Fermi Gamma-ray Space Telescope – science highlights for the first two years on orbit

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Fermi Gamma-ray Space Telescope was launched on June 11, 2008.

"There are two possible outcomes: If the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery." Enrico Fermi

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The Fermi LAT Collaboration

LAT collaboration

France
- IN2P3/LLR Ecole Polytechnique
- IN2P3/CENBG Bordeaux
- IN2P3/LPTA Montpellier
- CEA/Saclay
- CESR Toulouse

Germany
- MPI fuer extraterrestr. Physik, Garching

Italy
- INFN Bari, Padova, Perugia, Pisa, Rome, Trieste, Udine
- ASI
- INAF-IASF

Japan
- Hiroshima University
- ISAS/JAXA
- Tokyo Institute of Technology

Spain
- IEEC-CISC, Barcelona

Sweden
- Royal Institute of Technology (KTH)
- Stockholm University

United States
- Stanford University (HEPL/Physics, SLAC, KIPAC)
- UC Santa Cruz
- Goddard Space Flight Center
- Naval Research Laboratory
- Sonoma State University
- Ohio State University
- University of Washington
- University of Denver
- Purdue University – Calumet

Spacecraft with LAT and GBM before shipping to KSC

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Fermi Science Questions

Fermi science objectives cover probably everything in high energy astrophysics:

- 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?
- How does the Sun generate high-energy γ-rays in flares?
- How do the pulsars operate? How many of them are around and how different are they?
- What are the unidentified γ-ray sources found by EGRET?
- What is the origin of the cosmic rays that pervade the Galaxy?
- What is the nature of dark matter?

Multiwavelength observations in cooperation with gamma-ray, X-ray, radio, and optical telescopes

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Fermi results recognized as one of the top 10 science breakthroughs of 2009 (Science, December 2009)

Many discoveries in different topics. Fermi LAT Collaboration just has published its 100-th paper (~ 2,500 citations to date)

Each of these paper is a complete high-level analysis covering one of the topics listed above.

It is impossible to address all of them in one talk!
I will briefly go through the main results. Please do not hesitate to ask me for the details off line
Some Highlights

Fermi LAT successfully operates on the orbit for more than 2 years and demonstrates excellent performance, which is continuously monitored and calibrated. LAT collected > 100 billion on-orbit triggers.

- Discovery and study of >70 gamma-ray pulsars, 24 of which are found in “blind” search. 16 are millisecond (or “recycled” pulsars)
  - 20 new millisecond radio-pulsars discovered thanks to LAT data (more are being found almost every week)!
- Remarkable high-energy emission from gamma-ray bursts
- Very high statistics measurement of the cosmic ray $e^+e^-$ flux to 1 TeV
- Nailing down the diffuse galactic GeV emission

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Some Highlights (cont.)

- First Fermi determination of the isotropic (extragalactic) diffuse flux
- Early searches for Dark Matter signatures in different kinds of sources
- Many new results on supermassive black hole systems (AGN), including sources never seen in the GeV range
- More cosmic accelerators: Galactic X-ray binaries and supernova remnants. Probing the cosmic ray distributions in other galaxies: LMC and SMC
- Extragalactic Background Light constraints
- Year-one source catalog: 1451 sources
- High energy gamma-ray flares of Crab nebula detected
Fermi Large Area Telescope (LAT)

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Two instruments onboard:

- **Large Area Telescope LAT**
  - main instrument, gamma-ray telescope, 20 MeV - >300 GeV
  - scanning (main) mode - 20% of the sky all the time; all parts of sky for ~30 min. every 3 hours

- **GLAST Burst Monitor GBM**
  - 8 KeV – 40 MeV
  - observes whole unocculted sky all the time, searching for gamma-ray bursts

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Large Area Telescope LAT

Heritage from OSO-III, SAS-II, COS-B, and EGRET, but:

- large field of view (2.4 sr at 1 GeV, 4 times greater than EGRET) and large effective area (~8000 cm² on axis at 1 GeV)
- large energy range, overlapping with EGRET under 10 GeV and with HESS, MAGIC, CANGAROO and VERITAS above 100 GeV, including poorly-explored 10 GeV – 100 GeV range.
- Good energy (<15% at E>100 MeV) and spatial resolution
  - Unprecedented PSF for gamma-rays, >3 times better than EGRET for E>1GeV
- Small dead time (<30 µs, factor of ~4,000 better than EGRET) – GRB time structure!
- Excellent timing to study transient sources
- No consumables – chance for longer mission!
The LAT Instrument Overview

Pair-conversion gamma-ray telescope: 16 identical “towers” providing conversion of \( \gamma \) into \( e^+e^- \) pair and determination of its arrival direction (Tracker) and energy (Calorimeter). Covered by segmented AntiCoincidence Detector which rejects the charged particles background.

Silicon-strip tracker: 18 double-plane single-side (\( x \) and \( y \)) interleaved with 3.5% \( X_0 \) thick (first 12) and 18% \( X_0 \) thick (next 4) tungsten converters. Strip pitch is 228 \( \mu \)m; total \( 8.8 \times 10^5 \) readout channels.

Segmented Anticoincidence Detector: 89 plastic scintillator tiles and 8 flexible scintillator ribbons. Segmentation reduces self-veto effect at high energy.

Hodoscopic Csl Calorimeter Array of 1536 Csl(Tl) crystals in 8 layers.

Electronics System Includes flexible, robust hardware trigger and software filters.

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LAT Construction: An international effort

Integration & Data System: US

Tracker: US, Italy, Japan

Calorimeter: US, France, Sweden

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LAT Performance

100 sec 1 day

1 orbit 1 year

Flux > 100 MeV (phot cm^-2 s^-1)

Sensitivity to point sources

One of the main features: most of the time the LAT is operating in the sky-scanning mode, making it all-sky monitor, unlike EGRET and AGILE, and especially ground-based ACTs.
Gamma-Ray Sources
What we measure?

Gamma-ray sources, galactic and extragalactic:
- Persistent sources. They should be detected against a diffuse background. This background allegedly comes from interactions of CR with ISM
  - The “background” includes unresolved sources and possibly some contribution from “new physics” phenomena
  - Source identification requires as high as possible angular resolution and as good as possible knowledge of background in order to determine statistical significance of the source
- Variable sources. Long (month-year scale) and short (day-hour-min etc) flare-like variability. Periodical variation (pulsars)

Diffuse gamma-ray radiation (background). Accuracy depends on accounting for as many as possible discrete sources (whose contribution should be subtracted), reliable modelling of CR interaction with ISM and IC scattering of CR electrons with CMB
  - Galactic
  - Extragalactic (high latitude)

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## The Fermi LAT 1FGL Source Catalog

<table>
<thead>
<tr>
<th>Description</th>
<th>Designator</th>
<th>Number Assoc. (ID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar, X-ray or radio, identified by pulsations</td>
<td>psr (PSR)</td>
<td>7 (56)</td>
</tr>
<tr>
<td>Pulsar, radio quiet (LAT PSR, subset of above)</td>
<td>PSR</td>
<td>24</td>
</tr>
<tr>
<td>Pulsar wind nebula</td>
<td>pwn (PWN)</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Supernova remnant</td>
<td>† (SNR)</td>
<td>41 (3)</td>
</tr>
<tr>
<td>Globular Cluster</td>
<td>glc (GLC)</td>
<td>8 (0)</td>
</tr>
<tr>
<td>Micro-quasar object: X-ray binary (black hole or neutron star) with radio jet</td>
<td>mqa (MQO)</td>
<td>0 (1)</td>
</tr>
<tr>
<td>Other X-ray binary</td>
<td>hxb (HXB)</td>
<td>0 (2)</td>
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<tr>
<td>BL Lac type of blazar</td>
<td>bzb (BZB)</td>
<td>295 (0)</td>
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<tr>
<td>FSRQ type of blazar</td>
<td>bzq (BZQ)</td>
<td>274 (4)</td>
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<tr>
<td>Non-blazar active galaxy</td>
<td>agn (AGN)</td>
<td>28 (0)</td>
</tr>
<tr>
<td>Active galaxy of uncertain type</td>
<td>agu (AGU)</td>
<td>92 (0)</td>
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<tr>
<td>Normal galaxy</td>
<td>gal (GAL)</td>
<td>6 (0)</td>
</tr>
<tr>
<td>Starburst galaxy</td>
<td>sbg (SBG)</td>
<td>2 (0)</td>
</tr>
<tr>
<td>Unassociated</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Possible Association with SNR and PWN
- AGN
- AGN-Blazar
- AGN-Non Blazar
- No Association
- Possible Association with SNR and PWN
- Possible confusion with Galactic diffuse emission

Credit: Fermi Large Area Telescope Collaboration
Fermi two-year all-sky map
Pulsars in 1FGL: LAT Pulsar Catalog

- Comprehensive, uniform presentation of 46 pulsars detected by the LAT using the first 6 months of LAT data (now >60 LAT-detected pulsars)
- Of the 46, 16 resulted from blind searches, and 24 were discovered using ephemerides from radio monitoring*, including 8 MSPs

- Light curves (with tabulated peak phases), spectral fits, log N-log S

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* Consortium of radio & X-ray astronomers; Smith et al. (2008)
The Pulsing gamma-ray Sky. More than 60 gamma-ray pulsars are now known.

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by EGRET

Pulses at 1/10th true rate

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AGNs in 1FGL: First LAT AGN Catalog (1LAC)

Based on 1FGL sources associated with AGN, but for $|b| > 10^\circ$ & includes lower-confidence associations (down to $P = 0.5$)

- 671 1FGL sources: 300 BL Lacs, 296 FSRQs, 41 AGNs of other types, 72 of unknown type (some multiple associations)

1LAC paper also lists 51 low-latitude associations and 104 high-latitude 'affiliations' (plausible associations for which quantitative probabilities could not be defined)

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AGNs – most numerous sources (about half of 1FGL) detected by Fermi LAT

- Powered by accretion onto a central, supermassive black hole
- Accretion disks produce optical/UV/X-ray emission via various thermal processes
- Jets: highly collimated outflows with $\Gamma \sim 10$
  - Large brightness temps, superluminal motion, rapid variability in $\gamma$-rays
- Unified Model: observer line-of-sight determines source properties, e.g., radio galaxy vs blazar
- Other factors: accretion rate, BH mass and spin, host galaxy
CTA 1 – First gamma-ray pulsar discovered by Fermi in blind search

Exhibits all characteristics of a young high-energy pulsar (characteristic age $\sim 1.4 \times 10^4$ yr), which powers a synchrotron pulsar wind nebula embedded in a larger SNR.

This source was a very bright AND well positioned unidentified EGRET source. This source was deliberately targeted during LAT checkout.

Gamma-ray source at $l, b = 119.652, 10.468$; 95% error circle radius $= 0.038^\circ$ contains the X-ray source RX J00070+7302

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Vela Pulsar – very first target for Fermi, used for calibration

- Outer magnetosphere
- Near the NS surface

LAT data consistent with simple exponential cut-off

- favors outer-gap model

\[
N(E) = N_0 E^\Gamma e^{-(E/E_c)^b}
\]

\[
\Gamma = -1.5^{+0.05}_{-0.04}
\]

\[
E_c = 2.9 \pm 0.1 \text{ GeV}
\]

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Pulsar Wind Nebulae - Powerful Particle Accelerators

Crab Nebula Spectral Energy Distribution. Red points are Fermi LAT data, showing transition from synchrotron to Compton components.

E>800 MeV Test Statistic (significance) map. PWN Vela X

E>2 GeV counts map. PWN HESS J1640-465

E>10 GeV counts map. PWN MSH 15-52

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Neutron star or black hole binary system, accelerating particles to high energies. The system remains largely a mystery.

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Supernova Remnants (SNR) - Spatially Resolved

Note: LAT does not resolve Cas A

W51C

W44

IC 443
Supernova remnant W44

Well spatially resolved. 2-10 GeV front-converting (high quality) events, deconvolved image.

Green contours are from Spitzer IRAC, shocked H$_2$

Black cross is PSR B1853+01, not seen as a pulsed.

Note: leptonic models are not excluded. Neutrinos could confirm the acceleration of hadrons by SNB.
A Surprise - A Gamma-ray Nova

- In early March, the LAT skywatchers found a new, flaring gamma-ray source in the Cygnus region.
- To our surprise, we learned that an optical flare of the symbiotic system V407 Cyg (red giant/white dwarf binary) had occurred at about the same time. It was observed by amateur Japanese astronomers Koichi Nishiyama and Fujio Kabashima.

Central Bureau for Astronomical Telegrams
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URL http://www.cfa.harvard.edu/iau/cbat.html

V407 CYGNI
Hiroyuki Maehara, Kwasan Observatory, Kyoto University, discovery by Koichi Nishiyama (Fukuoka, Japan) and Fujio Kabashima (Japan) of an apparent unusually bright outburst (mag 6.8) of star V407 Cyg on an unfiltered CCD image taken on Mar. 10.814 with a 105-mm camera lens (+ SBIG STL6303E camera). Nishiyama and Kabashima confirmed the outburst on two unfiltered CCD frames taken on Mar. 10.813 (mag 6.8) and 10.814 (mag 6.9) using a 0.40-m reflector (+ SBIG STL1001E camera).

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Crab Flares in high energy!

- Remnant from 1054 AD SN at 2 kpc
- Standard candle in X-rays and VHE
- Yearly variable in X-rays ~ 3.5%, 1-150 MeV ~ 40%

Spectrum between pulses (off-pulse) to remove pulsar contribution

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Crab Flares (cont.)

Two flares detected by Fermi LAT:
• flux increase by a factor ~4 during ~16 days (January 26 to February 11, 2009)
• Flux increase by a factor of ~6 during ~4 days (September 18-22, 2010). First reported by AGILE
• No variation (< 5%) found in pulsed emission and nebula IC component

Second (short) flare has harder spectrum and extends > 1 GeV at >3σ
• Energy release small compared to pulsar spin down

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Nothin