PROCEEDINGS OF SCIENCE

Towards a Phase-Resolved Study of Bright *Fermi* LAT Pulsars

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Pulsars are rotating neutron stars that emit electromagnetic radiation across the electromagnetic spectrum. The Third Pulsar Catalog (3PC) of the *Fermi* Large Area Telescope (LAT) contains more than 300 γ-ray pulsars and pulsar candidates. However, to date phase-resolved spectroscopy has been performed on only a few of them, which is not sufficient to reveal new trends that could improve our understanding of the γ-ray pulsar emission mechanism and geometry. Our objective is to conduct a systematic study using phase-resolved spectroscopy on two pulsar samples that appear in the recently released 3PC (young and millisecond pulsars) in order to identify novel trends, such as a relationship between the phase-resolved spectrum's hardness (slope and cutoff energy) and the light curve peak brightness, hints of which have been found in prior preliminary studies. We focused on the brightest pulsars with a range of light curve profile shapes, spin-down power ranges, and radio pulse characteristics for these pulsars, we specifically analyze only the two brightest peaks in their light curves. In this paper, we discuss our source selection, phase selection, and spectral pipeline adjustments that we have made.

High Energy Astrophysics in Southern Africa (HEASA2025)
16-20 September, 2025
University of Johannesburg, South Africa

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1. Introduction

Pulsars are rotating neutron stars that emit pulsed emission over a wide range of the electromagnetic spectrum as they spin down. Most of their radiated power is produced in the γ-ray band. They are broadly classified either as young or millisecond pulsars (MSPs) according to their position in the $P - \dot{P}$ diagram, which plots the spin period (P) versus its derivative ($\dot{P}$). Since the launch of the *Fermi* satellite in 2008 [1], the number of detected γ-ray pulsars has increased dramatically due to the high sensitivity of the *Fermi* Large Area Telescope (LAT). The LAT detects γ-ray photons from 20 MeV to 2 TeV and measures their time of arrival, energy, and incoming direction using the pair conversion technique [2]. The *Fermi* First Pulsar Catalog (1PC) contained 46 γ-ray pulsars based on six months of data [3]. This number increased to 132 with three years of data in the Second Pulsar Catalog (2PC) [4] and to about 300 in the Third Pulsar Catalog (3PC) after 12 years of data [5].

Phase-resolved spectroscopy is an important tool to disentangle the spatial origin and spectral characteristics of the beamed photons that we observe as light curves. However, this has only been performed for a handful of pulsars including the three brightest young pulsars, Vela [6, 7], Crab [8, 9], and Geminga [10, 11]. Phase-resolved studies have also been performed for J0007+7303 [12], J1057-5226, J1709-4429, and J1952+3252 [10], as well as for the mode-changing pulsar J2021+4026 [13]. More recently, [14] performed phase-resolved spectroscopy on a sample of 38 MSPs. This sample size is not sufficient to reveal possible new trends across the pulsar population that could improve our understanding of particle acceleration and gamma-ray emission in the magnetosphere. In the most recent global magnetosphere models, the bright gamma-ray peaks are thought to arise from particles, accelerated in or near the current sheet, that are emitting in the curvature radiation-reaction limit [15]. The index and cutoff of the spectrum in the peaks are then directly linked to the caustic peaks of this emission. Our objective is therefore to conduct a systematic study using phase-resolved spectroscopy across the bright peaks of young pulsars and MSPs included in the 3PC catalogue. Below, we discuss our source selection (Section 2) and phase selection (Section 3) to this end. Our conclusions follow in Section 4.

2. Source Selection

First, we split the 266 pulsars contained in 3PC with spin-down information according to their spin period P. We labelled the pulsars with $P > 10^{-2}$ s as young and the faster ones as MSPs.

Second, we applied constraints on the pulsar positions with respect to the Galactic Plane to enhance the contrast between the pulsed emission and the interstellar background. Specifically, we excluded pulsars located within $\pm 2.5°$ of the Galactic Plane. After this cut, we were left with 124 MSPs and 38 young pulsars. See Figure 1.

The two samples were next filtered according to photon flux (Figure 2) and detection quality (H test significance [5], to keep objects with robust light curves and enough photon statistics for spectral studies. We aimed to cover a wide range in surface magnetic fields B_s, magnetic field strengths at the light cylinder B_{LC}, spin-down powers $\dot{E}$, radio emission fluxes (radio-loud or radio-quiet), and different radio peak multiplicities (Figure 3). For the two samples, we chose $H > 10^3$ to make

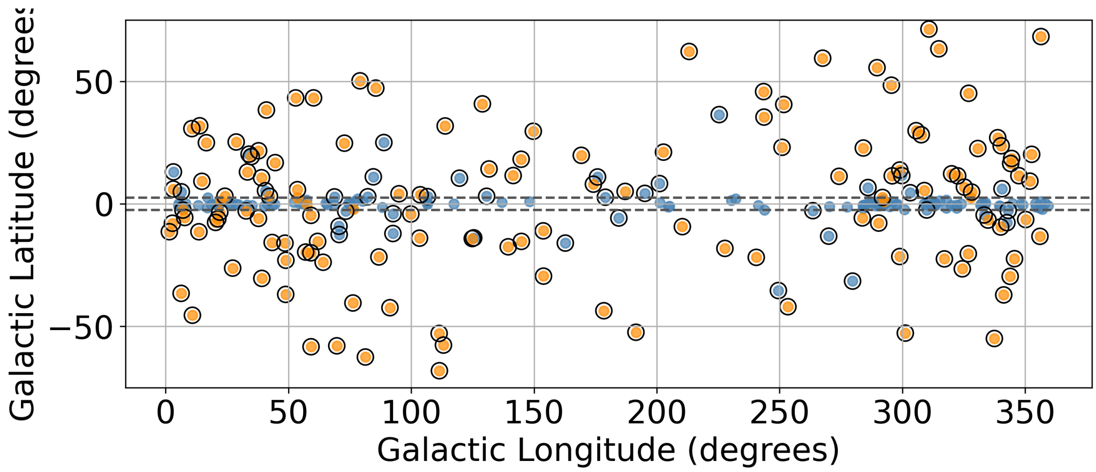

Figure 1: The spatial distribution of young pulsars (blue) and MSPs (orange), with the dashed lines marking $\pm 2.5°$ from the Galactic Plane. Symbols with black circles indicate selected pulsars.

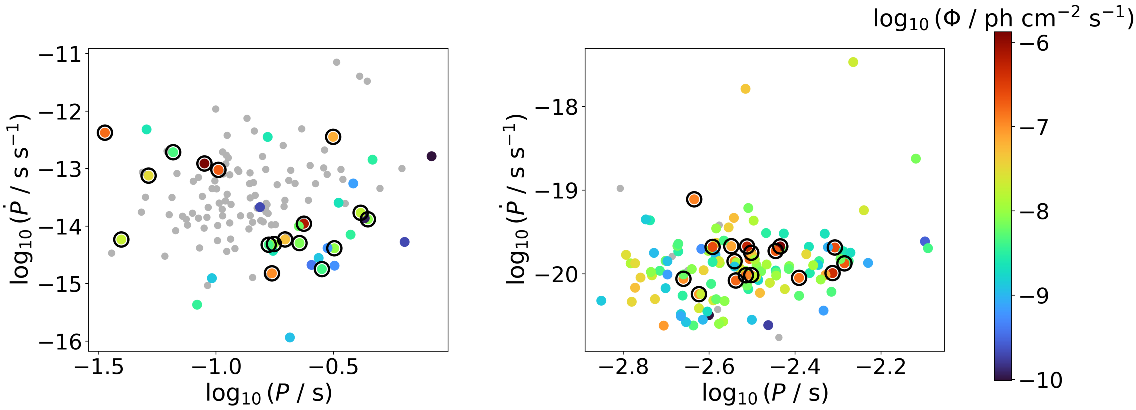

Figure 2: Young pulsars (left) and MSPs (right) in the $\log_{10}(P/\mathrm{s})$ versus $\log_{10}(\dot{P}/\mathrm{ss}^{-1})$ space for the full sample of 3PC pulsars with $\dot{E}$ information. Pulsars within 2.5° from the Galactic Plane are shown in grey, the others are colour coded as a function of their photon flux. The data points with black circles represent the sources that we selected as the brightest ones.

sure the pulsars have been detected at a reasonably high significance. We selected all sources with $\Phi > 3.89 \times 10^{-9}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which yielded 17 young pulsars and 17 MSPs.

3. Phase Selection

The morphology of the γ-ray light curve differs from one pulsar to another. Some light curves exhibit one peak, others show more. The peak widths and their separation also differ from one object to another. To allow comparisons of the spectral properties of the peaked emission across the selected population, we have defined the following method to locate the peak maximum in phase and to measure the peak width in a uniform way across the sample. We first convolved the light curve with a Gaussian kernel ($\sigma = 2$ phase bins) to suppress statistical fluctuations and reveal the

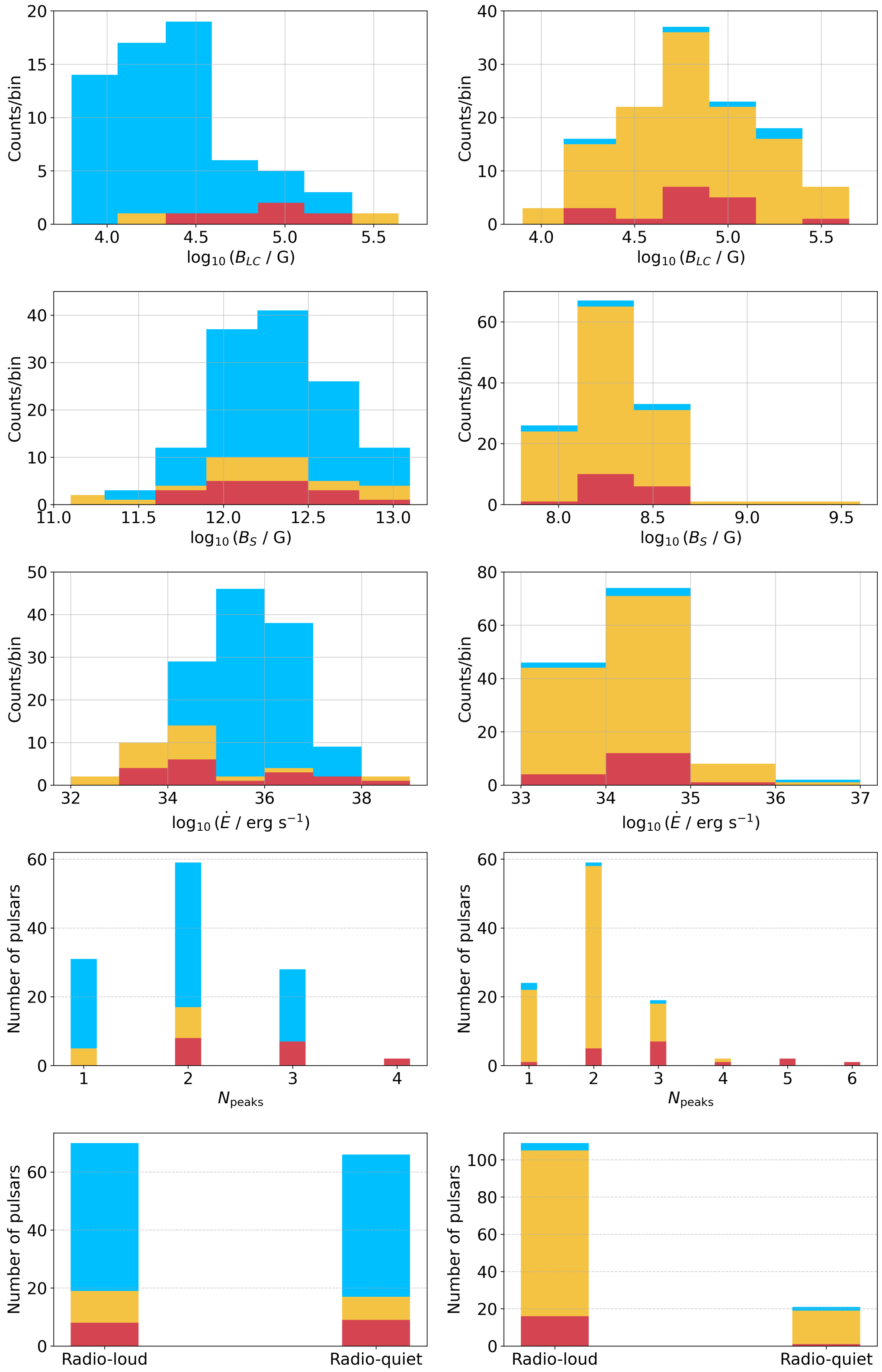

Figure 3: The plots in the left panels represent the young pulsars while those in the right correspond to the MSPs. These histograms show the distribution of $B_{\rm LC}$, $B_{\rm s}$, $\dot{E}$ values, as well as the number of peaks in the γ-ray light curve and the radio characteristics (quiet or loud) from top to bottom. Each histogram shows the full sample (blue), pulsars off the Plane $|b| > 2.5°$ (yellow), and the selected pulsars (red).

underlying emission profile. We also applied the smoothing to the light curve to identify the flat off-pulse phase interval and to measure the average background count per phase unit, see Figure 4.

We then subtracted the background counts level from the original light curve and applied less smoothing ($\sigma = 1$ phase bin) to define the peak position and to measure the core width on both sides of the peak (Figure 5). For the latter we adopted the width at half-maximum amplitude for most pulsars. However, for pulsars with overlapping peaks, i.e., when the peak separation was less than 0.25 in phase, we reduced the core to the width at 70% amplitude. For cases such as J0007+7303 and J1709-4429, the peaks were separated by splitting the distance between the two peak positions equally in phase (Figure 6 and 7).

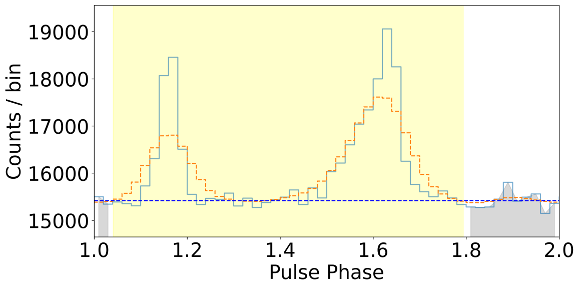

Figure 4: The light curve of PSR J1952+3252 overlaid with the smoothed orange profile used to define the grey off-pulse and yellow on-pulse phase intervals. The dashed horizontal line gives the average background counts.

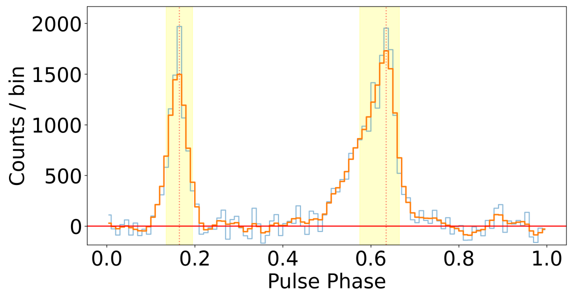

Figure 5: The light curve of PSR J1952+3252 and a smoothed profile that show the location of the two main peaks (dashed red lines) and the core widths at half maximum (yellow shade).

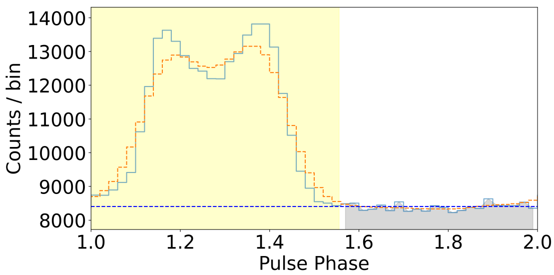

Figure 6: The light curve of PSR J0007+7303 overlaid with the smoothed orange profile used to define the grey off-pulse and yellow on-pulse phase intervals. The dashed horizontal line gives the average background counts.

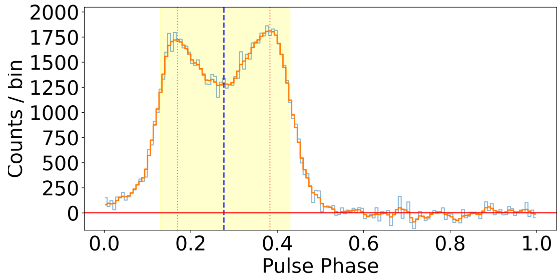

Figure 7: The light curve of PSR J0007+7303 and a smoothed profile that show the two main peak positions (red dashed lines) and the core widths (yellow shades) defined at 70% peak maximum on the edges and the midpoint between the two peak positions (blue dashed line).

4. Conclusions

In this work, we presented the methodology we adopted to choose the targets and select the relevant phase ranges to study the spectral evolution of the bright pulses in γ-ray light curves. Our future work will use the method described in this article to derive the spectral parameters and search for trends among the spectral and evolutionary (timing) parameters of young and recycled γ-ray pulsars.

Acknowledgements

This work is based on research supported wholly/in part by the National Research Foundation of South Africa (NRF). The Grant holder acknowledges that opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF-supported research is that of the author(s), and that the NRF accepts no liability whatsoever in this regard.

The *Fermi*-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. This work performed in part under DOE Contract DE-AC02-76SF00515.

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