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Latest results on gamma-ray pulsars with *Fermi*

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Summary. — The *Fermi* Large Area Telescope (LAT) has been scanning the gamma-ray sky since 2008. The number of pulsars detected by the LAT now exceeds 200, making them by far the largest class of Galactic gamma-ray emitters. I will present some of the latest pulsar discoveries made by the LAT, describe the properties that make some of these systems unique and discuss them in the context of current pulsar emission models.

1. – Gamma-ray pulsars pre-*Fermi*

Gamma-ray astronomy has a long history, going back to the 1960s. In the 1990s, the Energetic Gamma Ray Experiment Telescope (EGRET), on board the *Compton Gamma-Ray Observatory* (CGRO(1), 1991–2000), detected almost 300 gamma-ray sources, a majority of which were unidentified [1]. The seven gamma-ray pulsars detected by CGRO (6 by EGRET, and PSR B1509–58 by COMPTEL), shared many characteristics (*e.g.* young and highly energetic, mostly double-peaked) but also covered various categories: *radio-loud*, *radio-quiet* (Geminga), *soft* (MeV), but the somewhat limited statistics (particularly above 5 GeV), made it challenging to discriminate between the leading pulsar emission models [2]. For a review of the EGRET era results, immediately preceding the launch of *Fermi*, see [3].

2. – The *Fermi* era

The *Fermi* gamma-ray space telescope, launched on 11 June 2008, is a giant leap forward for gamma-ray astronomy. The Large Area Telescope [4] (LAT), the main instrument on *Fermi*, uses silicon strip detectors (far superior to the old gaseous detectors),

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(1) The second of NASA's great observatories.

making it the most sensitive instrument in the ∼0.5–300 GeV energy range for the foreseeable future. Indeed, the LAT recently detected its billionth gamma ray (∼1000 times the number of gamma rays detected by EGRET in its lifetime) and is showing no signs of aging. Not surprisingly, *Fermi* quickly made a big impact in many areas, and pulsars in particular, for example uncovering a large population of *radio-quiet* gamma-ray pulsars hiding among the *previously unidentified* EGRET sources [5,6]. The most recent catalog released by the LAT Collaboration, the Third LAT source catalog (3FGL), contains over 3000 sources, of which approximately one third are *unassociated* [7]. Uncovering the nature of LAT *unassociated* sources is (and will remain for many years) a key pursuit for the gamma-ray (and broader) astrophysics community. In this context, a number of statistical methods (*e.g.* machine learning techniques, neural networks), in combination with multi-wavelength follow-up observations are helping to identify the likely nature of many of these sources [8,9]. For a detailed review of the "Gamma-ray Pulsar Revolution", see [10].

2˙1. *Recent pulsar results with Pass 8*. – The event selection algorithms developed for the LAT are the result of a long, iterative process, with the various releases known as *Passes*. *Pass 6* data were publicly released after launch but based only on *pre-launch* information. *Pass 7* data, released in August 2011, incorporated knowledge gained from the first few years in orbit. The *Pass 8* release represents a complete redesign of every aspect of the event selection, leading to a significant increase in effective area, an improvement in the point-spread function, and a reduction in background contamination [11]. Because every *Pass* results in the entire *Fermi* data (from the beginning of the mission) being reprocessed, the release of *Pass 8* produced scientific results immediately after its release, without the need to wait for *additional* data.

A significant number of known pulsars suddenly showed gamma-ray pulsations with *Pass 8*, despite being previously undetected [12]. The *Pass 8* data also improved significantly the sensitivity of LAT blind searches for pulsars. The Einstein@Home survey, for example, recently reported 17 new (mostly radio-quiet) gamma-ray pulsars [13]. The number of gamma-ray pulsars detected by *Fermi* (now over 200) continues to increase, with the rate of discovery showing no signs of tapering off(2). Interestingly, millisecond pulsars (MSPs) represent roughly half the entire gamma-ray pulsar population, with some of them meeting the stringent criteria to be added to the pulsar timing arrays, thus aiding in the search for graviational waves [14]. One of the most interesting new gamma-ray pulsars detected by the LAT is PSR J0540–6919, in the Large Magellanic Cloud (LMC), located at ∼50 kpc, making it the first extra-Galactic gamma-ray pulsar (and hence the most distant) ever detected [15]. Curiously, PSR J0537–6910, also in the LMC and with very similar characteristics, still shows no gamma-ray pulsations.

2˙2. *Gamma-ray binaries with Fermi*. – Another gamma-ray source in the LMC that has recently attracted a great deal of attention was first identified, rather mundanely, as P3 [16]. This source turns out to be a gamma-ray binary with a 10.3 day orbital period, as confirmed also by radio and X-ray observations [17]. Coming over four years after the discovery of 1FGL J1018.6–5856 (J1018), the first gamma-ray binary discovered by *Fermi* [18, 19], this new gamma-ray binary broke several records

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(2) `https://confluence.slac.stanford.edu/x/5Jl6Bg`

(most luminous gamma-ray binary, first extra-Galactic gamma-ray binary), and like J1018, is likely powered by an energetic pulsar [17].

While many (if not most) gamma-ray binaries are thought to contain pulsars, in most cases the pulsar has eluded detection (*e.g.* LSI+61°303, LS 5039). In one recent case, however, the pulsar (J2032+4127) was discovered *first*, while the binary nature of the system was uncovered subsequently. When first discovered in a blind search by *Fermi*, PSR J2032+4127 was thought to be an isolated gamma-ray pulsar [5]. Long-term timing in radio, however, reveals it to be in a binary system with a very long ($\sim$decades) orbital period [20]. Recent multi-wavelength monitoring observations report an increase in X-ray emission from the system (by a factor of $\sim$20 since 2010 and a factor of $\sim$70 since 2002) and refined its orbital period to be 45–50 yr, with its time of periastron predicted to be in November 2017 [21].

The LAT has also been very successful at finding the so-called "black widow" or "redback" systems: eclipsing binary millisecond pulsars *eating* away their low-mass companion star, with their radiation beams. Some of these systems are first identified through their multi-wavelength emission, such as the case of 0FGL J2339.8–0530 [22]. Radio follow-up searches in this case revealed a pulsar [23] and gamma-ray pulsations were also detected(3). Long-term gamma-ray timing of PSR J2339–0533 recently revealed dramatic orbital-period modulations ascribed to a change in the gravitational quadrupole moment [24]. Due to the eclipsing nature of these systems, radio non-detections are frequent, making gamma-ray searches complementary. Indeed, in one case, the pulsar was discovered in gamma rays first [25], with radio pulsations coming later [26]. A number of redback candidates have been identified (*e.g.* 3FGL J2039.6–5618 [27,28], 3FGL J0212.1+5320 [29,30]) and searches for these pulsars are ongoing.

2˙3. *Variable and transition gamma-ray pulsars*. – Until recently, gamma-ray pulsars were thought to be *steady* sources(4). The long-term monitoring of large numberes of pulsars over a period of years, however, has started to reveal more complicated behavior in some sources. PSR J2021+4026, a bright, *radio-quiet* gamma-ray pulsar discovered by *Fermi* early on in the mission [5] experienced an abrupt drop in flux of $\sim$20%, associated with a $\sim$4% increase in spindown rate, also accompanied by changes in the pulse profile, making this the first known variable gamma-ray pulsar [31]. The most recent observations appear to show that the flux of J2021+4026 has now gone back to its original values [32].

An even more dramatic transition was detected in PSR J1023+0038, the so-called "missing link" pulsar known to have previously been in a Low Mass X-ray Binary state, subsequently switching to a rotation-powered state. Recently, this system experienced new state transition, with a five-fold increase in gamma-ray flux accompanying the disappearance of the radio pulsations [33].

Another pulsar that has benefitted from the long-term monitoring capabilities of the LAT is PSR J1119–6127 [34]. This young, energetic pulsar associated with supernova remnant G292.2–0.5 has an extremely large inferred surface magnentic field ($\sim 4\times10^{13}$G), and was detected as a gamma-ray pulsar early on by the LAT [35]. Recently, the *Fermi* GBM [36] and *Swift* [37] detected a series of strong SGR-like bursts, followed by hard X-ray pulsations [38], in conjunction with a large spin-up glitch [39]. Radio pulsations

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(3) See talk by A. Belfiore at the 2013 Aspen Meeting on Physical Applications of Millisecond Pulsars, `http://aspen13.phys.wvu.edu/aspen_talks/Belfiore_Gamma_Ray_Searches.pdf`

(4) In fact, a key characteristic distinguishing pulsars from AGN is precisely the *low variability*.

disappeared [40], reappearing two weeks later [41]. Unfortunately, despite a one-week LAT Target of Opportunity (TOO) pointed observation (increasing the exposure by a factor of $\sim$2.4), no significant changes in gamma-ray flux were detected [42], and no significant pulsations were detected post-burst [43].

Finally, the recent possible detection of pulsed *soft* gamma-ray emission from PSR J1846–0258 (up to 100 MeV) is of great interest [44]. This pulsar shares many similarities with PSR J1119–6127: large magnetic field and past *magnetar-like* bursts following a large glitch. Thus, it represents another possible “transition” pulsar, making it a worthwhile target to monitor, going forward.

3. – Conclusions

Since its launch, almost nine years ago, *Fermi* has produced a long list of discoveries in the field of gamma-ray pulsars. More surprisingly, the rate of these discoveries does not appear to be slowing down. *Fermi* continues to detect new pulsars in every category: young, MSPs, radio-loud, radio-quiet, etc. Finally, the longer data sets and the development of *Pass 8* are now enabling *Fermi* to delve deeper into new parameter space, revealing a range of *variability* in gamma-ray pulsars that was hitherto unknown.

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