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Fermi Large Area Telescope observations of gamma-ray pulsars

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In two years of observation of the gamma-ray sky, the Large Area Telescope (LAT) aboard Fermi has enabled a considerable advance in our understanding of high-energy emission from pulsars and their population in the Galaxy. The number of known gamma-ray pulsars has increased by an order of magnitude, including pulsars discovered in blind searches of the gamma-ray data, and a population of gamma-ray millisecond pulsars. Furthermore, searches for radio pulsars in Fermi sources with no known counterparts yielded a burst of discoveries of new millisecond pulsars, with more than twenty detections of these particularly interesting objects in one year. I will review Fermi LAT observations of gamma-ray pulsars and the multiwavelength follow-up of pulsars discovered in Fermi unidentified sources.

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1. Introduction

The Large Area Telescope (LAT), main instrument of the *Fermi* observatory launched on 11 June 2008, is sensitive to photons with energies between 20 MeV and more than 300 GeV [12]. Its large field of view of ~ 2.4 sr, large effective area of ~ 9500 cm^2 at normal incidence, and improved angular resolution of 0.8° at 1 GeV make it an instrument with unprecedented sensitivity. Additionally, with its excellent timing accuracy below 1 μs, the LAT can detect sharp structures in gamma-ray light curves from pulsars accumulated over months to years. Finally, the survey observation strategy of *Fermi* allows the LAT to cover the sky uniformly, making it a prime instrument for the discovery of new gamma-ray sources. In this paper we briefly summarize pulsar observations with the *Fermi* LAT during its first two years of activity and the results of searches for new pulsars in LAT sources with no known associations. We finally discuss the prospects for the coming years.

2. Observing pulsars with the *Fermi* LAT

2.1 Known pulsars

Before *Fermi* and AGILE were launched, seven pulsars had been detected in gamma rays with high significance, by EGRET and COMPTEL on the CGRO observatory (See [26] for a review), plus a few marginal detections, including that of the millisecond pulsar PSR J0218+4232 [21]. These seven pulsars had been found to emit pulsed gamma rays by phase-folding the photon arrival times using pulsar rotational parameters measured in radio and X-rays. Collecting accurate pulsar ephemerides contemporaneous with the *Fermi* mission was therefore important, and for that a pulsar timing campaign involving several large radio telescopes around the world as well as X-ray telescopes has been organized, to monitor the best candidates for detection in gamma rays on a regular basis [25]. This campaign has been a great success, the number of radio and X-ray pulsars monitored for *Fermi* having increased from 224 pulsars with spin-down luminosities $\dot{E} = 4\pi^2 I\dot{P}/P^3 \geq 10^{34}$ erg s^{-1} initially (where P denotes the rotational period, $\dot{P}$ its time derivative, and I is the moment of inertia of the neutron star, usually assumed to be 10^{45} g cm^{-2}) to over 700 objects with a wide range of characteristics now, enabling *Fermi* to study the population of pulsars as a whole.

Among all these objects, pulsars detected by previous gamma-ray telescopes were prime targets for studies in high details, because of their brightness. For instance, high-resolution temporal analyses of the Vela pulsar resulted in the detection of a third component between the two main peaks, shifting to larger phases with increasing energy, while important variations of the spectral cutoff have been revealed by detailed phase-resolved spectroscopy [6]. Complex behaviors of the spectral index and the cutoff energy as a function of rotational phase have also been observed for the other EGRET pulsars (see e.g. [7, 8]), giving us an insight into gamma-ray emission mechanisms in pulsar magnetospheres.

In addition to observing EGRET pulsars in great details, the LAT has detected pulsed gamma-ray emission from 24 other "normal pulsars" (with rotational periods P above a few tens of ms) and 19 "millisecond pulsars" (MSPs, $P < 30$ ms) in two years of data taking, increasing the number of known normal gamma-ray pulsars and confirming MSPs as powerful sources of gamma-ray emission (see for example [1, 4]). Interestingly, gamma-ray light curves and spectra of normal pulsars and MSPs are observed to be similar: the typical gamma-ray light curve is two-peaked, with a separation between the two peaks of $\sim$0.4 rotations, and the first gamma-ray component lagging the main radio peak by $\sim$0.1 rotations. A few exceptions to this trend exist, such as the one-peaked PSR J2229+6114 [3] or the MSPs PSR J0034−0534, J1939+2134 and J1959+2048, for which radio and gamma-ray peaks are observed to be in close alignment [5, 19]. On the other hand, energy spectra are generally well fit with exponentially cutoff power laws with cutoff energies below 10 GeV (see e.g. Table 5 of [4]). For both pulsar populations, light curve and spectral shapes match well the predictions of models placing the high-energy emission at high altitude in the magnetosphere, such as the *Two Pole Caustic* (TPC) [18] or *Outer Gap* (OG) models [15].

2.2 Searching for new pulsars in the LAT data

Some gamma-ray pulsars may be faint in radio and X-rays, and could have been missed by past searches. Alternatively, pulsars may only point their gamma-ray beams toward the Earth, for geometrical reasons. For these objects, the underlying periodicity of the gamma-ray signal can only be found by means of blind searches. The LAT data are sparse though, with a few hundreds of photons for several months of observation for a typical gamma-ray pulsar. The long integration times required to detect a pulsed signal with high significance make traditional Fourier transforms computationally intensive. For that reason a novel technique was developed, which reduces the required computational power dramatically by searching for pulsations in differences between arrival times. This "time-differencing technique" [11] has proven to be very efficient, with 25 new pulsars discovered in gamma-ray data up to now [2, 24].

Many of the LAT-discovered pulsars are found to be associated with supernova remnants or pulsar wind nebulae, and a large fraction of them coincide with unidentified EGRET sources. Their light curve and spectral properties are similar to those of other gamma-ray pulsars, as expected. They nevertheless provide the opportunity to constrain the ratio of radio-loud to radio-quiet pulsars, which is an important discriminator for theoretical models of emission from pulsars. Similarly to the searches for gamma-ray pulsations from known pulsars using ephemerides measured at radio or X-ray wavelengths, the LAT-discovered pulsars have been searched for radio pulsations at different large radio telescopes around the world, using ephemerides obtained by applying pulsar timing techniques to the LAT data [23]. These searches have so far yielded the detection of radio pulsations for only three of the new pulsars, with very low radio fluxes [9, 13]. Some of the new pulsars may be too distant to be detectable by current radio telescopes. Nevertheless the small number of radio detections reported so far indicates that many of them could be genuinely radio-quiet.

3. New millisecond pulsars found in *Fermi* LAT sources

In its first year of activity, the LAT has detected 1451 sources, including 631 with no known counterparts [10]. These "unassociated sources" can hide unknown pulsars missed by previous radio surveys. Gamma-ray sources typically are localized by the LAT to within a few arc minutes, which is comparable in size to radio telescope beams, whereas many pointings where required to cover EGRET error boxes entirely (see e.g. [14]). As a consequence of this dramatic enhancement in localization accuracy, *Fermi* "points" radio telescopes to unknown pulsars, and more than 30

Galactic disk MSPs have so far been discovered at the position of LAT unassociated sources, at the Parkes, Nançay, Effelsberg, and Green Bank telescopes [16, 20, 22]. These ∼30 new MSP detections represent a significant increase in the number of known Galactic disk MSPs (∼70 objects known prior to *Fermi*), which has a number of important consequences for pulsar population studies, searches for gravitational waves with millisecond pulsar timing, neutron star mass measurements, tests of theories of gravity, and many other areas. Additionally, these MSPs are expected to be gamma-ray pulsars as they were discovered in LAT unassociated sources. Figure 1 shows an example of radio MSP found in a *Fermi* source at the Nançay radio telescope, and later found to emit pulsed gamma rays. Also shown on this plot are the results of radio and gamma-ray light curve modeling with theoretical models of high-energy emission from pulsars. As mentioned earlier, gamma-ray light curves observed by the LAT match well the predictions of outer magnetospheric emission models.

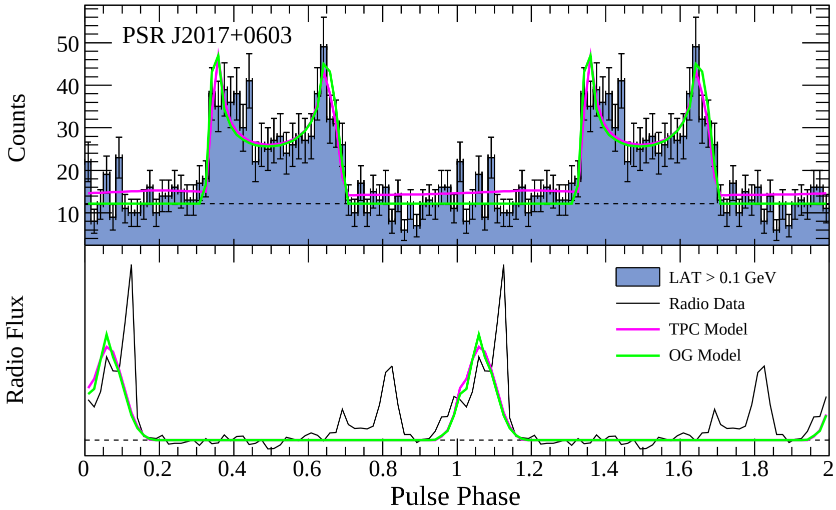

Figure 1: Top panel: gamma-ray light curve for the millisecond pulsar discovered at Nançay PSR J2017+0603 with 60 bins per rotation, and light curves modeled with the *Two Pole Caustic* (TPC) and *Outer Gap* (OG) emission geometries. Bottom panel: Nançay 1.4 GHz radio profile and modeled light curves. See [16] for details on the analysis of the radio and gamma-ray data, and the light curve modeling.

As the *Fermi* mission continues, the LAT will detect additional gamma-ray sources with no known associations. With the high rate of pulsar discoveries in LAT sources in only a year, it is expected that *Fermi* will continue to point radio telescopes to unknown pulsars.

4. Which pulsars are we seeing?

Figure 2 shows the location of pulsars detected by the LAT after two years of operation in the classical $P-\dot{P}$ diagram. As expected, the gamma-ray-detected pulsars tend to have the largest values of the spin-down luminosity $\dot{E}$. However, it can be seen from Figure 2 that a number of high $\dot{E}$ pulsars have not been detected in gamma rays with the LAT. Several reasons can explain these non-detections. The pulsars may simply be faint or too distant, so that additional LAT data is required to detect them. Emission geometry is also a possibility: some pulsars with large $\dot{E}$ values may be

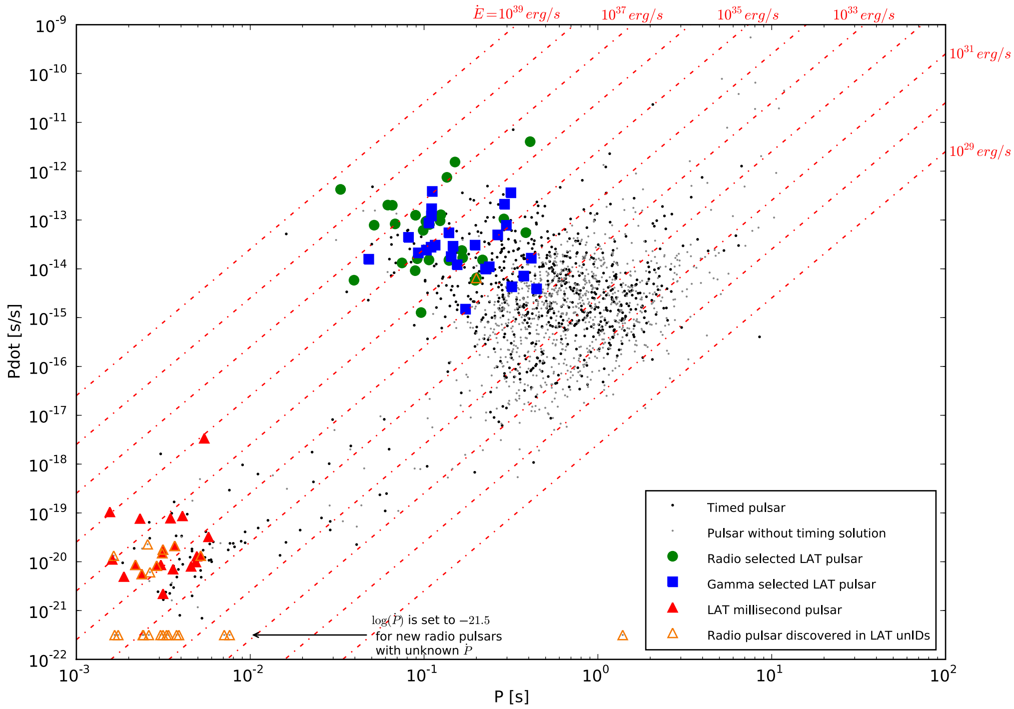

Figure 2: Period – period derivative diagram for the $\sim$ 2000 currently known pulsars. Red triangles and green circles indicate millisecond and normal pulsars so far detected in gamma rays using radio ephemerides, while pulsars discovered in a blind search of the gamma-ray data are indicated by blue squares. The $\sim$30 new pulsars discovered at radio wavelengths in *Fermi* LAT unassociated sources, likely to be gamma-ray pulsars as well, are indicated by empty triangles. Note that for several of these newly discovered objects the period derivative $\dot{P}$ is not known yet, for them $\dot{P}$ was set to $10^{-21.5}$ in this diagram. *Credit: Denis Dumora and David A. Smith.*

bright gamma-ray pulsars, with beams that do not point toward the Earth. Detailed geometrical studies of individual objects, possibly helped by radio polarization measurements giving access to pulsar orientation angles (angle between the rotation axis and the magnetic axis of the pulsar, α, and between the rotation axis and the observer's line-of-sight, ζ) might help understand the causes of non-detection. See [17] for additional details on Figure 2 and causes of non-detections.

5. Summary and prospects

In its first two years of operation, the *Fermi* LAT has detected pulsed gamma-ray emission from over 75 pulsars, an order of magnitude increase over previous experiments. This includes normal pulsars and MSPs detected by phase-folding the data with radio or X-ray ephemerides, and normal pulsars discovered in the LAT data with Fourier-based techniques. In addition, many previously unknown radio MSPs have been discovered at the positions of *Fermi* unassociated sources, opening great prospects for a wide range of physics and astrophysics. The LAT will continue to detect

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pulsars in gamma rays as well as new gamma-ray sources as the *Fermi* mission goes on. The support of radio and X-ray telescopes for both pulsar timing and searching has been essential so far and thus needs to be maintained.

A number of important questions concerning gamma-ray emission from pulsars remains to be explored. For instance, the relationship between spin-down luminosity $\dot{E}$ and gamma-ray luminosity is still unclear. For many gamma-ray pulsars the only available distance estimate is based on models of free electron density in the Galaxy, known to be relatively uncertain. VLBI parallax measurements for *Fermi* pulsars are being undertaken[1] and will hopefully result in accurate distance estimates, thereby constraining the fraction of spin-down luminosity that is converted into gamma-ray emission. It is also important to understand why some high $\dot{E}$ pulsars are not detected by the LAT. Detailed geometrical studies will certainly help understand some of the non-detections.

Another example is the search for gamma-ray emission from other types of pulsars. Young binaries such as LS I +61 303 may hide gamma-ray pulsars that could be detected with blind search techniques. Despite having relatively large spin-down luminosities, magnetars have not been detected with the LAT yet. Finally, some of the unassociated *Fermi* sources may hide radio-quiet MSPs. Extending blind searches of the LAT data to MSPs may help uncover this hidden population, thereby helping to understand the Galactic population of pulsars.

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