DISCOVERY OF A POPULATION OF GAMMA-RAY MILLISECOND PULSARS BY FERMI

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We report the discovery of pulsed gamma-ray emission from the 4.86 ms pulsar PSR J0030+0451 with the *Fermi*-LAT telescope. This detection makes PSR J0030+0451 the first to be firmly detected in gamma-rays, after the weak detection of PSR J0218+4232 by EGRET. This very old pulsar (characteristic age of 7.6 10^9 yrs) lowers the empirical spin-down energy lower bound of previously known gamma-ray pulsars by an order of magnitude, with an $\dot{E}$ of 3.5 10^{33} erg/s. The emission profile is reminiscent of younger gamma-ray pulsars, with two sharp peaks, separated by 0.4, and the first peak lagging the radio one by 0.1. The latest weeks of *Fermi*-LAT data though showed that not only do we firmly detect PSR J0030+0451 and confirm PSR J0218+4232, but we also detect pulsations from several other millisecond pulsars. We will review their gamma-ray characteristics and discuss which millisecond pulsars we are seeing. Finally we will discuss the emission of gamma-rays from globular clusters, where millisecond pulsars are known to be abundant.

1 Introduction

1.1 Millisecond pulsars ?

Millisecond pulsars (MSPs) are neutron stars in extremely fast rotation ($P \leq 30$ ms) and with small period derivatives ($\dot{P} \leq 10^{17}$ s/s). Roughly 10% of the pulsars listed in the ATNF catalogue [a] are MSPs [1], located at the lower-left corner of the classical $P - \dot{P}$ diagram [2]. Their high rotational rate is thought to have been acquired by accretion of matter and hence angular momentum from a binary companion [3]. Most MSPs are indeed in binary systems, while less than 1% of normal pulsars are. From the simple description of pulsars as magnetic dipoles in rotation, we know that MSPs are old stars, having characteristic spin-down ages $\tau = P/(2\dot{P})$ of the order of (0.1 - 10) $\times$ 10^9 yrs. Their characteristic surface dipole magnetic fields $B_{surf} \simeq 3.2$

[a] Available at http://www.atnf.csiro.au/research/pulsar/psrcat/expert.html

$\times\ 10^{19}\ \sqrt{P\dot{P}} < 10^{10}$ G are lower than for the normal population of pulsars, yet the magnetic field strength at the light cylinder $B_{LC} = B_{surf} \times \left(\frac{2\pi R}{cP}\right)^3$ is comparable. Furthermore, the so-called spin-down luminosity $\dot{E} \propto \dot{P}/P^3$ which represents the power output of the pulsar through electromagnetic braking, and hence the available power to be emitted from radio wavelength to gamma-rays, is comparable for MSPs and the normal population of pulsars.

1.2 MSPs at high energy

Of the nearly 170 known MSPs with $P < 30$ ms, 41 are detected as point X-ray sources, including 10 pulsed detections [4]. Although normal pulsars are much more numerous than MSPs, the number of detections reported by the different X-ray telescopes among the two populations is actually equivalent. Before the *Fermi* Gamma-Ray Telescope (FGST) was launched in June 2008, only young pulsars had been detected in gamma-rays [5], though marginal pulsations from PSR J0218+4232 in the EGRET had been reported [6]; and the various theoretical models of gamma-ray emission from pulsars predicted that some MSPs should be detectable by the *Fermi* Large Area Telescope (LAT) [7,8]. A lot of questions thus had to be answered by the LAT: *do MSPs emit gamma-rays? If they do, are the mechanisms of emission the same as for normal pulsars? Are they bright sources of gamma-rays?*

2 A search for gamma-ray MSPs with *Fermi*

2.1 The Large Area Telescope (LAT) and pulsars

The LAT on the *Fermi* spacecraft (formerly GLAST) began operating in June 2008 [9]. In brief, gamma-rays entering the LAT are converted to e^+/e^- pairs in a tracker, yielding direction information. Below the tracker is the calorimeter, giving access to the energy of the incident photon. The LAT is surrounded by an anticoincidence detector, which helps reject the charged cosmic-ray background. The LAT is sensitive to photons with energies below 20 MeV to over 300 GeV. The effective area of 8000 cm^2 at 1 GeV, the angular resolution (0.5° of 68% PSF containment at 1 GeV), the scanning observing mode and the small trigger deadtime of 26.5 μs make the LAT much more sensitive than EGRET. In addition, the timing chain from the GPS-based satellite clocks to the pulsar phase-folding software have been shown to be accurate to a few μs, which is crucial for long-term studies of MSPs [10,11].

Gamma-ray photon data are sparse: the Vela pulsar, which is the brigthest steady source of gamma-rays, triggers the LAT once every 4 minutes on average in survey operation mode. Detecting pulsars in gamma-rays therefore requires weeks to months of continuous observation; representing billions of rotations for MSPs. Accurate knowledge of rotational phase as a function of time is thus essential. We hence began a comprehensive campaign of pulsar timing observations with different radio telescopes around the world, as well as X-ray telescopes [10]. This campaign provided accurate timing for hundreds of pulsars, including MSPs, thought to be promising sources of gamma-ray emission. MSPs are stable pulsars compared to their "normal" cousins, which are usually affected by rotational instabilities (glitches, timing noise). For MSPs, the pulsar timing campaign enabled μs precision of the knowledge of the rotational phase during LAT observations.

2.2 PSR J0030+0451: first firm detection

The 4.86 ms nearby isolated millisecond pulsar J0030+0451 turned out to be the first firm detection ever of an MSP in gamma-rays [12]. The gamma-ray data was acquired during the first months of the *Fermi*'s first-year all-sky survey, from August 3 to November 2. The pulsar is

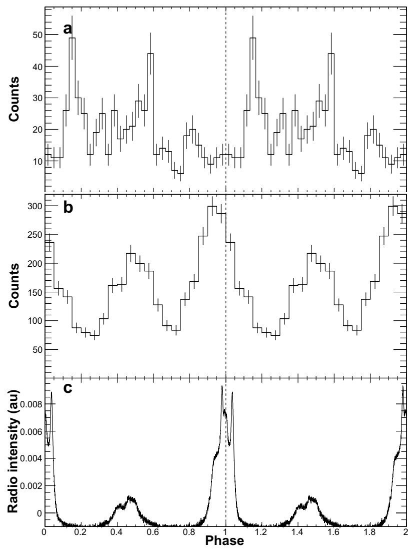

Figure 1: Multi-wavelength phase histograms of PSR J0030+0451. Two rotations are shown for clarity. a: Gamma-ray phase histogram over 100 MeV within an energy dependant ROI. Each bin is 160 μs. b: 20 bin 0.3 - 2.5 keV XMM-*Newton* light curve. c: 1.4 GHz radio profile recorded at Nançay.

outside the Galactic plane ($b = -57.6°$) and is hence in a zone of low background. We phase-folded the 563 events recorded in an energy-dependent region of interest (ROI) using high-quality radio ephemerides (rms of 4 μs) derived from seven hundred Nançay radiotelescope observations between July 1999 and November 2008. The resulting gamma-ray phase histogram is shown in Figure 1. Also shown is the XMM lightcurve that we obtained using the same ephemeris, yielding the first absolute phase alignment of radio, X-ray and gamma-rays for this pulsar. The X-ray and radio components are phase aligned, indicating that these emissions have a common origin in the magnetosphere. Conversely to what we see in X-rays, the gamma-ray profile is shifted by $\delta = 0.15$ relative to the radio; and shows two narrow peaks, separated by $\Delta = 0.44$, similarly to what is seen for normal gamma-ray pulsars, such as Vela, or B1951+32 [5]. The misalignment supports the idea that gamma-rays are produced in a different zone of the magnetosphere, as is assumed by *e.g.* Outer-Gap models [8].

A fit of the emission spectrum with an exponentially cutoff power-law of the form $\frac{dN_\gamma}{dE} = N_0 \left(\frac{E}{10^3 \text{ MeV}}\right)^{-\Gamma} e^{-E/E_c}$ where N_0 is a normalization factor, Γ is the spectral index and E_c is the energy cutoff yields $\Gamma \simeq 1.4$, $E_c \simeq 1.7$ GeV. Integrating over 100 MeV, this leads to photon and energy fluxes of 6.8 $\times 10^{-8}$ ph cm^{-2} s^{-1} and 4.9 $\times 10^{-11}$ ergs cm^{-2} s^{-1} respectively. The spectral properties of PSR J0030+0451 in gamma-rays do not differ fundamentally from what was previously seen for normal pulsars. However, with a spin-down luminosity $\dot{E}$ of 3.5 $\times 10^{33}$ erg/s, this pulsar lowers the empirical $\dot{E}$ threshold for gamma-ray emission by an order of magnitude, compared to PSR B1055−52 seen by EGRET [13]. In addition, PSR J0030+0451 seems to break from the trend noted for EGRET pulsars, for which the gamma-ray luminosity is in good approximation inversely proportional to $\sqrt{\dot{E}}$. However this trend is expected to saturate for low $\dot{E}$ pulsars, as they can not convert more than 100% of their spin-down luminosity into gamma-ray emission.

2.3 A whole population of gamma-ray MSPs

Two months worth of data later, PSR J0030+0451 was no longer the only gamma-ray MSP: a comprehensive search for pulsations in the LAT data from 72 galactic field millisecond pulsars

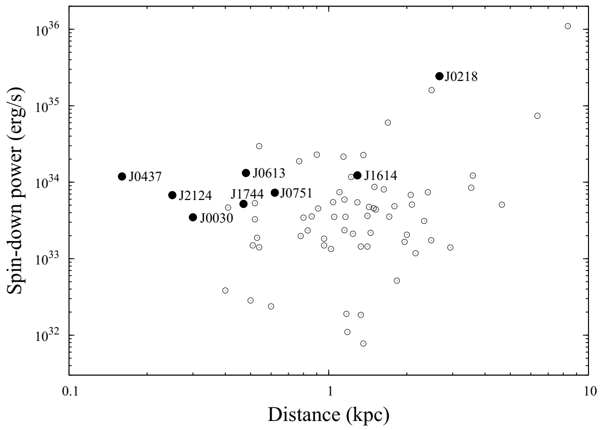

Figure 2: Spin-down luminosity $\dot{E}$ as a function of the distance for the known galactic field millisecond pulsars. Filled dots indicate pulsed gamma-ray detections. When available, parallax distances are used instead of Galactic electron density based distances.

Table 1: Galactic coordinates (l,b), rotational period P, distance D and spin-down luminosity $\dot{E}$ for the detected millisecond pulsars, as of January 2009.

JName	l (°)	b (°)	P (ms)	D (kpc)	$\dot{E}$ (10^{33} erg/s)
J0030+0451	113.1	-57.6	4.865	0.3	3.5
J0218+4232	139.5	-17.5	2.323	2.7	244
J0437−4715	253.4	-42.0	5.757	0.16	11.9
J0613−0200	210.4	-9.3	3.062	0.48	13.2
J0751+1807	202.7	-21.1	3.479	0.62	7.3
J1614−2230	352.54	20.30	3.151	1.29	12.3
J1744−1134	14.8	9.2	4.075	0.47	5.2
J2124−3358	10.9	-45.4	4.931	0.25	6.8

(that is, outside of globular clusters), again based on accurate pulsar ephemerides, led to the discovery of a whole population of pulsed gamma-ray emitters [14]. We confirmed the low-confidence EGRET detection of PSR J0218+4232 [6], a 2.32 ms pulsar in a binary orbit, relatively distant (2.7 kpc) but with a high $\dot{E}$ of 2.4 × 10^{35} erg/s, among the highest of MSPs. We also detected PSR J0437−4715, a nearby MSP in a binary orbit, searched in gamma-rays during the EGRET era, with negative results [15]. In total, we have discovered 8 MSPs in the first 6 months of LAT observations. Figure 2 shows the spin-down luminosity $\dot{E}$ as a function of the distance for the detected MSPs. Table 1 lists some of their properties.

The 8 pulsed detections, shown by filled dots in Figure 2, tend to group towards large values of the so-called spin-down flux $\dot{E}/D^2$, as expected: pulsars with high $\dot{E}$ are likely to convert more energy loss rate into gamma-ray emission. However, it is clear that some of the high $\dot{E}/D^2$ pulsars shown in this plot are missed, which can be interpreted in different ways. First, parallax distances are available for a small number of MSPs, so that distances are often calculated using the NE2001 model of Galactic electron distribution [16], which has proved to be inaccurate in some cases: for example, parallax measurements for J0613−0200 lead to $D = 480^{+190}_{-110}$ pc [17], whereas the NE2001 model gives $D = 1.7$ kpc. Second, the effective detectability of the pulsar in gamma-rays is highly dependent on the viewing geometry: depending on the inclination of the magnetic axis relative to the rotation axis (angle α) and on the inclination of the observer's line-of-sight relative to the rotation axis (angle ζ), the pulsar may radiate little gamma-ray flux towards the observer, if at all [18].

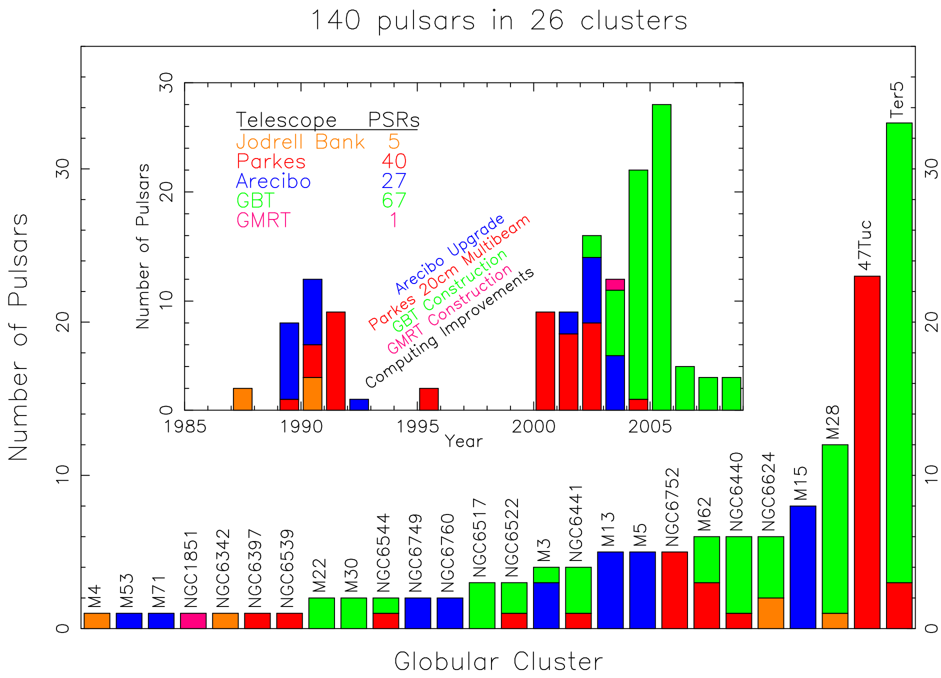

Figure 3: Number of known pulsars in globular clusters, and number of discoveries per year. Courtesy: Scott Ransom (see http://www.naic.edu/ pfreire/GCpsr.html)

3 Prospects

As the LAT continues to accumulate gamma-ray photons in the months to come, the sample of detected gamma-ray MSPs should increase, revealing high $\dot{E}/D^2$ pulsars with unfavourable geometrical configurations or conversely farther and less energetic pulsars with gamma-ray beams pointed towards the Earth. A larger sample of detections should help constrain how MSPs accelerate charged particles to high energies in their magnetosphere, and how MSPs differ from the normal population. Current analyses show that MSP spectral shapes resemble those of young pulsars [14]. In support of gamma-ray observations, precise distance measurements may enhance the interpretation of observed gamma-ray fluxes as well as the non-detections. Polarization observations, which give access to the configuration angles α and ζ, might also help understand which geometrical configurations are preferred for detection, and which ones are not.

In addition to the known galactic field millisecond pulsars, more than 100 MSPs are known in 26 globular clusters [19]. Figure 3 shows the number of known pulsars in globular clusters. The LAT has already detected steady emission from the globular cluster 47 Tuc [20], which is known to contain at least 23 MSPs. There are hence prospects that the LAT may see pulsations from individual MSPs in globular clusters. Finally, the discovery of a whole population of gamma-ray emitting millisecond pulsars strongly suggests that there must be unknown pulsars among the unidentified gamma-ray sources, such as in the *Fermi* Bright Source List [21], that could be searched for pulsations in radio wavelengths.

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