Fermi LAT Observations of Gamma-ray Pulsars

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Fundamental Physics in Radio Astronomy, on behalf of the Fermi Collaboration

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Overview

A year after Fermi was launched, the number of known gamma-ray pulsars has increased dramatically. For the first time, millisecond pulsars have been confirmed as powerful sources of gamma-ray emission. A sizable population of normal pulsars have been discovered in a blind search of the gamma-ray data. The other gamma-ray pulsars are normal pulsars detected via an efficient collaboration with radio and X-ray telescopes. Many previously unidentified EGRET sources turn out to be pulsars. The Fermi LAT data already revealed that gamma-ray pulsars generally emit fan-like beams sweeping over a large portion of the celestial sphere, and produced in the outer magnetosphere. In addition to the detection of gamma-ray pulsars, the Fermi LAT has discovered several hundreds of previously unknown gamma-ray sources. A good fraction of these unidentified sources are expected to hide unknown pulsars. There is therefore much to expect from the follow-up of these sources across the spectrum, and first searches for pulsations in the radio domain at the position of Fermi unidentified sources have already been successful, with the discovery of 18 new millisecond pulsars, including one detected at Effelsberg.

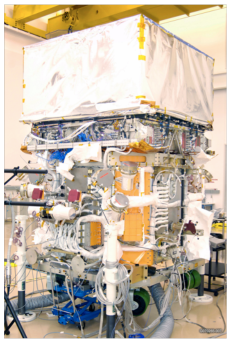
The Large Area Telescope on the Fermi Observatory

The Large Area Telescope (LAT) is the primary instrument on the Fermi Gamma-ray Space Telescope [1]. The LAT is a pair-conversion telescope sensitive to gamma rays between 20 MeV to more than 300 GeV. It has a wide field-of-view of 2.4 sr, a peak effective area of ~7000 cm^2 at 1 GeV on axis, and a 68% containment radius of 0.6° at 1 GeV for events converting in the front section of the LAT. **The LAT is approx. 30 times more sensitive than its predecessor, the EGRET telescope.**

In nominal operation mode, the whole sky is observed every two orbits (~3h). The gamma-ray sky is covered very uniformly, making the LAT **an ideal instrument for the discovery of new sources.**

Events are time-stamped to an **accuracy better than 1 μs**, which is crucial for the study of rapidly-rotating pulsars [2].

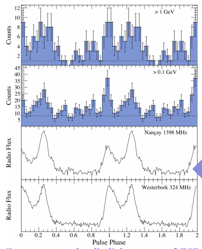
Fermi was launched on the 11th of June 2008. It should operate for five to ten years.



The Large Area Telescope (LAT) on top of the Fermi Gamma-ray Space Telescope

A population of gamma-ray millisecond pulsars

For the first time, millisecond pulsars (MSPs) have been firmly established as a class of high-energy sources. **The LAT has detected pulsations from at least nine MSPs above 0.1 GeV** [3,4]. Observed light curves and spectra are similar to those of normal gamma-ray pulsars, indicating that the basic emission mechanism is the same for the two distinct pulsar populations.



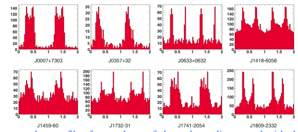
Gamma-ray and radio light curves of PSR J0034-0534 [4]

A total of 56 pulsars have been detected in gamma rays with high confidence during the first year of operation of the LAT. These include:

- 32 radio and X-ray loud pulsars, among which are nine millisecond pulsars, and 23 normal pulsars. The properties of the brightest gamma-ray pulsars can be analyzed in great detail across their rotation.
- 24 previously unknown normal pulsars, discovered in a "blind search" of the LAT data.

Previously unknown pulsars discovered in a blind-search

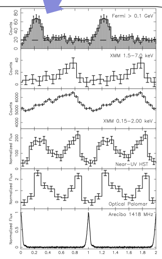
Some unidentified gamma-ray sources can hide unknown gamma-ray pulsars. The gamma-ray data can be searched for periodicity using Fourier-based techniques. So far, **24 previously unknown normal pulsars have been discovered in a blind search** [10]. Several of them are found in supernova remnants, or are powering TeV nebulae.



Gamma-ray pulse profiles for a subset of the pulsars discovered with the LAT [10]

Normal radio and X-ray loud pulsars

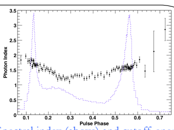
Besides the detection of nine radio-loud MSPs (see above), the Fermi LAT also detected pulsed emission from a number of normal radio and X-ray loud pulsars, all highly energetic (spin-down energy above 10^{33} erg/s). **These include the seven pulsars seen in gamma rays before Fermi by EGRET and COMPTEL, plus 16 new detections.** Many of these pulsars lie in the error box of EGRET unidentified sources: like J1028-5819 in 3EG J1027−5817 [5] or J2021+3651, also seen with the AGILE telescope, in 3EG J2021+3716 [6,7]. Like radio-loud MSPs, these pulsars have been detected using rotational parameters measured by radio or X-ray telescopes, illustrating the **importance of multi-wavelength timing observations of pulsars in support of Fermi.**



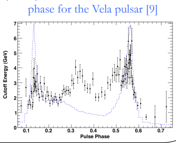
Light curves of PSR J0659+1414 at multiple wavelengths [8]

Phase-resolved spectroscopy of bright gamma-ray pulsars

The brightest gamma-ray pulsars such as those detected by EGRET or other experiments are in general prime targets for detailed spectral analysis because of their brightness. **Large amounts of gamma-ray photons enable fine analysis of the emission properties as a function of the rotational phase, the phase-resolved spectroscopy**. Important variations of the cutoff energy between the two gamma-ray peaks are for instance observed for the Vela pulsar [9]. Similar complex behaviors of the spectral index or the cutoff energy are observed for other bright pulsars, providing valuable input for models of particle acceleration in pulsar magnetospheres.



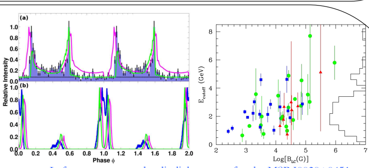
Spectral index (above) and cutoff energy (below) as a function of the rotational phase for the Vela pulsar [9]



What do we learn?

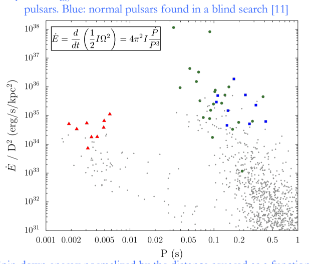
For both normal and millisecond pulsars, most gamma-ray light curves exhibit two sharp peaks, while a few objects have one broad peak. **The gamma-ray emission beam then seems to consist of a "fan-like" beam.** Models that place the emission in the outer magnetosphere, like the Outer Gap or the Slot Gap, are preferred [11].

The observed spectra of the gamma-ray pulsars are consistent with exponentially cutoff power laws, with cutoff energies below 10 GeV in all cases. **This also supports high altitude emission.**



Left: gamma-ray and radio light curves for the MSP J0030+0451, fitted with the Outer Gap (green) and Slot Gap (magenta) [12]. Right: cutoff energy as a function of the magnetic field at the light cylinder, B_{LC}. Red: radio-loud MSPs. Green: radio-loud normal pulsars. Blue: normal pulsars found in a blind search [11]

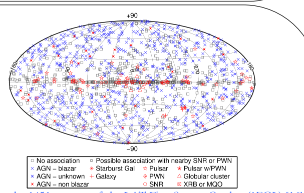
The detected gamma-ray pulsars are relatively close and have the highest spin-down energy loss rates, $\dot{E}$. Detected MSPs and normal pulsars lie above a common threshold, **again suggesting similarities in emission mechanisms**. The undetected high $\dot{E}/D^2$ pulsars may have larger distances, gamma-ray beams not pointed towards the Earth or simply may not emit gamma rays at all.



Spin-down energy normalized by the distance squared as a function of the rotational period for pulsars with known distances. Colored symbols indicate pulsars detected by Fermi (see above for the color code). Gray dots indicate undetected pulsars [13].

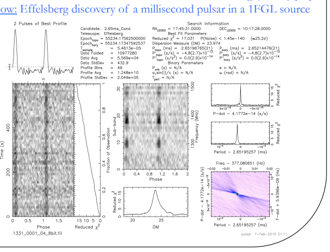
Multi-wavelength follow-up of Fermi sources

There is much to expect from the study of Fermi sources across the spectrum. Pulsars detected in a blind search of LAT data can be searched for lower energy emission. PSRs J1741-2054, J1907+0602 & J2032+4127 are first examples of radio detections among gamma-ray-discovered pulsars [14,15]. These detections provide crucial information on beam geometry at different energies.



Above: the 1451 sources of the LAT First Source Catalog (1FGL) [16]

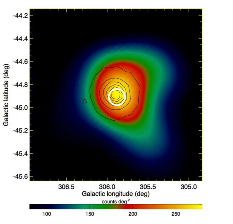
More generally, several hundreds of Fermi sources such as those of the First Year Catalog [16] have no known counterparts. A good fraction of these sources hide unknown pulsars. Searches for radio pulsations at the position of Fermi unidentified sources are being conducted in several radio telescopes around the world, including Effelsberg. These searches have been extremely successful, with 18 new MSPs discovered, as of February 2010. **One of these MSPs is a P = 2.65 ms pulsar in a binary orbit discovered at Effelsberg!**



Below: Effelsberg discovery of a millisecond pulsar in a 1FGL source

Prospects

The Fermi LAT mission should last five to ten years, so that the LAT will eventually be two to three times more sensitive than it was during the first year. Many distant and/or low $\dot{E}$ pulsars will become detectable. More than half known MSPs are in globular cluster and are therefore relatively distant. The LAT detects gamma-ray emission from globular clusters (GCs) consistent with emission from groups of MSPs [17,18]. As data accumulate, the LAT might be able to detect individual MSPs in globular clusters. Finally, other new pulsars will be discovered as the search for pulsars in Fermi unidentified sources continues. The number of known galactic-disk MSPs has increased by ~20% with 18 MSPs detections in a few months, so the LAT is already providing an important contribution to pulsar astronomy at all wavelengths.



1.5° × 1.5° region around the 47 Tucanae globular cluster, as observed by the LAT [17]. The observed spectrum is fully consistent with the cumulative emission of a realistic number of internal MSPs.

References

[1] Atwood W. B. et al., ApJ 697, 107 (2009)
[2] Abdo A. A. et al., Astropart. Phys. 32, 193 (2009)
[3] Abdo A. A. et al. Science 325, 848 (2009)
[4] Abdo A. A. et al. ApJ accepted (2010). arXiv:1002.2607
[5] Abdo A. A. et al. ApJL 695, 72 (2009)
[6] Abdo A. A. et al. ApJ 700, 1059 (2009)
[7] Halpern J. P. et al. ApJL 688, 33 (2008)
[8] Weltevrede P. et al. ApJ 708, 1426 (2010)
[9] Abdo A. A. et al. ApJ accepted (2010), arXiv:1002.4050
[10] Abdo A. A. et al., Science 325, 840 (2009)
[11] Abdo A. A. et al., ApJS accepted (2010), arXiv:0910.1608
[12] Venter C. et al., ApJ 707, 800 (2009)
[13] Guillemot L., proc. Fermi Symposium (2009), arXiv:0912.3666
[14] Camilo F. et al., ApJ 705, 1 (2009)
[15] Abdo A. A. et al., ApJ 711, 64 (2010)
[16] Abdo A. A. et al., ApJS submitted (2010), arXiv:1002.2280
[17] Abdo A. A. et al., Science 325, 845 (2009)
[18] Kong A. K. H. et al., ApJL accepted (2010), arXiv:1002.2431