

Fermi Gamma-ray Space Telescope: Science highlights for the first 8 months

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Abstract

The Fermi Gamma-ray Space Telescope was launched on June 11, 2008 and since August 2008 has successfully been conducting routine science observations of high energy phenomena in the gamma-ray sky. A number of exciting discoveries have been made during its first year of operation, including blazar flares, high-energy gamma-ray bursts, and numerous new gamma-ray sources of different types, among them pulsars and Active Galactic Nuclei (AGN). Fermi-LAT also performed accurate measurement of the diffuse gamma-radiation which clarifies the GeV excess reported by EGRET almost 10 years ago, high precision measurement of the high energy electron spectrum, and other observations. An overview of the observatory status and recent results as of April 30, 2009, are presented.

Key words: gamma-ray astronomy, cosmic rays, gamma-ray burst, pulsar, blazar, diffuse gamma-radiation
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1. The Fermi Mission

The Fermi observatory was launched from Cape Canaveral by a Delta-II rocket on June 11, 2008, into a near-circular 565 km orbit with 25.6° declination. It consists of two instruments: Large Area Telescope (LAT) [1] and Gamma-ray Burst Monitor (GBM) [2]. A mission overview is given in [3]. The main instrument, the LAT, is a wide field-of-view, imaging high energy gamma-ray telescope for detecting celestial gamma rays in the energy range from ≈ 20 MeV to above 300 GeV. The main mode of LAT operation is scanning mode, with the whole sky observed for 30 minutes every 3 hours. The GBM covers the energy range from 8 keV to 40 MeV and observes the whole unocculted sky all the time, searching for gamma-ray bursts (GRB).

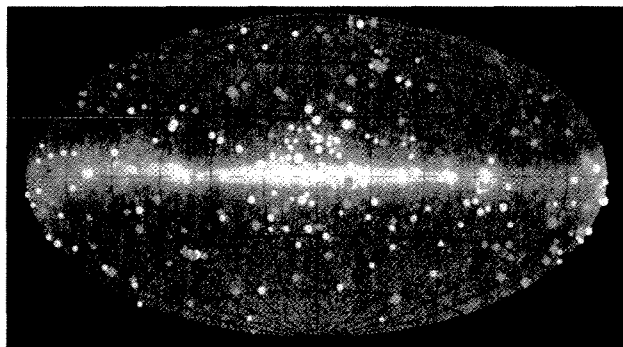


Figure 1: EGRET gamma-ray sources, obtained for almost 9 years of orbit operation

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The LAT predecessor, Energetic Gamma Ray Experiment Telescope (EGRET) [4] on the Compton Gamma Ray Observatory, which operated in orbit from 1991 to 2000, made the first complete survey of the sky in the energy range from 30 MeV to about 10 GeV. EGRET performed extensive observations on Active Galactic Nuclei (AGN), pulsars, and diffuse gamma radiation, and left 170 sources (out of 271 sources in 3rd EGRET catalog [5]) as unidentified, raising questions for future experiments (fig.1). These results, along with the modern achievements of other astrophysical experiments and theoretical investigations established the main science questions for the Fermi:

- How do supermassive 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 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 fill the Galaxy?
- What is the nature of dark matter?

The complexity of the science tasks requires multiwavelength approach in observations: cooperation with gamma-ray, X-ray, radio, and optical telescopes.

1.1. The LAT instrument overview

LAT conceptual design inherits from its predecessors OSO-III, SAS-II, COS-B, and EGRET but is significantly improved. The main LAT features are:

- large field of view (2.4 sr at 1 GeV, 4 times greater than EGRET) and large effective area ($\approx 8000\text{cm}^2$ on axis at 1 GeV)
- large energy range, overlapping with EGRET below 10 GeV and with HESS, MAGIC, CANGAROO and VERITAS above 100 GeV, including the poorly-explored 10 GeV - 100 GeV range
- good energy ($\sim 15\%$ at E 100 MeV) and spatial resolution with unprecedented point-spread function (PSF) for gamma-rays, >3 times better than EGRET for $E \geq 1$ GeV
- small dead time ($\leq 30 \mu\text{s}$, factor of $\approx 4,000$ better than EGRET) - important for GRB time structure
- excellent timing to study transient sources
- no consumables: chance for longer mission

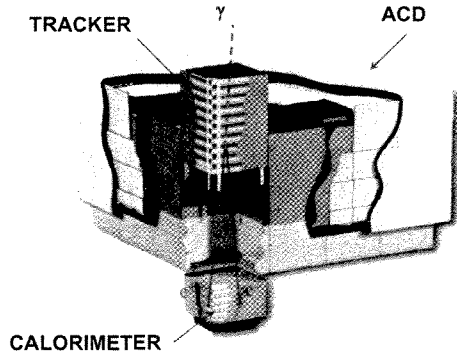


Figure 2: Schematic diagram of the LAT. The telescope dimensions are 1.8m x 1.8m x 0.72m

LAT is a pair-conversion gamma-ray telescope with 16 identical towers providing conversion of a gamma-ray into e^+e^- pair and determination of its arrival direction (Tracker) and energy (Calorimeter) - fig.2. The instrument is covered by a segmented Anticoincidence Detector which rejects the charged particle background. The silicon-strip tracker consists of 18 double-layer single-side (x and y) detectors interleaved with 3.5% X_0 thick (first 12) and 18% X_0 thick (next 4) tungsten converters. Strip pitch is $228\mu\text{m}$; total 8.8×10^5 readout channels. Segmented Anticoincidence Detector comprises 89 plastic scintillator tiles and 8 flexible scintillator ribbons. Segmentation reduces self-veto effect at high energy. Hodoscopic CsI calorimeter is an array of 1536 CsI(Tl) crystals, arranged in eight alternating orthogonal layers. Electronics system includes flexible, robust hardware trigger and software filters.

Basic LAT performance is shown in fig.3: top panel gives the instrument effective area, and the bottom one - the angular resolution (point-spread function).

1.2. Mission initiation: on-orbit calibration and first light

The first 13 days after the launch were used for initialization of the spacecraft systems, navigation and ori-

entation, and radio-communication. The LAT and GBM were turned on for the first time on June 24, the 13-th day of the mission. After the initial check-out of instrument commanding and data transmission, the first 7 days of instruments operation were used for primary calibration. After the completion of this step, on the 20-th day of the mission (!), the LAT started the first collection of science data. During four days the LAT revealed the image of gamma-ray sky with clearly seen Galactic plane, Galactic Center and Anticenter, major gamma-ray sources such as pulsars Vela, Crab and Geminga, the Cygnus region and 3C454.3. Shortly after that, accurate light curves for Crab, Vela and Geminga pulsars were obtained (fig.4).

The LAT and GBM tests and calibrations were mainly completed on August 3-rd [6], and nominal science operation started. On August 26 the mission, formerly known as GLAST, was named after genius Italian scientist Enrico Fermi who inspired a whole generation of physicists. The Fermi-era in gamma-ray astronomy started.

2. Pulsar observations

Pulsars were the natural primary target for the initial Fermi observations due to their relatively easy identification. Also, due to known properties, Vela pulsar was used for the instrument calibration. During the first 8 months of operation Fermi detected 31 pulsars, including 8 millisecond (mature) pulsars and 16 pulsars discovered by their gamma-ray emission.

2.1. First discovery: radio-quiet pulsar CTA 1

After about 2 months of nominal science operations the LAT discovered in a blind search (no known pulsed emission) the pulsar in the young galactic Supernova remnant CTA 1 [7], fig.5. This source was a very bright and well positioned unidentified EGRET source and was deliberately targeted during the LAT checkout, but there was no pulsed X-ray or radio emission from that region. It was discovered only through its gamma-ray pulsation, with a period of 316.86 ms, a period derivative of 3.614×10^{-13} s/s and estimated age of 10^4 yrs, which is compatible with the estimated age for that SNR.

2.2. Observations on Vela and other pulsars

Vela is the brightest persistent gamma-ray point source with well known position and flux, so it was used for the timing and angular calibration purposes. Fermi obtained the light curve (fig.6) and spectrum in gamma-rays for Vela with high precision [8]. The pulse structure was measured with 0.3 ms precision with $\sim 32,000$ pulsed photons above 30 MeV, and revealed a third peak, which shifts in phase with energy. The spectrum suggests a phased-averaged power-law index of 1.51 with an exponential cutoff at $E_C = 2.9$ GeV. The result favors outer-magnetosphere emission models. Fermi also discovered pulsed gamma-emission from the young radio pulsar PSR

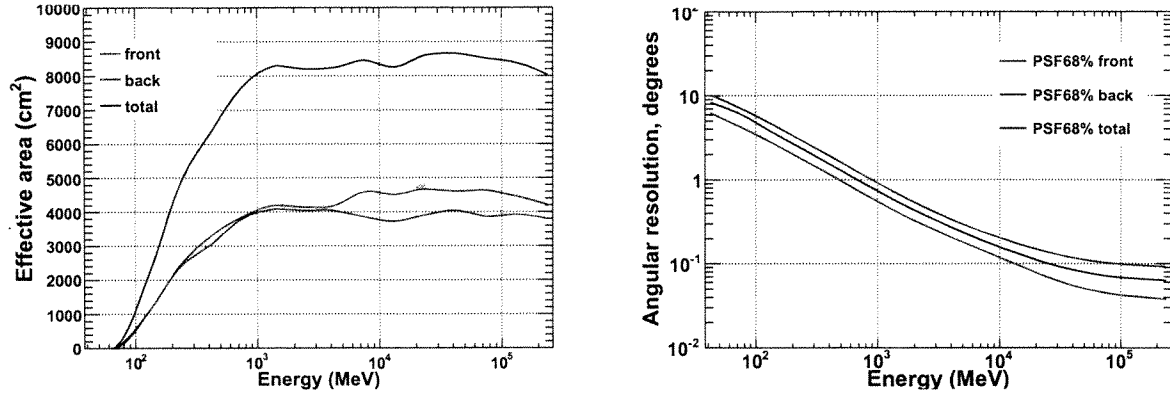


Figure 3: LAT performance plots for normal incidence events. Left panel - effective area vs. energy. Right panel - angular resolution, or point-spread function PSF (68% event containment radius) vs. energy. Lines labelled as "front" are for events converted in thin converters, "back" - converted in thick converters, and total - for all events.

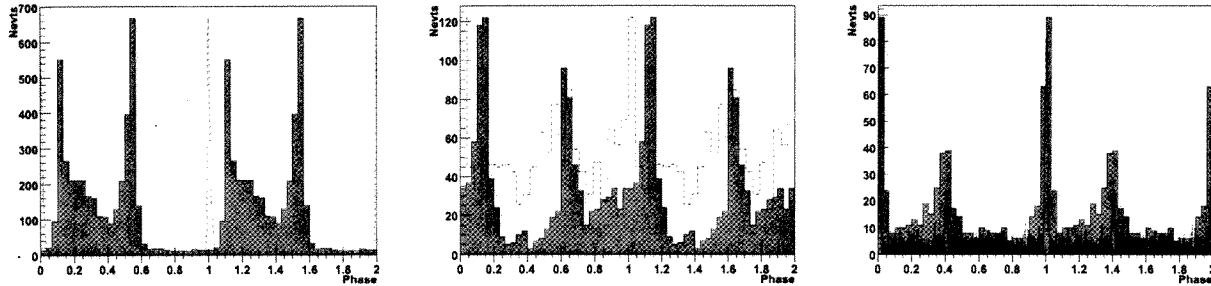


Figure 4: Light curves for pulsars Vela (left panel), Geminga (middle panel) and Crab (right panel) for 2 cycles of pulsing, obtained for 16 days of LAT data

J1028-5819 [9] and from millisecond pulsar J0030+0451 [10].

The main outcomes of early pulsar observations by Fermi are: a) there probably is a large population of millisecond gamma-ray pulsars which represent pulsar "second life" after spin-up of the rotating neutron star in a binary system, and b) there are likely many still unknown gamma-pulsars in our Galaxy. Also, measurement of the pulsed emission fine time structure is a very valuable contribution to the pulsar modeling.

3. List of bright sources

Based on 3-month observations, a list of 205 significant gamma-sources was produced [11] and named as 0FGL (0-th Fermi Gamma LAT). All these sources have statistical significance greater than 10 sigma for the flux above 100 MeV. Fig. 7 shows their locations on the sky (Galactic coordinates). Below are some specifics for 0FGL:

- EGRET for its entire lifetime of approximately 9 years, detected 31 sources with confidence level > 10 sigma
- out of 205 sources in 0FGL, 73 sources are found within 10° of the Galactic Plane, and the remaining 132 are seen at higher Galactic latitudes

- 66 sources show variability
- 60 LAT sources have nearby counterparts in the 3EG catalog [5]
- most of the sources seen by EGRET in the 1990-s are not seen by LAT as bright sources in 2008. They are probably variable
- 121 sources in 0FGL are associated with Active Galactic Nuclei (AGN), 30 with pulsars, two with High Mass X-ray Binary (HMXB) sources, one globular cluster (47 Tuc), also Large Magellanic Cloud (LMC) and some other. 37 0FGL sources have no obvious counterparts at other wavelengths

The main purpose of the 0FGL list is to inform the community about the most active gamma-ray celestial sources seen by Fermi, and coordinate accordingly observations on those sources.

4. Active Galactic Nuclei

The study of AGN is one of the main science tasks of the Fermi mission. Almost every galaxy has a massive black hole, but 99% of them are silent, as our own Galaxy. The remaining ~ 1% of galactic centers are active (AGN) and emit radio-optical-UV-X-ray-gamma radi-

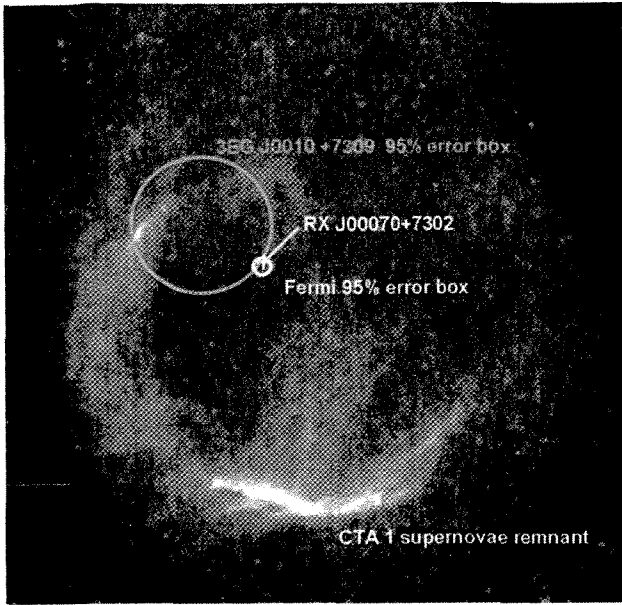


Figure 5: Gamma-source at $l, b = 119.652, 10.468$; 95% error circle radius = 0.038° contains the X-ray source RX J00070+7302

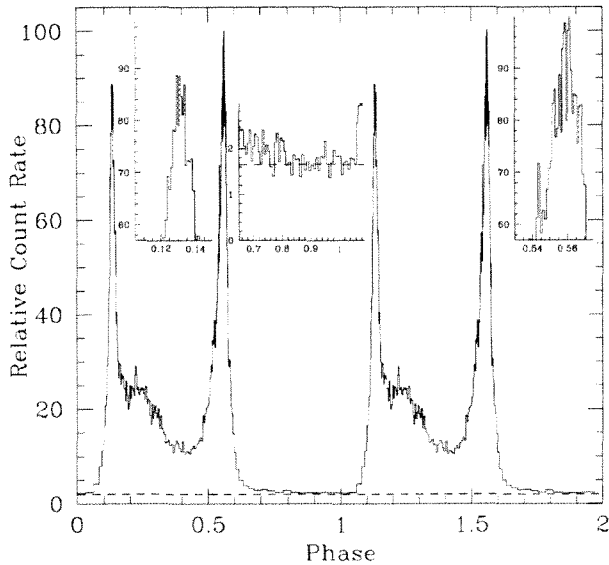


Figure 6: Light curves for Vela pulsar. Main panel - 2 cycles are shown. Top left inset - fine structure of the first peak. Top right inset - fine structure of the second peak. Top middle inset - fine structure between the peaks

ation. Some emission is normally highly collimated (jets) and time-variable. The study of AGN spectral and timing properties is critical for understanding of their operation. Also, the study of AGN emission attenuation by extragalactic background light (EBL) contributes to understanding of the early Universe. Taking into account the importance of AGN observations and their expected rapid variations, the dedicated software Automated Science Pro-

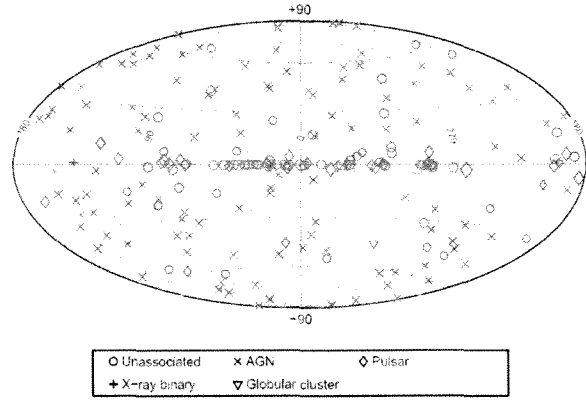


Figure 7: 205 Fermi bright sources from 0FGL list

cessing has been developed. It monitors the appearance of new bright sources, and issues an alert if there is a signal ($E > 100$ MeV) above $2 \times 10^{-6} \text{ph cm}^{-2} \text{s}^{-1}$ (recently reduced to 1×10^{-6}). Each such case is assigned to a Flare Advocate for detailed investigation.

In the first three months of operation, Fermi detected 106 high galactic latitude ($|b| > 10^\circ$) sources with high-confidence associations with AGNs (referred to the LAT Bright AGN Sample, or LBAS sample) plus 10 others with lower confidence associations, all with significance greater than 10 sigma [12]. Out of the LBAS sources, 102 have optical classifications, 89 have redshifts, 58 are flat spectrum radio quasars (FSRQ), 42 are BL Lac objects and two are radio-galaxies. The brightest AGN is 3C454.3, which was seen from the very beginning of LAT operation [13]. Also Fermi has detected fast flaring blazar PKS 1454-354 [14] where the rapid increase of high energy emission above 100 MeV by a factor of ~ 5 occurred during 12 hours, and PKS 1502+106. A classic example of a radio galaxy NGC 1275 with variable emission was also reliably detected [15].

A very important feature of the Fermi blazar observations is active participation in multiwavelength campaigns. In a case of confirmed detection of AGN activity, an Astronomers Telegram (ATeL) is issued in order to alert the scientists of other experiments to this event. Since the beginning of operation, Fermi issued 29 ATeLs (as of April 30, 2009). Some targets for multiwavelength campaigns are (but not limited to) 3C 454.3, BL Lac, PKS 2155-304, 1ES 1959+650, PKS 0528+134, 3C 273, 3C 279, Mrk 421 and involve UV, optical, radio, IR, X-ray and UHE gamma-ray instruments.

5. Galactic diffuse radiation

Diffuse gamma-ray emission, both galactic and extragalactic, is of the special interest for the Fermi LAT team, but it is also one of the most complicated subjects. The knowledge of diffuse radiation is also necessary for recognition and identification of Galactic sources. The spectrum

of Galactic diffuse radiation published by the EGRET team [16] with an excess of flux at around several GeV has been discussed for several years, and its interpretation varied from instrumental and analysis problems [17] to dark matter [18]. The Fermi LAT team carefully analysed the data and obtained a spectrum which differs from that published by EGRET and does not suggest an excess at a few GeV energy range (fig. 8, [19]). The analysis was performed for the galactic latitude bands $10^0 < |b| < 30^0$, in order to eliminate the contribution from many Galactic plane sources. The spectrum errors are $\sim 10\%$ and mainly systematic dominated. This result agrees well with the spectrum predicted by GALPROP [20] but still needs to be extended to the full sky and broader energy range.

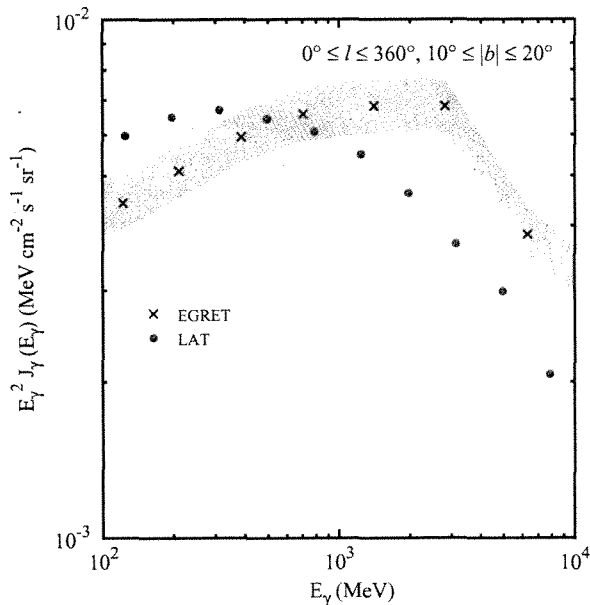


Figure 8: Diffuse emission intensity averaged over all Galactic longitudes for latitude range $10^0 < |b| < 30^0$. Dots are for LAT data, crosses are for EGRET data

6. Gamma ray bursts

EGRET reported detection of high energy photons (a few GeV) from 5 gamma-ray bursts (GRB) [21] and ignited a big interest to the nature of such events. Due to large dead time EGRET was not able to see the timing structure of arriving photons, but the LAT with its very short dead time ($\sim 30 \mu s$) is very capable to such a task. Presence of the GBM onboard Fermi provides prompt information to LAT about the direction of the burst. So far LAT detected 7 bursts with high energy gamma ray emission (080825C, 080916C, 081024B, 081215A, 090217, 090323, 090328), fig.9, and one of them, 080916C is the GRB with the highest ever seen gamma-ray isotropic luminosity E_{iso} [22]. The Gamma-ray Burst Optical/Near-Infrared Telescope (GROND) determined the redshift for

this event to be $z=4.35 \pm 0.15$, and Fermi reports the estimated burst energy $E \approx 8.8 \times 10^{54}$ erg, which is the largest for GRBs so far. The high energy photons are observed to arrive later and persist longer than the lower energy photons, with the most energetic photon of 13.2 GeV showing a delay of ≈ 16 s compared to the low-energy emission, which implies a robust lower limit on the quantum gravity mass $M_{QG} > 1.3 \times 10^{18} \text{ GeV} \setminus c^2$. This value is only one order of magnitude smaller than the Planck mass.

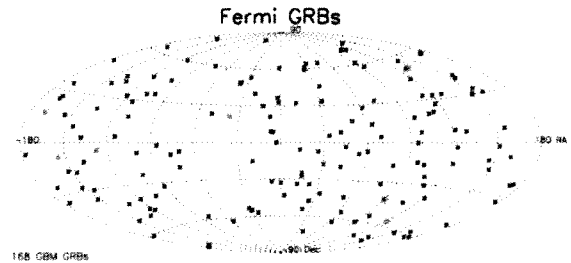


Figure 9: Sky map of GRB's as detected by Fermi. Crosses mark GRB's with high energy gamma radiation detected by LAT

In order to coordinate GRB observations with other instruments, 9 Gamma-ray burst coordination network (GCN) circulars have been issued.

7. The Sun and the Moon

EGRET reported the presence of high energy photons from solar flares [23], and Fermi also monitors the gamma-radiation from the Sun. Another aspect of the observation of the Sun, as well as the Moon, is detection of photons originating in cosmic ray interactions with their surfaces (π^0 photons). In this scenario the Sun and the Moon should be seen as gamma-ray point sources. Fermi obtained images of both of these objects and measured their spectra, which are consistent with the model predictions [24]. It is worthwhile to mention that the spectrum from the Sun is harder than that observed from the Moon, which can be explained by the presence of Inverse Compton (IC) photons generated by cosmic ray electron interactions with the sun light. The gamma-ray image and spectrum of the Moon can be used for cosmic ray spectrum monitoring and as a source for calibrating the LAT detector [25].

8. Cosmic ray electrons

Cosmic ray electrons are the very natural probe of cosmic ray origin and propagation in the local interstellar medium due to their rapid energy losses by the synchrotron radiation in Galactic magnetic field and inverse-Compton scattering. Currently available data on high energy electrons is obtained mainly in ballon-borne experiments (except AMS-01) and statistically limited. The

Fermi team carefully investigated the capability of the LAT to measure cosmic ray electrons and developed the analysis method based on numerous Monte Carlo simulations and beam tests. As a result, a high statistics spectrum of electrons for the energy range 20 GeV - 1 TeV was obtained (fig.10, [26]). This spectrum was based on more than 4 million electrons collected for 6 months of observations, with more than 400 electrons in the highest energy bin (770 GeV - 1 TeV). This spectrum, considered together with recently reported Pamela positron fraction result [27], suggests that there is a nearby source(s) of electrons and positrons, which is responsible for the excess with respect to the conventional model based on contribution from quasi-uniformly distributed distant sources, believed to be pulsars or SNR, electron and positron flux. The nature of this source, astrophysical (pulsars) or exotic (dark matter) is still unclear.

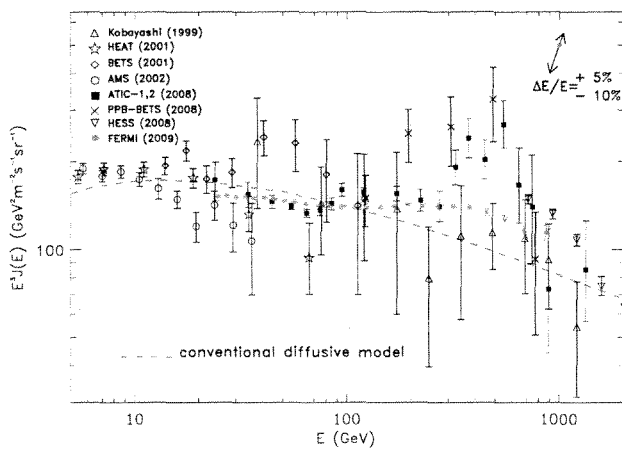


Figure 10: Spectrum of cosmic ray electrons as measured by Fermi. Shaded area shows systematic errors

9. Summary

After 8 months in orbit, the Fermi Gamma-ray Space Telescope has already made several new discoveries. Just after the first three months of mission the LAT had already reached the EGRET point source sensitivity, and now is exploring a universe that has never been explored before, both in sensitivity and spectral coverage.

Major Fermi results for 8 months of the 1-st year all-sky survey phase are:

- Large number of pulsars detected, approximately half in γ -rays,
- Many flaring active galaxies observed; about half not seen by EGRET,
- Flaring sources observed along the galactic plane,
- High-energy emission seen from 7 GRBs; first time seen from short-duration burst,
- Quiescent Sun detected at high energies,
- Major progress in understanding Galactic diffuse emission.

- First precise measurement of high energy electron spectrum,

- Extensive search for dark matter signatures.

The results are reflected in 13 papers in major journals (7 published, 6 accepted), 5 more papers already submitted, and 4 more are ready for submission.

With time, Fermi will probe deeper and deeper into the high-energy Universe

10. Acknowledgements

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