Gamma-Ray Pulsars with the GLAST Large Area Telescope

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Abstract. The Large Area Telescope (LAT) on the Gamma-ray Large Area Space Telescope (GLAST) will see first light in mid-2008, and is expected to discover scores of pulsars in GeV γ-rays. For most, days to weeks will separate recorded gamma events. Rotation parameters provided by radio or X-ray instruments permit pulsation searches with greater sensitivity than what the LAT can achieve alone. But the gamma pulsar candidates tend to be the young ones with large timing noise, meaning that the ephemerides need to be updated relatively frequently over the years of the GLAST mission. We describe the criteria used to identify gamma pulsar candidates, and the observation campaign underway to provide ephemerides useful for the pulsed gamma searches, with some illustrations of the LAT's capabilities.

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INTRODUCTION

Nearly 1800 pulsars are currently listed in the ATNF Pulsar Catalog [1]. Six of them were detected with high confidence as γ-ray pulsars by EGRET on the Compton Gamma Ray Observatory, and three others were seen with lower confidence. The sensitivity of the Large Area Telescope (LAT) on the GLAST satellite will be over 25 times greater than EGRET's, leading to dozens [2] to hundreds [3] of new detections, depending on the assumptions used.

The LAT will usually scan the sky continously, with complete coverage every two orbits (three hours). The result is few percent uniformity of sky exposure, excellent for population studies, but a reduced duty-cycle of observations on any given object. This and the intrinsically low gamma fluxes mean that signals for the fainter pulsars will be accumulated over years. (The GLAST mission is for 5 years, extendable to 10.) Sensitivity to gamma pulsations is about 10 times better if good rotation parameters are available, as compared to blind searches.

From both empirical observations and theoretical considerations, the best γ-ray pulsar candidates are those with large spin-down energy, $\dot{E}$. But these are also mostly the ones with the most timing noise! Therefore, as for EGRET [4], the GLAST LAT collaboration needs the help of the radio community to perform long-term timing of young, noisy pulsars.

Pulsars may not emit gamma-rays when $\dot{E}$ falls below 3×10^{34} erg/s, the lowest value for the known γ-ray pulsars. For GLAST pulsar timing the following cut-off value has been chosen:

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

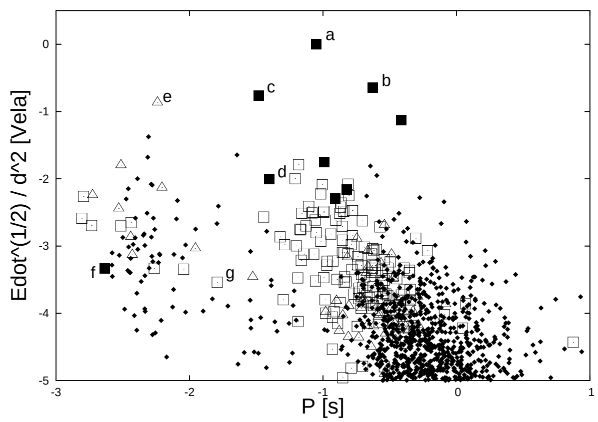

FIGURE 1. $\sqrt{\dot{E}}/d^2$, normalized to Vela, versus rotation period, for the GLAST LAT γ-ray pulsar candidates. The labels are identified in Table 1 and in the text. Squares: $\dot{E} > 3 \times 10^{34}$ erg/s. Triangles: $\dot{E} > 10^{34}$ erg/s. Full squares: EGRET pulsed detections and possible detections. Dots: other pulsars.

We remove the millisecond pulsars that are in the globular clusters Tuc 47 and M15 from this list, since gravitational acceleration towards the cluster core increases some measured $\dot{P}$'s compared to the pulsar's true value. The list at the URL in [5] contains **215 γ-ray candidates**. These candidates are then sorted by $\sqrt{\dot{E}}/d^2$, where d is the distance to the pulsar. This choice stems essentially from the observation that an efficiency to convert spin-down energy into gamma radiation of $\dot{E}^{-1/2}$ is consistent with observations and theoretically defensible [6]. Figure 1 shows $\sqrt{\dot{E}}/d^2$ normalized to Vela's value versus the rotation period for the γ-ray pulsar candidates. Vela is "a", the other labels are defined in Table 1.

Timing Campaigns

The total radiotelescope time needed for GLAST depends on the number of pulsars, the integration time to detect a given object, and the number of times per year that the object needs to be re-observed.

The former scales with the radio intensity, e.g. S_{1400} in the ATNF database. Some gamma candidates, like many "normal" pulsars, are faint enough that they require long exposures on the biggest (and often oversubscribed) radiotelescopes. Geminga ("b" in Figure 1) illustrates the fact that radio and gamma intensities aren't necessarily correlated, and also suggests (along with other evidence) that gamma beams may be wider than the radio beams: there could be a large number of radio-faint, gamma-bright pulsars waiting to be discovered.

Timing noise is correlated with $\dot{P}$, and thus $\dot{E}$ [7]. In [4] they define a stability measure $\Delta_8 = \log \frac{|\dddot{\nu}| t^3}{6\nu}$ with $t = 10^8$ s, if $|\dddot{\nu}|$ is larger than twice its statistical uncertainty (otherwise, an upper limit is set). Here, $\dddot{\nu}$ is the cubic term of the Taylor series expansion of the radio phase $\phi(t) = \phi_0 + \nu t + \frac{1}{2}\dot{\nu}^2 + \frac{1}{6}\ddot{\nu}^3 + ...$ Together with S_{1400}, Δ_8 allows a rough forecast of telescope time needed to monitor a pulsar list. The dispersion in Δ_8 vs $\dot{P}$ is large, so that the actual time alotted to individual pulsars is determined on a case-by-case basis.

The upshot is that a small number of gamma candidates could overwhelm the observation schedules: the case in point is PSR J0205+6449, requiring hours of 100-meter class telescope time, and needing to be revisited several times per year to maintain phase knowledge.

Three radio telescopes will routinely time the bulk of the 215 γ-ray candidates: the Parkes observatory in the southern sky, and the Jodrell and Nançay telescopes in the north. The more sensitive but less available instruments such as the Green Bank Telescope or Arecibo will be involved in timing pulsars which are difficult to detect in radio, or in performing deep searches for radio counterparts to γ-ray sources, pulsed or un-pulsed, that the LAT will detect. In addition to radio observations, some interesting radio-faint pulsars will be timed in X-rays, for example by the RXTE telescope while it remains active. In this case only sparse long term monitoring can be considered though.

The monitoring must be sustained for 5 to 10 years, a strain for any observatory, so other contributions are welcome. In particular, very frequent monitoring of high $\dot{E}$, large S_{1400} pulsars could allow significant contributions to LAT science by smaller radiotelescopes.

"Normal" pulsars

Table 1 samples the list of 215 γ-ray emitting candidate pulsars, sorted by $\sqrt{\dot{E}}/d^2$. The top part lists the 7 high-confidence CGRO detections. The lower part gives examples of promising γ-ray candidates. PSR B0656+14, B1046-58 and J0218+4232 are the three EGRET lower-confidence detections. Associations with supernova remnants (SNR), pulsar wind nebulae (PWN), and/or HESS sources are indicated. TeV emission from PWNs is believed to be powered by the high-energy emission from the pulsar in its core and so, conversely, it might be a good indicator for possible γ-ray pulsars. We tallied the events with $E > 10$ GeV within 1 degree around the pulsar's position, from the photon lists in [8], as a low background indicator of pulsars that could have very hard spectra even if too faint for an EGRET detection.

To illustrate some LAT capabilities, consider PSR B1951+32 ("d" in Figure 1). It is in a PWN associated with SNR CTB80, and is too faint compared to the diffuse gamma emission in the surrounding Cygnus region to appear as a point source in the EGRET catalogs: without reliable radio ephemerides it would have been missed. The superior angular resolution of the LAT reduces the effective background for B1951+32, which we expect to appear as a 7σ DC excess within a month of sky survey [9]. The LAT's good energy resolution, and especially the large effective area at high energy, will allow accurate determination of the spectral cut-offs for this and many pulsars, a key observable in many models.

Millisecond pulsars

PSR J0218+4232 is the only MSP among the CGRO detections [10], in spite of a medium ranking ("f" in Figure 1). PSR J0537-6910 is distant, and thus far down in the table even with the largest spindown energy ("g" in the figure). PSR J0437-4715 has $\dot{E}$ barely above the selection cut, but is ranked fourth in $\sqrt{\dot{E}}/d^2$, yet has no obvious 3EG counterpart ("e" on the plot). The figure of merit should clearly not be taken too literally. Both the "outer gap" and the "polar cap" models predict detectable γ-ray emission from millisecond pulsars (see [11], [12] and [13]). The GLAST LAT should rapidly tell us whether J0218+4232 is the tip of an iceberg, or a lone black sheep.

With $P = 2.3$ ms, J0218+4232 illustrates the LAT's timing capabilities. [10] shows about 300 EGRET photons above 100 MeV, so that we expect over 7500 gammas with the LAT in 2 years of sky survey, enough to easily fill a 100-bin light curve (23 μs per bin). The design requirement of the LAT is 10 μs absolute time preci-

TABLE 1. Pulsars sorted by $\sqrt{\dot{E}}/d^2$. Top: high-confidence CGRO detections. Bottom: Some promising candidates. (*)PSR B1509-58 was seen only by COMPTEL below 10 MeV, not by EGRET above 100 MeV. The 4^{th} column gives the number of high energy photons within 1° of the pulsar location, and the notes (a,b,c...) correspond to the labels in Figure 1, as well as to the discussion in the text. References: [8], [15], [16]

Rank $\sqrt{\dot{E}}/d^2$	Name	$\dot{E}$ (erg/s)	>10 GeV EGRET	3EG association	PWN/SNR association	HESS association
1	B0833-45	6.92e+36	5 (a)	3EG J0834-4511	Vela	HESSJ0835-456
2	J0633+1746	3.25e+34	10 (b)	3EG J0633+1751	Geminga	
3	B0531+21	4.61e+38	10 (c)	3EG J0534+2200	Crab	HESS J0534+220
6	B1706-44	3.41e+36	8	3EG J1710-4439	G343.1-2.3	
10	B1951+32	3.74e+36	2 (d)		CTB 80	
14	B1509-58*	1.77e+37			G320.4-1.2	HESS J1514-591
39	B1055-52	3.01e+34		3EG J1058-5234		
4	J0437-4715	1.19e+34	(e)		G253.4-42.0	
5	B0656+14	3.81e+34			Monogem Ring	
12	J1747-2958	2.51e+36	5	3EG J1744-3011	Mouse	HESS J1745-303
20	B1046-58	2.01e+36		3EG J1048-5840	Puppy	
22	J1811-1925	6.42e+36	3		G11.2-0.3	
45	B1727-33	1.23e+36	9			
59	J2229+6114	2.25e+37		3EG J2227+6122	G106.6+2.9	
73	B1830-08	5.84e+35	6			
94	J0218+4232	2.44e+35	(f)	3EG J0222+4253		
121	J0537-6910	4.88e+38	(g)		SNR:N157B	

sion for each event. We recently used atmospheric muons traversing both the LAT and a standalone particle detector with a GPS clock to demonstrate that, at least on the ground, we attain closer to 2 μs accuracy.

Furthermore, in EGRET the signals from PSR J0218+4232 and the blazar 3C66A were spatially confused (the two objects are 1° apart). The LAT will provide clean separation, especially at high energies [14]. If Nature provides the fluxes, the LAT should be able to discern fine structures in the lightcurves and spectra.

New class(es) of gamma-ray pulsars?

A recurring theme over 40 years of pulsar research is that pulsars are full of surprises, often revealed by instrumental breakthroughs. The all-sky capacity of the LAT makes it an especially powerful discovery tool, but only if its users keep an open mind... Therefore, in addition to the ephemerides of the high $\dot{E}$ pulsars, the LAT team will also search for pulsations from *any* pulsar for which reliable rotation parameters are available. RRATs, AXAPs, and anything else will be fair game. Blind searches of the entire LAT catalog will be performed. After the first year of operation, the LAT data will be made public, and the searches will become even broader.

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