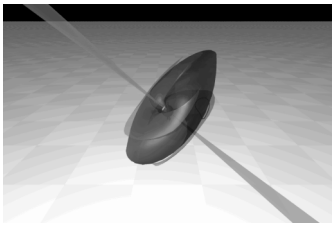
Producing Gamma-ray Pulsations

Radio along the magnetic field axis
Gamma rays from the equator

Lighthouse beam vs "fan" beam

Observer's angle reveals different emission patterns

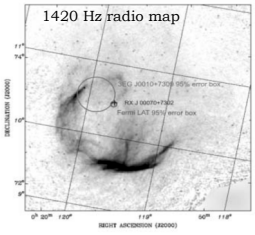
- Radio only
- Radio + Gamma
- No radio or gamma
  - Thermal only
- Gamma only



Discovery of Pulsar in CTA 1

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

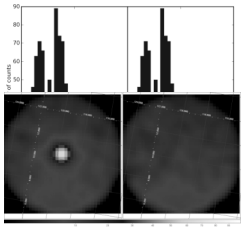
1420 Hz radio map



LAT 95% error radius = 0.038 deg

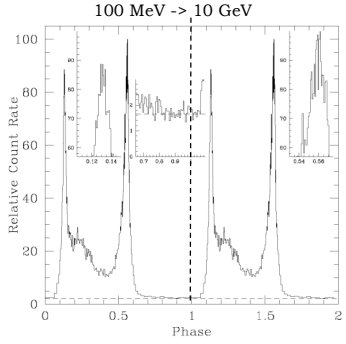
P ~ 316 ms
Pdot ~ 3.6 x 10^{-13}
Characteristic age ~ 10 kyr
Flux (>100MeV) = 3.8 ± 0.2 x 10^{-7} ph cm-2 s-1

Pulse undetected in radio/X-ray



Vela Pulsar Lightcurve

100 MeV -> 10 GeV



Timestamps accurate to 300 ns

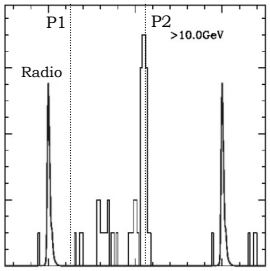
Phase analysis accurate to ~1 us

Abdo et al. 2009 ApJ in press, arXiv:0812.2960

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



Rotational Phase

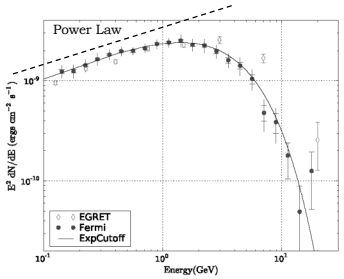
Vela Pulsar Spectrum

[redacted]

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…

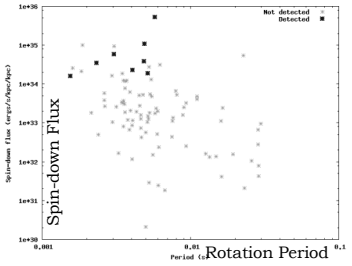
LAT Millisecond Pulsars

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

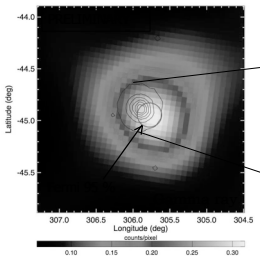
Detecting high Edot/d^2

Nearby - most within 1/2 kpc

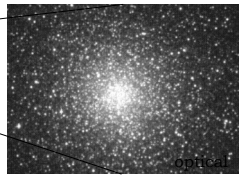
Pulses are complex - work for theorists



Detection of Globular Star Cluster



47 Tucanae contains 23 radio ms pulsars

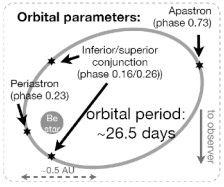


Consistent with Fermi PSF for point source

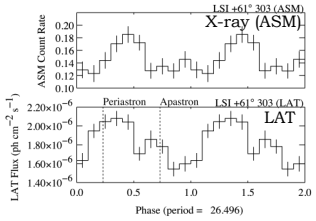
Fermi could be detecting combined emission from ms pulsars assuming average gamma-ray efficiency of ~10 %
- Search for pulsations from individual pulsars is ongoing

LS I +61 303 - a binary system

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



Cesares 2005

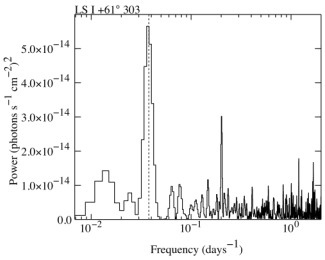


Strong GeV emission at periastron
TeV emission only detected at apastron

LS I +61 303 Periodicity

Orbital periodicity confirmed with gamma rays

26.5 ± 0.5 days

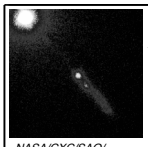


A Multi-TeV to GeV Connection?

- 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)?

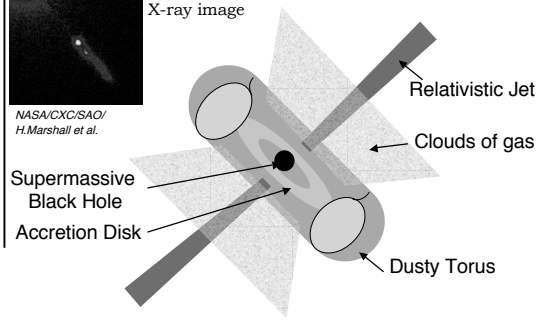
GeV emission from beyond our Galaxy

Active Galactic Nucleus



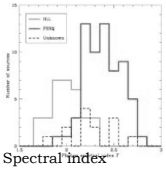
NASA/CXC/SAO/ H.Marshall et al.

3C 273
X-ray image

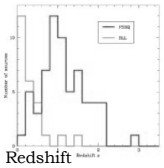


What's New?

- 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

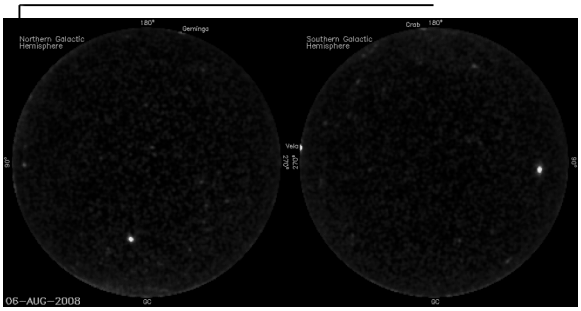


Spectral index



Redshift

3 Month Gamma-Ray Variability



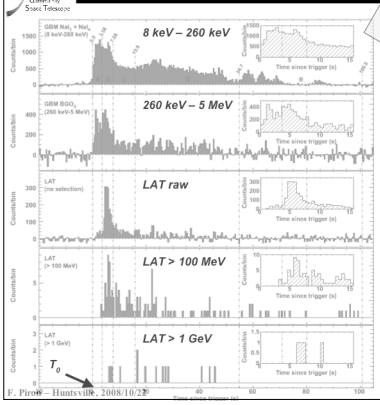
Fermi Gamma-Ray Bursts

- 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 10^{-5} 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

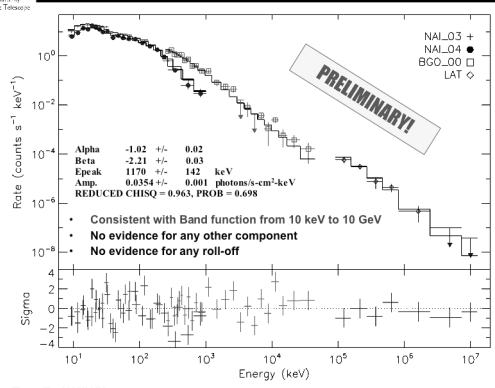
Multiple detector light curve



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 intervals for time-resolved spectral analysis: 0 – 3.6 – 7.7 – 16 – 55 – 100 s**
  - **14 events above 1 GeV**

Spectroscopy of the main LAT peak



Alpha	-1.02	+/-	0.02
Beta	-2.21	+/-	0.03
Epeak	1170	+/-	142 keV
Amp.	0.0354	+/-	0.001 photons/s-cm^2-keV

REDUCED CHISQ = 0.963, PROB = 0.698

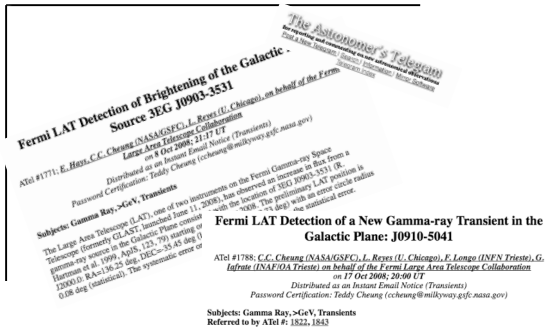
- **Consistent with Band function from 10 keV to 10 GeV**
- **No evidence for any other component**
- **No evidence for any roll-off**

How Relativistic is the Jet?

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

Transients Unidentifieds and the Unexpected

Transients in the Galactic Plane



The Astronomer's Telegram

Fermi LAT Detection of Brightening of the Galactic Source 3EG J0903-3531

ATel #1771; E. Hays, C.C. Cheung (NASA/GSFC), L. Reyes (U. Chicago), on behalf of the Fermi Large Area Telescope Collaboration
on 8 Oct 2008; 21:17 UT
Distributed as an Instant Email Notice (Transients)
Password Certification: Teddy Cheung (ccheung@milkyway.gsfc.nasa.gov)

Subjects: Gamma Ray, >GeV, Transients

The Large Area Telescope (LAT), one of two instruments on the Fermi Gamma-ray Space Telescope (formerly GLAST, launched June 11, 2008), has observed an increase in flux from a gamma-ray source in the Galactic Plane consis with the location of 3EG J0903-3531 (R. Hartman et al. 1999, ApJS, 123, 79) starting or "68% - <1 deg) with an error circle radius 12000.0: RA=136.25 deg, DEC=-35.45 deg (J 0.08 deg (statistical). The systematic error or ing statistical error.

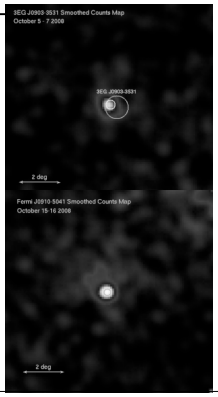
Fermi LAT Detection of a New Gamma-ray Transient in the Galactic Plane: J0910-5041

ATel #1788; C.C. Cheung (NASA/GSFC), L. Reyes (U. Chicago), E. Longo (INFN Trieste), G. Iafrate (INAF/OA Trieste) on behalf of the Fermi Large Area Telescope Collaboration
on 17 Oct 2008; 20:00 UT
Distributed as an Instant Email Notice (Transients)
Password Certification: Teddy Cheung (ccheung@milkyway.gsfc.nasa.gov)

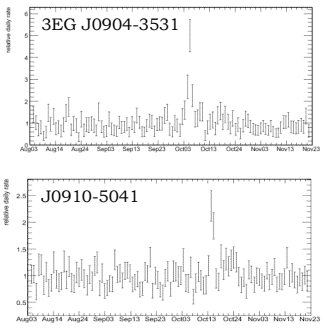
Subjects: Gamma Ray, >GeV, Transients
Referred to by ATel #: 1822, 1843

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

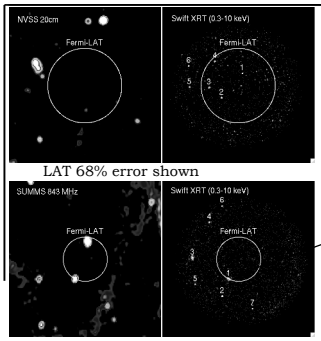


Transient Light Curves



Daily rate
(exposure corrected, relative to background)

Transient Multiwavelength Search



3EG J0903-3531

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

J0910-5041
1 Swift XRT source in error circle

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

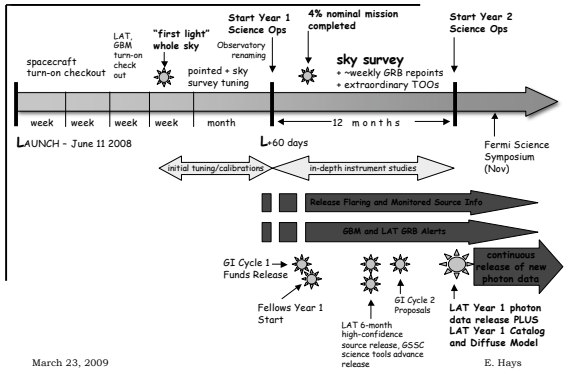
Summary

- 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

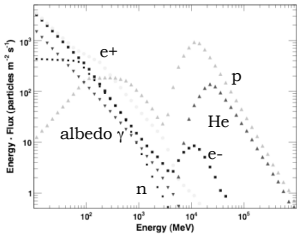
Back up slides…

Year 1 Science Operations Timeline



LAT Background Model

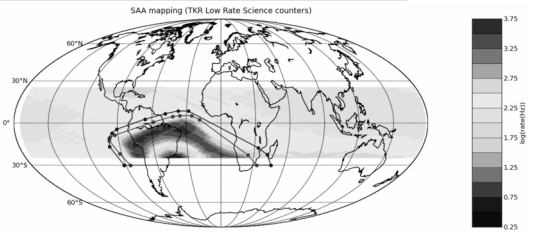
Orbit-averaged background fluxes by component



Green triangles --> protons
Magenta triangles --> helium
Red squares --> electrons
Light Blue circles --> positrons
Dark Blue triangles --> Earth albedo gammas
Black squares --> Earth albedo neutrons

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

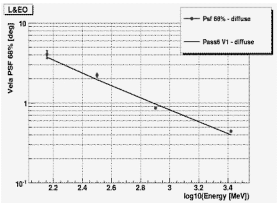


✦ South Atlantic Anomaly (SAA): region with a high density of trapped particles (mostly low energy protons)
✦ No physics data taken (ACD HV turned off); TKR and CAL triggers counted to map the radiation intensity
✦ Conservative boundary defined pre-launch; new polygon now uploaded on the spacecraft (down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

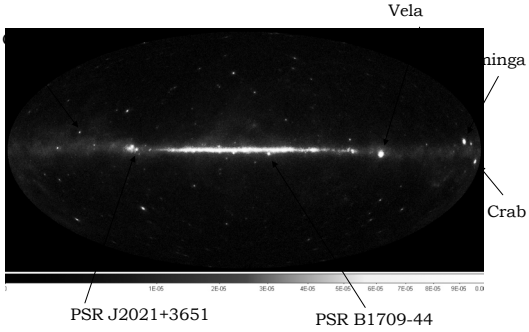
Vela the Calibrator

+ 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

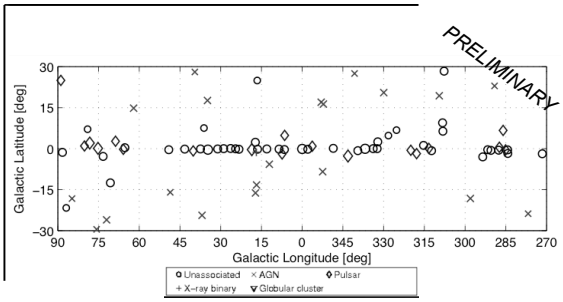
68% containment radius measured using Vela (points) and simulated (line)



3 Month Skymap: Pulsars!



Source Associations in Inner Galaxy

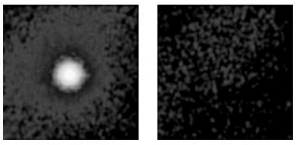


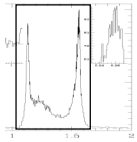
Vela: Off-pulse Limit

LAT Counts Map 300 MeV - 3 GeV

On pulse Off pulse

10 deg

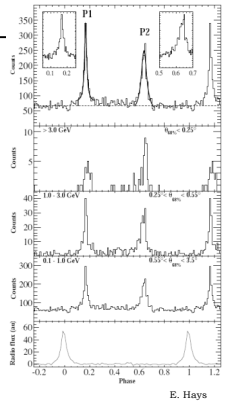




<2.8% phase-average flux (95%)

PSR J2021+3651

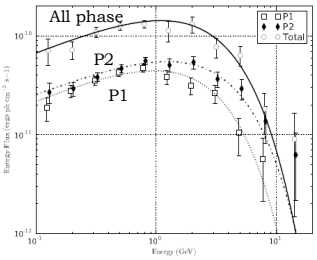
- Pulse profile similar to Vela pulsar
  - $\Delta\phi_\gamma$ = 0.468 ± 0.002
  - $\Delta\phi_{\gamma\text{-radio}}$ = 0.182 ± 0.004
  - P1/P2 ratio decreases at higher energy



J2021+3651 LAT Spectrum

$$\frac{dF}{dE} = kE^{-\Gamma}e^{(-E/E_c)^b}$$

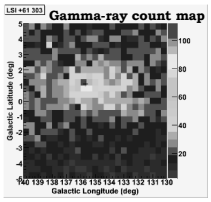
- Γ = 1.5 ± 0.1
- E_c = 2.4 ± 0.3 ± 0.5 GeV
- Integral energy flux = 4.6 ± 0.7 x 10^{-10} ergs cm^{-2} s^{-1}



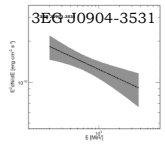
Simple exponential ==> Near-surface emission excluded

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

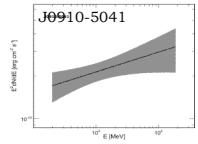
LSI Count Map



Transient Flux and Spectra



Historical
EGRET avg flux (E>100 MeV)
~0.16 x 10^{-6} ph cm^{-2} s^{-1}
EGRET peak flux
~0.32 x 10^{-6} ph cm^{-2} s^{-1}
(Hartman et al. 1999)
During flare (Oct 5-7)
LAT flux ~1 x 10^{-6} ph cm^{-2} s^{-1}
Index = 2.2 ± 0.1 (stat)



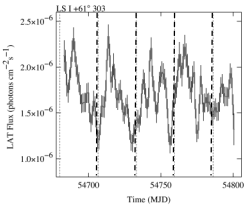
During flare (Oct 15-16)
Flux (E>100 MeV)
~1 x 10^{-6} ph cm^{-2} s^{-1}
Index = 1.9 ± 0.1 (stat)

Galactic Transients

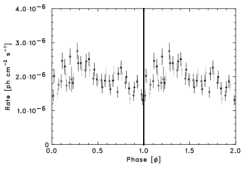
- Monitored by the LAT team
  - Weekly shifts covered by an AGN and galactic advocate
- Announced by ATels
  - E-mail notice, request for observations
  - 24 hr response time
  - LAT contact person for updates and to coordinate multiwavelength follow-up
- Data release plan (1st year)
  - *F (E>100 MeV)*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

LS I +61 303 Variability

LAT flux Aug 4 - Dec 1 2008 (smoothed)



Orbit to orbit rate variations



1st
2nd
3rd
4th
5th

TeV Added Value

- GeV + TeV detections
  - Our pulsars are your PWNe?
  - Identifiying 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