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# FAINT GAMMA-RAY PULSARS

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**Abstract.** During over 10 years on orbit, the Large Area Telescope (LAT) on the *Fermi* satellite has been discovering gamma-ray pulsations from about 23 pulsars per year. The more recent ones tend to be fainter and fainter, as the LAT's all-sky survey accumulates deeper and deeper exposure. They sample not just a larger space volume and higher-background regions, but also neutron star magnetosphere configurations that generate broad and/or faint beams. We describe an analysis method particularly well-suited for faint gamma-ray pulsars.

Keywords: catalogs – gamma rays: observations – pulsars: general – pulsars: individual (J2208+4056) – stars: neutron

## 1 Pulsars in the gamma-ray sky

Intense diffuse emission from the Milky Way dominates the GeV gamma-ray sky. It comes from the decay of pions created when cosmic rays collide with interstellar gas and dust. Another striking feature of the GeV sky is an isotropic distribution of point sources, mostly blazars and other active galactic nuclei. The next largest source category in the LAT catalogs is pulsars. Over half are near the Galactic plane, the rest being recycled (millisecond, or MSP) pulsars at higher latitudes. Over 240 gamma-ray pulsars have been discovered since *Fermi*'s launch in 2008*. See J. Ballet's contribution to these proceedings for a description of the upcoming $4^{th}$ LAT source catalog ("4FGL"), and B. Lott's contribution for details on source categories. Abdo et al. (2013, "2PC") characterizes the pulsars from the early mission, and a third pulsar catalog, 3PC, will follow 4FGL.

## 2 Finding gamma-ray pulsars

We use a rotation ephemeris to translate the arrival times of gamma-ray photons in the LAT to neutron star rotational phases, and then "fold" the photons into a phase histogram. A non-flat histogram means we've discovered gamma-ray pulsations.

The origin of the ephemeris defines the 3 main discovery paths. The first two paths start with pulsar-like catalog sources, and then search for periodicity either in the gamma-ray arrival times, or in radio data at the source's sky position. In both cases, the gamma-ray source must be bright enough to see if it is pulsar-like, that is, non-variable and with a spectral cut-off. Otherwise it is more likely to be a blazar, and radio telescope and/or CPU time will be spent for nought. In the case of the gamma-ray "blind period" search, the source must also be bright enough for adequate photon statistics for a periodicity analysis. Since blind searches perform large numbers of trials, pulsed significance before trials-corrections must also be large. In both cases, a successful search is crowned by the creation of an ephemeris which then yields a clear pulse in the phase histogram.

Our work concerns the third path. Radio and X-ray astronomers provide rotation ephemerides from pulsars discovered independently of *Fermi*. Phase calculation involves no additional trials, and a catalog source need not have been detected (pulsed significance is generally higher than phase-integrated significance). Before launch, we organized a "Pulsar Timing Consortium" to provide ephemerides for LAT pulsar searches (Smith et al. 2008). We focussed on the $\sim 240$ pulsars with spin-down power $\dot{E} > 10^{34}$ erg s$^{-1}$ which seemed at the time to be the minimum for gamma-ray emission by a pulsar. The Consortium is going well, and the LAT team has

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*https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

received an additional thousand ephemerides covering all $\dot{E}$ values. We remind the non-specialist that for spin frequency $\nu$ and moment of inertia $I$, $\dot{E} = 4\pi I\nu\dot{\nu}$ is the rate at which a neutron star loses rotational energy due to electromagnetic braking induced by its spinning magnetic dipole and/or other mechanisms. Most of the power is transferred to an electron wind, though gamma-rays can radiate between $< 1\%$ and $> 50\%$ of the power. Most of the $> 2800$ known pulsars are seen only in radio ; but the power in the radio beams is tiny, $< 10^{-5}\dot{E}$ in general.

The tricky part is: just *which* LAT photons should we phase-fold? LAT's Point Spread Function (PSF) may be the best ever at MeV to GeV energies, but it is terrible compared to other wavelengths: the 68% containment radius is $> 5°$ at 100 MeV, decreasing to $< 1°$ at 1 GeV. Pulsar's spectra are generally hard power-laws ($\Gamma < 2$), with a cut-off $E_{\rm cut}$ at a few GeV, $\frac{{\rm d}N}{{\rm d}E_\gamma} = K\left(\frac{E_\gamma}{1\,{\rm GeV}}\right)^{-\Gamma} \exp\left(-\frac{E_\gamma}{E_{\rm cut}}\right)$. Unknown $\Gamma$, $E_{\rm cut}$, and background intensity and spectral shape vary across the sky, hence $E_{min}$ and $\Delta\theta$ vary from pulsar to pulsar. Early in the mission we would keep only photons with some minimum energy $E_{min}$, within some angular radius $\Delta\theta$ of the pulsar position. A scan of pulsed significance versus a grid of $E_{min}$ and $\Delta\theta$ values then, alas, required decreasing the maximum significance for the number of trials in the grid.

*Weighting* (Kerr 2011) was a great improvement: the spatial and spectral map of the gamma rays around the pulsar position, combined with the LAT's energy-dependent PSF, translates into the probability of a given photon being signal or background. Having analysed the region $\approx 15°$ around the pulsar, the weights are calculated, and then the phase-histogram's pulsed significance can be evaluated with one single trial. Essentially all LAT pulsar discoveries these last years have used Kerr's weights.

Two problems persist, however: i) the complex and computer-intensive analysis becomes a major project when folding hundreds of pulsars ; ii) many gamma-ray pulsars are undetected in phase-integrated analyses.

Bruel (2018) provided the next big improvement: a greatly simplified weighting method, implemented with a formula with a single parameter, $E_r$, reflecting the relative intensities and spectral shapes of the pulsar and the local background. Scanning the pulsed significance of the phase histogram versus $E_r$ yields a bell-shaped curve, easy to fit and/or interpolate. In practice, we correct for at most 6 trials, preserving a weak signal.

## 3 Results – Phase-folding a Thousand Radio Pulsars

In Smith et al. (2018) we have applied Bruel's weights to over a thousand ephemerides provided mainly by Parkes Observatory in Australia, Jodrell Bank Observatory in England, and Nançay in France. We demonstrated, with the data and simple Monte Carlo simulations, that a $4\sigma$ detection threshold leads to $\ll 1$ false positive detections in our sample.

We discovered gamma-ray pulsations from 16 pulsars: 12 are young, and 4 are MSPs. Only six are detected in 4FGL "precursor" lists. Some lie deep in the Galactic plane, with very high background, and are detectable because their pulses are very narrow. Others are well off the plane and are simply faint. One, PSR J2208+4056, has lowered the minimum $\dot{E}$ known for any gamma-ray pulsar by a factor of 3, to $8 \times 10^{32}$ erg s$^{-1}$, challenging our understanding of the "deathline" of the emission mechanism.

Overall, increasing the number of pulsars, and faint pulsars in particular, allows us to sample as wide a variety as possible of neutron star magnetosphere configurations, in the aim of providing modelers with the least-biased selection as possible. The faint sample should also help better evaluate pulsar's contributions to the diffuse emission.

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