Fermi LAT observations of 3 new young gamma-ray pulsars

Massimiliano Razzano*, **on behalf of the *Fermi* LAT Collaboration and the Pulsar Timing Consortium**

Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy.

***Abstract*. Thanks to its large effective area, resolution and sensitivity, the Fermi Gamma-ray Space Telescope is opening a new era for gamma-ray astronomy. In particular the Large Area Telescope, the main instrument aboard Fermi, is going to detect and identify many new gamma-ray pulsars, helping to better understand the emission mechanism of these fascinating sources. I will report here on the observations of PSR J1028-5819, PSR J1048-5832 and PSR J2229+6114,three young radio pulsars that lie within EGRET unidentified source error circles. PSR J1028-5819 has been recently discovered in a search of 3EG error circles, while J1048-5832 was detected as a low-confidence gamma-ray pulsar by EGRET. PSR J2229+6114 shows a single gamma-ray peak, which makes it unusual among gamma-ray pulsars. Studies of their gamma-ray light curves and energetics are powerful tools for probing gamma-ray emission mechanisms and the importance of the geometry for these gamma-ray sources.**

***Keywords*: gamma-ray, pulsars, observations**

I. Introduction

One of the main tasks of the Large Area Telescope (LAT)[1] aboard the recently launched $Fermi$ Gamma-ray Space Telescope (previously known as GLAST) is the identification of most of the unidentified EGRET gamma-ray sources. The main contribution to the Galactic population of gamma-ray sources is believed to come from pulsars [14], [23]. $Fermi$ has already shown its potential in studying in great details the already known pulsars [2] and detecting new ones [2], [5]. I report on the recent results on PSR J1028-5819, PSR J1048$-$5832 and PSR J2229+6114, three young gamma-ray pulsars located within well-known unidentified EGRET sources [14].

II. Three young gamma-ray pulsars

PSR J1028-5819, that lies in the error circle of the EGRET source 3EG J1027-5817, has been discovered in radio few months prior to $Fermi$ launch during a search of three EGRET sources at high frequency[18]. It is a young pulsar, with period P = 91.4 ms, period derivative $\dot{P}$ = 1.61 $\times$ 10^{-14} s s^{-1} and a derived characteristic age τ_c = 9.21 $\times$ 10^4 yr. Moreover, the derived spin-down power, $\dot{E}_{SD}$ = 8.43 $\times$ 10^{35} erg s^{-1} combined with its dispersion measure derived distance of 2.3 kpc makes it a plausible counterpart for the EGRET source with flux of (6.6$\pm$0.7) $\times$ 10^{-7} ph cm^{-2} s^{-1} (E $>$ 0.1 GeV). PSR J1048-5832 (PSR B1046-58) was discovered within the error circle of the EGRET source 3EG J1048-5840 during a radio survey conducted at Parkes[8]. It has a period P = 123.7 ms a period derivative $\dot{P}$ = 9.6 $\times$ 10^{-14} s s^{-1}, and a derived characteristic age of τ_c = 2.0 $\times$ 10^4 yr. The derived spin-down power, $\dot{E}_{SD}$ = 2.0 $\times$ 10^{36} erg s^{-1} combined with its HI derived distance of 2.5-6.6 kpc [9] makes it a plausible counterpart for the EGRET source 3EG J1048-5840 with flux of (6.2$\pm$0.8)$\times$ 10^{-7} ph cm^{-2} s^{-1} (E $>$ 0.1 GeV). A previous analysis of the EGRET data suggested a low confidence identification of this 3EG source with PSR J1048-5832[17], that the $Fermi$-LAT has now confirmed with high confidence. PSR J2229+6114 is located within the error box of the EGRET source 3EG J2227+6122 [14]. Detected as a compact X-ray source by *ROSAT* and *ASCA* observations of the EGRET error box, it was later discovered to be a radio and X-ray pulsar with a period of P = 51.6 ms [12]. The radio pulse profile shows a single sharp peak, while the X-ray light curve at 0.8 – 10 keV consists of two peaks, approximately separated by $\Delta\phi = 0.5$. *AGILE* has recently reported the discovery of $> 100\,$MeV γ-ray pulsations [19]. It is almost as young as the Vela pulsar (characteristic age $\tau_c = 10\,$kyr), as energetic ($\dot{E} = 2.2 \times 10^{37}\,\mathrm{ergs\,s^{-1}}$), and is evidently the energy source of the “Boomerang” arc-shaped PWN G106.65+2.96. Studies of the radial velocities of both neutral hydrogen and the molecular material locate the system at $\sim$ 800 pc [10],[11] suggest a distance of 3 kpc estimated from its X-ray absorption. The DM-derived distance is estimated to be 7.5 kpc according to the NE 2001 model, making a large discrepancy with the association distance.

III. Gamma-ray observations

The data used for the analysis of the three pulsars have been collected during the initial 35 days of on-orbit verification, including sky-survey tuning and pointed-mode tuning on Vela pulsar [3], from 2008 June 30 to 2008 August 4, for start of survey mode. To this initial dataset an additional dataset was added, including data acquired in survey mode under nominal configuration starting from 2008 August 4. The dataset used for PSR J1028-5819 extends to 2008 November 16, while the one for PSR J1048-5832 and PSR J2229+6114 extend to 2009 March 12 and 2009 March 23 respectively. Only photons from the ’Diffuse’ class have been selected, i.e. those reconstructed events having the highest probability of being photons. In addition, photons coming from zenith

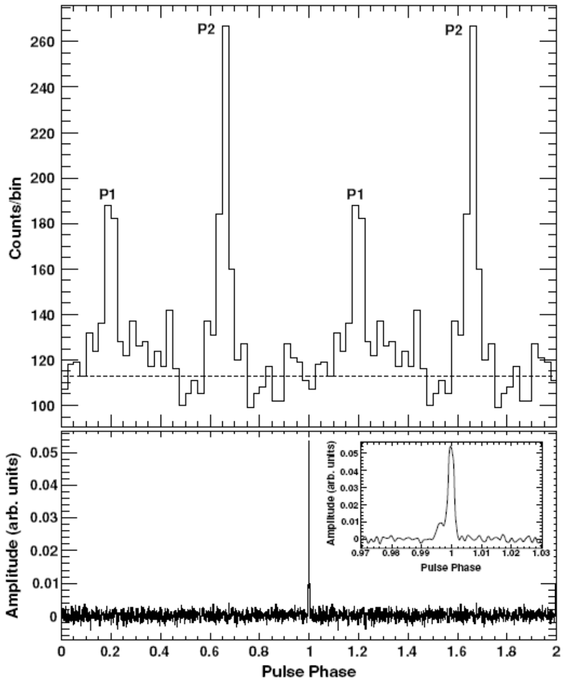

Fig. 1: Light curve of PSR J1028-5819 for E $>$ 0.1 GeV, shown over two pulse periods (40 bins/period), compared with the radio profile obtained at Parkes 64 m telescope.

angles $>105^\circ$ to the instrument axis (where the Earth's albedo gamma-rays produce an excessive background contamination) have been excluded. In order to better explore the energy evolution of the light curve, we apply an energy-dependent selection to each photon within a specific Region Of Interest (ROI). In order to minimize contamination from nearby sources, the ROIs have been chosen to be 1.5° for both PSR J1028-5819 and PSR J1048-5832 and 2.0° for PSR J2229+6114. The energy-dependent selection has been exploited by selecting only photons at an angular distance from the source $\theta < 0.8^\circ E_{GeV}^{-0.75}$, which approximates the LAT point spread function (PSF). The estimate of the contribution of the diffuse gamma-ray background, has been performed using an annulus surrounding the pulsar and selecting only those photons in the 'off pulse' phase interval.

IV. RESULTS

Fig. 1 shows the light curve of PSR J1028-5819 in gamma-rays at E $>$ 0.1 GeV compared with the radio profile obtained at Parkes 64 m. telescope. The gamma-ray light curves have been obtained by folding photons at an ephemeris obtained at the Parkes 64 m. radio telescope [15], [22] at frequency near 1.4 and 3.1 GHz. The full details of the results have been recently published [5] and here we highlight the main results will be reported. Two peaks P1 and P2 are clearly visible at ϕ = 0.200 $\pm$ 0.003 and ϕ = 0.661 $\pm$ 0.003, separated by $\sim$ 0.46 in phase. In Fig. 2 we show the energy-dependent light curve in four energy bands, where the horizontal

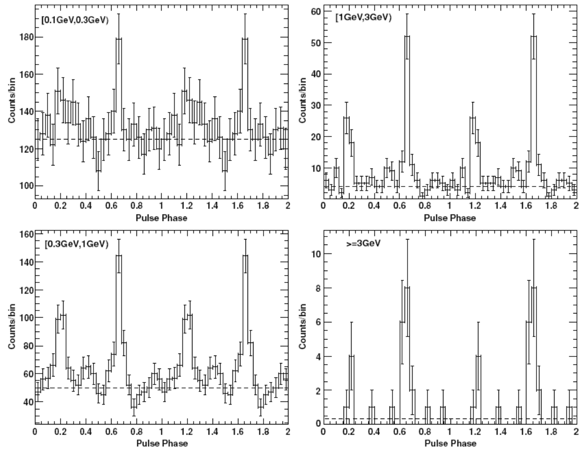

Fig. 2: Light curve of PSR J1028-5819 at four energy ranges (0.1 – 0.3 GeV, 0.3 – 1 GeV, 1 – 3 Gev, $>$3 GeV), over two pulse periods (25 bins/period). Dashed line represents the estimated contribution from the diffuse gamma-ray background.

dashed line indicates the estimated contribution of the diffuse background. The two main peaks are visible at all energies, although no significant evolution of the pulse profile with energy is visible in that plot. The study of this source shows the LAT capabilities of disentangling unidentified EGRET sources. The spatial analysis shows that the LAT point source 0FGL J1028.6-5817 (R.A.,dec.=157.166, -58.292) from the Fermi LAT Bright Source List (BSL)[4] corresponds to PSR J1028-5819, while two new other LAT point sources have been discovered nearby, namely 0FGL J1024.0-5754 and 0FGL J1018.2-5858, respectively 0.73° and 1.52° away. The COS-B source 2CG 284-00 was apparently made up of contributions from all three LAT sources, while the EGRET source 3EG J1027.5817 has now been resolved by the Fermi LAT into contributions from the two sources, 0FGL J1028.6-5817 and 0FGL J1024.0-5754. The spectrum of PSR J1028-5819 has been fit using a standard maximum likelihood estimator (gtlike) provided in the $Fermi$ Science Tools, with a power law with index Γ = 1.22$\pm$0.2$\pm$0.12 and energy cutoff E_c = 2.5$\pm$0.6$\pm$0.5 GeV (the first errors are statistical and the second are systematic). These values lead to a gamma luminosity of 1.1 $\times$ 10^{35} f erg/s (f is a beaming correction factor) and an efficiency η_γ = 0.13 f/I_{45} (I_{45}= I/10^{45}gcm^2). Using the gamma-ray light curve Atlas of Watters et al.[24] we have estimated $f \sim 1.1$ for the Outer Gap model [20] and $f \sim$ 0.9-1.0 for the Two Pole Caustic Model[7]. Fig. 3 shows the light curve of PSR J1048-5832 at different energies. The gamma-ray light curves have been obtained by folding photons on a rotational ephemeris obtained using observations at radio frequency of 1.4 GHz at the 64 m. Parkes radio telescope [15], [22] in Australia. The gamma-ray light curve at E$>$ 0.1 GeV (top panel), compared with the radio profile (bottom panel), shows two clear asymmetric

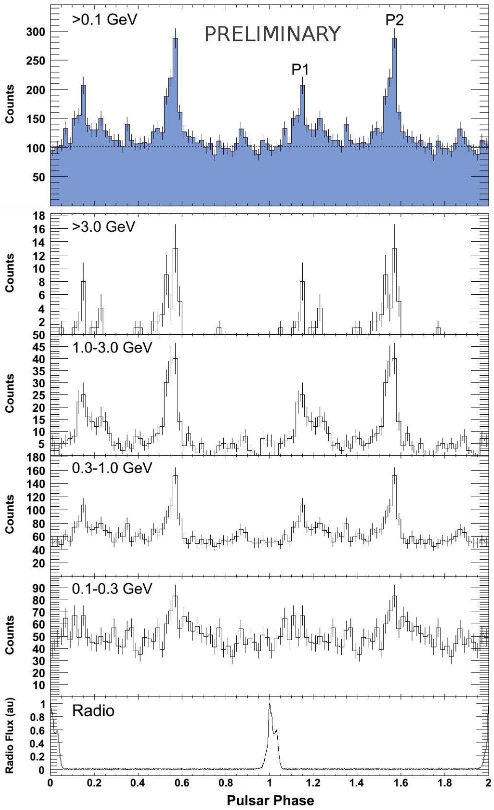

Fig. 3: *Top panel*: Light curve of PSR J1048−5832 above 0.1 GeV, shown over two pulse periods (50 bins/period).Dashed line represents the estimated contribution from the diffuse gamma-ray background. *4 following panels:* Energy dependent phase histograms for PSR J1048−5832 in the 4 energy ranges (50 bins/period). *Bottom panel:* Radio pulse profile from Parkes 64 m. Telescope.

peaks at $\phi \sim 0.14 \pm 0.1$ and $\phi \sim 0.56 \pm 0.1$, and a profile that clearly resembles that of the Vela pulsar, with a peak separation of $\sim$ 0.42 in phase. A structure related to a shoulder or 'bridge' can be observed between 0.17 and 0.30 in phase, which trails the first peak. We estimate the diffuse background using as 'off pulse' region the phase interval 0.7 and 1.0 in phase, finding a contribution of 101 counts/bin (dashed line). We thus estimated a total of 1188 $\pm$ 106 pulsed photons from the source. The energy dependent light curve in Fig. 3 in four energy bands (0.1 – 0.3 GeV, 0.3 – 1 GeV, 1 – 3 Gev, >3 GeV) shows an evolution in the light curve, although more data are needed in order to constrain the peak widths. There also is no evidence for a variation of the ratio P2/P1 with energy, as seen by EGRET for Vela, Crab, Geminga, PSR B1951+32 [21] and seen by the *Fermi* LAT for Vela [3]. As for PSR J1028-5819, the LAT was able to disentangle the EGRET unidentified source 3EG J1048−5840 into two sources, listed in the LAT BSL[4]. The source 0FGL J1047.6−5834, which is located at (RA,Dec) = (161.922°, −58.577°) with a 95% confidence level radius of 0.138° has been now identified with PSR J1048-5832, while the other (0FGL J1045.6−5937), is located $\sim$1° away and turns out to be a new gamma-ray source. According to the fluxes from the LAT Bright Source List, which is based on two power law joined at 1 GeV, 0FGL J1047.6−5834 has a total flux of (1.8 $\pm$ 0.4) $\times$ 10^{-7} ph $cm^{-2}s^{-1}$ (E $>$ 0.1 GeV) and 0FGL J1045.6−5937 has a total flux of (3.6 $\pm$ 0.3) $\times$ 10^{-7} ph $cm^{-2}s^{-1}$ (E $>$ 0.1 GeV), that lead to a total of (5.5 $\pm$ 0.8) $\times$ 10^{-7} ph $cm^{-2}s^{-1}$, which is consistent with the flux of 3EG J1048−5840 of (6.2 $\pm$ 0.7) $\times$ 10^{-7} ph $cm^{-2}s^{-1}$ [14]. The contribution of this second source, together with the low angular resolution and effective area of EGRET, has probably caused the low confidence identification of this pulsar by EGRET. Fig. 4 shows the light curve of PSR J2229+6114 at various energies. The gamma-ray light curves have been obtained by folding photons on a rotational ephemeris obtained at the NRAO Green Bank Telescope (GBT) [6], [22] observing at a central frequency of 2.0 GHz and the Lowell telescope at Jodrell Bank [13], [22] observing at frequency of 1.4 GHz. The top panel show the light curve above 0.1 GeV compared with the phase-aligned radio pulse profile (bottom panel). The most prominent feature is that light curve at E $>$ 0.1 GeV shows a single, asymmetric peak ($\phi = 0.15 - 0.65$), that has been fit by a two half-Lorentzian function. The fit places the peak at 0.49 ± 0.01 with FWHM of 0.23 ± 0.03. Using the phase interval 0.1 - 0.15 we estimated the residual background as 103 counts/bin (dashed line in Fig. 4. To examine the energy-dependent trend of the γ-ray pulse profile (middle panels of Fig. Fig. 4), phase histograms are plotted over 4 energy intervals ($0.1 - 0.3$ GeV, $0.3 - 1$ GeV, $1 - 3$ GeV and >3 GeV), showing a possible drift of the peak. Between 0.1 – 0.3 GeV, the peak is offset from the radio pulse by 0.51 ± 0.02 according to a two half-Lorentzian fit, while the offsets for 0.3 – 1 GeV, 1 – 3 GeV and $>$ 3 GeV are 0.48 ± 0.01, 0.49 ± 0.01 and 0.45 ± 0.01, respectively. This trend could explain the dealignement between the X-ray and γ-ray profiles, suggesting thus a spectral energy dependence of the high energy light curve. We also show the 1–10 keV X-ray profile of PSR J2229+6114 obtained from an *XMM* observation on 2002 June 15 (MJD 52440) with effective exposure time of 20 ks. The data were folded using a contemporaneous ephemeris based on Jodrell Bank [13] and Green Bank Telescope observations. The highest peak of the X-ray profile lags the radio pulse by $\phi = 0.17 \pm 0.02$, while the second peak lags it by 0.63 ± 0.02. There is no energy dependence of the X-ray pulse shape within the 1–10 keV range, while the sharpness of the peaks indicates that the emission is predominantly non-thermal. The LAT BSL source 0FGL J2229.0+6114 is located at (R.A.,dec.=337.257, 61.24)with 0.076° or 95% error radius. The total listed flux above 0.1 GeV is (4.7 $\pm$ 0.6) $\times$ 10^{-7} ph $cm^{-2}s^{-1}$, well in agreement with the value of (4.1 $\pm$ 0.6) $\times$ 10^{-7} ph $cm^{-2}s^{-1}$ reported for 3EG J2227+6122 [14].

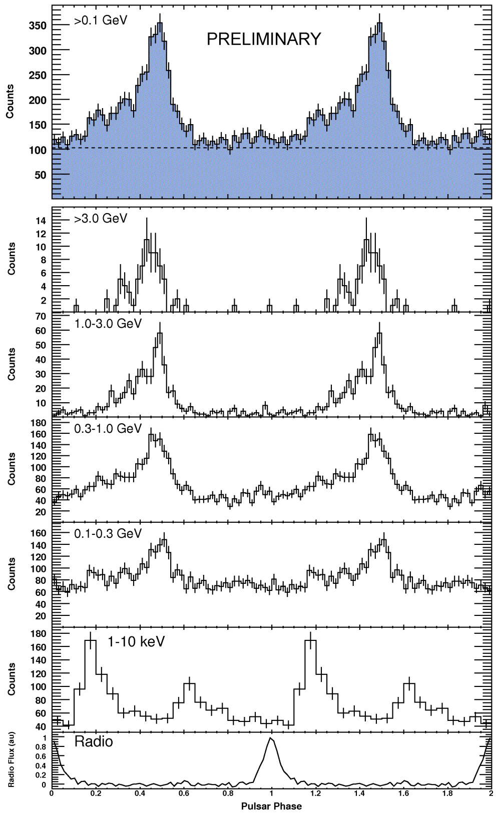

Fig. 4: *Top panel:* Light curve of PSR J2229+6114 above 0.1 GeV, shown over two periods (50 bins/period). Dashed line represents the estimated contribution from the diffuse gamma-ray background. *4 following panels:* Energy dependent phase histograms for PSR J2229+6114 in 4 energy ranges (50 bin/period). *2nd panel from bottom:* Light curve in the 1–10 keV band from the *XMM* pn CCD in small window mode. The instrumental time resolution is 5.7 ms (2.2 phase bins). Phase alignment with respect to the radio pulse is accurate to ≈ 0.4 phase bins of this 20-bin light curve. *Bottom panel:* Radio pulse profile from Green Bank Telescope.

V. Conclusions

In this contribution we have shown a short highlight of the results of observations of three young gamma-ray pulsars, PSR J1028-5819, PSR J1048-5832, PSR J2229+6114, which turn out to give clear pulsed signals modulated at the same period as the radio pulsar. The analysis of the light curve parameters shows that all three are consistent with outer magnetosphere models. These LAT observation of these pulsars give a clear example of the large potential of identification of gamma-ray source. In particular those located on the Galactic plane will be of primary importance to understand the population of gamma-ray sources in the Galaxy.

Acknowledgements

The $Fermi$ LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy for science analysis during the operations phase is also gratefully acknowledged. The Parkes radio telescope is part of the Australia Telescope which is funded by the Commonwealth Government for operation as a National Facility managed by CSIRO. We thank our colleagues for their assistance with the radio timing observations. The Green Bank Telescope is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Lovell Telescope is owned and operated by the University of Manchester as part of the Jodrell Bank Centre for Astrophysics with support from the Science and Technology Facilities Council of the United Kingdom. We thanks Jules P. Halpern and Fernando Camilo of the Columbia Astrophysics Laboratory of the Columbia University for having provided the analysis of XMM data used in this paper.

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