# Gamma Ray Pulsar Candidates for GLAST


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## Abstract

The GLAST satellite (Gamma-ray Large Area Space Telescope) will be launched less than a year from now, and its Large Area Telescope (LAT) is expected to discover scores to hundreds of gamma ray pulsars. This poster discusses which of the over 1700 known pulsars, mostly visible only at radio frequencies, are likely to emit > 100 MeV gamma rays with intensities detectable by the LAT. The main figures of merit used to select gamma ray pulsar candidates are Ė and √Ė /d², where Ė is the energy loss due to rotational spindown, and d is the distance to the pulsar. A few individual objects are cited to illustrate the issues. Since large Ė pulsars also tend to have large timing noise, their ephemerides can become inaccurate in weeks to months, and the GLAST LAT will need timing measurements contemporaneous to the continuous gamma ray observations. The poster will describe efforts to coordinate pulsar radio timing of the candidate gamma ray pulsars.


## Which pulsars might emit gamma rays over 100 MeV ?

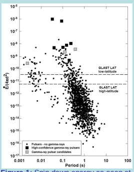


**Figure 1:** Spin-down energy as seen at earth as a function of period for the pulsars. The GLAST LAT sensitivity depends on the diffuse gamma background, a function of galactic latitude (Thompson, 2003).

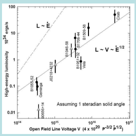


**Figure 2:** High-energy luminosity as a function of the open field line voltage. Circles represent high-confidence pulsars. Triangles represent pulsars detected with lower confidence (Thompson, 2003).

1627 pulsars are currently listed in the ANTF Pulsar Catalog. The Vela pulsar and six additional pulsars were seen at high energies by EGRET or COMPTEL with high-confidence and at least three more objects like the millisecond pulsar J0218+4232 were seen by EGRET with lower-confidence. The GLAST LAT (Large Area Telescope), with its unprecedented sensitivity, is expected to increase the number of known gamma ray emitting pulsars substantially, see Figures 1 and 3 (between 30 and 100 for Thompson, 2003, up to 750 for McLaughlin and Cordes, 2000).

However, to succeed in discovering gamma ray emission from known pulsars, it will be essential to have high-precision ephemerides : that is, for a typical pulsar, an uncertainty on its period ΔP < 2% of P. Hence, it is important to determine which of the 1627 pulsars may be potential gamma ray sources.

Study of model predictions and the EGRET sample suggest various parameters that could be well correlated with gamma ray intensity. We have chosen a quantity illustrated in Figure 2:

$$\frac{\sqrt{\dot{E}}}{d^2} = \frac{\dot{E}}{d^2} \times \frac{1}{\sqrt{\dot{E}}} = \frac{1}{d^2}\sqrt{4\pi^2 I \frac{\dot{P}}{P^3}} \propto \frac{V}{d^2}$$

In this expression, Ė denotes the energy loss due to the pulsar spindown, d the distance to the pulsar, I the moment of inertia of the neutron star, and V the open field line voltage. The factor Ė/d² is the available energy of the pulsar and 1/√Ė is the gamma ray radiation efficiency according to Arons, 1996. Pulsars are expected to stop being gamma ray emitters when Ė falls to a « death-line » which is below 3 10³⁴ erg/s, so that the following cut-off has been chosen :

$$\dot{E} \approx 10^{34}\ \mathrm{erg/s}$$

The previous criterion leads to a list of 215 gamma ray emitting candidates, which are then sorted by √Ė /d². A few examples are cited on the poster.

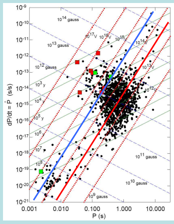


**Figure 3:** Distribution of pulsars as a function of their period and period derivative, derived from the ATNF Pulsar Catalog. Dots: no known gamma ray emission. Green squares: lower-confidence gamma ray pulsars like J0218+4232 in the lower-left of the graph. Red squares: high-confidence gamma ray pulsars, like the Vela pulsar or the Crab pulsar. Solid lines: timing age. Dotted line: open field line voltage. Dashed line: surface magnetic fields (Thompson, 2003).

The bold blue line represents the EGRET limit for gamma ray pulsar detection. The bold red line represents a potential limit for detection of gamma ray pulsars by the LAT.

## #1: Vela, first instrument test

*Vela is well-studied from radio waves to gamma rays, thanks to EGRET. Vela is the brightest pulsar known in gamma rays. The LAT will point Vela for two weeks during the 60 days of GLAST L&EO (Launch & Early Orbit), providing a « standard candle » to test LAT performance. The LAT effective area is half of its maximum value at an inclination of 45° from the instrument axis, and about 25 other pulsars with Ė>10³⁴ erg/s will be in that field-of-view.*

| | |
|---|---|
| Name | B0833-45 |
| Galactic longitude l | 263.55° |
| Galactic latitude b | −2.79° |
| Period $P$ | 89.328385024 $ms$ |
| Period derivative $\dot{P}$ | $1.25008 \times 10^{-13}$ |
| Distance | 0.29 $kpc$ |
| Characteristic age | $1.13 \times 10^{4}$ $yrs$ |
| Spin-down luminosity $\dot{E}$ | $6.9 \times 10^{36}$ $erg/s$ |
| Flux $\frac{\sqrt{\dot{E}}}{D^2}$ | $3.22 \times 10^{19}$ $erg^{1/2} \cdot s^{-1/2} \cdot kpc^{-2}$ |
| Association | $SNR\ Vela$ |
| | $PWN\ G263:9-3:3$ |
| Coincidence | $3EG\ J0834-4511$ |
| | $HESS\ J0835-455$ |

**Table 1:** Characteristics of Vela pulsar

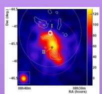


**Figure 6:** Smoothed map of region surrounding Vela pulsar, as seen by HESS. White contours represent X-ray observations by ROSAT. Strong X-ray and gamma ray emission around the pulsar is indicated in position I. Position II indicates the centre of gravity of the emission excess (Aharonian et al., 2006).

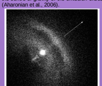

**Figure 7:** X-ray image of the Vela pulsar surrounded by its nebula, taken with the *Chandra* High-Resolution Camera. The arrow indicates the proper motion of the pulsar (Caraveo et al., 2001).

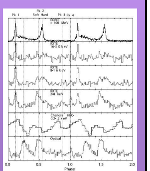


**Figure 8:** Example of lightcurves in three energy bands : gamma rays (EGRET), X-rays (RXTE and *Chandra*) and optical band (Harding et al., 2002).

## #31: J2229+6114, noisy pulsars need fresh ephemerides

*Associated to the unidentified EGRET source 3EG J2227+6122 and to the SNR G106.3+2.7 (Kothes et al., 2001), PSR J2229+6114 is a young and energetic pulsar, surrounded by an X-ray pulsar wind nebula (Figures 10 et 11), (Halpern et al., 2002). Pulsar timing noise hinders application of recent timing measurements to old EGRET data. Consequently, evidence of gamma ray pulsation has not been confirmed (Figure 5).*

| | |
|---|---|
| Name | $J2229+6114$ |
| Galactic longitude l | 106.647° |
| Galactic latitude b | 2.949° |
| Period $P$ | 51.624 $ms$ |
| Period derivative $\dot{P}$ | $7.83 \times 10^{-14}$ |
| Distance | 12.03 $kpc$ |
| Characteristic age | $1.05 \times 10^{4}$ yrs |
| Spin-down luminosity $\dot{E}$ | $2.25 \times 10^{37}$ $erg/s$ |
| Flux $\frac{\sqrt{\dot{E}}}{D^2}$ | $3.241 \times 10^{16}$ $ergs^{1/2}.s^{-1/2}.kpc^{-2}$ |
| Coincidence | 3EG J2227+6122 |
| Association | SNR G106.3+2.7 |

**Table 2:** Characteristics of J2229+6114

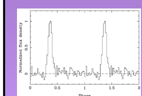


**Figure 9:** Radio lightcurve of PSR J2229+6114 at 1412 MHz from Jodrell Bank (Halpern et al, 2001).

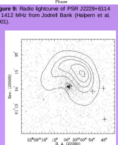


**Figure 10:** X-ray image of PSR J2229+6114 and its associated PWN, taken with Chandra ACIS-I (Halpern et al., 2002).

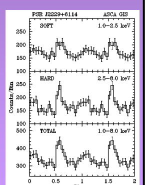


**Figure 11:** X-ray lightcurves in three energy bands of PSR J2229+6114 from the ASCA GIS. Unpulsed flux is dominated by nebular emission (Halpern et al., 2002).

## #42: J0218+4232, first of many gamma MSP's ?

*PSR J0218+4232 is a millisecond pulsar (MSP) orbiting around a low mass white dwarf companion. Many authors predict gamma ray emission by MSPs, yet J0218+4232 is the only MSP with evidence of gamma ray emission, using EGRET (Kuiper et al., 2000, 2002). J0218+4232 is close to the blazar 3C66A, which made detection by EGRET difficult. The superior LAT localisation will be very helpful to separate the two sources.*

| | |
|---|---|
| Name | J0218+4232 |
| Galactic longitude l | 139.51° |
| Galactic latitude b | 17.53° |
| Period $P$ | 2.3230904678309 $ms$ |
| Period derivative $\dot{P}$ | $7.7389 \times 10^{-20}$ |
| Distance | 5.85 $kpc$ |
| Characteristic age | $4.76 \times 10^{8}$ |
| Spin-down luminosity $\dot{E}$ | $2.4 \times 10^{35}$ |
| Flux $\frac{\sqrt{\dot{E}}}{D^2}$ | $1.44 \times 10^{16}$ $erg^{1/2} \cdot s^{-1/2} \cdot kpc^{-2}$ |
| Coincidence | $2EG\ J0220+4228$ |

**Table 3:** Characteristics of PSR J0218+4232

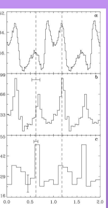


**Figure 12:** Multiwavelength pulse profiles of PSR J0218+4232. Figure a shows the radio pulse profile at 610 MHz. Figure b shows a X-ray pulse profile, in the 0.8-10 keV band, taken with *Chandra* HRS-C. Figure c shows the EGRET gamma ray pulse profile, in the 0.1-1 GeV band (Kuiper et al., 2002).

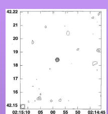

**Figure 13:** Map of PSR J0218+4232 from the VLA array, at 333 MHz. In this image, the pulsar is the central source (Navarro et al., 1995).

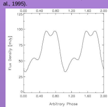


**Figure 14:** Radio profile of PSR J0218+4232, at 410 MHz. This example shows how complex a pulse shape can be (Kuiper et al., 1998).

## GLAST needs contemporaneous timing measurements

With a large effective area (10000 cm² at 1 GeV), a narrow point spread function, and a large field of view (2.4 sr), GLAST will record enough photons for gamma-ray pulsation searches far more sensitive (for 1 year, $4 \times 10^{-9}$ ph/cm²/s (E>100 MeV)) than EGRET's and should detect scores to hundreds of large Ė radio pulsars. Figure 4 illustrates GLAST's superior source localisation. However, timing noise also scales with Pdot and timing ephemerides become inaccurate within weeks to months for many of the best gamma pulsar candidates (Arzoumanian et al 1994).

The hi Edot radio pulsar J2229+6114 discovered at the end of the CGRO mission is a concrete example. A search in EGRET data archives using different methods failed to find significant evidence of pulsation (Figure 5) since the EGRET photons are too few, and too old compared to the ephemerides (Thompson et al., 2002).

Good ephemerides will dramatically enhance the number of detectable pulsars, as well as phase-resolved and multiwavelength studies. GLAST needs timing measurements contemporaneous to the continuous gamma ray observations.

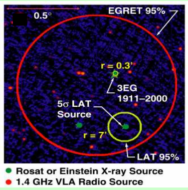


**Figure 4 :** Comparison of EGRET observations with simulated GLAST LAT error boxes.

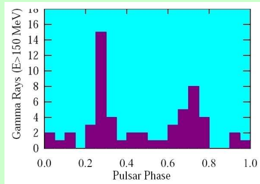


**Figure 5:** Best EGRET light curve for PSR J2229+6114. After taking N trials into account, the statistical significance of a positive detection is low, and no detection is claimed (Thompson et al., 2002.

## Gamma ray candidates

An extract of the list of 215 gamma ray candidates pulsars sorted by normalized flux (defined by $(\sqrt{\dot{E}}/d^2) / (\sqrt{\dot{E}_{Vela}}/d_{Vela}^2)$ ).

| Rank | Name | Normalized Flux |
|---|---|---|
| 1 | B0833-45 | 1 |
| 2 | J0633+1746 | 0.2237 |
| 3 | J0437-4715 | 0.179 |
| 4 | B0531+21 | 0.1717 |
| 5 | B0656+14 | 0.07422 |
| 6 | B0743-53 | 0.05373 |
| 7 | J0034-0534 | 0.01902 |
| 8 | J0205+6449 | 0.01625 |
| 9 | J1747-2958 | 0.01253 |
| 10 | B1706-44 | 0.01116 |
| 11 | B1055-52 | 0.0107 |
| 12 | J1833-1034 | 0.0101 |
| 13 | J1740+1000 | 0.009987 |
| 14 | B1951+32 | 0.009855 |
| 15 | J1357-6429 | 0.009241 |
| ⋮ | ⋮ | ⋮ |
| 31 | J2229+6114 | 0.002857 |
| ⋮ | ⋮ | ⋮ |
| 42 | J0218+4232 | 0.0022 |

## Coordinated pulsar timing campaigns for GLAST

As for EGRET (Fierro 1994), we have an *a priori* list of radio pulsars most likely to be detectable with the GLAST LAT (https://confluence.slac.stanford.edu/display/GLAMCOG/GLAST+LAT+Multiwavelength+Coordinating+Group). Also as before (see e.g. Arzoumanian et al 1994), timing campaigns have begun. However, GLAST's timing needs are substantially greater than EGRET's were:

- The number of known radio pulsars has more than tripled since the CGRO launch.
- The LAT's gamma ray sensitivity will be 25x better than EGRET's.
- GLAST will scan the whole sky continuously during the first year, and generally thereafter: *All pulsars will be observed all the time.*

Three observatories will routinely time most of the gamma ray candidates: Parkes for the southern sky (contact: dick.manchester@ciro.au), and Jodrell (contact: mkramer@jb.man.ac.uk) and Nançay (contact: icognard@cnrs-orleans.fr) in the north. The most sensitive but less available instruments, Green Bank and Arecibo, will be used for pulsars particularly interesting in gamma rays but difficult to detect in radio, and to perform deep searches for radio counterparts to gamma ray sources that the LAT will detect, pulsed or unpulsed.

*We need help from other radio telescopes*: the *a priori* list reflects current theoretical prejudices, heavily influenced by the very small number of currently known gamma ray pulsars, yet the LAT will see *all* radio pulsars so we want valid ephemerides for as many as possible. Some radio-bright, glitch-prone pulsars merit more frequent observations. The monitoring must be sustained for 5 to 10 years, a strain for any observatory.

A database (http://glast.gsfc.nasa.gov/ssc/dev/psr_tools/) readable by the Science Tools package (http://glast-ground.slac.stanford.edu/workbook/sciTools_Home.htm) will allow analysis of data as it becomes available on the servers (http://glast.gsfc.nasa.gov/cgi-bin/ssc/LAT/DC2DataQuery.cgi) For pulsars more easily detectable in X-rays than in radio, we welcome any help in providing the GLAST LAT with accurate ephemerides.

Those who provide ephemerides used to obtain gamma ray results will co-author publications. While true that GLAST data becomes public after the first year, GLAST data analysis is complex, especially for weaker sources not seen during the first year: radio, Xray and gamma ray astronomers are likely to all benefit from cooperation.

If you can contribute to LAT pulsar timing, please contact the GLAST pulsar IDS (InterDisciplinary Scientist), Stephen Thorsett (thorsett@ucolick.org) and/or the "Pulsar, Supernova, and Pulsar Wind Nebula Science Working Group" leaders, David Thompson (djt@egret.gsfc.nasa.gov) and Roger Romani (rwr@astro.stanford.edu).

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