Pulsar Results with the Fermi Large Area Telescope

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Abstract The launch of the Fermi Gamma-ray Space Telescope has heralded a new era in the study of gamma-ray pulsars. The population of confirmed gamma-ray pulsars has gone from 6–7 to more than 60, and the superb sensitivity of the Large Area Telescope (LAT) on Fermi has allowed the detailed study of their spectra and light curves. Twenty-four of these pulsars were discovered in blind searches of the gamma-ray data, and twenty-one of these are, at present, radio quiet, despite deep radio follow-up observations. In addition, millisecond pulsars have been confirmed as a class of gamma-ray emitters, both individually and collectively in globular clusters. Recently, radio searches in the direction of LAT sources with no likely counterparts have been highly productive, leading to the discovery of a large number of new millisecond pulsars. Taken together, these discoveries promise a great improvement in the understanding of the gamma-ray emission properties and Galactic population of pulsars. We summarize some of the results stemming from these newly-detected pulsars and their timing and multi-wavelength follow-up observations.

1 Introduction

1.1 Gamma-ray Pulsars in the Year 2000

Ten years ago, on 4 June 2000, the Compton Gamma Ray Observatory (CGRO) was de-orbited, ending nine years of operation, during which it revolutionized...
gamma-ray astronomy. In particular, the Energetic Gamma Ray Experiment Telescope (EGRET) surveyed the sky at energies > 100 MeV with much better sensitivity than previous experiments. The landmark Third EGRET (3EG) Catalog [Hartman et al., 1999] reported the characteristics of 271 gamma-ray sources. The largest class of identified sources were blazars, with 66 sources, followed by 5 pulsars (Crab, Vela, Geminga, PSR B1055−52, and PSR B1706−44), 1 solar flare, the Large Magellanic Cloud, and one probable radio galaxy (Centaurus A). Interestingly, the majority of the 3EG sources (170 of them) were not associated with any known classes of gamma-ray emitting objects. It was widely believed that a large number of the unidentified EGRET sources, particularly along the Galactic plane, could be pulsars (e.g. [Yadigaroglu & Romani, 1995]), and several radio pulsars were, in fact, discovered by searching the error circles of EGRET unidentified sources (e.g. [Halpern et al., 2001, Roberts et al., 2002]). Further work on EGRET data revealed one more high-confidence pulsar (PSR B1951+32) and several candidates, including one millisecond pulsar (Kuiper et al., 2000). An excellent observational summary of what was known about gamma-ray pulsars at the end of the EGRET era was presented by Thompson (2001). It is also worth noting that a 7th gamma-ray pulsar (PSR B1509−58) was detected by the COMPTEL experiment up to 10 MeV [Kuiper et al., 1999], though it was never seen with EGRET. Pre-launch predictions of the number of gamma-ray pulsars that Fermi LAT would detect (as well as the fraction of those that would be radio quiet) are highly dependent on the assumed gamma-ray emission model, ranging from a few tens to many hundreds (e.g. Ransom, 2007), with the larger number (and fraction of radio-quiet pulsars) usually predicted by outer-magnetosphere models, where the gamma-ray beam is expected to be broader (Jiang & Zhang, 2006, Harding et al., 2007). It should be noted that the detection of a gamma-ray pulsar, in this context, does not necessarily imply the detection of its pulsations; most models, for example, “predict” that EGRET detected far more than the 6 gamma-ray pulsars for which high-confidence pulsations were actually observed, a view that is supported by the subsequent detection of pulsations from many formerly unidentified EGRET sources by the LAT.

1.2 Fermi and AGILE

After almost a decade without an orbiting GeV telescope, two new satellites were launched in 2007–2008, ushering in a new era of gamma-ray astronomy. AGILE (an Italian acronym for Astro-rivelatore Gamma a Immagini LEggero) was launched on 23 April 2007 and the Fermi Gamma-ray Space Telescope (formerly GLAST) was launched on 11 June 2008. The prime instruments on both spacecraft are pair production gamma-ray telescopes, like EGRET. However, instead of a gas spark chamber, they employ more modern solid-state silicon strip detectors to track the gamma-ray and particle events. While AGILE had a 14-month head start on Fermi, and has made many important contributions, it represents a modest improvement in
sensitivity compared to EGRET. In this paper we focus on the pulsar results made possible by the enormous leap in sensitivity afforded by Fermi.

The primary instrument on Fermi is the Large Area Telescope (LAT) (Atwood et al., 2009). The LAT is a pair conversion gamma-ray telescope where incoming gamma rays are converted to electron-positron pairs in a set of tungsten foils. The resulting electron-positron pair and shower of secondary particles are tracked by a stack of silicon strip detectors to determine the incident direction of the photon before the energy of the shower is recorded in a CsI calorimeter. The instrument is wrapped in a segmented anti-coincidence detector that aids in the separation of events due to charged particles from those resulting from photons. This is critical because charged particle events outnumber photon events by a factor of $10^4$. The LAT is sensitive to photons in the energy range 30 MeV to $>300$ GeV, with an effective area of $\sim8000$ cm$^2$ at 1 GeV. The point spread function is $\sim0.8^\circ$ at 1 GeV and is a strong function of energy, scaling like $E^{-0.8}$ until the resolution becomes limited by position resolution in the tracker at about 0.07$^\circ$. Compared to EGRET, the LAT represents a major improvement in effective area, field of view, and angular resolution. In addition, it operates in a sky survey mode which avoids loss of observing efficiency from Earth occultations and covers the sky nearly uniformly every two orbits ($\sim3$ hours). These characteristics give the LAT unprecedented sensitivity for discovery and study of gamma-ray pulsars. The First Fermi LAT catalog (1FGL; Abdo et al., 2010) of 1451 gamma-ray sources detected during the first 11 months of science operations contains 56 sources that have been firmly identified as pulsars through their gamma-ray pulsations. Several additional gamma-ray pulsars have been identified since the release of the catalog, bringing the total number to more than 60. In the following sections, we describe the various populations of gamma-ray pulsars being explored by the LAT, and the different techniques employed in their detection, as well as some of the new insights being gained through these new findings. We end with a brief summary and some thoughts on the future goals and expectations for pulsar astrophysics with the LAT in the coming years.

2 The EGRET Pulsars in Exquisite Detail

The EGRET experiment represented a major improvement relative to previous gamma-ray missions (e.g., SAS-2 and COS-B). In addition to increasing the number of high-confidence gamma-ray pulsars from 2 to 6, the higher sensitivity of EGRET led to a better understanding of the known gamma-ray pulsars (at the time, only the Crab and Vela). Similarly, the LAT, with its improved sensitivity and broader energy range is not only enabling the discovery of a large number of new gamma-ray pulsars, but is also greatly expanding our knowledge of the previously known EGRET-detected pulsars. Because these pulsars are among the brightest known gamma-ray sources, the LAT is able to accumulate enough statistics to allow for detailed (and

1 This is the individual photon angular resolution. Bright sources can be localized more precisely via centroiding.
phase-resolved) spectral analyses, in many cases answering some questions left over from the EGRET era, or challenging some of the previous EGRET results which in most cases were based on limited statistics.

Early LAT observations of Vela, the brightest steady gamma-ray source, confirmed some of the basic features of this pulsar: It has two asymmetric peaks that evolve differently with energy, and a phase-averaged spectrum well modeled by a hard power-law with an exponential cutoff in the 2–4 GeV energy range. In addition, the much better statistics and time resolution of the LAT data reveal pulse structures as fine as 0.3 ms, and a hitherto unknown third peak in the light curve, which evolves with energy (see Figure 1). Spectral fits to the LAT data suggest that a simple exponential cutoff is preferred over a super-exponential one, indicating that outer-magnetosphere emission models are favored over polar cap type models (Abdo et al., 2009f). More recent results on Vela, using 11 months of observations, show detailed phase-resolved features which confirm the EGRET results on the spectral evolution of the two main peaks. In addition, while the first peak is seen to fade at higher energies, the newly-discovered third peak, along with the second peak, are present up to the highest detected pulsed energies (Abdo et al., 2010k).

LAT results on the Crab pulsar confirm that it shares many of the properties of Vela, with two asymmetric peaks evolving differently with energy. The Crab pulsar spectrum is also best modeled with a power law with an exponential cutoff, but the cut-off energy in this case is much higher than Vela (≈ 6 GeV), with pulsed gamma-ray photons being detected at least up to ≈ 20 GeV (Abdo et al., 2010h). One of the new features uncovered by the LAT is an apparent phase shift between the main radio peak and the first gamma-ray peak. Previously, it was thought that these two were aligned, but the fine time resolution of the LAT allows us to determine that the first gamma-ray peak leads the main radio pulse by \((281 ± 12 ± 21)\) ms (see Figure 2).

In addition to being the second brightest non-variable source in the GeV sky, Geminga was the first known radio-quiet gamma-ray pulsar. As such, it cannot be timed in radio and until now, a good timing solution relied on X-ray observations.

**Fig. 1** Pulse profile of the Vela pulsar, as a function of energy. The different behavior of the two main peaks is evident. A third peak is seen to appear at higher energies, with its position shifting in phase, as a function of energy (from Abdo et al., 2010k, reproduced by permission of the AAS).
Using ~1 year of observations, consisting of over 60,000 photons, a timing solution was obtained based solely on gamma rays (Abdo et al., 2010a). Geminga shows many similarities to Vela and the Crab. The phase-averaged spectrum is also well represented by a power law with exponential cutoff, with a hard spectral index and a cutoff energy between 2–3 GeV, leading to pulsed gamma rays being detected up to at least 18 GeV (Abdo et al., 2010a). Detailed phase-resolved spectroscopy shows an evolution of the spectral parameters with phase and appears to indicate that there is emission coming from the pulsar at all rotational phases, favoring, once again, outer-magnetospheric emission models (Abdo et al., 2010a).

The remaining EGRET pulsars, PSRs J1057−5226, J1709−4429, and J1952+3252, while still bright, were not as bright as Vela, the Crab, and Geminga. LAT observations of these pulsars shed light on some of the key questions left over from the EGRET era. All three pulsars, once again, can be fit with a power law with a simple exponential cutoff. This contradicts earlier EGRET results that indicated that PSR J1709−4429 could be fit with a broken power law and PSR J1952+3252 showed no signs of a cutoff below 30 GeV (Abdo et al., 2010b). It is interesting to note that the conclusion about the EGRET spectrum of PSR J1952+3252 was based on the detection of 2 photons above 10 GeV.

Finally, although not detected by EGRET, PSR B1509−58 was seen by the COMPTEL instrument, and is therefore one of the 7 gamma-ray pulsars detected by CGRO. More recently, its detection has also been reported by the AGILE collaboration (Pellizzoni et al., 2009). Using 1 year of data, the LAT was able to detect pulsations from PSR B1509−58 up to 1 GeV, and confirmed that, unlike the EGRET-detected pulsars, PSR B1509−58 has an energy spectrum that breaks at a few tens of MeV (Abdo et al., 2010d).

The high precision phase-resolved spectral measurements made possible with the LAT will be critical for theoretical modeling efforts, which must confront these new data. With the simple question of polar cap vs. outer magnetosphere origin now largely resolved, the important questions become more subtle: Where exactly in the outer magnetosphere is the acceleration occurring? Which magnetosphere geometry is appropriate (e.g. vacuum dipole or force-free magnetosphere)?

3 Young Pulsars Found Using Radio Ephemerides

In addition to the 7 young (or middle-aged) gamma-ray pulsars previously detected by CGRO, the LAT has also detected gamma-ray emission from an additional dozen or more “young” (non-millisecond) radio-selected pulsars. PSR J2021+3651 holds the distinction of being the first new gamma-ray pulsar in the post-EGRET era. The pulsations were detected with the LAT during the commissioning phase of the instrument (Abdo et al., 2009), although the original discovery of the gamma-ray pulsar was independently reported using AGILE data (Halpern et al., 2008). Other pulsars detected early in the mission include PSR J1028−5819, shown to be at least partly responsible for the EGRET source 3EG J1027−5817, the single-
peaked PSR J2229+6114 in the “Boomerang” pulsar wind nebula (PWN) (Abdo et al., 2009e), and the very energetic PSR J0205+6449, in SNR 3C 58 (Abdo et al., 2009d). Several of the newly-detected gamma-ray pulsars were already proposed as marginal EGRET detections, including PSRs J1048−5832 and J0659+1414. Figure 3, for example, shows the folded light curves of PSR J1048−5832, including that generated with EGRET data. While the significance of the EGRET pulsation is clearly limited by the much lower statistics, the perfect alignment of the peaks with the LAT profile confirms that this was, indeed, a real detection, as originally reported by Kaspi et al. (2000). Other young pulsars now seen by the LAT were originally discovered in radio searches of EGRET unidentified sources, and thus proposed as the energetic radio counterparts of the known gamma-ray sources (e.g. PSRs J2021+3651 and J2229+6114). Many, however, had no previous gamma-ray associations. While the brightest new gamma-ray pulsars (particularly those coincident with formerly-unidentified EGRET sources) could have been detected in blind searches of LAT data (or searching around the extrapolation of the original radio timing solution), the detection of pulsations from fainter gamma-ray pulsars (e.g. PSR J0205+6449) requires contemporaneous phase-connected timing solutions spanning the entire LAT data set. In anticipation of such needs, a comprehensive pulsar monitoring campaign (known as the Pulsar Timing Consortium) was set up, prior to launch, between the LAT collaboration and the major radio telescopes, to ensure periodic monitoring of hundreds of pulsars with large spin-down energies, with the goal of providing the necessary ephemerides (Smith et al., 2008).
Fig. 3 Folded light curves of the young energetic pulsar PSR J1048−5832 (from Abdo et al., 2009e, reproduced by permission of the AAS). The second panel from the bottom shows the EGRET light curve. The Fermi LAT data allow us not only to confirm the marginal EGRET detection (note that the peaks line up), but also to study much finer time scales, as well as the energy evolution of the light curve.

4 Millisecond Pulsars

At first glance, millisecond pulsars (MSPs) might not seem like great candidates for gamma-ray emission. After all, they are several orders of magnitude older than the gamma-ray bright young pulsars and their surface magnetic fields are about four orders of magnitude weaker. On the other hand, their very rapid rotation rates give them open field line voltages that are competitive with the young pulsars and their magnetic fields at the light cylinder \(B_{LC}\) are at about the median value for the young gamma-ray pulsars. This, plus the marginal detection of PSR J0218+4232 with EGRET (Kuiper et al., 2000), gave some reason to be optimistic. One particularly prescient paper (Story et al., 2007) used a detailed population study based on the pair-starved polar cap model to predict that the LAT should be sensitive enough to detect tens of gamma-ray millisecond pulsars, most of which should be radio quiet and thus form a high-latitude population of unidentified gamma-ray pulsars. They also pointed out that, since the high latitude regions have been very poorly covered by millisecond pulsar surveys so far, radio searches of LAT point sources with pulsar-like spectra should be an efficient way to find new MSPs.
Over the first 18 months of the Fermi mission, it has become abundantly clear that millisecond pulsars are a significant contributor to the population of high latitude gamma-ray sources being detected with the LAT. Figure 4 shows the distribution, in Galactic coordinates, of all the MSPs detected to date with Fermi LAT. We describe these discoveries in the following subsections.

4.1 Radio MSPs

The first LAT results on MSPs came from folding the gamma-ray data using radio ephemerides for the \( \sim 72 \) field MSPs (i.e. \( P < 30 \text{ ms} \) and outside of the globular cluster system). Within the first 8 months of data taking, significant gamma-ray pulsations were discovered from 8 MSPs, including confirmation of the EGRET detection of PSR J0218+4232 (Abdo et al., 2009j,a). In addition to the 8 pulsed detections, it was noted that there were significant LAT point sources positionally coincident with 5 other MSPs (Abdo et al., 2009a). With continued exposure accumulating, 3 of those 5 now have reported pulsation detections above the 5 \( \sigma \) significance level: PSR J0034−0534 (Abdo et al., 2010c), PSR B1937+21 and PSR B1957+20 (Kerr et al., 2010), bringing the total number of radio-timed millisecond gamma-ray pulsars to 11.

The initial 8 MSP discoveries tended to resemble the normal pulsar population in most of their characteristics, including the peak separations, fraction that showed single vs. double peaks, and radio lags. This led to the conclusion that MSPs had essentially the same gamma-ray emission mechanism operating in the outer magnetosphere as the young pulsars, as suggested by the similar values of \( B_{LC} \). Interestingly, the three latest discoveries all have gamma-ray light curves that appear to have peaks that are aligned in phase with the radio pulses. This characteristic is very rare among the normal pulsars, with the primary counter-example being the Crab pulsar (where the radio peaks overlap the gamma-ray ones, even though they aren’t perfectly aligned, as described above). It has been suggested that these are cases where the gamma-ray and radio emission are coming from nearly co-located regions of the magnetosphere and that both result from caustic formation (Abdo et al., 2010c).

4.2 Searches of LAT Unassociated Sources

As mentioned earlier, a promising technique for discovering new MSPs is to perform radio searches in the direction of gamma-ray point sources that have pulsar-like characteristics (e.g. lack of variability and exponentially cutoff spectra). This technique was used, with modest success, on many of the EGRET unidentified sources (Crawford et al., 2006; Champion et al., 2005; Keith et al., 2008, for example). These searches were challenging because the EGRET error boxes were many times larger than a typical radio telescope beam, requiring many pointings to cover the
source region. With the LAT, the unassociated source localizations are a much better match to radio telescope beam sizes and can generally be searched in a single pointing. The Fermi Pulsar Search Consortium (PSC) was conceived to organize search observations of LAT-discovered pulsars and unassociated sources using several large radio telescopes around the world. Thus far, over 100 LAT unassociated sources, mostly at high Galactic latitudes (See Figure 4), have been searched at 350, 820, or 1400 MHz resulting in the discovery of 18 new millisecond pulsars (Ransom & Fermi Pulsar Search Consortium [2010]). These searches are ongoing, and there is no apparent strong correlation between the gamma-ray and radio fluxes of these pulsars, so more discoveries can be expected as fainter LAT unassociated sources are searched.

These discoveries represent a ∼25% increase in the number of known millisecond pulsars outside of the globular clusters, which is an impressive achievement considering the enormous effort that has gone into radio MSP searches over the last three decades. The new pulsars include several highly interesting sources. Five of them are so-called “Black Widow” pulsars, with minimum companion masses of 0.01–0.05 $M_\odot$ and one other has a more typical mass companion, but exhibits radio eclipses. These more than double the known population of such pulsars in the field of the Galaxy and will be important systems for understanding the formation and evolution of millisecond pulsars as well as excellent systems to look for unpulsed gamma-ray emission from intra-binary shocks. Several others are very bright with sharp radio profiles that have the potential to be important additions to pulsar timing array projects that seek to detect nanoHertz gravitational waves via their effect on pulse arrival times (Hobbs et al., 2010).

Since all of these pulsars are positionally coincident with LAT gamma-ray sources, it is expected that once sufficiently accurate timing models are available, they will all be found to be gamma-ray pulsars and, indeed, LAT pulsations have already been discovered for the first 3 of the new MSPs (Ransom & Fermi Pulsar Search Consortium [2010]).

### 4.3 Globular Cluster MSPs

Although there are some 140 pulsars known in globular clusters most of which are MSPs, there have been no reported gamma-ray pulsations from individual millisecond pulsars in globular clusters with the LAT. However, in at least 8 cases, there are point-like gamma-ray sources spatially coincident with globular clusters (Abdo et al. [2009c], Kong et al. [2010], Abdo et al. [2010c]). In general, these 8 LAT sources are consistent with being the combined emission of a population of millisecond pulsars in each cluster. Most have spectra that show an exponential cutoff.

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2 The 1FGL catalog, compiled with 11 months of data, lists 630 unassociated sources and many more are expected as the LAT pushes down in sensitivity. Note, however, that AGN (which represent about half of the current associations) will likely comprise a significant fraction of these.

3 [http://www.naic.edu/~pfreire/GCpsr.html](http://www.naic.edu/~pfreire/GCpsr.html)
in the few GeV range, as seen with MSPs, but for a couple the significance of the
cutoff is too low for it to be considered evidence for an association of the gamma-ray
source with the cluster. The fluxes are largely consistent, within the substantial un-
certainties, with estimates of the total number of MSPs in each from from radio and
X-ray observations. However, in three cases, there are no known MSPs in clusters
with associated LAT sources, providing a strong motivation for deeper radio pulsar
searches of those clusters.

It is worth noting that the AGILE collaboration reported the detection of pulsa-
tions from PSR J1824−2452, in the globular cluster M28 (Pellizzoni et al., 2009),
but the detection was marginal and appeared in only one subset of the AGILE data.
Thus far, this result has not been confirmed by Fermi. In general, the detection of
individual gamma-ray pulsars in globular clusters will likely be difficult because of
the typically large distances to the clusters (4–12 kpc for the likely LAT-detected
clusters) and because of the background provided by the rest of the pulsars in the
cluster. However, in cases where there is one pulsar (like PSR J1824−2452) that has
a very large $\dot{E}$, it may outshine the rest of the pulsars in the cluster and be detectable
individually. Searches with the LAT are ongoing, using radio timing models for a
large number of individual pulsars in globular clusters.

![Sky map, in Galactic coordinates, showing millisecond pulsars detected with the Fermi LAT. The background image is made from 16 months of LAT data (2008-08-04 through 2009-12-02) with $E > 100$ MeV. The white crosses mark the 11 previously known radio pulsars found to be gamma-ray pulsars with the LAT. The yellow circles indicate the 18 new radio MSPs discovered in searches of pulsar-like LAT unassociated sources.](image-url)
5 Blind Periodicity Searches

As described in previous sections, it was long thought that many of the EGRET unidentified sources could, in fact, be pulsars—in particular radio-quiet pulsars like Geminga. Previous attempts to carry out blind searches on EGRET data using coherent FFT techniques were unsuccessful (e.g. Chandler et al., 2001). The sparse data sets and sensitivity to timing irregularities make such searches incredibly challenging. A new technique was developed to try and ameliorate the problem, by calculating the FFT of the time differences (instead of times of arrival) of events. Time differences are calculated between all events in the time series with respect to events lying within a relatively short sliding window (~weeks). The lower frequency resolution of the resulting FFTs make these searches less sensitive to frequency shifts (such as those caused by the spindown of the pulsar), while at the same time resulting in great savings in computational time (Atwood et al., 2006). This new time-differencing technique was shown to work with EGRET data (Ziegler et al., 2008), and has since proven extremely successful with the LAT data, leading to the discovery, so far, of 24 pulsars found in blind searches (Abdo et al., 2009b; Saz Parkinson et al., 2010). Figure 5 shows an example of the output from a successful blind search of a formerly unassociated LAT source, now identified as PSR J1957+5033 (Saz Parkinson et al., 2010). After determining that the highly significant peak at 2.668 Hz is promising, standard pulsar packages such as PRESTO (Ransom, 2001), and tempo2 (Hobbs et al., 2006), are used to refine the result and obtain a final timing solution for the pulsar.

Most of the initial 16 pulsars found in blind searches of LAT data were associated with formerly unidentified EGRET sources. In fact, only 3 of the 16 had no EGRET counterpart (Abdo et al., 2009b). Many of these sources were long-suspected of hosting pulsars, including 3EG J1835+5918, the brightest unidentified EGRET source off the Galactic plane, which was even dubbed the ‘Next Geminga’ (Halpern et al., 2007). Six out of the sixteen pulsars were discovered by assuming a counterpart position derived from observations at other wavelengths (mostly X-ray), instead of the less precise LAT position. A prime example is the discovery of PSR J1836+5925 powering 3EG J1835+5918 (Abdo et al., 2010g). More recently, the last 8 pulsars found in blind searches have mostly been found from newly-discovered LAT sources, with no corresponding EGRET counterpart, except in some cases where the EGRET source might have been confused and is now being resolved into multiple separate gamma-ray sources by the LAT (Saz Parkinson et al., 2010).

Although radio beaming fractions for MSPs appear to be large (Kramer et al., 1998), there are still expected to be radio quiet millisecond pulsars detected as point sources with the LAT. A discovery of a radio-quiet MSP in a blind search would be an important result. Unfortunately, the parameter space that needs to be searched is vast. For the case of binary MSPs the problem may be essentially intractable. However, about 25% of MSPs are isolated, including at least two of the LAT-detected...
radio MSP. For these pulsars the search is daunting, but not impossible. On the plus side, MSPs have low period derivatives and are extremely stable rotators, so the pulse will remain phase coherent for a long integration time. Counteracting this is the fact that the fast spin rates require that the pulsar position be known very precisely (∼0.1 arcsec). For a typical LAT point source position uncertainty of 3 arcmin, this requires $3.2 \times 10^6$ trial positions to cover the region, and each trial position requires a search over frequency and frequency derivative.

Current efforts on blind searches of LAT data are concentrating on both searching deeper for young and middle aged pulsars as well as expanding the search parameter space to include isolated MSPs.

### 6 Pulsar Timing with the LAT

Pulsar timing is a powerful technique that involves fitting a model to measured pulse arrival times that can account for every rotation of the neutron star over a time span of years (Lorimer & Kramer [2005], chap. 8). Of course, such timing yields extremely precise measurements of the spin period and spindown rate of the neutron star, quantities from which estimates of the magnetic field, age, and energy loss rate of the pulsar can be derived. In addition, because of the motion of the Earth around the solar system barycenter, the pulse arrival times are highly sensitive to the pulsar position on the sky. Once those major effects are accounted for, timing is sensitive to

![Fig. 5 Results from a blind search on a formerly unassociated LAT source (now PSR J1957+5033; Saz Parkinson et al. [2010]), indicating the presence of a highly significant pulsation at 2.668 Hz. The FFT has been computed using the differences between binned photon arrival times up to a maximum difference of 262,144 s, and the power at each frequency has been normalized to represent the inverse of the probability that it could be due to a random fluctuation, as described in Ziegler et al. [2008]. Note that the logarithmic scale results in the majority of the 33,554,432 FFT bins not showing up in the figure.](image-url)
a host of other parameters of the system including binary orbital parameters, timing noise, glitches, and even proper motion and parallax in some cases.

Traditionally, pulsars have been discovered and timed using radio telescopes. Working in the gamma-ray band, EGRET was not very effective for pulsar timing both because of its limited sensitivity and because of its pointed viewing plan that meant that most pulsars were only observed for a few 2-week observations scattered over the mission. The situation is completely different with Fermi, which now has both the sensitivity to detect a large number of pulsars and a sky survey viewing plan that allows observations of every pulsar in the sky continuously. For most of the 24 blind search pulsars, timing using the LAT data is the only option since they are undetectable or extremely faint at radio wavelengths. In addition there are some very faint radio pulsars, such as PSR J1124−5916 where the observation time required to do radio timing is prohibitive, but which can be readily timed with the LAT.

There are several key differences between pulsar timing with the LAT and radio pulsar timing. First, the satellite is not affixed to the Earth, like a ground-based radio telescope. Second, the data are very sparse, with often fewer than 100 photons being used to make a pulse time-of-arrival (TOA) measurement. The first issue is dealt with by transforming the photon arrival times as observed at the satellite to a fictional observatory at the geocenter, thus removing the effects of the spacecraft motion on the measurement. The second difference drives one to adopt a TOA measurement technique different than the traditional radio method of cross correlating a folded pulse profile with a high signal to noise binned template. Instead, TOAs are determined by a maximum likelihood fit to the offset between the measured photon times and an analytic template profile (Ray et al., 2010).

What is impressive is that even with so few photons, timing models can be determined for most detectable LAT pulsars with RMS residuals of order a millisecond using TOAs spaced by a few weeks. This enables arcsecond position determinations as shown in Figures 6 and 8 (right panel).

In addition to these precise positions that enable multiwavelength counterpart identifications, pulsar timing with the LAT has provided spindown measurements for the gamma-ray selected pulsars, detection and measurement of glitches, and studies of the timing noise observed in these systems. The precise long-term timing models are also critical for other studies such as blanking a pulsar to remove confusion in the study of a nearby source, as was required for Cygnus X-3 (Abdo et al., 2009b) or searches for off-pulse emission, such as from an SNR or PWN (Grondin & Lemoine-Gourmand, 2010).

7 Multiwavelength Connections

The 24 blind-search pulsars were all discovered in gamma-ray searches and thus are gamma-ray selected pulsars, but targeted radio observations are required to determine if they are also radio quiet, or could have been discovered in radio surveys
independently. Radio detections also yield distance estimates from dispersion measure, information on the emission region from radio to gamma-ray offset, and geometry from radio polarization studies. In addition, the population statistics of radio quiet vs. radio loud gamma-ray pulsars have important implications for gamma-ray emission models.

Deep radio searches have now resulted in the detection of radio pulsations from three of the 24 blind search pulsars, with strong upper limits on the others (Ray et al., 2010; Saz Parkinson et al., 2010). The pulsations from J1741−2054 were found in archival Parkes Multibeam survey data and confirmed using the Green Bank Telescope (GBT) (Camilo et al., 2009). For J2032+4127, the pulsations were discovered using the GBT (Camilo et al., 2009). The third radio pulsation discovered was from PSR J1907+0602 (Abdo et al., 2010) using a very deep observation with the 305-m Arecibo telescope. The detections provide distance estimates from the dispersion measure, which allow conversion of the radio fluxes into pseudo-luminosities. As shown in Figure 7, two of these pulsars are exceptionally faint, with luminosities about an order of magnitude lower than the faintest radio-discovered young pulsars. This is forcing a reevaluation of what is meant by a 'radio quiet' pulsar.

Observations of PWNe at TeV energies go back to the very first firm detection of emission from the Crab nebula (Weekes et al., 1989). Since then, over 100 TeV sources have been detected, and more than half of these have associated LAT sources (Abdo et al., 2010), which is perhaps not altogether surprising given that the energy ranges of the LAT and ground-based Cerenkov detectors overlap. PWNe represent the largest class of Galactic TeV sources. In fact, the first unidentified

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**Fig. 6** Comparison of position determinations of PSR J1836+5925. The large ellipse (0.45 arcmin semimajor axis) is the 95% confidence region from positional analysis of 18 months of LAT data (M. Kerr, private communication). The small ellipse (0.8 × 0.4 arcsec) is from the pulsar timing model fit over the same interval (Ray et al. [2010]). The background image is a Chandra X-ray image showing the point source at the location of the pulsar.

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5 For an up-to-date catalog of TeV sources, see http://tevcat.uchicago.edu/
**Fig. 7** Pseudo-luminosities of the gamma-ray selected pulsars that have since been detected as radio pulsars (red stars), compared to the general population of radio pulsars (blue dots).

**Fig. 8** Left – *Fermi* LAT counts map of the region around PSR J1023−5746. The green contours represent the HESS significance. Right – *Chandra* X-ray image of the Westerlund 2 cluster. The X-ray counterpart of PSR J1023−5746 is approximately 8 arcminutes away from the core of the cluster. Inset: Zoomed-in image of a 1 square arcminute region around the location of the pulsar. Note that the 95% (statistical) error ellipse obtained from pulsar timing (shown in white) overlaps with the X-ray source. Figures from Saz Parkinson et al. (2010), reproduced by permission of the AAS.

TeV source, discovered by the HEGRA telescope in the Cygnus OB2 region, is associated with PSR J2032+4127, one of the pulsars found in blind searches of LAT data (Abdo et al., 2009b; Camilo et al., 2009). HESS observations of the Galactic plane uncovered a large number of unidentified TeV sources, and many of these are thought to be associated with PWNe. In some cases, the discovery of new LAT pulsars coincident with known TeV sources can put into question previous interpretations of the TeV emission. Figure 8, for example, shows the positional coincidence of the highly energetic pulsar PSR J1023−5746 (Saz Parkinson et al., 2010) with the bright TeV source, HESS J1023-575. Located in the vicinity of the young stellar cluster Westerlund 2, the TeV emission from this source was previously thought to be due mainly to the wind interaction from massive stars (Aharonian et al., 2007). The presence of such a pulsar, however, must lead to a re-examination of such con-
clusions. Furthermore, the identification of the counterpart (right panel in Figure 8) shows that the association with the Westerlund 2 cluster is highly questionable.

At higher energies still, the Milagro observatory detected significant (>5σ) TeV emission at a median energy of 35 TeV from the location of 6 gamma-ray pulsars detected by the LAT, and evidence for emission (3−5σ) from the location of an additional 8 sources from the Bright Source List (Abdo et al., 2009g). Four of those sources are gamma-ray pulsars, and two more are associated with supernova remnants.

This strong connection between young energetic GeV pulsars and their TeV PWNe can play an important role not only in understanding the nature of the emission from such sources, but also as a means to identify likely candidates for gamma-ray pulsars, ultimately leading to the identification of both TeV and GeV sources.

X-ray observations of gamma-ray pulsars and pulsar candidates are particularly important. First, the precise positions of neutron star candidates allow for more sensitive blind searches to take place (as in the case of PSR J0007+7303 or PSR J1836+5925). Secondly, for those pulsar candidates found using the less precise LAT position, X-ray positions can serve to refine the candidate and determine whether it is a real detection. In 4 out of the original 16 pulsars discovered in blind searches, a short observation with the Swift satellite was enough to identify a plausible X-ray counterpart which resulted in a much higher significance of the pulsation (Abdo et al., 2009b). In several other cases (e.g. Gamma Cygni SNR, Cygnus OB2 association), archival observations could be analysed in search of the best possible counterpart.

8 The LAT Pulsar Population

A Period-Period Derivative diagram showing all 63 gamma-ray pulsar detections made with the LAT to date is shown in Figure 9. This is an update of Figure 2 from the Fermi LAT First Pulsar Catalog (Abdo et al., 2010j), which summarizes the characteristics of the 46 gamma-ray pulsars detected with the LAT in the first 6 months of the Fermi mission. The LAT-detected pulsars generally have high values for the detectability metric $E^{1/2}/D^2$ and large $E$ and $B_{\perp}$. Which one of these is really telling us about the gamma-ray emission physics at work in these sources remains to be seen. With a large number of detections spanning a range of $E$ from $10^{33.5}$ to $>10^{38}$ erg s$^{-1}$, we can start to address the evolution of gamma-ray luminosity (i.e. efficiency) with $E$. Unfortunately, the large distance uncertainties for most pulsars combined with the model-dependent uncertainty in the beaming factor (see below) prevent strong conclusions from being drawn at present (Abdo et al., 2010j).

The spectra of LAT pulsars are well characterized by exponentially cutoff power laws with photon indices near 1.5. The cutoff energies are in the 1–4 GeV range with a small number of outliers on the high and low side. The observed pulse profiles frequently evolve with energy, but generally fall into one of three categories: two peaks separated by ∼0.4–0.5 in phase, two overlapping peaks separated by ∼0.2
Fig. 9 Period-Period Derivative diagram showing the LAT-detected pulsars. Included are 24 young or middle-aged radio-timed pulsars (green circles), 25 gamma-ray selected pulsars (blue squares), where all but Geminga were discovered in LAT blind searches, and 14 millisecond pulsars (red triangles), for a total of 63 gamma-ray pulsars. Note that this does not include 15 of the radio millisecond pulsars discovered in searches of LAT unassociated sources, essentially all of which can be expected to be detected as gamma-ray pulsars once their timing models are well determined.

in phase, and single peaked profiles. Most of the LAT pulsars are consistent with being 100% pulsed in the gamma-ray band. However, a few (e.g. Geminga and PSR J1836+5925) seem to show magnetospheric emission across all rotational phases. In other cases, an analysis of the ‘off-pulse’ region of pulse phase reveals GeV
emission from a pulsar wind nebula, typically with a much harder spectrum than that of the pulsar itself. A review of LAT observations of PWNe is presented elsewhere in this volume (Grondin & Lemoine-Gourmard, 2010).

The large number of radio and gamma-ray selected pulsars found with the LAT, combined with deep radio searches of the new gamma-ray selected population will enable population studies that will help shed light on the beaming fractions in the two bands and test predictions of the various models for the emission region geometries. One such early study (Ravi et al., 2010) finds that the radio beaming fraction is near unity for the the highest $\dot{E}$ pulsars and decreases to $\sim 0.5$ for the lower $\dot{E}$ gamma-ray pulsars, implying that very high-$\dot{E}$ pulsars may produce their radio emission in the outer magnetosphere. If confirmed, this would have major implications.

The current challenge is to use the abundance of well-measured light curves to constrain the geometry of the emitting region and the relevant magnetospheric physics. The favored approach is to choose an emission region location (e.g. polar cap (PC), outer gap (OG), or two-pole caustic (TPC)), combine it with an assumed magnetic field geometry and compute an ‘atlas’ of predicted gamma-ray light curves that can be compared with observations. This has been done for vacuum dipole field geometries (Watters et al., 2009), as well as for numerically-modeled ‘force-free’ geometries (Bai & Spitkovsky, 2010). Other groups have specifically targeted millisecond pulsars (Venter et al., 2009). The predicted light curve morphologies are sensitively dependent on both the misalignment between the spin and magnetic axes of the neutron star ($\alpha$) and the viewing angle ($\zeta$) between the spin axis and the line of sight. Without a priori knowledge of these angles, it can be hard to discriminate among models based on light curve fits. However, if the angles can be constrained by other methods, such as radio polarization measurements or X-ray PWN geometry, the degeneracies can be broken. An important output of these model fits is the ‘flux correction factor’ $f_{\Omega}$, defined such that the true gamma-ray luminosity, $L_\gamma$ of a pulsar is

$$L_\gamma = 4\pi f_{\Omega} F_{\text{obs}} D^2,$$

where $F_{\text{obs}}$ is the observed gamma-ray flux and $D$ is the distance. In the EGRET era it was commonly assumed that $f_{\Omega} \sim 1/4\pi$, but current models predict values much closer to 1. This parameter is crucial for understanding the energetics of these systems and the efficiency ($\eta$) with which they convert rotational energy into gamma-rays. Recent model comparisons with a few LAT pulsar light curves (Romani & Watters, 2010) suggest that OG models with alternate field geometries are preferred in these cases. However, other objects may be consistent with lower altitude emission, and additional comparisons are needed to see if the data are consistent with emission beyond the light cylinder, as suggested by the force-free models. With many more high quality light curves being collected by the LAT, it should be possible to make powerful tests of these models, especially if when angle constraints from radio and X-ray observations are available.
9 Future Expectations

The next few years promise a continued stream of exciting pulsar results from the LAT. With the very reasonable assumption that the 18 new millisecond pulsars found in radio searches of LAT unassociated sources will all turn out to be gamma-ray pulsars, there will soon be more than 75 solid gamma-ray pulsar detections. This number is not totally unexpected, according to several pre-launch predictions. What is more surprising is that the population is divided into three essentially equal groups: young or middle-aged radio-selected pulsars, young or middle-aged gamma-ray selected pulsars, and millisecond pulsars.

Modeling the spectra, light curves, and population statistics of the LAT pulsars will be extremely important over the next few years to turn the powerful observations into improved understanding of the physical mechanism for pulsar gamma-ray emission. But, since this is a primarily observational review, we close with a few of the important observational questions that we expect to be addressed in the coming years.

- Are there radio quiet millisecond pulsars? This is both a great challenge for the observers and has very important implications for the emission mechanisms and geometry.
- If the ‘gamma-ray binaries’ LS I +61 303 and LS 5039 (see review in this volume \cite{Hill et al. (2010)}) are powered by energetic pulsars, can we detect the gamma-ray pulsations with the LAT?
- What are the non-detections of known pulsars telling us? While the new pulsar discoveries have grabbed most of the attention, it may be that one or more key non-detections will tell us something important about what drives gamma-ray pulsars. However, these studies are critically reliant on accurate distance determinations, so this is really a reminder that improved VLBA or timing parallax measurements for as many pulsars as possible will be of great value in increasing the science return from LAT pulsar studies.

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