Gamma-Ray Pulsars Discovered by Blind Search with Fermi LAT

F. Giordano
For the Fermi LAT Collaboration
Department of Physics and INFN Sez. Bari

Just three months after launch, the Large Area Telescope (LAT) aboard the Fermi Gamma Ray Space Telescope is providing a new image of the gamma ray pulsar sky. The discovery of a new class of pulsating gamma ray emitters applying the blind period search technique is reported and discussed. These new pulsars are mostly coincident with previously unidentified EGRET gamma-ray sources, opening a new window in the studies of emission geometry, population studies and the connections with the surrounding environment

1 The EGRET heritage

Before the Fermi launch the telescopes on the Compton Gamma Ray Observatory [1] detected seven pulsating gamma ray emitters with very high confidence. In fig.1 the light curves of these seven gamma-ray pulsars are shown in five different energy bands from radio to optical, soft X-ray (<1 keV), hard X-ray/soft gamma ray (10 keV ÷ 1MeV), and hard gamma ray (above 100 MeV). Directly from the light curves of each pulsar in each energy bin some crucial aspects regarding the acceleration mechanisms and emission model can be interpreted. For example all the light curves of the Egret pulsars show a double peak feature, but not all seven are seen at the highest energies, as well as not all the seven pulsars display a clear radio pulsations like Geminga. Before Fermi, Geminga was the unique "radio-quite" known pulsar.

2 The Fermi Era

The Fermi satellite, consisting of the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT), was launched on 11 June 2008 into a low Earth circular orbit at an altitude of 550 km and an inclination of 28.5°. The LAT [2] is a pair-production telescope with large effective area (∼8000 cm^2) and field of view (2.4 sr), sensitive to gamma rays between 30 MeV and > 300 GeV. A The LAT began normal science operations on 11 August 2008, and since then has been observing mostly in survey mode, scanning the entire gamma-ray sky every three hours. The overall sensitivity of the LAT is about 25 times that of EGRET, while the angular resolution is also signicantly improved (it ranges from 3÷6° at 100 MeV to 0.1÷0.2° at 10 GeV). The mission was designed with a five year lifetime and a goal of at least ten years of operations. The scientic goals of the mission include understanding particle acceleration in Active Galactic Nuclei (AGN), pulsars, and supernova remnants (SNRs), exploring the high energy emission of Gamma-ray Bursts (GRB), and probing the nature of dark matter.

Although its commissioning phase (30 June to 30 July 2008) was primarily intended for instrument performance verification and calibration, important scientic results have been obtained

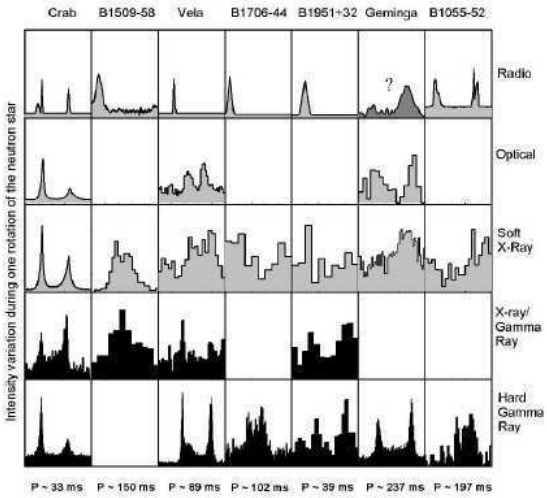


Figure 1: Light curves in different energy bands for the CGRO detected pulsars (from [1])

with these early data. The six Egret pulsars have been confirmed just during the early phase of the mission. Vela, Crab and Geminga was detected in only 15days, while the other three weaker Pulsars, the B1951+32, the B1706-44 and the B1055-52 was detected in 25 days, still during the commissioning of the mission. Moreover, after only three months of sky survey, the Fermi LAT was capable not only to confirm the 6 known Egret pulsars but also to discover 10 radio loud young galactic pulsars, 7 new ms pulsars, and 13 new $gamma - ray\ selected$ pulsars. Figure 2 shows how the Fermi pulsating gamma-ray sky looks like.

2.1 The Geminga Candidates

Radio campaigns have not always been capable to detect pulsation even from sources appearing positionally coincident with supernova remnants (SNR) or pulsar wind nebulae (PWN). Geometry consideration can explain the lack of radio pulsations from these potential pulsars, in particular in those cases where the narrow radio beams are expected to be not oriented close to the line of sight towards the Earth. According to current models of pulsar gamma-ray emission which predict a much wider gamma-ray beams than radio beams, a much larger population of potentially radio-quiet gamma-ray pulsars than the one observed is expected to be observed. A list of locations of potential pulsars which would have been investigated with the blind search was compiled almost immediately after launch. About 100 $Geminga-like$ sources was included in the list due to some peculiar features like the location in the Galactic plane, the spectral index and the emission cut-off or the lack of long-term variability as well as the presence of a very promising environment like pulsar wind nebula or SNRs. Many of these sources have been detected by EGRET, and have also been investigated in other wavelengths. Moreover, Fermi was able to detect 205 bright sources [3] in the first three months of sky survey; these sources have also been included in the $Geminga-like$ list, rejecting those clearly associated with Active Galactic Nuclei (AGN).

2.2 The Blind Period Search

Even with the advantages of the LAT in terms of field of view and timing capabilities, gamma-ray photon data are extremely sparse. For example, for the Vela pulsar, which is the brightest

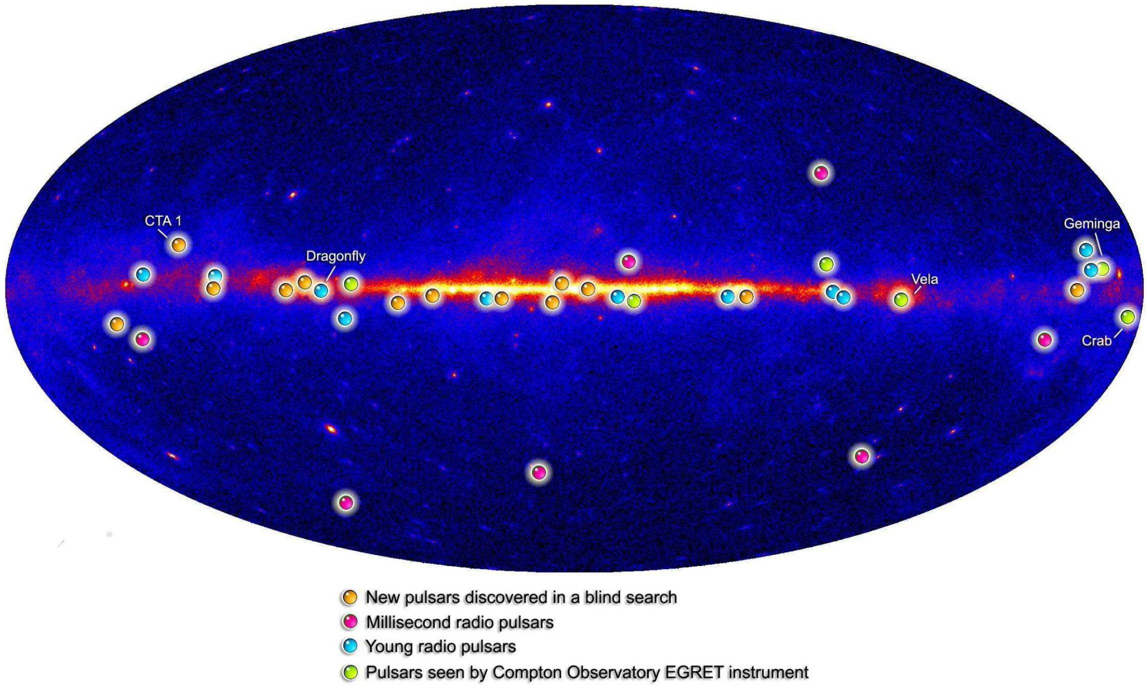


Figure 2: The Fermi pulsating gamma ray sky.

gamma-ray source in the sky, we have fewer than one photon every 4 minutes in the LAT. As a result, the detection of gamma-ray pulsations requires the accumulation of weeks or months of data. Because there is no a priori knowledge of the frequencies of any pulsars in the $Geminga - Candidates$ list, a blind frequency search over a broad range of frequencies and frequency derivatives needed to be performed. To discover a gamma ray pulsation two techniques are mostly used: the first is called epoch folding, which uses information from the ephemeris coming from other wavelengths observation. The second method uses fully coherent FFT. In a FFT the number of frequency bins increases with the length of the observational time and due to the spinning down of a pulsar which radiate away energy, in order to have a realistic scan over a frequency and frequency derivative parameter space tens of thousands FFTs need to be performed. For these reasons a fully coherent FFT is very CPU consuming and computationally intensive. An alternative method that uses truncated time differences to allow sensitive searches of sparse gamma-ray data with modest computational requirements was developed[4]. This $time - differencing$ technique was implemented and used obtaining a great simplification of the computational burden simply using a fixed coherency window of 1 week (T = 21952 s) and, despite the reduced frequency resolution due to a lower number of bins, the sensitivity is not much reduced because of a compensating reduction in the number of ferquency derivative trials

2.3 The Blind Period Pulsars

The first major Fermi discovery in blind search was the detection of the pulsation from CTA 1[6]. This young, nearby, shell-type SNR was discovered in radio in the 1960s and X-ray observations show a well-localized central point source, RXJ0007.0+7303, embedded in a pulsar wind nebula (PWN)[7]. High energy (> 100 MeV) emission was detected by EGRET from 3EG J0010+7309, coincident with this source (see Figure 3). Moreover the period measurement and the derivative, about 315.9ms and 3.615×10^{-13} s s^{-1} respectively are very consistent with a typical young,

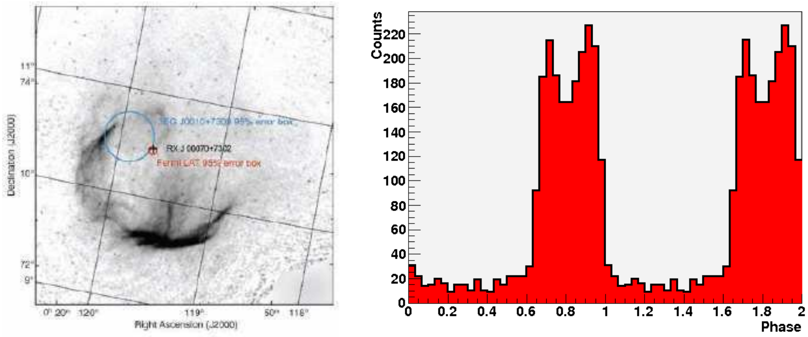


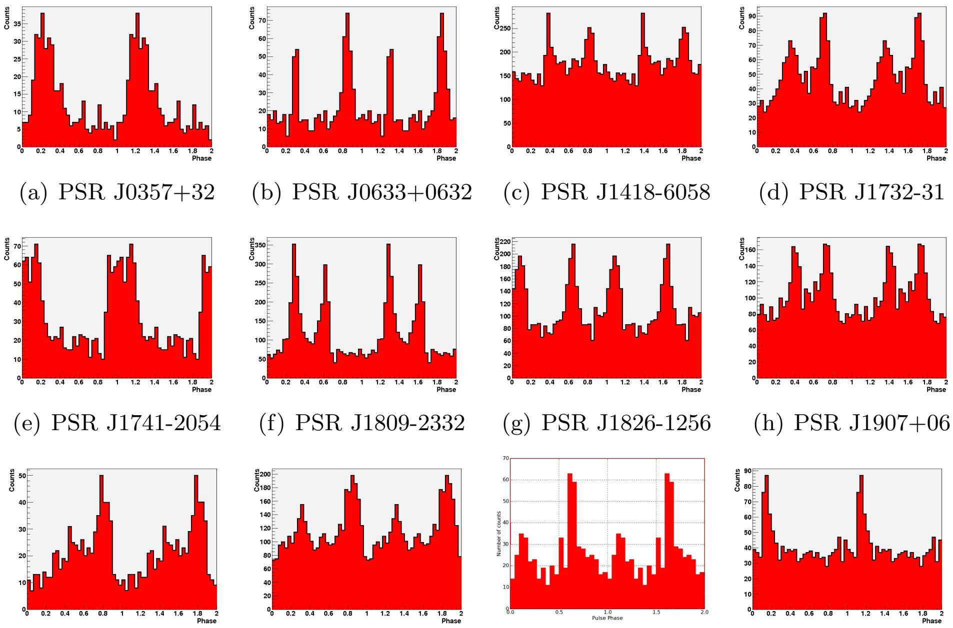
Figure 3: Left: LAT gamma-ray source location of CTA 1, superimposed on a 1420-MHz radio image of the CTA 1 SNR [6]. The red circle shows the Fermi-LAT 95% containment radius, while the cross represents the location of the X-ray point source. The large circle shows the corresponding EGRET 95% error circle . Right: Gamma-ray ($>$ 100 MeV) folded light curve of the CTA 1 pulsar shown with two periods of rotation [6].

energetic pulsar, with a characteristic age of 14,000 years (in agreement with the estimated age of the SNR) and a spin-down power of 4.5×10^{35} erg s^{-1}.

Together with the LAT PSR J0007+7303 which was long suspected of being a pulsar because of its clear association with SNR CTA1 containing a PWN, also the LAT PSR J1418-6058, in the Kookaburra region of the Galactic plane, very close to the PSR J1420-6048, likely associated with the Rabbit PWN G313.3+0.1, [8] and the LAT PSR J1809-2332 likely powering the Taz PWN[9], have been studied with blind search and pulsation was detected (4) Another candidate pulsar investigated with the blind search was the LAT PSR J1826-1256, probably powering the Eel PWN[10] and close to the PWN HESS J1825-137, which shows emission at higher energies[12]. Fermi was capable to detect pulsation also from the LAT PSR J2021+4044, answering to the question of whether a pulsar exists in the Gamma Cygni region[13]. Also LAT PSR J0633+0632 and LAT PSR J1907+0601 had association with SNR in the complex Monoceros Loop SNR (G205.5+0.5)[14] and SNR G40.5−0.5[15] respectively, and thus they have been object of blind period search. All the light curves of all pulsar discovered are shown in Figure 4. Almost all the light curves exhibit two peaks, like the Egret ones. Eleven pulsars out of the 13 discovered in the early three months are associated with unidentified EGRET sources, while the J1907+0601, the J0357+3211 and the J2238+59 are not mentioned in the 3rd Egret Catalog, though the MGRO J1908+06 has been detected by EGRET with a energy threshold greater than 1GeV.

3 Conclusions

A time-differencing technique was used to search pulsation from gamma-ray sources whose pulsation was not detected in any other wavelengths. Thirteen new pulsars have been discovered with an age distribution from 10 kyr to 1.8 Myr and a spin-down luminosity distribution in the range 10^{33} erg/s 10^{36} erg/s. From a first preliminary comparison with the radio pulsars, this new class of gamma ray emitters show to be mostly younger, energetic and strong magnetic field gamma-ray pulsars. The detection these new gamma ray pulsars in only three months of data taking suggests that many more will be discovered in the next five years of nominal operation, which will have important implications for an entire population of previously undetected neutron stars and open a new window of new deep radio searches of these new objects, in order also to get strong constraints on the radio luminosity, geometry and emission mechanisms.



(a) PSR J0357+32 (b) PSR J0633+0632 (c) PSR J1418-6058 (d) PSR J1732-31

(e) PSR J1741-2054 (f) PSR J1809-2332 (g) PSR J1826-1256 (h) PSR J1907+06

(i) PSR J1958+2846 (j) PSR J2021+4044 (k) PSR J2032+4127 (l) PSR J2238+59

Figure 4: Light curves of the new gamma ray pulsar detected by Fermi with blind period search

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