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Gamma-ray pulsars in the *Fermi* LAT era

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Summary. — Observations over the past two years with the Large Area Telescope (LAT) onboard the *Fermi* Gamma-ray Space Telescope have led to a tenfold increase in the number of known γ-ray pulsars. Roughly one third of this population consists of young radio-loud pulsars, one third are radio-quiet pulsars discovered in blind searches of LAT data, and one third are γ-ray millisecond pulsars (MSPs). In this paper I discuss what we have learned about these three populations, as well as prospects for further discoveries.

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1. – Introduction

The phenomenal success of the *Fermi* Large Area Telescope (LAT) over the past two years is widely demonstrated by the tremendous progress made in the field of γ-ray pulsars; without any doubt we have entered a golden age in γ-ray pulsar astrophysics. This paper gives a brief summary of some of the highlights of this new *Fermi* LAT era, though given the limited space, it will hardly do justice to all the results presented. A slightly more extensive review can be found elsewhere [1], and throughout this paper I refer the reader to the refereed publications where the results are described in full detail. This review is organized as follows: I start with a brief history of γ-ray astronomy before the LAT, and summarize the status of our knowledge of γ-ray pulsars prior to the launch of *Fermi*. I then briefly describe the LAT instrument, pointing out the key advantages over its predecessors. The main part of the article focuses on the three populations of γ-ray pulsars being detected by the LAT. I begin with the young γ-ray pulsars found by folding LAT events with a known radio ephemeris. Next, I discuss the new pulsars discovered by the LAT in blind searches of the γ-ray data. The third type of pulsars are millisecond pulsars, some of which were known prior to the launch of *Fermi*, and others which have recently been discovered by radio telescopes targeting unassociated LAT sources. I conclude with a brief summary and an outlook for the future.

1·1. *Prior γ-ray missions.* – Three γ-ray satellites paved the way for *Fermi*. The first of these, NASA's Second Small Astronomy Satellite (SAS-2), was launched in November 1972 and collected $\sim$ 10000 (20 MeV–1 GeV) photons in approximately six months of operations. Among its successes was the discovery of the first unidentified γ-ray source, later known as Geminga [2]. The European satellite, COS-B, launched in 1975, collected $\sim$ 200000 (2 keV–5 GeV) photons in its more than six years of operations. COS-B produced a catalog of 25 γ-ray sources, of which 21 were unidentified [3]. Finally, the EGRET instrument, onboard NASA's *Compton Gamma-Ray Observatory* (CGRO), collected $\sim$ 1.5 million (30 MeV–10 GeV) events between April 1991 and June 2000, producing a wealth of results, including a catalog of 271 sources [4], of which more than half remained unidentified at the time of the launch of *Fermi* (née GLAST), in June 2008.

1·2. *γ-ray pulsars in the year 2000.* – CGRO was deorbited in June 2000, and until the launch of AGILE and GLAST, provided the best data on γ-ray pulsars. Six pulsars were firmly detected by EGRET (Crab, Vela, Geminga, PSR B1055–52, PSR B1706–44, and PSR B1951+32), and one more, PSR B1509–58, was detected at lower energies by COMPTEL. A few others were detected with marginal significance, including a millisecond pulsar. Only one pulsar, Geminga, was radio quiet, and predictions of the number (and type) of pulsars the LAT would detect varied widely. For a review of the observations of γ-ray pulsars at the end of the EGRET era, see [5]. While it was thought that a large number of unidentified EGRET sources (especially along the Galactic plane) could be pulsars [6], and a few pulsars were indeed discovered in radio searches of the EGRET error circles (*e.g.* [7]), the insufficient sensitivity of EGRET, and its poor angular resolution, resulted in the majority of the EGRET sources remaining unidentified, making their identification one of the primary goals of the GLAST mission.

1·3. *The Fermi Large Area Telescope.* – The LAT is the primary instrument onboard the *Fermi* Gamma-ray Space Telescope. It is a pair-conversion telescope that consists of a silicon tracker, sitting on a cesium iodide calorimeter, each made of 16 modules arranged in a 4×4 array, covered by a segmented anticoincidence detector. The key advantages of the LAT, compared to EGRET, are a larger field of view ($\sim$ 2 sr), larger effective area (9500 cm^2, at 1 GeV, normal incidence), a better point spread function ($\sim 0.6°$ at 1 GeV), much broader energy range (from 20 MeV to $>$ 300 GeV), and a significantly shorter deadtime. In addition, the LAT operates in continuous sky survey mode, making a more efficient use of its time in orbit. For a detailed description of the LAT, see [8].

2. – The Pulsar Timing and Search Consortia

Prior to *Fermi*, all γ-ray pulsars were first discovered in other wavelengths (mostly radio, except for Geminga, which was discovered in X-rays(1)). The γ-ray pulsations were subsequently obtained by folding the photons with the known timing solution. Recognizing the importance of contemporaneous radio and X-ray observations of pulsars in the *Fermi* era, the Pulsar Timing Consortium was set up, between the LAT Collaboration and observers using the largest radio telescopes in the world, and RXTE, with the goal of timing nearby energetic pulsars, to enable the detection of γ-ray pulsations with the LAT [9]. Similarly, the Pulsar Search Consortium was set up after the *Fermi* launch,

(1) Although it could have been discovered in blind searches of EGRET γ-ray data [19].

between essentially the same group of radio astronomers(²) and members of the LAT Collaboration, with the somewhat different goal of searching for radio pulsations from LAT-discovered pulsars, as well as for new radio pulsars in LAT unassociated sources.

3. – Young radio-loud gamma-ray pulsars

3·1. *The EGRET pulsars as seen by the LAT*. – Before discussing any new pulsars detected by the LAT, it is important to highlight some results from LAT observations of the so-called EGRET pulsars. Because these pulsars are so bright, and the LAT sensitivity so much greater than that of EGRET, these observations offer a great opportunity to study features of the pulsar light curves and spectra that were until now unimaginable. The huge number of photons collected in LAT observations of Vela [10, 11], allow us to see some exquisite details, as well as to extend the detection of pulsed emission up to at least 20 GeV, while at the same time detecting a third peak in the pulse profile which was hitherto unknown, and which has an evolution with energy that is markedly different to the other two peaks, hinting at an origin in a different part of the magnetosphere. Observations of the Crab pulsar [12], with the improved timing resolution of the LAT, make it possible to determine that the γ-ray peak leads the radio peak by $281 \pm 12 \pm 21\,\mu$s, whereas it was previously thought that the two peaks were aligned [12]. LAT observations of Geminga [13], and of the three remaining EGRET pulsars [14] similarly illustrate the enormous leap in capabilities of the LAT, allowing, thanks to the increased statistics, phase-resolved spectral analyses to be carried out.

3·2. *Young gamma-ray pulsars found using ephemerides*. – As of the time of this conference(³) there were 22 new young *radio selected* γ-ray pulsars detected by the LAT (not counting the EGRET pulsars). Early detections included some bright γ-ray pulsars, such as PSRs J1048–5832 and J2229+6114 [15]. In the case of J1048–5832, the LAT detection confirmed a previous claim of a marginal detection with EGRET [16]. More recently, the LAT has detected the highest B-field γ-ray pulsar so far, J1119–6127, with an implied surface magnetic field of $\sim 4 \times 10^{13}$ G [17].

4. – Blind-search pulsars

The sparseness of gamma-ray data makes traditional FFT searches computationally expensive. A new method, based on taking time differences of events was devised [18] and demonstrated to work very effectively on EGRET data [19]. The application of the time differencing technique on LAT data has been one of the early successes of *Fermi*.

4·1. *Gamma-selected pulsars in blind searches*. – Following the discovery of the first 16 γ-ray pulsars found in blind searches of LAT data [20], an additional 8 pulsars were found using one year of data [21]. A large number of these LAT-discovered pulsars (13 of the first 16) had a corresponding EGRET source, thus at least partly solving the problem of EGRET unidentified sources. Some of these sources had been the object of deep searches (both in radio and X-ray) and were sometimes even expected to harbor radio

(²) Telescopes used by the Pulsar Timing and/or Search Consortia: Arecibo (US/Puerto Rico), Effelsberg (Germany), GBT (US), GMRT (India), Jodrell Bank (England), Nançay (France), and Parkes (Australia). In addition, RXTE is used for timing certain X-ray pulsars.
(³) 8–10 September 2010.

quiet pulsars; such was the case of 3EG J1835+5918, the brightest unidentified EGRET source off the Galactic plane, affectionately known by some as the *Next Geminga*, and now shown to contain the fairly old ($\tau \sim 1.8$ million years) PSR J1836+5925 [22]. Many of the pulsars found in LAT blind searches are associated with previously known supernova remnants (SNRs) or pulsar wind nebulae (PWNe). The discovery of many of these pulsars by the LAT not only ends some long-running searches for individual "missing" pulsars, but also improves our understanding of such systems and ultimately will result in a more complete census of the neutron star population in our Galaxy.

4˙2. *Multiwavelength connections*. – As discussed in sect. **2**, in order to search for possible radio pulsations from LAT-discovered pulsars, the Pulsar Search Consortium was set up between all the major radio telescopes and the LAT Collaboration. Deep searches of all 24 *gamma-selected* pulsars discovered by the LAT(4) resulted in only 3 radio detections [23, 24], meaning that approximately 50% of all young γ-ray pulsars detected by the LAT remain radio quiet, or at least radio faint. The very low radio flux ($\sim 3.4\,\mu$Jy) from PSR J1907+0602, detected in a long observation using the 305-m Arecibo telescope [24], suggests that maybe sometimes only a faint section of the radio beam sometimes could be crossing the Earth, blurring the distinction between the so-called radio loud and radio quiet pulsars; this means that future more sensitive radio telescopes may actually be able to detect radio pulsations from some of the pulsars currently classified as radio quiet.

X-ray observations have proven invaluable in the discovery and further study of LAT blind-search pulsars. In some cases, X-ray observations served to identify, *a priori*, likely PWNe being powered by a radio-quiet pulsar. This was the case for PSRs J0007+7303 (in CTA1), J1418–6058 (aka the *rabbit*), or J1809–2332 (aka *Taz*). In other cases, X-ray observations served, *a posteriori*, to refine the LAT timing solution, by providing a more accurate position of the likely counterpart. Such was the case for PSRs J0633+0632 and J1741–2054, where short (~ 5 ks) *Swift* observations were sufficient to reveal the likely X-ray counterparts [20].

A strong connection exists between GeV γ-ray pulsars detected by the LAT and TeV sources seen by ground-based Cerenkov telescopes. In a study of the TeV emission coincident with sources from the *Fermi* Bright Source List, the Milagro detector found a surprisingly high number of young LAT pulsars coincident with significant sources of emission (presumably from the PWNe) at TeV energies [25]. For example, the blind-search pulsar PSR J2032+4127 is coincident with TeV J2032+4130 (aka MGRO J2031+41), the first unidentified TeV source, originally discovered by the HEGRA experiment, about ten years ago [26]. In some cases, the discovery of an energetic γ-ray pulsar coincident with a TeV source can change the probable interpretation of the TeV emission. A case in point is PSR J1023–5746 (the most energetic γ-ray pulsar found in blind searches so far), coincident with HESS J1023–575. Originally, the TeV emission from this source was believed to be primarily due to colliding winds from massive stars, while the TeV PWNe interpretation now seems more likely [21].

(4) Not all LAT-discovered pulsars required new radio follow-up observations. For example, 3EG J1835+5925 had been searched deeply enough prior to the launch of *Fermi*, so that folding the radio data with the LAT timing solution already produced a very low upper limit on the radio pulsations of PSR J1836+5925 [22]. In the case of PSR J1741–2054, on the other hand, radio pulsations were detected in archival Parkes multibeam survey data from the year 2000 [23].

5. – Millisecond pulsars

5˙1. *Previously known millisecond pulsars*. – Aside from the marginal detection of PSR J0218+4232 with EGRET [27], millisecond pulsars were not known to be a class of γ-ray emitters prior to *Fermi*, so it was one of the early surprises when the LAT detected, within a few months, strong γ-ray emission from a population of MSPs [28]. Perhaps more surprising was the fact that both the light curves and spectra of these first 8 γ-ray MSPs resembled so much those of young γ-ray pulsars, indicating that the emission mechanism for both types of pulsars is likely to be the same. Following the initial detection of the first 8 MSPs with the LAT, γ-ray millisecond pulsars continue to be detected, including PSR J0034-0534, of particular interest due to the co-alignment of the radio and γ-ray peaks, suggesting that at least in some cases the two regions of emission might be co-located [29].

5˙2. *New millisecond pulsars in LAT sources*. – Perhaps a bigger surprise than the detection of γ-ray emission from MSPs was the discovery, in a matter of months, of $\sim$ 20 new radio MSPs in searches of LAT unassociated sources. Unlike in the case of EGRET, where the large positional uncertainty required numerous pointings with radio telescopes, LAT sources typically have error regions that are comparable in size to the radio beam. Initial searches with the GBT of promising bright unassociated sources from the Bright Source List uncovered the first three MSPs [30], followed in rapid succession by others found with the Nançay [31], and Parkes [32] radio telescopes. The discovery, in a relatively short time (under a year), of such a large number of MSPs outside of globular clusters illustrates the difficulty of finding these pulsars in standard radio surveys. Unlike young pulsars, MSPs are distributed isotropically in the sky and therefore are harder to find. This, perhaps, explains why some of the extremely bright MSPs being discovered thanks to *Fermi*, would have been missed. It is also encouraging to note the apparent lack of correlation between the γ-ray and radio fluxes of these pulsars, suggesting that additional MSP discoveries can be expected as fainter LAT unassociated sources are searched [30]. Because these radio MSPs were discovered by pointing at LAT sources, it is also reasonable to expect that most of these will eventually turn into γ-ray pulsars too, and in fact that has already turned out to be the case for at least seven of them [30-32].

6. – Conclusions and future prospects

The enormous progress made by *Fermi* in the field of γ-ray pulsars is attested to by the fact that the discovery of new pulsars with the LAT was considered the runner-up scientific breakthrough of 2009 by the journal Science [33]. While the results so far have been impressive, the prospects for future discoveries with the LAT remain just as exciting. In addition to finding increasing numbers of γ-ray pulsars, there are different types of pulsars yet to be fully explored by the LAT: high B-field pulsars, young binary pulsars, and maybe even radio quiet millisecond pulsars. In addition to this, the increase in statistics will no doubt result in more precise measurements of the relevant parameters of each and every pulsar detected by the LAT. Work has already begun towards the generation of a second *Fermi* LAT pulsar catalog, which will contain approximately twice the number of pulsars contained in the first pulsar catalog and will provide an unprecedented level of detail for theorists and modellers to measure their predictions against.

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