

Article

Timing Analysis of Bright Pulsars with Nine Years of DAMPE Data

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Abstract

Based on nine years of flight data from the DArk Matter Particle Explorer (DAMPE) and a novel gamma-ray selection algorithm developed in previous work, we recalculate the instrument response functions (IRFs) in the 1–10⁴ GeV energy range. We present PSF-weighted phase-folded light curves of the bright gamma-ray pulsars Vela and Geminga, obtained with an extended version of the PINT Is Not TEMPO2 (PINT) software adapted to our analysis needs. This work lays the groundwork for further refinement of the IRFs through pulsar analyses, improving DAMPE's performance for gamma-ray astronomy and searches for potential dark-matter signatures.

Keywords: gamma rays; pulsars; catalogue; DAMPE

1. Introduction

The DArk Matter Particle Explorer (DAMPE), operated by a Sino–Swiss–Italian collaboration [1], is a satellite-borne experiment designed to detect charged cosmic rays and gamma rays. Since its launch on 17 December 2015, DAMPE has operated almost continuously and has collected more than a decade of data, leading to a number of significant scientific achievements. These include the first direct detection of a softening in the $e^+ + e^-$ spectrum at 0.9 TeV [2], the observation of a softening in the helium energy spectrum [3], the discovery of a hardening in the secondary boron spectrum [4], and improved measurements of the boron-to-carbon and boron-to-oxygen flux ratios, providing new insights into cosmic-ray propagation and the properties of the interstellar medium [5]. DAMPE is also particularly well suited for gamma-ray astronomy [6]. These very energetic photons allow the characterisation of extreme transient events such as supernovae [7], along with massive radiating objects such as Active Galactic Nuclei [8] or, importantly for this work, pulsars [9]. A major milestone in the field was the launch of the Fermi Large Area Telescope (Fermi-LAT) [10], whose observations have revolutionised our understanding of the gamma-ray sky. DAMPE has independently confirmed two of the most intriguing diffuse gamma-ray structures previously observed by the Fermi-LAT, namely Fermi bubbles and the Galactic Centre GeV excess. The origin of the latter remains debated, with both a dark-matter-annihilation interpretation and an unresolved population of millisecond pulsars proposed as leading explanations [11]. Building on the first DAMPE pulsar analyses performed in 2017 [12,13], the collaboration has recently released a gamma-ray source catalogue that complements and extends previous Fermi-LAT studies [14]. In this work, we analyse a sample of gamma-ray pulsars using nine years of DAMPE data. We develop a



Academic Editors: Larissa Bravina, Sonia Kabana and Armen Sedrakian

Received: 11 June 2026

Revised: 15 July 2026

Accepted: 17 July 2026

Published: 20 July 2026

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dedicated analysis pipeline based on the novel gamma-ray selection algorithm previously implemented within the collaboration [15]. Probability-weighted pulse profiles are derived using state-of-the-art pulsar timing techniques. This study paves the way for further refinement of the DAMPE gamma-ray source catalogue and for future high-energy astrophysics investigations with DAMPE.

2. Materials and Methods

2.1. The DAMPE Detector

The DAMPE payload comprises four vertically stacked subdetectors (Figure 1). Those relevant to the present work are briefly outlined below.

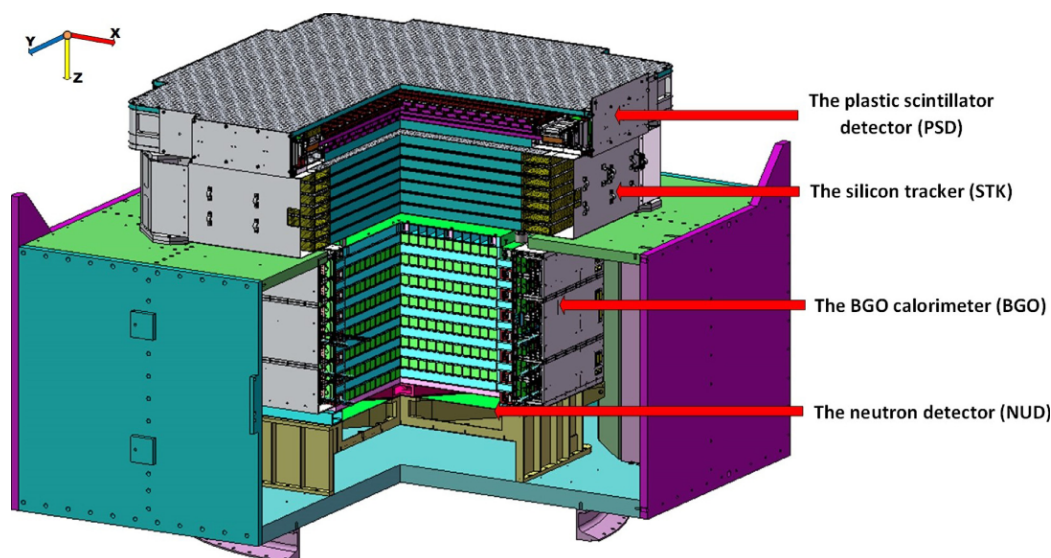


Figure 1. Layout of DAMPE’s subdetectors, taken from [1]. Local satellite frame coordinate system axes are indicated in top left hand corner.

Plastic Scintillator Detector (PSD): The PSD consists of four layers of plastic scintillator bars, arranged as two X-oriented and two Y-oriented planes, and serves as an anti-coincidence detector. Signals produced by charged particles are used to suppress the overwhelming charged-particle background, thereby enabling gamma-ray event selection. This task is complicated by back-scattered particles from electromagnetic showers, which can generate hits in the PSD even for genuine photon events.

Silicon–Tungsten tracKer–converter (STK): The STK comprises six silicon micro-strip planes with alternating X and Y orientations and three 1 mm tungsten converter layers. Charged particles leave ionisation signals in the silicon strips, enabling trajectory reconstruction and charge measurement. Gamma rays convert into e^+e^- pairs in the tungsten layers, and the resulting signals provide the information required to reconstruct the incoming photon direction.

Bismuth Germanium Oxide (BGO): The BGO calorimeter consists of fourteen hodoscopic layers of BGO crystals arranged in alternating X and Y orientations and read out at both ends by photomultiplier tubes. The recorded scintillation light provides a measurement of the deposited energy (E_{BGO}) together with the longitudinal and transverse shower profiles. This information is used to distinguish electromagnetic from hadronic showers and to reconstruct the energy of incident particles.

2.2. The γ -Ray Event Selection

In this analysis we use 9 years of DAMPE flight data recorded from 1 January 2016 to 31 December 2024. Events recorded during passages through the South Atlantic Anomaly

are excluded. The data sample is further filtered through the following event-selection procedure [15].

(i) *High-Energy Trigger selection*: Only events satisfying the High-Energy Trigger (HET) [16] condition are retained. Since the HET is based on large energy depositions in the upper BGO layers, this requirement selects events with an early shower development in the calorimeter, as expected for electromagnetic cascades induced by electrons and converted gamma rays.

(ii) *BGO energy requirement*: The total energy deposited in the BGO calorimeter is required to exceed 1 GeV. Events below this threshold typically exhibit limited shower development and poorer reconstruction performance. This requirement therefore ensures reliable energy and track-direction measurements.

(iii) *Shower-core selection*: To suppress hadronic background, the shower-core energy E_{core} is calculated by summing, in each BGO layer, the energy deposited in the crystal with the largest signal and in its two adjacent crystals:

$$E_{\text{core}} = \sum_{j=1}^{14} (E_{j,i_{\text{max}}} + E_{j,i_{\text{max}}-1} + E_{j,i_{\text{max}}+1}).$$

The ratio between the shower-core energy and the total energy deposited in the BGO calorimeter is required to satisfy

$$\frac{E_{\text{core}}}{E_{\text{BGO}}} > 0.9.$$

This requirement efficiently rejects the majority of hadronic showers while preserving electromagnetic cascades.

(iv) *BGO trajectory selection*: The shower axis reconstructed in the BGO calorimeter is required to intersect the fiducial volume of the PSD, ensuring that the event traverses the full detector acceptance and allowing a reliable charge-veto determination.

(v) *STK track reconstruction*: Candidate gamma-ray events are required to exhibit a conversion in the STK and to contain at least one successfully reconstructed STK track. If multiple STK tracks are reconstructed, the track with the highest track-quality parameter is selected as the best track [17].

(vi) *Geometrical selection*: The selected track is required to intersect the PSD fiducial volume, have a zenith angle smaller than 60° , deposit less than 35% and 40% of the total BGO energy in the first and second BGO layers, respectively, and not cross the outermost PSD bars.

(vii) *CNN selection*: A convolutional neural network trained on BGO shower images is employed to reject residual proton background [18].

(viii) *BDT selection*: Residual electron contamination is further suppressed using a boosted decision tree based on 22 variables reconstructed from the PSD and STK detectors [15]. Gamma-ray candidates are selected by applying an energy-dependent threshold on the BDT response.

To provide a visual assessment of the selected gamma-ray sample, we generate the total-count map shown in Figure 2 using HEALPix [19,20].

2.3. Instrument Response Functions (IRFs)

Before analysing flight data, the response of DAMPE to different classes of events is characterised through a GEANT4 [21]-based Monte Carlo simulation chain, processed with the same gamma-ray selection algorithm used for flight data. The resulting instrument response functions (IRFs) quantify the detector performance as a function of the energy and direction of the incident particle. In particular, the effective area characterises the probability that an incoming gamma ray is detected and successfully reconstructed, while

the point-spread function (PSF) quantifies the angular resolution of the reconstructed arrival direction.

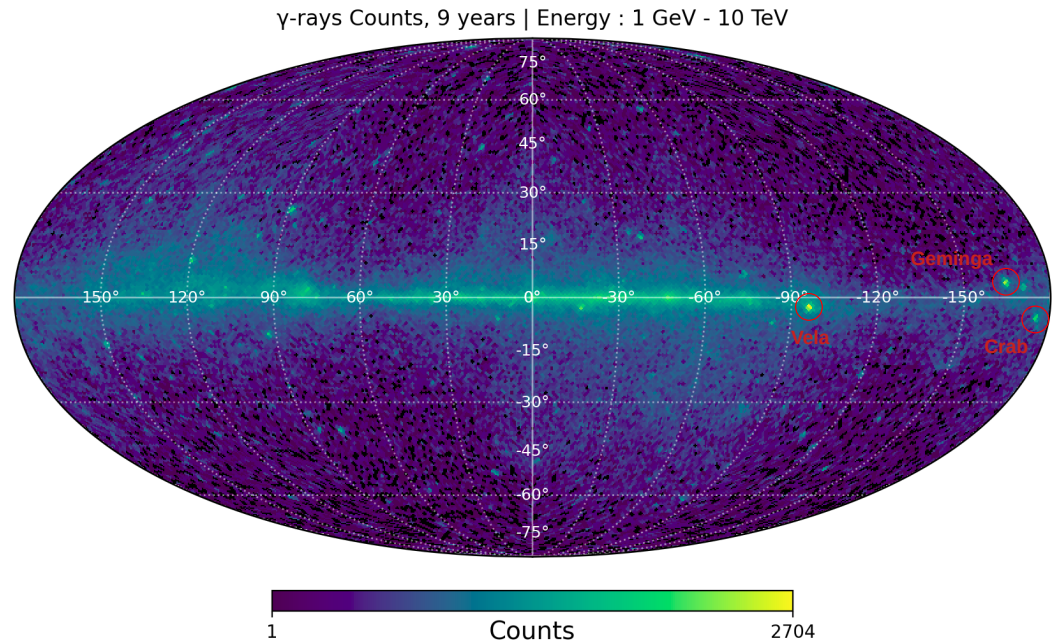


Figure 2. Nine-year DAMPE γ -ray count map in Galactic coordinates obtained after applying the event-selection procedure described in the text. Prominent γ -ray sources, including Vela, Geminga, and Crab, are clearly identified.

2.3.1. Effective Area

The effective area (A_{eff}) represents the geometrical acceptance of the detector folded with the probability that an incident γ ray passes the event-selection criteria.

$$\varepsilon = \frac{N_{\text{selected}}}{N_{\text{generated}}}, \quad A_{\text{eff}} = \varepsilon \times A_{\text{geom}}, \quad (1)$$

with $A_{\text{geom}} = 6 \text{ m}^2$, corresponding to the projected area of the hemispherical generation surface adopted in the simulations.

In this work, A_{eff} is computed on a three-dimensional grid in energy and arrival direction:

- 40 logarithmic energy bins from 1 GeV to 10 TeV,
- 10 linear $\cos \theta$ bins from 0.5 to 1,
- 360 linear ϕ bins from 0° to 360° .

Figure 3 shows the ϕ -averaged effective area and selection efficiency as a function of energy. The ϕ -averaging is performed for 2D visualization purposes only. In this work, the full effective area with ϕ dependency is used in all calculations.

2.3.2. Point-Spread Function (PSF)

The PSF is defined as the probability distribution of the angular deviation $\delta v = |\hat{v}' - \hat{v}|$ between the reconstructed incident direction ($\hat{v}'$) and the true one ($\hat{v}$) of a detected photon. The PSF depends on the photon incidence direction, parameterised by the zenith angle (θ) and the azimuth angle (ϕ) in the spacecraft reference frame. Since the PSF depends much more strongly on the zenith angle than on the azimuth angle [22], the azimuthal dependence is neglected. Following the approach adopted by the Fermi-LAT collaboration [23], the PSF (P) is parameterised as:

$$P(\delta v; E, \theta) = f_{\text{core}} K(x_p; \sigma_{\text{core}}, \gamma_{\text{core}}) + (1 - f_{\text{core}}) K(x_p; \sigma_{\text{tail}}, \gamma_{\text{tail}}), \quad (2)$$

where f_{core} is the relative weight (normalisation fraction) of the core component in the double King function, and $K(x_p; \sigma, \gamma)$ is the King function:

$$K(x_p; \sigma, \gamma) = \frac{1}{2\pi\sigma^2} \left(1 - \frac{1}{\gamma}\right) \left[1 + \frac{x_p^2}{2\gamma\sigma^2}\right]^{-\gamma}, \quad (3)$$

x_p is the scaled angular deviation:

$$x_p = \frac{\delta v}{S_P(E, \theta)}$$

with $S_P(E, \theta) = \frac{P_{84} - P_{16}}{2}$ denoting the 68% containment angle, and P_{16} , P_{84} are the 16th and 84th percentiles of the angular deviation distribution in each (E, θ) bin.

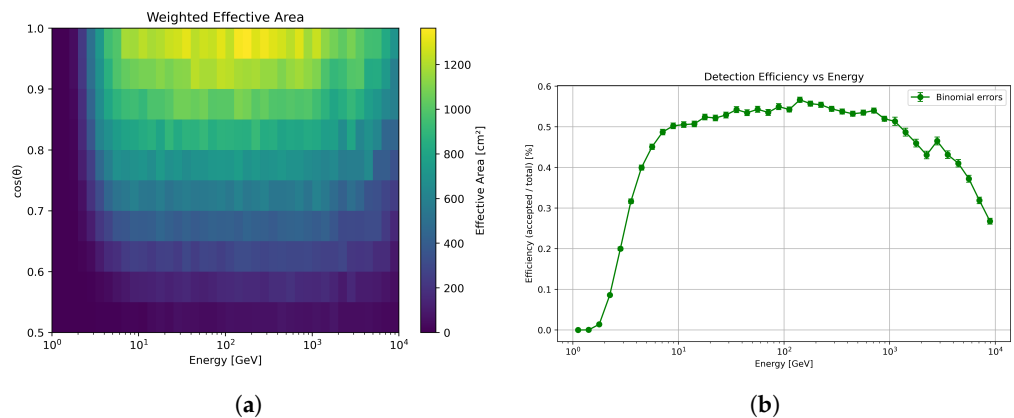


Figure 3. (a) Effective area (A_{eff}) for gamma rays as a function of energy and incidence direction (cosine of the zenith angle θ), averaged over the azimuthal angle (ϕ). (b) Gamma-ray selection efficiency (ϵ) as a function of energy. The definitions of A_{eff} and ϵ are given in Equation (1).

For a given direction in the celestial reference frame ($\hat{p}$), the observing-time map ($t_{\text{obs}}(\theta, \phi)$) is constructed to describe the distribution of detector-frame directions (θ, ϕ) from which the target is observed throughout the mission. Following Ref. [22], the dependence of the PSF on the incidence direction is accounted for by defining an exposure-weighted PSF ($\bar{P}$):

$$\bar{P}(\delta v; E) = \frac{\int P(\delta v; E, \theta) A_{\text{eff}}(E, \theta, \phi) t_{\text{obs}}(\theta, \phi) d\Omega}{\int A_{\text{eff}}(E, \theta, \phi) t_{\text{obs}}(\theta, \phi) d\Omega}, \quad (4)$$

In the numerical implementation, the integral is evaluated using binned $\cos \theta$ and ϕ coordinates, yielding

$$\bar{P}(\delta v; E) = \frac{\sum_{l=1}^5 P(\delta v; E, \cos \theta_l) \left[\sum_{m=1}^{360} A_{\text{eff}}(E, \cos \theta_l, \phi_m) t_{\text{obs}}(\cos \theta_l, \phi_m) \right]}{\sum_{l=1}^5 \sum_{m=1}^{360} A_{\text{eff}}(E, \cos \theta_l, \phi_m) t_{\text{obs}}(\cos \theta_l, \phi_m)}. \quad (5)$$

In this work, the angular resolution $S_P(E, \theta)$ is computed in 8 logarithmically spaced energy bins between 1 GeV and 10 TeV, 5 linearly spaced bins in $\cos \theta$ and 360 linear ϕ bins from 0° to 360°. The resulting matrix is shown in Figure 4a, together with an example fit of the angular-deviation distribution in a representative $(E, \cos \theta)$ bin, shown in Figure 4b. The fit of Equation (2) is performed using a two-stage approach. First, the core King function is fitted to an inner percentile of the x_p distribution, for example 60%. The parameters of

the core component are then fixed, and the tail component is fitted within the full model to the remaining outer percentile, for example 40%. This procedure is repeated iteratively over 20 inner-percentile values spanning the range from 10% to 90%, and we choose the fit with reduced chi squared value closest to 1.

The observing-time maps t_{obs} in the two local angular coordinates used in computation of Equations (4) and (5) are shown in Figure 5 for two well-known and bright pulsars, Vela and Geminga. This example targets choice was made to enable qualitative validation of the γ -ray selection algorithm.

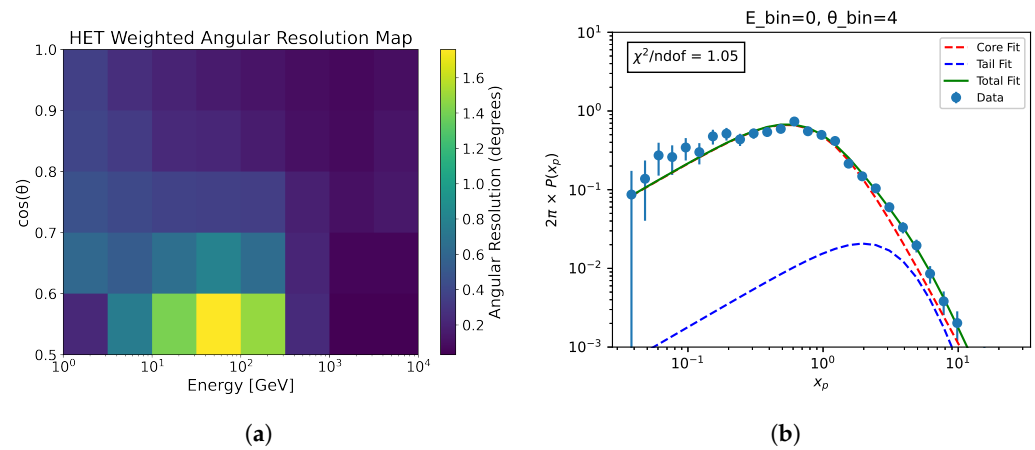


Figure 4. Angular-resolution matrix and PSF fitting. (a) DAMPE angular resolution for gamma-ray observations as a function of energy and incidence direction, expressed through $\cos \theta$, and averaged over the azimuthal angle ϕ . (b) Best fit of the angular-deviation distribution in the logarithmic energy bin [1,3] GeV and incidence-angle bin $\cos \theta \in [0.8,0.9]$, obtained using a double King function. The red and blue dashed lines show the core and tail King components, respectively, while the green solid line shows their sum.

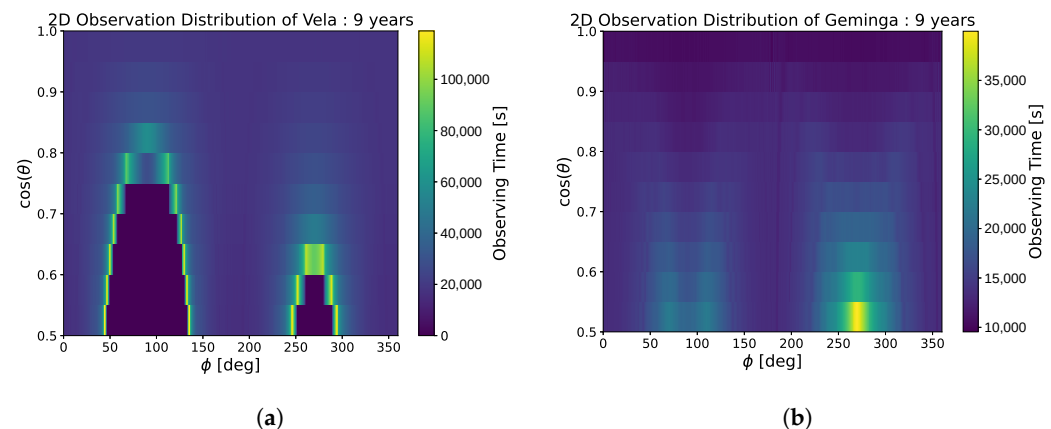


Figure 5. Observing-time maps in the detector reference frame for the sky directions of the Vela pulsar (a) and the Geminga pulsar (b), computed using the first nine years of DAMPE data. The exposure patterns originate from the orbital geometry of the mission and the source position in the sky, and are consistent with previous results in [22].

2.4. Pulsar Light Curves

This analysis aims to derive phase-folded light curves by folding the detected photon events over the pulsar rotational period. The high stability of pulsar rotation ensures that the resulting pulse profiles are reproducible in rotational phase.

2.4.1. Time-of-Arrival (TOA) Phase Folding

Photons are selected within a 3° region of interest (ROI) around the pulsar position. Their time of arrival (TOA), recorded by the on-board GPS clock, is first converted from Mission Elapsed Time (MET), expressed in GPS time and referenced to 1 January 2013, to Terrestrial Time (TT) using *astropy* [24]. The two leap seconds introduced during the data-taking period, on 1 July 2015 and 1 January 2017, are accounted for in this conversion. The TT-corrected TOAs are then combined with the satellite position, expressed in GCRS (Geocentric Celestial Reference System) frame, and transformed to the Solar System barycentre using a fork of the PINT is not TEMPO2 (PINT) software [25] available in a public repository (https://github.com/Lgtlebrun/PINT_dampe; accessed on 15 July 2026). A dedicated interface was developed to apply the PINT barycentring tools to DAMPE event and orbit data. Finally, the barycentric TOAs are converted to pulsar rotational phases using the corresponding TEMPO2-format .par timing solutions, provided by P. Ray and M. Kerr. These timing models account for the pulsar motion, the Earth gravitational redshift, and Solar-System gravitational effects, including the Sun and Jupiter potentials, using the JPL DE440s ephemeris.

2.4.2. PSF-Weighting of Photons

Each selected photon is assigned a PSF-based weight, w_k , corresponding to the probability that it originates from the target source, given its angular separation from the source position, energy, and incidence angle. The weights are computed from the exposure-weighted PSF described above and are used to construct the phase-folded light curve. In this way, photons closer to the source direction and with a higher source-association probability contribute more strongly to the pulse profile. Two validation methods are used. First, a weighted phaseogram is produced with PINT, using the photon phases and PSF-based weights described above. Second, the later-described pipeline is applied to estimate the background level, quantify the statistical fluctuations, and identify significant peaks in the phase-folded light curve. The number of phase bins is chosen adaptively according to

$$n_{\text{bins}} = \max \left[n_{\text{min}}, \min \left(n_{\text{max}}, \frac{N}{c_{\text{target}}} \right) \right], \quad (6)$$

where N is the number of selected photons, $n_{\text{min}} = 10$, $n_{\text{max}} = 200$, and $c_{\text{target}} = 30$. The background level is estimated as the 20th percentile of the phase histogram. The empirical noise level is estimated using the median absolute deviation (MAD) [26], rescaled to an equivalent Gaussian standard deviation as $\tilde{\sigma} = 1.4826 \text{ MAD}$. A peak is considered significant if it matches the three following conditions: (1) its height exceeds the estimated background level by at least $5\tilde{\sigma}$; (2) its prominence, i.e., the height by which it stands above the higher of the two minima separating it from any taller neighbouring peak (or from the edge of the data), is at least $1.5\tilde{\sigma}$; and (3) it is separated from neighbouring peaks by at least 0.05 in rotational phase. For the unweighted histogram, Poisson uncertainties are computed as $\varepsilon_j = \sqrt{N_j}$, where N_j is the number of photons in phase bin j . For the weighted light curve, the uncertainty in phase bin j is estimated as $\tilde{\varepsilon}_j = \sqrt{\sum_{k \in j} w_k^2}$, where w_k denotes the PSF-based weight of the k -th photon contributing to that bin.

2.4.3. H-Test

The pulsation significance is quantified using the revised H -test [27]:

$$H = \max_{1 \leq m \leq M_{\text{max}}} \left(Z_m^2 - 4m + 4 \right), \quad Z_m^2 = \frac{2}{N} \sum_{n=1}^m \left[\left(\sum_{i=1}^N \cos 2\pi n \phi_i \right)^2 + \left(\sum_{i=1}^N \sin 2\pi n \phi_i \right)^2 \right] \quad (7)$$

where Z_m^2 is the Z^2 statistic obtained by summing the first m Fourier harmonics of the pulse-phase distribution, ϕ_i is the rotational phase of the i -th photon, N is the number of selected photons, n is the harmonic index, and $M_{\max}$ is the maximum number of harmonics considered. The false-alarm probability is approximated as

$$P(H > h) \simeq e^{-0.4h}, \quad (8)$$

from which the corresponding p -value and Gaussian-equivalent significance are derived. Since the test optimises the number of harmonics, it is particularly sensitive to the narrow pulse features commonly observed in gamma-ray pulsars.

3. Results

Figures 6–8 present the timing analysis results for the bright Vela and Geminga pulsars, with panel (a) corresponding to Vela and panel (b) to Geminga in each figure. Figure 6 shows the PSF-weighted pulse profiles, expressed as weighted counts as a function of pulse phase, together with the corresponding phaseograms in the Modified Julian Date (MJD)–pulse-phase plane. Figure 7 presents the weight-density distribution as a function of pulse phase, providing a complementary view of the pulse-profile structure. Figure 8 reports the H -test results. The same analysis was also performed for the Crab, J0007+7303, J0030+0451, J0614-3329, J1057-5226, J1709-4429, and J2021+3651 pulsars; the corresponding results are available upon request.

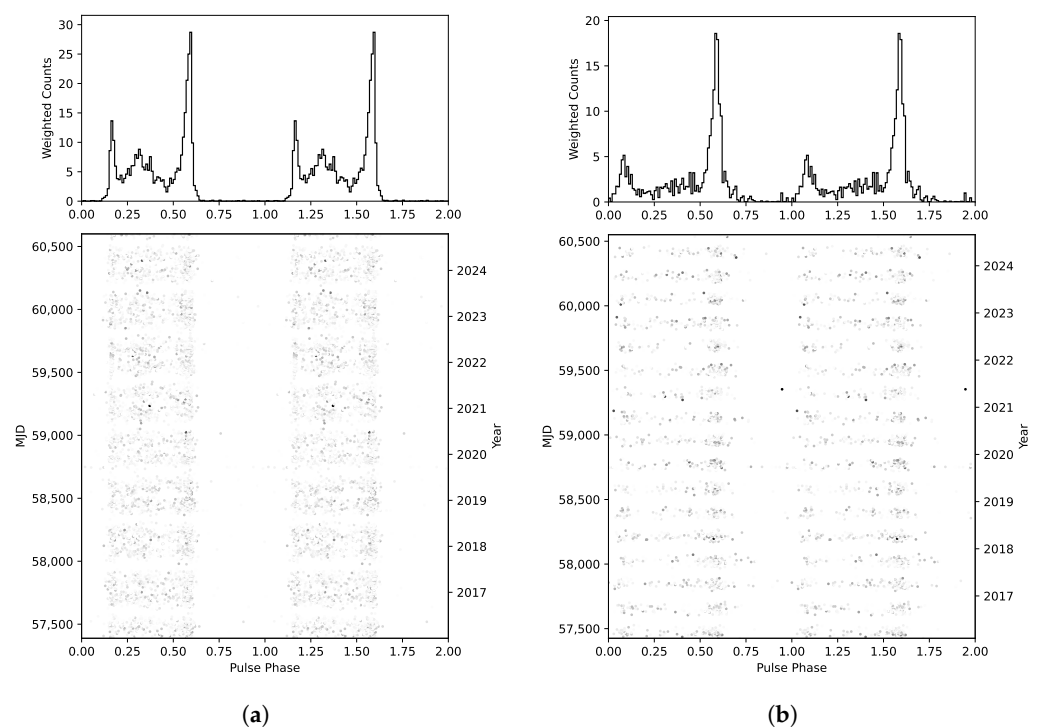


Figure 6. PSF-weighted pulse profile and phaseogram for Vela (a) and Geminga (b). The phaseogram grayscale refers to PSF weighing. Data are duplicated over a second phase range for visualisation. The regular gaps in the time series show lacks of coverage due to target laying outside of the FoV.

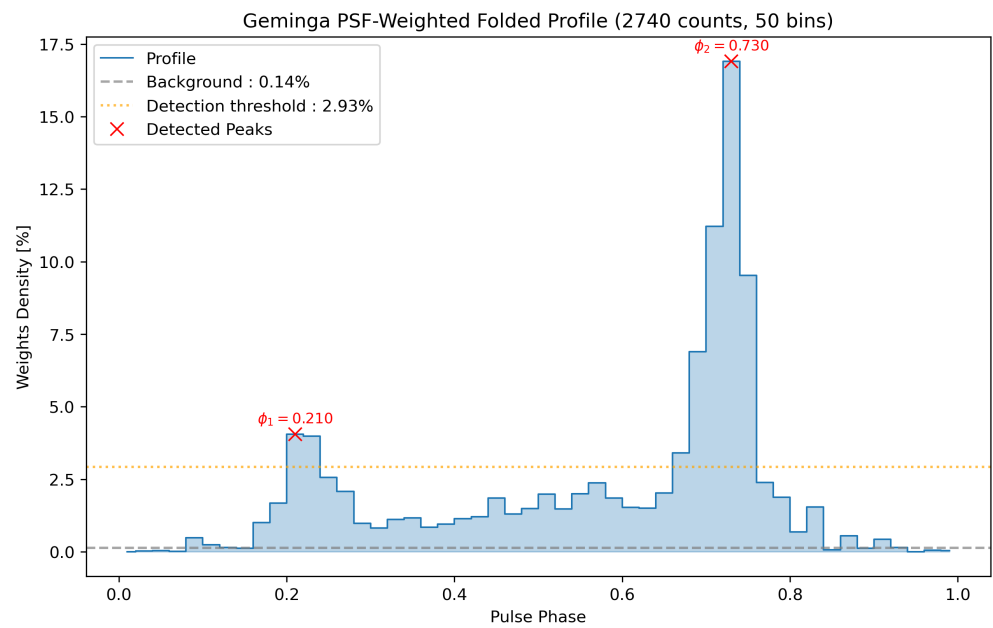
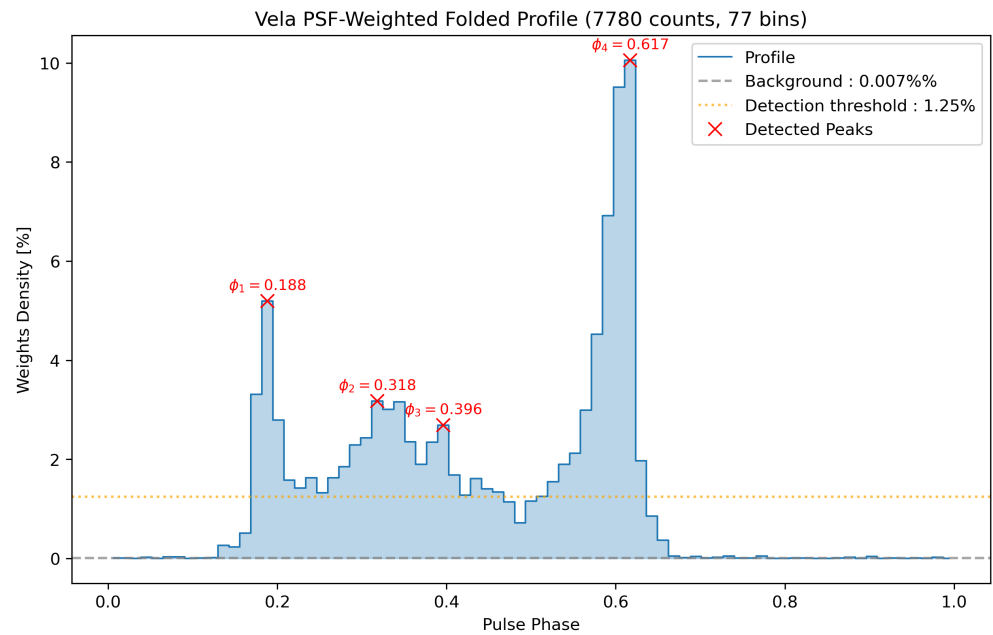


Figure 7. PSF-weighted light curves for the Vela pulsar (a) and the Geminga pulsar (b). The highlighted ϕ_i values mark significant peaks, selected using a threshold of $5\tilde{\sigma}$ above the estimated background, a minimum prominence of $1.5\tilde{\sigma}$, and a minimum separation of 0.05 in rotational phase, with $\tilde{\sigma} = 1.4826$ MAD. The off-pulse structure in the Vela light curve, commonly referred to as bridge emission, is clearly resolved, whereas no corresponding bridge component is visible for Geminga.

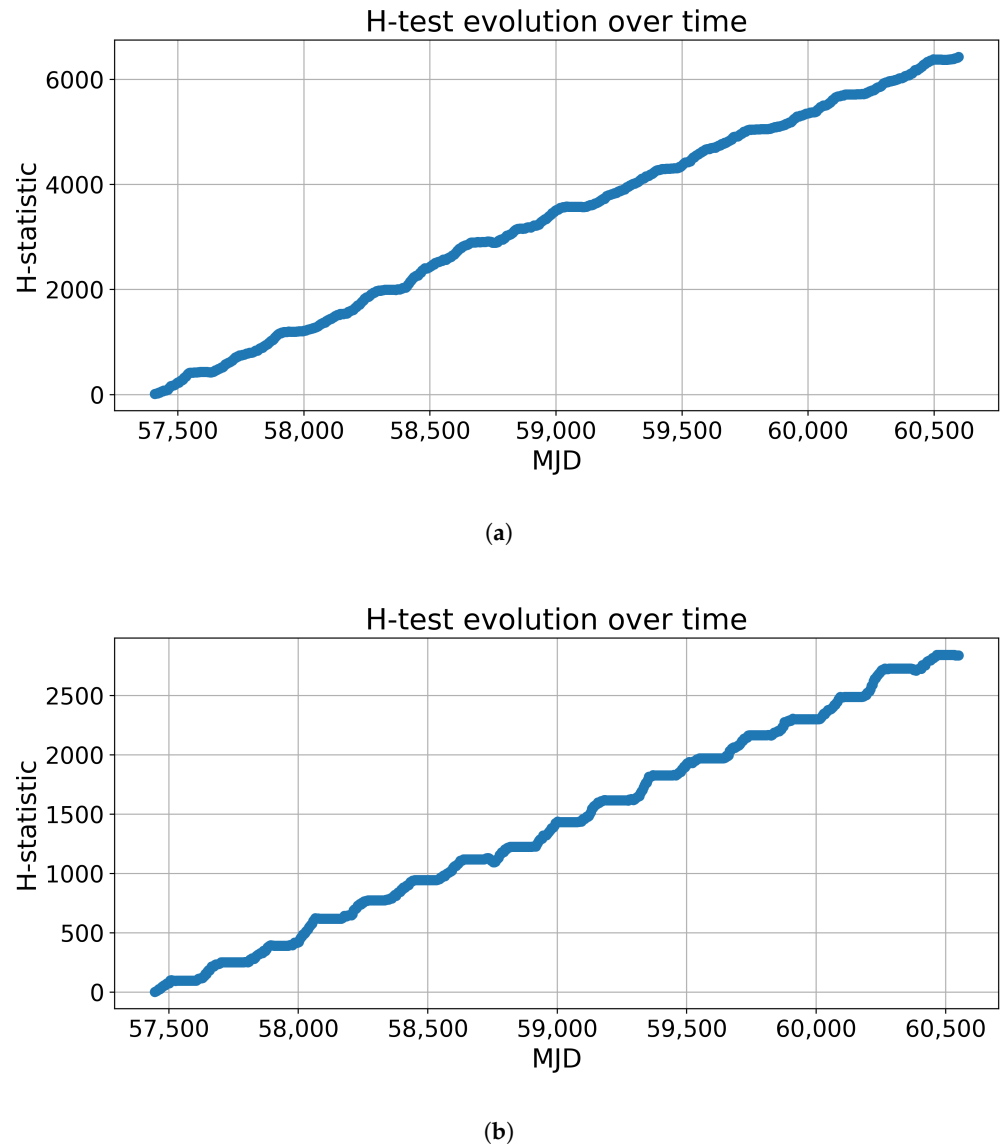


Figure 8. Temporal evolution of the H -test statistic, defined in Equation (7), as a function of the Modified Julian Date, for Vela (a) and Geminga (b), computed over nine years of DAMPE γ -ray observations.

4. Discussion

The phase-folded light curves obtained in this work demonstrate the robustness of the timing procedure and of the PSF-weighting approach. For the Vela and Geminga pulsars, the phaseograms extend over several years of data taking and show stable periodic patterns throughout the analysed time interval. The pulse profiles are clearly resolved and yield high values of the H -test statistic ($H \simeq 6000$ for Vela and $H \simeq 2700$ for Geminga). Formally applying Equation (8), these correspond to nominal significances of the order of tens of σ ; given that this approximation was calibrated by [27] against a limited number of Monte Carlo trials, we do not regard the exact numerical value as physically meaningful beyond stating that both detections vastly exceed the 5σ threshold conventionally required to claim a firm detection. For both Vela and Geminga, this 5σ detection level, roughly equivalent to $H \geq 20$, is achieved within the first month of data taking. The characteristic pulse shapes are successfully reconstructed, including source-specific features such as the well-known bridge emission in the off-pulse region of Vela. The application of PSF-based photon weights enhances the contrast of the pulse profiles by reducing the contribution of photons

less likely to originate from the target source, with a particularly visible improvement in crowded regions of interest. The light curves presented here are integrated over the full energy range from 1 GeV to 10 TeV. This choice maximises the available photon statistics and provides robust phase profiles for the brightest pulsars. Since gamma-ray pulsar profiles may evolve with energy, a natural extension of this work will be to study the energy dependence of the light curves for the brightest sources, such as Vela and Geminga, following approaches similar to those adopted in previous studies [28]. Overall, the results presented in this work confirm the capability of DAMPE to detect and characterise gamma-ray pulsations from bright pulsars. The high H -test values obtained for several sources also support the use of on-orbit gamma-ray observations of bright pulsars as a valuable data-driven tool for validating and refining the instrument response functions, particularly the PSF, in line with recent calibration studies [29].

5. Conclusions

Pulsars are among the brightest astrophysical gamma-ray sources and provide valuable targets for high-energy observations. Using nine years of DAMPE data, this work demonstrates the capability of the instrument to detect and characterise gamma-ray pulsations from several bright pulsars. The new DAMPE event-selection algorithm was applied together with the corresponding instrument response functions. Phase-folded light curves were obtained for nine pulsars using a timing pipeline based on PINT, with the results for Vela and Geminga presented in detail in this work. The reconstructed pulse profiles, together with the high values of the H -test statistic, confirm the robustness of the timing and weighting procedures adopted in this analysis. These results also underline the importance of pulsar observations as a data-driven tool for validating and refining the instrument response functions, particularly the PSF. Previous DAMPE studies have already demonstrated the feasibility of gamma-ray pulsar analyses with early mission data [30]. The present work extends this effort by exploiting a longer data set, updated event selection, dedicated IRFs, and a PSF-weighted timing analysis based on PINT. Overall, this work strengthens the role of DAMPE in gamma-ray astronomy and highlights the potential of space-borne cosmic-ray detectors for studies of high-energy astrophysical sources.

Author Contributions: Conceptualization, L.L. and C.P.; methodology, L.L.; validation, L.L. and C.P.; formal analysis, L.L.; investigation, L.L.; resources, C.P.; data curation, J.M.F.; writing—original draft preparation, L.L.; writing—review and editing, C.P. and L.L.; visualization, L.L.; supervision, C.P.; project administration, C.P.; funding acquisition, C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the financial contributions from the Swiss National Foundation (SNSF—TMSGI2_226294). The DAMPE mission was funded by the strategic priority science and technology projects in space science of the Chinese Academy of Sciences (CAS). In China, the data analysis is supported by the National Key Research and Development Program of China (No. 2022YFF0503302) and the National Natural Science Foundation of China (Nos. 12220101003, 11921003, 11903084, 12003076 and 12022503), the CAS Project for Young Scientists in Basic Research (No. YSBR061), the Youth Innovation Promotion Association of CAS, the Young Elite Scientists Sponsorship Program by CAST (No. YESS20220197), and the Program for Innovative Talents and Entrepreneur in Jiangsu. In Europe, the activities and data analysis are supported by the Swiss National Science Foundation (SNSF), Switzerland, the National Institute for Nuclear Physics (INFN), Italy, the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (No. 851103), and the Swiss State Secretariat for Education, Research and Innovation (SERI).

Data Availability Statement: DAMPE gamma-ray data are publicly available according to the data policy available at <https://dampe.nssdc.ac.cn/dampe/datapolicy.php> (accessed on 6 March 2026).

Acknowledgments: The authors gratefully acknowledge Paul Ray and Matthew Kerr for their invaluable assistance with the PINT software, guidance on pulsar phase-folding techniques, and provision of the ephemerides used in this study. Their expertise substantially enhanced the quality of our analysis.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BDT	Binary Decision Tree
BGO	Bismuth Germanium Oxide
CNN	Convolutional Neural Network
DAMPE	Dark Matter Particle Explorer
GCRS	Geocentric Celestial Reference System
GPS	Global Positioning System
HET	High-Energy Trigger
IRF	Instrument Response Function
MAD	Median Absolute Deviation
MET	Mission Elapsed Time
PINT	PINT Is Not Tempo2
PSD	Plastic Scintillator Detector
PSF	Point Spread Function
STK	Silicon–Tungsten tracKer-converter
TOA	Time Of Arrival
TT	Terrestrial Time

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