SF2A 2011
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FERMI LARGE AREA TELESCOPE OBSERVATIONS OF GAMMA-RAY PULSARS

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Abstract. Since Fermi was launched in June 2008, its main instrument, the Large Area Telescope (LAT), has observed the gamma-ray sky with unprecedented sensitivity, establishing pulsars as the largest gamma-ray source class in the Galaxy and enabling a considerable advance in our understanding of their high-energy emission properties. The number of known gamma-ray pulsars is approaching a hundred, including pulsars discovered in blind searches of the Fermi LAT data, and a population of gamma-ray millisecond pulsars. Supporting radio observations have been key to the success of pulsar studies with Fermi. As an example, searches for radio pulsars in Fermi sources with no known counterparts yielded a burst of discoveries of new millisecond pulsars, with more than thirty detections of these particularly interesting objects to date. We review Fermi LAT observations of gamma-ray pulsars and the multi-wavelength follow-up of pulsars discovered in Fermi unidentified sources.

Keywords: gamma rays: general, pulsars: general

1 Introduction

The Large Area Telescope (LAT), is the primary instrument on the *Fermi* observatory launched on 11 June 2008, is a pair conversion telescope sensitive to gamma-ray photons with energies between 20 MeV and more than 300 GeV. With its large field of view > 2 sr, large effective collecting area of ~ 6500 cm^2 at 1 GeV and normal incidence, and improved angular resolution of $0.8°$ at 1 GeV, the LAT represents a major improvement compared to previous gamma-ray observatories, such as EGRET. Moreover, gamma-ray photons are time-stamped with an accuracy better than 1 μs, so that it can observe sharp structures in gamma-ray pulse profiles of pulsars accumulated over several years. Finally, *Fermi* operates in survey mode, allowing the LAT to cover the sky uniformly and detect many previously unknown sources. A detailed description of the LAT and of its performances can be found in Atwood et al. (2009) and Abdo et al. (2009a). Gamma-ray pulsations have been firmly detected for 88 pulsars so far, and this number is expected to increase as the *Fermi* mission continues. In this paper we summarize the results of pulsar observations with the LAT during its first two and a half years of activity and the results of searches for new pulsars in gamma-ray sources with no known associations. We finally discuss the prospects for the coming years.

2 Fermi LAT observations of pulsars

2.1 Known pulsars

Seven pulsars had been detected in gamma rays with high significance by EGRET and COMPTEL on the CGRO observatory (see Thompson 2004, for a review) before *Fermi* and AGILE were launched, plus another few marginal detections, including that of the millisecond pulsar (MSP) PSR J0218+4232 (Kuiper et al. 2000). All seven pulsars had been detected as sources of pulsed gamma-ray emission by phase-folding the photon arrival times using pulsar "ephemerides" (giving astrometric, rotational and binary parameters as a function of time) obtained from radio and X-ray pulsar timing measurements. A pulsar timing campaign involving several large radio telescopes around the world as well as X-ray telescopes has therefore been organized in the context of the *Fermi* mission, to monitor the best candidates for detection in gamma rays on a regular basis (see Smith

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et al. 2008). While the initial list of pulsars to be observed in radio and X-rays for *Fermi* comprised 224 pulsars with spin-down luminosities $\dot{E} = 4\pi^2 I\dot{P}/P^3 \geq 10^{34}$ erg s^{-1} (where P denotes the rotational period, $\dot{P}$ its time derivative, and I is the moment of inertia of the neutron star, typically assumed to be 10^{45} g cm^{-2}), more than 700 objects with a wide range of properties are now monitored, allowing the *Fermi* LAT to study the gamma-ray properties of a wide variety of pulsars.

Because of their brightness, pulsars detected in gamma rays before the launch of *Fermi* were prime targets for studies with unprecedented details with the LAT. Observations of the brightest steady gamma-ray source in the sky, the Vela pulsar, resulted in the discovery of a third component between the two main peaks, shifting to larger rotational phases with increasing energy (Abdo et al. 2009d, 2010a). Detailed phase-resolved spectroscopy revealed important variations of the spectral properties (photon index and exponential cutoff energy) across the pulse profile. Complex behaviors of the spectral properties as a function of rotational phase have also been observed for the other EGRET pulsars (see Abdo et al. 2010d,f), giving us an insight into gamma-ray emission mechanisms in pulsar magnetospheres.

Pulsed gamma-ray emission has also been detected for 27 other known "normal pulsars" (with rotational periods P of more than a few tens of ms) and 27 MSPs ($P < 30$ ms), including many MSPs that were discovered in *Fermi* unassociated sources (see Section 2.3), in two and a half years of data taking (see for example Abdo et al. 2009c, 2010c). The gamma-ray spectra of pulsars from both populations are well fit with exponentially cutoff power laws with typical cutoff energies in the GeV range. As is observed for EGRET pulsars, the gamma-ray pulse profiles of these pulsars is typically composed of two sharp peaks separated by 0.4 to 0.5 rotations, with the first gamma-ray peak lagging the main radio emission component by $0.1 - 0.2$ rotations, or one broad gamma-ray peak offset from the main radio peak by $\sim 0.4 - 0.6$ rotations. Exceptions to this trend exist, in particular for gamma-ray MSPs: the MSP PSR J1231−1411 shows three gamma-ray peaks (Ransom et al. 2011), and radio and gamma-ray peaks in close alignment have been observed for a small population of MSPs (Abdo et al. 2010b; Guillemot et al. 2011). 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) Dyks & Rudak (2003) or *Outer Gap* (OG) models Cheng et al. (1986).

2.2 Searching for new pulsars in the LAT data

Blind searches of the gamma-ray data are necessary for finding gamma-ray pulsars that are very faint or quiet in the radio and X-ray domains. Attempts to discover pulsars in the data recorded by EGRET by means of blind searches were unsuccessful (see e.g. Chandler et al. 2001), mainly because of the sparseness of the data and because of the irregularities in the rotation of pulsars as a function of time (the "timing noise"). In spite of the large leap in sensitivity compared to EGRET, the LAT data are still sparse; with a few hundreds of photons recorded over several months for a typical gamma-ray pulsar. Long integration times are required to detect gamma-ray pulsations with high significance, which makes traditional Fourier methods time- and computer-intensive. The "time-differencing technique" (Atwood et al. 2006) was developed to address this problem. With this technique, pulsations are searched in the differences between arrival times, which reduces the computational cost dramatically. This technique has proven to be very efficient, with the discovery of 27 new pulsars so far Abdo et al. (2009b); Saz Parkinson et al. (2010).

Many of the gamma-ray pulsars discovered in blind searches of the LAT data are associated with previously unidentified EGRET sources. Several are associated with supernova remnants or pulsar wind nebulae. Their gamma-ray properties (light curves and spectra) are similar to those of other gamma-ray pulsars, however their discovery provides the opportunity to constrain the ratio of radio-loud to radio-quiet pulsars, which is an important discriminator of theoretical models of emission from pulsars. Searches for pulsed radio signal from the LAT-discovered pulsars have been conducted at several large radio telescopes around the world and resulted in only three detections up to now, with very low radio fluxes (Abdo et al. 2010e; Camilo et al. 2009). The small number of radio detections reported so far indicates that many of the new gamma-ray pulsars could be truly radio-quiet.

2.3 New millisecond pulsars found in Fermi LAT sources

The Second *Fermi* LAT catalog (2FGL; Abdo et al. 2011) contains 1873 sources detected by the LAT over 24 months between 100 MeV and 100 GeV. In these 1873 sources, 576 ($\sim 30\%$) are "unassociated": they are not associated with sources known at other wavelengths. Some of these unassociated sources exhibit gamma-ray emission properties that resemble those of known gamma-ray pulsars: lack of flux variability and spectra with sharp cutoffs at 1 – 10 GeV, and could thus hide unknown radio and gamma-ray pulsars that could have been missed by past surveys for pulsars for different reasons (sensitivity, binary motion, dispersion and scintillation, insufficient sky coverage, *etc.*). Searches for radio pulsars at the positions of EGRET sources were challenging, as the EGRET error boxes were several times larger than typical radio telescope beams, so that many radio pointings were necessary to cover the gamma-ray sources entirely (see e.g. Champion et al. 2005). In contrast, gamma-ray sources are typically localized to within a few arc minutes, which is comparable in size to radio telescope beams. Because of this dramatic enhancement in localization accuracy, *Fermi* can "point" radio telescopes to unknown pulsars, and 33 Galactic disk MSPs have so far been discovered at the positions of LAT unassociated sources, at the Parkes, Nançay, Effelsberg, Green Bank and GMRT telescopes (Cognard et al. 2011; Keith et al. 2011; Ransom et al. 2011). Figure 1 shows the locations of the new MSPs. These > 30 new MSP detections represent a significant increase in the number of known Galactic disk MSPs (∼70 objects known prior to *Fermi*), which opens important prospects for a number of studies involving MSPs, including searches for gravitational waves with millisecond pulsar timing, neutron star mass measurements, tests of theories of gravity, pulsar formation and evolutions scenarios, and many other areas. As the LAT continues to accumulate data, it will detect additional gamma-ray sources with no known associations, while further improving the localization of the sources that are already detected. In addition, no strong correlation between the radio and gamma-ray fluxes of pulsars discovered in LAT unassociated sources has been observed. It is thus expected that *Fermi* will continue to point radio telescopes to new radio pulsars.

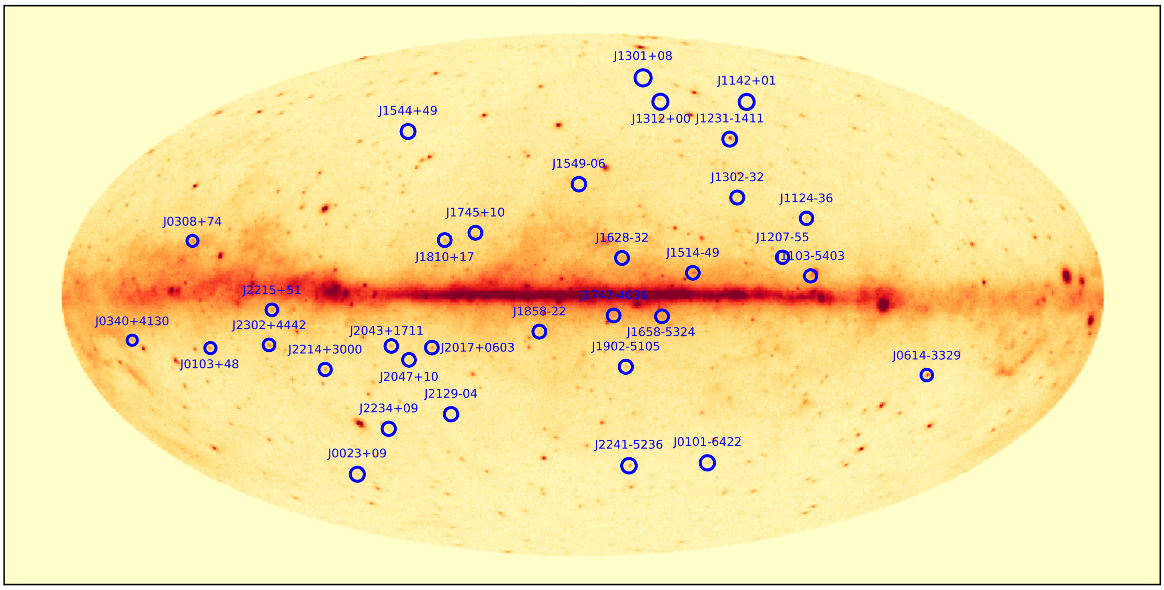

Fig. 1. Sky map of the gamma-ray data taken by the *Fermi* LAT during its first two years of operation and above 0.1 GeV, in Galactic coordinates. Blue circles indicate the 33 new MSPs discovered at radio wavelengths at the position of LAT sources with no known association, as of June 2011. *Credit: Paul S. Ray.*

2.4 Which pulsars are we seeing?

Figure 2 shows the classical period (P) – period derivative ($\dot{P}$) diagram with the ~ 2000 currently known pulsars. Pulsars detected in gamma rays with the *Fermi* LAT are shown as colored symbols. As can be seen from Figure 2, pulsars detected in gamma rays tend to have the largest values of the spin-down luminosity $\dot{E}$. Nevertheless, a number of high $\dot{E}$ pulsars have not been detected in gamma rays with the LAT, which could be due to several reasons. 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 bright gamma-ray pulsars, with beams that do not point toward the Earth. Detailed geometrical studies of individual objects, 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.

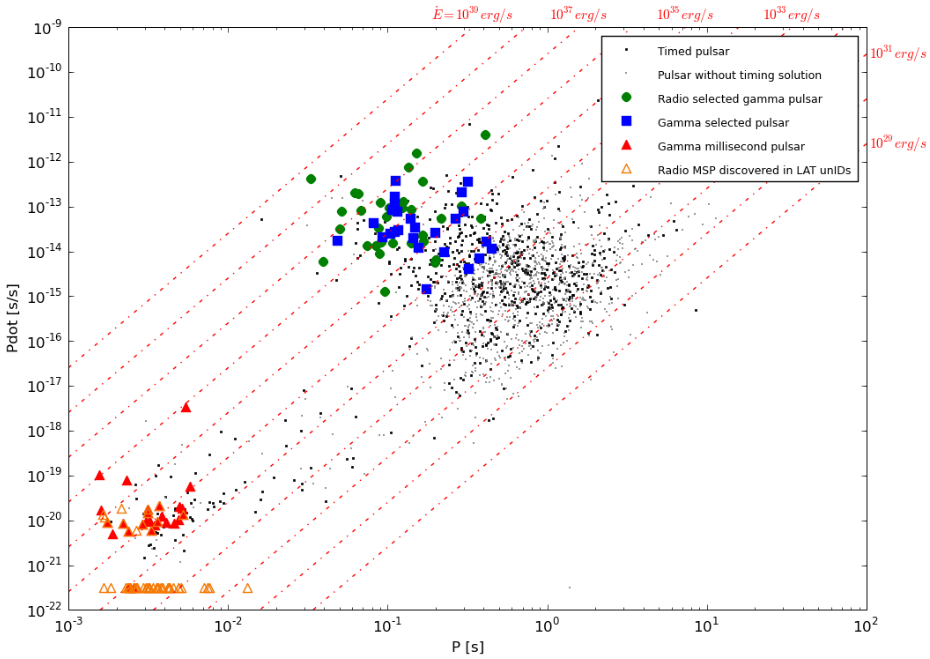

Fig. 2. Period – period derivative diagram for the $\sim$ 2000 currently known pulsars. Red triangles and green circles indicate millisecond and normal pulsars so far detected with the *Fermi* LAT using radio ephemerides, while pulsars discovered in a blind search of the LAT data are shown as blue squares. The new MSPs discovered at radio wavelengths in LAT unassociated sources are indicated by empty triangles. For several of these new objects the period derivative is currently unknown; for these pulsars $\dot{P}$ was set to $10^{-21.5}$ in this diagram. *Credit: Denis Dumora and David A. Smith.*

3 Conclusions and prospects

Two and a half years after *Fermi* was launched, the LAT has detected pulsed gamma-ray emission from 88 pulsars, including 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 blind search techniques. Many radio MSPs have been discovered in *Fermi* unassociated sources, opening prospects for a wide range of physics and astrophysics. In the next few years the LAT will continue to accumulate gamma-ray data, so that the number of known gamma-ray pulsars will soon reach the symbolic threshold of 100 objects, a major step forward in pulsar astronomy and high-energy astrophysics.

Important questions concerning gamma-ray emission from pulsars remain to be answered. The relationship between the gamma-ray luminosity and the spin-down luminosity $\dot{E}$ is badly known, in particular because of large uncertainties in the distances of many gamma-ray pulsars. VLBI parallax measurements for *Fermi* pulsars are being undertaken and will hopefully yield accurate distance measurements, which should help constrain the fraction of spin-down luminosity that is converted into gamma-ray emission. It is also important to understand the non-detection in gamma rays of some highly energetic pulsars. Another prospect for the coming years 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. Also, some of the unassociated *Fermi* sources may be radio-quiet MSPs. Most MSPs ($\geq 75\%$) have binary orbits, making blind searches in the gamma-ray data very challenging. Nevertheless, extending blind searches of the LAT data to isolated MSPs may help uncover the hidden population of radio-quiet MSPs, which would improve our understanding of pulsar emission mechanisms.

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

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