PROCEEDINGS OF SCIENCE

# Fermi – Galactic Sources

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**on behalf of the *Fermi*-LAT collaboration**

The unprecendented sensitivity and angular resolution at GeV energies allows the *Fermi* Large Area Telescope (LAT) to produce sharp images of the Galactic plane enabling the resolution of point sources from the diffuse emission and in crowded regions. The LAT scans the entire sky eight times a day producing uniform and regular monitoring of the galactic plane. A large variety of source types are revealed producing high energy emission from a variety of mechanisms. Some involve shocks in jets or winds; others are powered by neutron star dynamos, such that pulsars are observed in a growing range of systems. Presented here is an overview of many of the Galactic high energy results from the first year of operations of the *Fermi*-LAT.

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## 1. Introduction

The *Fermi* Gamma-ray Space Telescope was successfully launched on 2008 June 11, from Cape Canaveral, Florida. The primary instrument onboard, the Large Area Telescope (LAT) is an electron-positron pair production telescope, featuring solid state silicon trackers and cesium iodide calorimeters, sensitive to photons from ~20 MeV to > 300 GeV (Atwood et al., 2009). Relative to earlier high energy $\gamma$-ray missions the LAT has a large ~2.4 sr field of view, a large effective area (~8000 $\mathrm{cm}^2$ for >1 GeV on axis) and improved angular resolution or point spread function (PSF, better than 1° for 68% containment at 1 GeV). In the *Fermi* survey mode, the observatory is rocked north and south on alternate orbits to provide more uniform coverage so that every part of the sky is observed for ~30 minutes every 3 hours. Thus *Fermi* is ideally suited for long term all-sky observations.

The first year of operations has been very successful and a large population of sources, >1000, has been detected. While many of these sources are extragalactic in nature a large fraction are galactic objects including: pulsars, pulsar wind nebulae, globular clusters and $\gamma$-ray bianries.

### 1.1 Why are HE $\gamma$-rays from Galactic sources interesting?

There are a variety of reasons why studying the Galactic population of high energy (HE) $\gamma$-ray sources is both interesting and important for our understanding of the physical processes which occur within our galaxy and the universe in general.

- High energy emission from galactic sources by its very nature requires those galactic sources to exist in extreme environments. These can include supersonic shocks within winds/jets or with the surrounding interstellar medium as well as the electric dynamos around rotating, magnetized stars. Observations of these objects are the only viable method for exploring the physics in action in these extreme environments.

- The Galactic population of sources exist as foreground objects to the diffuse Galactic background. In order to understand and investigate the properties of this diffuse emission the foreground population must be well understood in order to subtract their contribution to the global emission.

- Both the Galactic diffuse and Galactic source populations are foreground noise to those physicists searching for high energy signals of dark matter.

Additionally, there is the challenge of following up and identifying the population of unidentified $\gamma$-ray sources discovered by EGRET in the 1990s. Finally there is the possibility of discovering new source types and classes which have heretofore not been known to emit $\gamma$-rays.

## 2. Pulsars

Prior to the launch of *Fermi* the sky above 100 MeV was surveyed by both COS-B and, most recently, EGRET. EGRET detected ~300 sources, of which many were unidentified. Six of these sources were rotation powered pulsars: Vela, Crab, Geminga, B1951+32, B1055-52 and B1706-44. Geminga was discovered to be a radio-quiet $\gamma$-ray pulsar and before *Fermi* was the only source

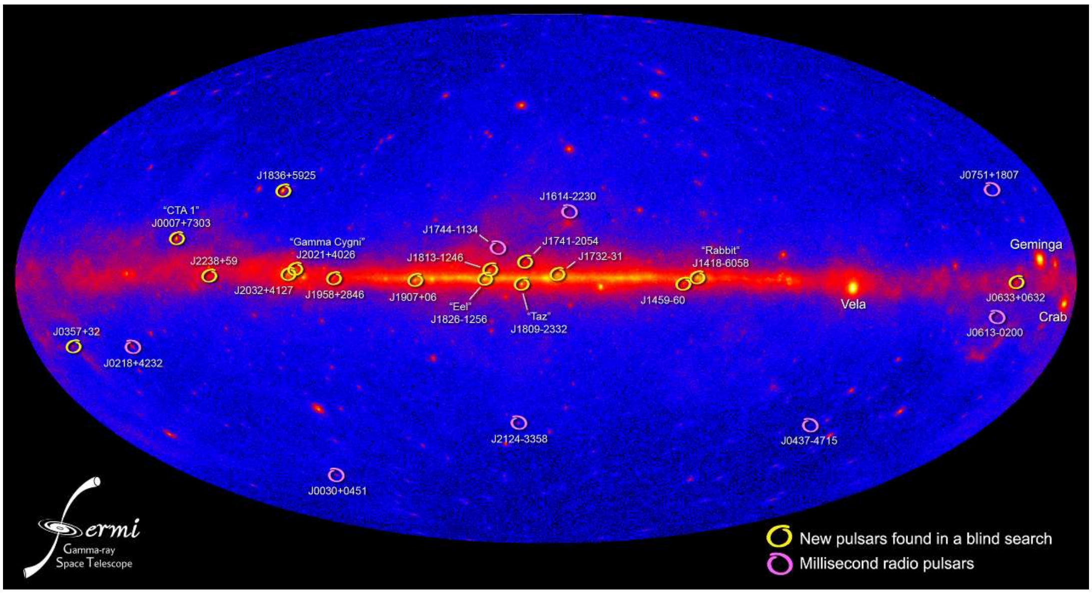

**Figure 1:** *Fermi*-LAT all-sky map indicating the locations and names of 16 new young pulsars (yellow) and 8 MSPs (magenta). Credit NASA/DOE/Fermi LAT collaboration

in its class. Many of the unidentified EGRET sources have been suspected to be pulsars despite deep radio and X-ray searchs failing to identify any pulsed emission.

Consequently, pulsars were anticipated to be a source class of great interest to *Fermi* and analysis pipelines to search for pulsars in the data set were immediatley implemented once *Fermi* was launched. The search is "blind" in the context that the timing parameters are a priori unknown. To facilitate the search the 'time-differencing technique' was developed (Atwood et al., 2006; Ziegler et al., 2008), once a good candidate is identified standard pulsar tools can be implemented (e.g. PRESTO, tempo2).

In its first year of operations *Fermi* has identified a large population of $\gamma$-ray pulsars, many of which are associated with unidentified sources detected by EGRET. Sixteen new pulsars were discovered using only 5 months of data (Abdo et al., 2009b). Additionally, a seperate analysis identified strong $\gamma$-ray pulsations from eight milli-second pulsars (MSPs) (Abdo et al., 2009d); this is the first definitive detection of MSPs at $\gamma$-ray energies. The locations of these two pulsar populations are shown in Fig. 1.

### 2.1 CTA 1, the first *Fermi* discovered pulsar

The first new pulsar detected by *Fermi* was a radio-quiet pulsar located near to the center of a compact, synchrotron nebula embedded within the CTA 1 supernova remnant. A blind search identified a spin period of 316.86 ms and a period derivative of $3.614\times10^{13}$ s s$^{-1}$ (Abdo et al., 2008). The LAT source is spatially consistent with the X-ray source RX J00070+7302 and lies on the edge of the 95% error radius of EGRET source 3EG J0010+7309 .

A search of archival data from *XMM*, *ASCA*, *Chandra*, and EGRET showed no indication of pulsed emission extrapolated from the LAT ephemeris. The source exhibits all of the characteristics of a young high-energy pulsar, which powers a synchrotron PWN embedded in a larger SNR.

## 3. The Crab Nebula & Pulsar

The Crab Nebula and associated pulsar are two well known and observed sources being clearly visible over 21 decades of frequency, from radio all the way to ~80 TeV. The emission is dominated predominantly by non-thermal processes. It is held to be the prototypical example of a pulsar wind nebula and is associated with a supernova explosion witnessed by Chinease astronmers in 1054 AD. An analysis of 8 months of *Fermi*-LAT data by (Abdo et al., 2010) shows two main peaks in the pulse profile with the primary peak leading the radio main pulse by ~281 $\mu$s.

In order to analyse the spectral properties of the nebula itself 'off-pulse' data was used; data was only taken from outside of the $\gamma$-ray pulses. Only 0.1–300 GeV photons arriving between phases 0.52–0.87 were included in the analysis(where phase 0 is defined as the main peak in the radio profile). The data is best represented by the summation of two power laws, one representing the inverse Compton (IC) component the other the synchrotron emission component. These are shown in the left of Fig. 2, clearly showing the falling edge the synchrotron component and the rising edge of the IC component. The spectral parameters are: spectral index (synchrotron), $\Gamma_{synch}$=3.99±0.12(stat)±0.08(sys); spectral index (IC), $\Gamma_{IC}$=1.64±0.05(stat)±0.07(sys); flux above 100 MeV, ~$9.8\times10^{-7}$ cm$^{-2}$ s$^{-1}$. No significant cut-off or variability is detected in either component.

To analyse the pulsar spectrum both on- and off-pulse events are considered. The best fit model to the pulsar spectrum is found to be a power law with an exponential cut-off of the form $E^{-\Gamma}\exp[-(E/E_c)]$ with parameters: spectral index, $\Gamma$=1.97±0.02(stat)±0.06(sys); cut-off energy, E$_c$=5.8±0.5(stat)±1.2(sys) GeV; integral flux above 100 MeV is ~$2.09\times10^{-6}$ cm$^{-2}$ s$^{-1}$. The right hand plot in Fig. 2 shows the pulsar spectrum and the best fit model. This spectral shape is typical of the pulsars detected by *Fermi* with a spectral index of ~1.5 and a cut-off energy of a few GeV. Pulsed $\gamma$-ray emission is detected up to 20 GeV.

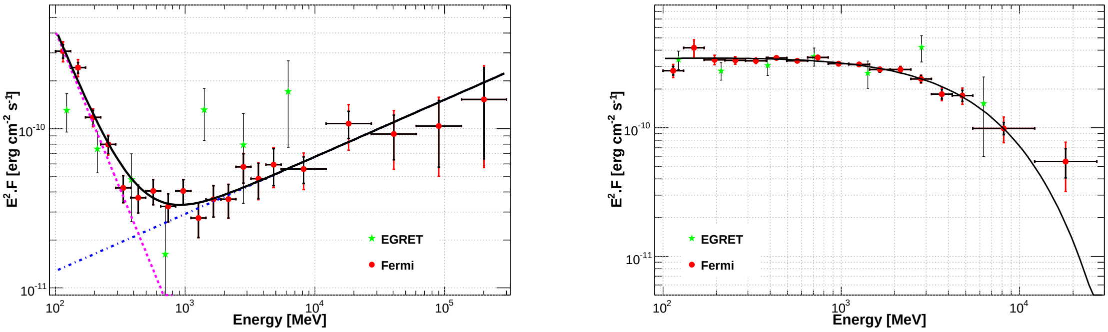

**Figure 2:** Left: Spectral energy distribution of the Crab Nebula. The fit of the synchrotron (purple dashed line) and IC (blue dash-dotted line) are represented separately with two power laws; the black curve is the sum of these two power laws. Right: Spectral energy distribution of the Crab Pulsar averaged over the whole pulse period. The black curve represents the best-fit model, obtained with a power law with an exponential cut-off. The statistical errors are shown in black, while the red lines take into account both the statistical and systematic errors. Horizontal bars delimit the energy intervals. EGRET data points are shown for comparison (green stars) taken from Fig.5 and Fig.6 of (Abdo et al., 2010).

## 4. The first detection of a Globular Cluster at HE

Globular clusters are some of the oldest constituents of our Galaxy with ages of the order $10^{10}$ years. These systems show a much higher number of interacting binaries per unit mass than within the Galactic plane, believed to be a consequence of the large number of dynamical interactions which occur within the dense cores. As a consequence these systems contain large numbers of MSPs. Also known as "recycled" pulsars these are pulsars which were spun up to millisecond periods by accretion from a low-mass X-ray binary companion. MSPs have been clearly detected by *Fermi* in the Galactic plane and make globular clusters potential sources of $\gamma$-ray emission.

47 Tucanae is a globular cluster known to contain a large number of MSPs and is relatively nearby (~4 kpc). From approximately 6 months of *Fermi*-LAT survey observations, 47 Tucanae is detected at the level of $\sim 17\sigma$ (Abdo et al., 2009g); this represents the first ever detection of a globular cluster at $\gamma$-ray energies. The spectrum of the source is best fit by a power law with exponential cut-off with index, $\Gamma$=1.3±0.3(stat)±0.1(sys) and cut-off, $E_c = 2.5^{+1.6}_{-0.8}$(stat)±0.3(sys) GeV. The 0.1–10 GeV integral flux is $\sim 2.6\times10^{-8}$ cm$^{-2}$ s$^{-1}$. There is no indication of any time variability and no significant detection of any of the pulse periods from the known 23 MSPs residing within the cluster. MSPs are intrinsically faint objects and at the distance of a globular cluster would be unlikely to be detected in isolation, the *Fermi* detection is consistent with the integral emission of a population of MSPs from within the cluster with an upper limit on the population size of ~60 (Abdo et al., 2009g).

## 5. Gamma-ray Binaries

Traditional X-ray binaries may not be obvious targets of interest for a HE $\gamma$-ray telescope however a small number of high-mass X-ray binary systems have been detected at energies >1 TeV by the current generation of ground based Cherenkov telescopes. PSR B1259−63 is a radio pulsar in a 3.5 year orbit of a Be companion star; the H.E.S.S. experiment has detected this source as it passed through periastron. LS 5039 is a binary system comprising of a compact object in a ~3.9 day orbit of an O6.5V star; the H.E.S.S. experiment detects a point source with a periodic flux modulation which matches the known orbital period. LS I +61°303 is a Be X-ray binary with an unknown compact object in a ~26.5 day orbit which shows periodic radio flares; both MAGIC and Veritas see the orbital modulation in the TeV flux. Both LS5039 and LS I +61°303 were spatially associated with unidentified EGRET sources, however, the EGRET error boxes were relatively large and no clear signal of variability was ever detected in order to definitively identify these systems as the source of the $\gamma$-ray emission.

### 5.1 LS I +61°303

The LAT clearly detects a $70\sigma$ source consistent with the known location of LS I +61°303 using data from the first ~9 months of survey observations. The source is bright and persistent source of $\gamma$-rays; it is the 14$^{th}$ brightest source in the 3-month *Fermi* Bright Source List (Abdo et al., 2009c). The source is highly variable and a clear periodic modulation is detected in the LAT data at a period of 26.6±0.5 days (Abdo et al., 2009e). This is consistent with the known orbital period of the system and definitively confirms LS I +61°303 as a $\gamma$-ray source. The average

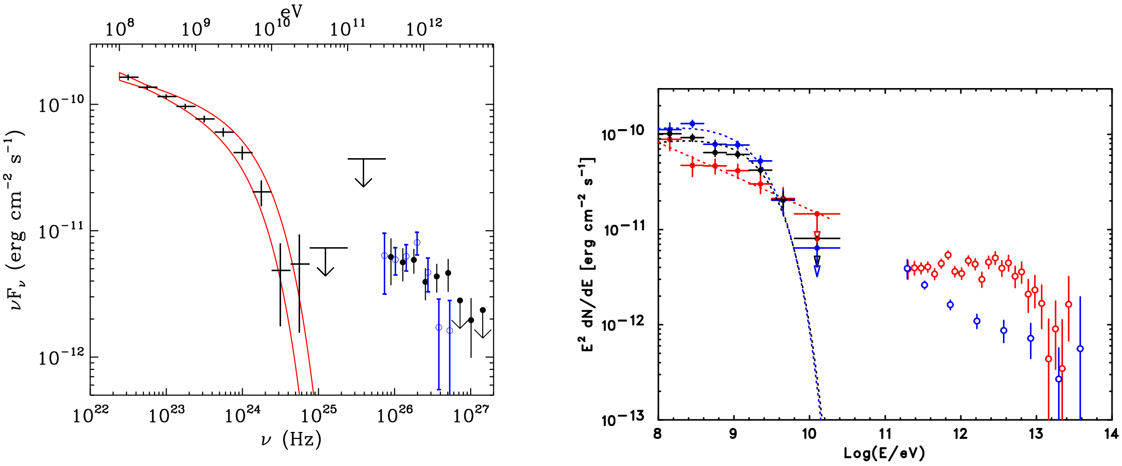

**Figure 3:** Left: Phase averaged fitted spectrum of LS I +61°303. The solid red lines are the $\pm 1\sigma$ limits of the *Fermi* cutoff power law; blue (open circle) data points from MAGIC (high state phases 0.5–0.7); black (filled circle) data points from VERITAS (high state phases 0.5–0.8). Data from the different telescopes are not contemporaneous and cover different phase ranges. Taken from Fig. 2 of (Abdo et al., 2009e). Right: Fitted spectrum of LS 5039; the black points (dotted line) represent the phase-averaged *Fermi*/LAT spectrum. The red data points (dotted line) represent the spectrum (overall fit) at inferior conjunction (Phase 0.45–0.9); blue data points (dotted line) represent the spectrum (overall fit) at superior conjunction (Phases, <0.45 and >0.9). Data points above 100 GeV are taken from H.E.S.S. observations; H.E.S.S. and LAT data are not contemporaneous. Taken from Fig. 3 of (Abdo et al., 2009f).

phase-folded light curve shows a large modulation amplitude with maximum flux occuring slightly after periastron passage (phase ~0.3). This is in contrast to the variability reported at very-high energies by both MAGIC and VERITAS where peak flux occurs at phases 0.6-0.7 and detections are achieved only at phases ranging from 0.5 to 0.8, before or at apastron.

A spectral analysis of the LAT data found that the source was best fit with a power law with an exponential cutoff with parameters: spectral index, $\Gamma$=2.21 ± 0.04(stat) ± 0.06(syst); cutoff energy is 6.3 ± 1.1(stat) ± 0.4(syst) GeV; flux above 100 MeV is (0.82 ± 0.03(stat) ± 0.07(syst))$\times 10^{-6}$ cm$^{-2}$ s$^{-1}$. The best fit spectrum to the LAT data is shown in the left panel of Fig. 3, together with TeV data points from literature. There was no indication of significant spectral variabilty with orbital phase.

## 5.2 LS 5039

Analysing the region around LS 5039, as seen by the LAT, is much more challenging due to it's location close to the Galactic plane in a region of high Galactic diffuse emission and the presence of a nearby, bright pulsar (PSR J1826−1256). Even so the LAT detects a source consistent with the known location of LS 5039 at the level of ~28.5$\sigma$ based upon 11 months of survey observations (Abdo et al., 2009f). Timing analysis of the dataset indicates a periodic flux modulation of, P = 3.903 ± 0.005 days, consistent with known orbital period of LS 5039 and unambiguously confirms the source identification. The $\gamma$-ray modulation peaks at phase ~0.0–0.1, close to superior conjunction (phase 0.06) while the TeV flux modulation peaks close to inferior conjunction (phase 0.72).

In analysing the spectrum of the source, contamination from the nearby pulsar was minimised by excluding events which arrive during the peaks in the pulsar phase cycle ($0.175 < \phi < 0.3$ and $0.625 < \phi < 0.775$ were excluded; see Abdo et al., 2009b). The source is best fit by a power law with an exponential cutoff with parameters: spectral index, $\Gamma = 1.9 \pm 0.1$(stat) ± 0.3(syst); cutoff energy is 2.1 ± 0.3(stat) ± 1.1(syst) GeV; flux above 100 MeV is (4.9 ± 0.5(stat) ± 1.8(syst))$\times 10^{-7}$ cm$^{-2}$ s$^{-1}$. The best fit spectrum to the LAT data is shown in the right panel of Fig. 3, together with TeV data points from literature.

Significant spectral variability with orbital phase is seen in the LAT data. The spectral shape varied such that the spectrum is softer around periastron and is harder around apastron (Abdo et al., 2009f). Spectra were extracted for inferior conjunction ($0.45 < \phi < 0.9$) and superior conjunction ($0.9 < \phi < 0.45$). The LAT data find a power-law spectrum with $\Gamma = 2.25 \pm 0.11$ at inferior conjunction with no energy cutoff statistically significant. At superior conjunction a power law with an exponential cutoff was preferred with $\Gamma = 1.91 \pm 0.16$ and a cutoff energy of 1.9±0.5 GeV.

Abdo et al., (2009f) raise the intringuing possibility that the emission in the *Fermi* range from both LS 5039 and LS I +61°303 is magnetospheric emission as seen in the dozens of pulsars that have now been detected by *Fermi* based upon the similarity in the spectra observed in the pulsars and these two binaries. In the case of the pulsars, the cutoff energy is thought to be set by the balance between acceleration and losses to curvature radiation. If this is the case in the binaries then we would expect some level of pulsed emission.

## 6. Conclusions

In its first year of operations the *Fermi*-LAT has made a large number of discoveries, many of them being Galactic objects. Many of these discoveries have been specifically related to pulsar emission; for the first time pulsars have been discovered on the basis of high energy emission alone. A large population of pulsars, some of them radio-quiet and a large number of millisecond pulsars, have been revealed. In many instances these are sources which have unidentified EGRET sources as counterparts, answering the long standing question of the nature of many of these objects. *Fermi* has revealed the first detection of $\gamma$-ray emission from a globular cluster, 47 Tucanae, which is believed to arise from the presence of up to 60 millisecond pulsars within the cluster, all contributing to the overall emission.

By its very nature pulsar emission is pulsed therefore making it possible to subtract the pulsar emission and investigate other astrophysical objects in the region more easily. An example of this technique has been shown in the analysis of the Crab Nebula, by subtracting the pulsed emission, the details of the nebula spectrum were unveiled allowing both the falling edge of the synchrotron and rising edge of the inverse Compton emission to be seen. Additionally, an anlysis of the Crab pulsar spectrum measured the $\gamma$-ray cutoff energy for the first time.

*Fermi*-LAT has confirmed that the high-mass X-ray binaries, LS 5039 and LS I +61°303, both emit at $\gamma$-ray energies; the detection of flux modulation on the known binary orbital periods removes any question about their association. However, *Fermi* has raised a new question about the nature of the emission as both sources show very similar spectral shapes to the many pulsars now observed. Do these systems have some magnetospheric component to their emission? If this is the case then there should be pulsed emission which would finally identify the nature of the compact objects within these systems.

With only a year of observations having passed there is plenty more work and discovery to be done.

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