

Session 3

Pulsar Discovery II

Fermi-LAT searches for γ -ray pulsars

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Abstract. The Large Area Telescope (LAT) on the *Fermi* satellite is the first γ -ray instrument to discover pulsars directly via their γ -ray emission. Roughly one third of the 117 γ -ray pulsars detected by the LAT in its first three years were discovered in blind searches of γ -ray data and most of these are undetectable with current radio telescopes. I review some of the key LAT results and highlight the specific challenges faced in γ -ray (compared to radio) searches, most of which stem from the long, sparse data sets and the broad, energy-dependent point-spread function (PSF) of the LAT. I discuss some ongoing LAT searches for γ -ray millisecond pulsars (MSPs) and γ -ray pulsars around the Galactic Center. Finally, I outline the prospects for future γ -ray pulsar discoveries as the LAT enters its extended mission phase, including advantages of a possible modification of the LAT observing profile.

Keywords. pulsars: general, gamma rays: observations

1. Introduction

In the first four decades since their discovery, pulsars were almost the exclusive domain of radio (and to a lesser extent X-ray) astronomy. Indeed, of the ~ 2000 known pulsars[†], the majority were discovered in radio. Since June 2008, however, with the launch of the LAT, on the *Fermi* satellite, γ -rays have become a viable means of discovering (and studying) pulsars. More important than the number of LAT-detected pulsars (a small fraction of the overall population), the LAT sample is subject to different biases than the radio sample. LAT pulsars are typically nearby (\sim few kpc) and energetic ($\dot{E} > 10^{33}$ erg s⁻¹), and a large fraction are *radio-quiet*. Furthermore, γ -rays, unlike the radio beams, carry a significant fraction of the rotational energy of pulsars, thus providing a powerful probe into these extreme objects. Finally, LAT pulsars provide a crucial input into our understanding of the overall neutron star population of the Galaxy.

The LAT is a pair conversion telescope consisting of a tracker, a calorimeter, and a segmented anti-coincidence detector, along with a programmable trigger and a complex data acquisition system. By incorporating the latest advances from particle physics[‡], including the use of silicon-strip detectors, the LAT has achieved a giant leap in capabilities compared to its predecessor, EGRET. The LAT extends to higher energies (>300 GeV vs ~ 10 GeV), has a larger effective area and field of view, improved angular and energy resolutions, and much lower deadtime (Atwood *et al.* 2009). In its first 4 years of operations, the LAT has collected >200 million “source” class events, compared to ~ 1.5 million photons collected by EGRET, in its 9-year lifetime.

Regarding pulsars, the progress made by the LAT has been spectacular. The γ -ray pulsar population has grown from 7 firm detections (plus a few candidates) at the time of the *Fermi* launch (Thompson 2008), to 117 detections in three years of LAT survey

[†] <http://www.atnf.csiro.au/research/pulsar/psrcat>

[‡] Bill Atwood was awarded the 2012 Panofsky Prize in Experimental Particle Physics “For his leading work on the design, construction, and use of the Large Area Telescope [...]”.

observations (The Second *Fermi*-LAT Catalog of γ -ray Pulsars, *in preparation*). Beyond the jump in the number of pulsars, the increased statistics enable detailed (e.g. phase-resolved) studies on individual pulsars, previously out of reach. The LAT has also opened up the unexplored 10–100 GeV window. EGRET detected a mere handful of >10 GeV photons from the brightest pulsars (Thompson 2005), whereas the LAT detects significant emission from over two dozen pulsars in this energy range and even >25 GeV pulsations from the brightest ones (e.g. Crab, Vela, Geminga, see Saz Parkinson 2012).

Of the 117 LAT detections, 61 pulsars were known prior to *Fermi*. Pulsations were obtained by folding the γ -rays with a radio (or X-ray) timing model. Of these 61, 20 are MSPs (e.g. Abdo *et al.* 2009c), a hitherto unknown class of strong γ -ray emitters. More surprisingly, a large number of MSPs (>40) were discovered in radio searches of LAT unassociated sources (Ray *et al.* 2012). Most (20 so far, e.g. Ransom *et al.* 2011) will likely exhibit γ -ray pulsations[†], once enough data and/or a precise timing model is obtained (usually from radio observations). Finally, 36 of the 117 γ -ray pulsars were discovered directly in blind searches of LAT data (Abdo *et al.* 2009b, Saz Parkinson *et al.* 2010, Saz Parkinson 2011, Pletsch *et al.* 2012a, Pletsch *et al.* 2012b). The rest of this paper discusses the challenges, results, and prospects of these searches.

2. Blind searches for γ -ray pulsars (compared to radio)

Two factors make γ -ray searches for pulsars particularly challenging, compared to radio searches. The first involves the scarcity of events. The LAT detects ~ 1 γ -ray per day from a typical (bright) pulsar. This means that LAT searches for pulsars span months to years (see Figure 1). The second complication involves the broad, energy-dependent PSF of the instrument (from $\sim 5^\circ$ at 100 MeV to $\sim 0.2^\circ$ at 100 GeV, 68% containment, normal incidence). This results in significant source confusion, especially in high background regions like the Galactic plane, where the diffuse γ -ray emission makes it hard to resolve individual sources. Essentially, it is impossible to select, with certainty, events coming from a source, so statistical techniques must be employed. Using these techniques, it is possible to determine the probability that each event is coming from the source of interest and improve the sensitivity of the search by assigning a weight to each event equal to this probability (Kerr 2011).

Searches over long (sparse) data sets make standard FFT techniques impractical. To tackle this problem, Atwood *et al.* (2006) developed the “time-differencing technique” and applied it successfully to EGRET data (Ziegler *et al.* 2008). The core of the technique involves computing the FFT of the differences between the times of events (up to a maximum, sliding, time window), rather than using the original time series. Using a time window of \sim weeks significantly alleviates the coherence requirements of the search.

2.1. Young pulsars

Within weeks of the launch of *Fermi*, the first *radio-quiet* γ -ray pulsar was discovered in the supernova remnant CTA 1 (Abdo *et al.* 2008). This was followed by many more discoveries (e.g. Abdo *et al.* 2009b, Saz Parkinson *et al.* 2010). Many of these early γ -ray pulsars discovered by the LAT are coincident with old EGRET unidentified sources. Many, like the pulsar in CTA 1, are also coincident with known supernova remnants or pulsar wind nebulae, and were thus long suspected of hosting pulsars (e.g. PSR J1836+5925, J2021+4026). Radio follow-up observations of the LAT-discovered pulsars showed that most of them are *radio-quiet* (or extremely radio-faint), suggesting that the

[†] Given that they are LAT γ -ray sources selected precisely for their *pulsar-like* qualities.

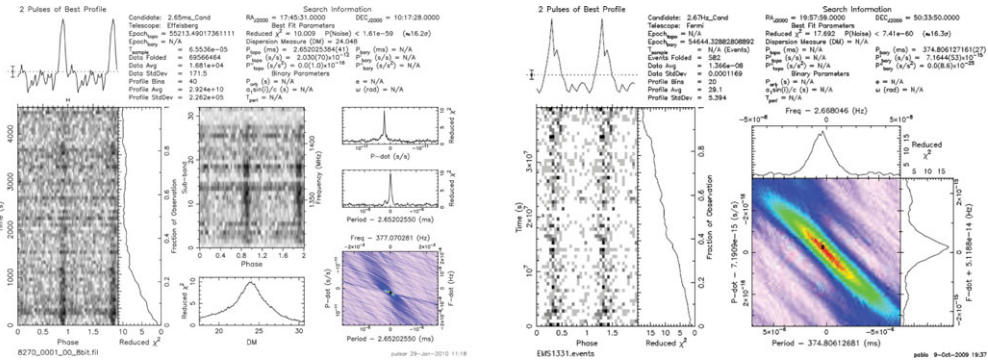


Figure 1. PRESTO (Ransom 2001) plots for two pulsars: one using radio data (left) and one using γ -ray data (right). *Left:* PSR J1745+1017, an MSP discovered in radio searches of *Fermi* unassociated sources with the Effelsberg telescope (Barr *et al.* 2012, MNRAS, *submitted*. Figure Credit: E. Barr). *Right:* PSR J1957+5033, a *radio-quiet* γ -ray pulsar discovered in a LAT blind search. Note that, although the pulse profiles and significances are similar, the γ -ray observation is $\sim 10,000$ times longer, and the number of γ -ray events (582) is approximately one per day ($\sim 200,000$ pulsar rotations!). On the other hand, unlike in radio, there is no need to scan in DM in a γ -ray search.

γ -ray emission originates far from the neutron star surface, resulting in broad beams. It is now clear that these radio-quiet γ -ray pulsars represent a significant fraction of the neutron star population of the Galaxy (see Guillemot *et al.* (2012), in these proceedings, for a detailed review of the radio observations of LAT γ -ray pulsars). All 36 pulsars found in LAT blind searches to date are young ($\tau < 1 \times 10^7$ yr) energetic (10^{33} erg $s^{-1} < \dot{E} < 10^{37}$ erg s^{-1}) pulsars with frequencies below ~ 20 Hz. These pulsars often exhibit timing irregularities, in the form of *timing noise* and glitches. Since most are not detected in radio, the LAT is the only instrument capable of timing them (Ray *et al.* 2011). While it is possible to time these noisy (or “glitchy”) pulsars, a good timing model often requires many frequency derivatives and other whitening terms, making their *discovery* over long data spans extremely challenging. Searches for these pulsars may only be possible over LAT observing periods lasting \sim months, rather than years (see Figure 2).

2.2. Millisecond pulsars

As mentioned above, the discovery of γ -ray MSPs (Abdo *et al.* 2009c) was largely unexpected. Equally unexpected was the large number of MSPs discovered by radio telescopes searching LAT unassociated sources (Ray *et al.* 2012). This fact, combined with the large fraction of *radio-quiet* young pulsars, raises the question of whether large numbers of *radio-quiet* γ -ray MSPs remain to be discovered in blind searches of LAT data. The answer, from examining the identified γ -ray sources in the *almost* flux-limited *Fermi*-LAT Bright Source List (Abdo *et al.* 2009a), appears to be no. Whereas at least two thirds of young γ -ray pulsars are *radio quiet*, at most one third of γ -ray MSPs are (Romani 2012).

Blind searches for MSPs are vastly more complicated than searches for young pulsars. Firstly, a majority ($\sim 80\%$) of MSPs are in binary systems, and a full blind search over unknown orbital parameters is out of reach given current computer capabilities. Searches for isolated MSPs are possible, but the high frequencies increase the memory and CPU requirements. Positional uncertainties become more relevant with increasing frequencies and the typical tolerance of a blind search using several years of data is of order a fraction of an arc second. This means that one must either perform a fine scan over the

LAT positions, or else identify a precise position of a plausible counterpart, using multi-wavelength (e.g. X-ray) observations. A number of LAT sources have been identified as promising pulsar candidates, by virtue of their variability and spectral properties (Ackermann *et al.* 2012). More recently, X-ray and optical studies of some of the brightest of these have identified some strong “black widow” candidates: eclipsing binary MSPs with very compact, almost circular orbits, where the pulsar is destroying its low-mass companion (Romani & Shaw 2011, Romani 2012). These studies derive extremely precise positions (to $\sim 0.1''$) and stringent constraints on two out of the three requisite orbital parameters (leaving only the projected semi-axis relatively unconstrained). Thus, for the first time, searches for such binary MSPs using γ -ray data are possible. A deep LAT search of 2FGL J2339.6+0532 (the most promising of these “black widow” candidates) unfortunately produced no significant candidate, but further efforts are in progress (see Belfiore 2012 for details).

3. Searches for pulsars around the Galactic Center

Understanding the γ -ray emission from the Galactic Center (GC) region is both challenging and controversial. Claims that γ -ray emission from the GC may be related to dark matter (e.g. Hooper & Goodenough 2011, Weniger 2012) should be measured up against more conventional explanations, such as a possible origin from γ -ray pulsars. As a site of massive star formation, it likely contains thousands of pulsars, but their radio detection is hampered by the large amount of interstellar scattering. Nevertheless, some pulsars have been discovered fairly close to the GC, and predictions for the number of radio pulsars that could be associated with the GC range in the thousands (Deneva *et al.*

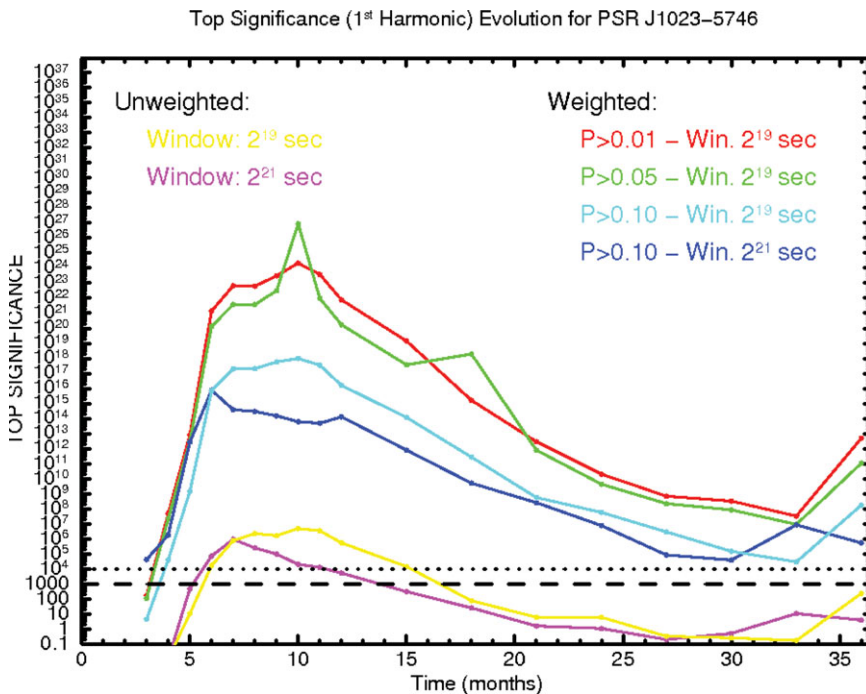


Figure 2. Blind-search significance of PSR J1023-5745, as a function of the cumulative observing time. Initially, the significance increases with time, but after a period of 7-10 months, the significance peaks and then decreases with the addition of more data.

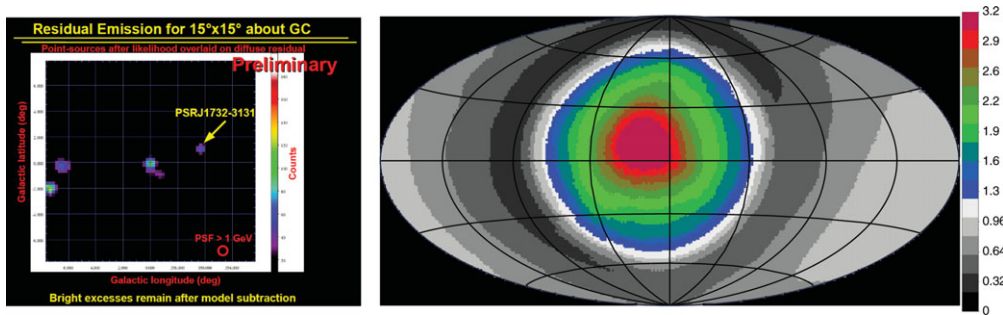


Figure 3. *Left:* LAT view of the GC (Porter, 2011 *Fermi* Symposium). The bright source at the GC (2FGL J1745.6-2858) is curved and non-variable, like most LAT pulsars. *Right:* Relative exposure (compared to survey mode) with a LAT viewing strategy favoring the GC. The gain in exposure is a factor of ~ 3 , while the exposure for other parts of the sky decreases to roughly one third, in the worst case.

2009). It is possible that some of the undiscovered pulsars in the region are *radio quiet*, like the majority of young pulsars found in LAT blind searches (e.g. PSR J1732-3131, see Figure 3).

Blind searches for γ -ray pulsars around the GC are affected by low fluxes (due to the large distance), and high levels of diffuse emission. Indeed, most LAT pulsars are likely nearby (\sim few kpc). The LAT has, however, detected pulsations from MSP J1823-3021A, in the globular cluster NGC 6624, at 8.4 kpc (roughly the distance to the GC). It is possible to estimate how far blind searches might be sensitive out to. From scaling arguments, considering that the γ -ray flux of the Crab is several thousand times brighter than the faintest γ -ray pulsar discovered in a blind search, we conclude that it is possible to discover a *Crab-like* γ -ray pulsar in a LAT blind search out to at least ~ 15 kpc.

Perhaps the biggest complication in searching for faint pulsars around the GC is the fact that such a pulsar may be young and *noisy* (or “glitchy”). As described above, the loss of coherence of the signal limits the amount of data that can be effectively searched (see Figure 2). Thus, regardless of the number of years of LAT data available, it may only be possible to search several months at a time. Thus, the sensitivity of searches in this region may only improve significantly with improvements in reconstruction (e.g. Pass 8, see Baldini 2011, *Fermi* Symposium), or a change in the observing mode. For the first four years of its mission, *Fermi* has operated mostly in survey mode. This has many advantages for most of the scientific goals of the mission, including pulsar searches (and timing). Modifying the observing profile, however, could enhance the sensitivity to detection of faint signals (both from pulsars and/or dark matter) from the GC. Figure 3 (right) shows the relative gain in exposure (compared to survey mode) with a modified mode in which the LAT points to a location slightly offset from the GC. Whenever the GC is occulted, the LAT could go back into survey mode, thus maintaining some level of exposure over the entire sky.

4. Conclusions and Prospects

The NASA Senior Review recently recommended that *Fermi* operations continue through 2016. In principle, *Fermi* could continue to operate well beyond this date[†]. As the LAT accumulates more data, it will detect γ -ray pulsations from ever fainter *radio-loud* pulsars. As for blind searches of γ -ray data, they too will continue to produce

[†] Unlike its predecessor, EGRET, the LAT has no consumables that limit its lifetime.

new discoveries, although the increasing computational demands will require additional resources (e.g. Einstein@Home[‡]) and efficient computational techniques to exploit them. Finally, multi-wavelength observations (radio, X-rays, and optical), will continue to play a crucial role in LAT pulsar studies, especially in facilitating the search for more exotic pulsar systems, such as “black widow” systems, young binary pulsars, and pulsars around the GC. In this last case, a modified observing profile enhancing the exposure to this region (by a factor of ~ 3) could play a crucial role in future discoveries.

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[‡] <http://einstein.phys.uwm.edu>