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Search for Pulsed VHE Gamma-Ray Emission from Young Pulsars with H.E.S.S.

M. FÜSSLING[1], S. SCHLENKER[2] AND C. VENTER[3] FOR THE H.E.S.S. COLLABORATION, T. EIFERT[4], R. MANCHESTER[5] AND F. SCHMIDT[6]

[1] *Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany*
[2] *CERN PH Department, CH-1211 Geneva 23, Switzerland*
[3] *Unit for Space Physics, North-West University, Potchefstroom 2520, South Africa*
[4] *Université de Genève, Section de physique, 24 Quai Ernest-Ansermet, CH-1211 Geneva 4, Switzerland*
[5] *Australia Telescope National Facility, CSIRO, PO Box 76, Epping NSW 1710, Australia*
[6] *Department of Astronomy and Astrophysics, The University of Chicago, IL 60637, USA*
fuessling@physik.hu-berlin.de

Abstract: We present the results of a search for pulsed very-high-energy (VHE) γ-ray emission from young pulsars using data taken with the H.E.S.S. imaging atmospheric Cherenkov telescope system. Data on eleven pulsars, selected according to their spin-down luminosity relative to distance, are searched for γ-ray signals with periodicity at the respective pulsar spin period. Special analysis efforts were made to improve the sensitivity in the 100 GeV γ-ray energy domain in an attempt to reduce the gap between satellite and ground-based γ-ray instruments. No significant evidence for pulsed emission is found in any data set. Differential upper limits on pulsed energy flux are determined for all selected pulsars in the approximate γ-ray energy range between 100 GeV and 50 TeV, using different limit determination methods, testing a wide range of possible pulsar light curves and energy spectra. The limits derived here imply that the magnetospheric VHE γ-ray production efficiency in young pulsars is less than 10^{-4} of the pulsar spin-down luminosity, requiring spectral turnovers for the high-energy emission of four established γ-ray pulsars, and constrain the inverse Compton radiation component predicted by several outer gap models.

Introduction

Rotating neutron stars are known to convert a significant part of their rotational energy into radiation that originates from within the magnetosphere. This emission is observable as a periodic signal at the neutron star rotation frequency (the *pulsar* phenomenon). For many of the known young and energetic pulsars, the emitted luminosity peaks at X-ray or γ-ray energies [2] and is usually attributed to curvature radiation of accelerated electrons in the strong magnetic fields pervading the pulsar magnetosphere. The luminosity of the pulsed high-energy emission was found to correlate significantly with the energy loss rate of the pulsar, i.e. its spin-down power $\dot{E}$ [3, 4]. For most of the pulsars with established γ-ray emission [5], there is evidence for a turnover in the pulsed spectrum at a critical energy $E_{\rm c}$ in the sub-GeV to 10 GeV range.

The two most commonly discussed scenarios for magnetospheric γ-ray emission place the emission regions either near the magnetic poles of the neutron star (*polar cap* model), or near the null surface in the outer magnetosphere of the pulsar (*outer gap* model) . Both models predict a cutoff in the curvature radiation spectrum at γ-ray energies of the order of GeV up to several tens of GeV. Additionally, in some outer gap model calculations, a spectral component in the TeV range due to inverse Compton (IC) up-scattering of soft ambient seed photons by the accelerated electrons is predicted [6, 7].

The prime candidates for the search for very-high-energy (VHE, energies above ~ 100 GeV) γ-ray emission are the pulsars with established γ-ray emission at energies below ~ 10 GeV which have been detected by CGRO instruments. Some of them have been subject to intensive searches for pulsed VHE γ-ray emission by ground-based in-

Table 1: The characteristics of the selected pulsars taken from [1]. Period, P, distance, D, spin-down age, spin-down luminosity, $\dot{E}$, and the corresponding value for $\dot{E}/D^2$, and calculated magnetic field strength at the neutron star surface, $B_{\rm surf}$, and the light cylinder, $B_{\rm LC}$, are listed. The last column shows the rank in $\dot{E}/D^2$ within the ATNF catalogue.

Pulsar name PSR		P [ms]	D [kpc]	Age [kyears]	$\log_{10}\left(\frac{\dot{E}}{\rm erg\,s^{-1}}\right)$	$\log_{10}\left(\frac{\dot{E}/{\rm erg\,s^{-1}}}{D^2/{\rm kpc^2}}\right)$	$B_{\rm surf}$ [10^{11} G]	$B_{\rm LC}$ [10^4 G]	Rank $\dot{E}/D^2$
B0531+21⋆	J0534+2200	33.1	2	1.24	38.7	38.1	37.8	98.0	1
B0833−45⋆	J0835−4510	89.3	0.29	11.3	36.8	37.9	33.8	4.45	2
B1706−44⋆	J1709−4429	102	1.8	17.5	36.5	36.0	31.2	2.72	6
B1509−58⋆	J1513−5908	151	4.4	1.55	37.3	36.0	154	4.22	7
	J1747−2958	98.8	2.5	25.5	36.4	35.6	24.9	2.42	13
B1259−63	J1302−6350	47.8	1.5	332	35.9	35.5	3.3	2.87	15
	J1811−1925	64.7	5	23.3	36.8	35.4	17.1	5.92	18
	J1524−5625	78.2	3.8	31.8	36.5	35.3	17.7	3.46	19
	J1420−6048	68.2	7.7	13	37.0	35.3	24.1	7.13	22
	J1826−1334	101	4.1	21.4	36.4	35.2	27.9	2.51	23
	J1801−2451	125	4.6	15.5	36.4	35.1	40.4	1.95	30

⋆ established as γ-ray pulsars below $\sim 10\,$GeV by EGRET

struments. Up to now, no evidence for pulsed emission has been found in these observations, and upper limits on the pulsed VHE γ-ray flux have been derived under various assumptions on the characteristics of the pulsed emission. However, the IC component predicted by outer gap models has not yet been significantly constrained.

H.E.S.S. Observations and Analysis

The High Energy Stereoscopic System (H.E.S.S.) [8], an array of imaging atmospheric Cherenkov telescopes located in the Khomas Highland of Namibia, detects cosmic VHE γ-rays by imaging the Cherenkov emission of their air showers in the atmosphere using optical telescopes. The superior sensitivity of H.E.S.S. with respect to previous ground-based instruments puts the predicted pulsed IC component from outer gap models within reach of testability.

Apart from the known γ-ray pulsars, other candidates for which H.E.S.S. data were available were selected from the ATNF pulsar catalogue [1] if their spin-down flux $\dot{E}/D^2$ was greater than $10^{35}\,{\rm erg\,s^{-1}\,kpc^{-2}}$. Table 1 lists all candidates chosen along with selected measured and derived characteristics collected from the literature.

The data used in this search for pulsed VHE emission were either obtained in pointed observations or accumulated in the Galactic Plane survey and were analysed using the standard method as described in detail in [9]. Since observational data indicate steep cut-offs in high-energy (GeV) γ-rays, special *low energy* cuts have been applied in addition to the standard cuts to reduce the gap in observational coverage between satellite and ground-based γ-ray observations of young pulsars.

Search for Pulsed Emission

In order to test for pulsed γ-ray emission at the pulsar position, the timestamps of each recorded shower passing selection cuts were transformed from the observer's frame into the pulsar frame and then folded with the pulsar spin period taken from observations in other energy domains. The resulting distribution of pulsar phases corresponding to each shower event was tested for variability using several statistical tests (χ^2-, Z^2_m-, H- and Kuiper-test).

As an example, the distribution of event phases from observations of the Vela Pulsar (PSR B0833−45) is shown in Fig. 1 for the signal (*on*) and background (*off*) region, obtained using the standard cuts. The difference between on and off results from the known γ-ray excess from HESS J0835−456 at the position of the pulsar.

No conclusive evidence for pulsed emission has been found with any of the statistical tests for pulsations for any data set of the complete sample of pulsars. The distribution of the test statistic H of the H-test is compatible with the expected distribution of H for the case when no pulsed signal is present in any data set, see Fig. 2.

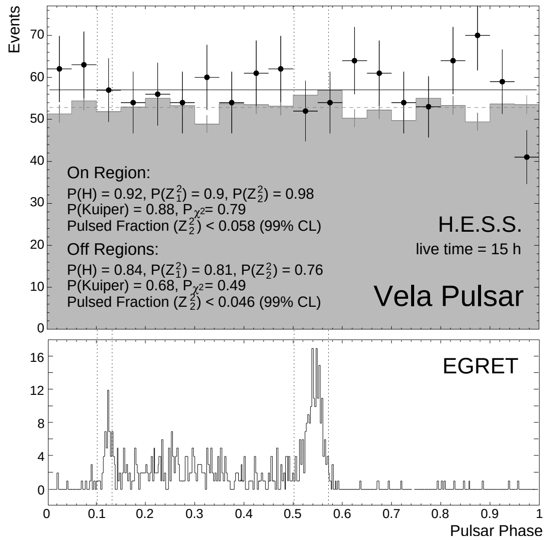

Figure 1: *Upper plot*: Distribution of event phases for the Vela pulsar (PSR B0833−45). The points represent the events in the on-region at the pulsar position and the histogram the normalised off-region events. For both regions the probabilities for being consistent with a uniform distribution according to the statistical tests on pulsations are listed. No significant deviation from uniformity was found within any of the statistical tests for pulsations. *Lower plot*: Phase distribution for γ-rays with energies between 2 and 10 GeV as measured by EGRET [5].

Several methods were applied to obtain upper limits on the γ-ray flux from the selected pulsars. They differ in the assumptions made concerning the characteristics of the pulsed emission. The *on-off-pulse* method assumes similar characteristics of the pulse position and shape as measured in other energy domains for the hypothetical VHE γ-ray emission whereas the *pulsed fraction* method only assumes a certain pulse shape. As an example, the calculated differential flux limits are shown for Crab and Vela, two of the four observed γ-ray pulsars, in Fig. 3 and 4, respectively. For more details on the analysis and the limits derived for all selected pulsars refer to [10].

For the complete sample of pulsars, the absence of pulsed VHE γ-ray emission already disfavours a significant contribution of the IC component to the energy loss mechanism of these pulsars. The flux

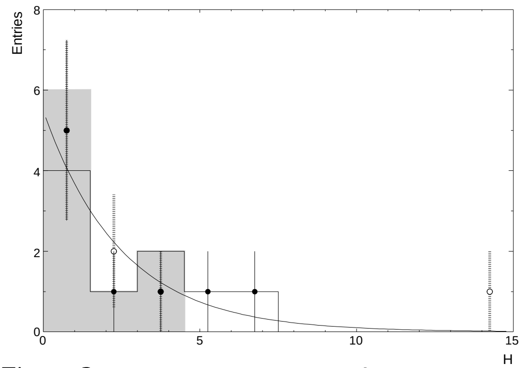

Figure 2: Ensemble distributions of the H-test statistic for the selected pulsars and their corresponding background control samples. The results for the on-region are shown as open and closed circles for the low energy and standard cut analysis, respectively. The distributions for the off-regions are displayed as grey filled and outlined histograms, respectively. The solid curve shows the expected distribution $N_{\rm H}(H) = N_0 \exp(-\lambda H) \,|_{\lambda=0.4}$ if no pulsed signals are present.

limits shown here for Crab and Vela significantly constrain the IC component of selected outer gap models for flux predictions in the TeV range.

Conclusions

No conclusive evidence for pulsed emission has been found and differential upper limits on the pulsed flux were derived, constraining the pulsed flux for a wide range of possible pulse shapes and spectra in the VHE γ-ray range.

Although in several cases there is spatial coincidence with extended TeV γ-ray emission, pulsed emission is not detected in VHE γ-rays. In particular, the flux upper limits derived are of the order of 10^{-4} to 10^{-6} of the pulsar spin-down flux, underlining the non-magnetospheric origin of the TeV radiation component and supporting the widely accepted scenario of an effective energy transport mechanism to, and strong particle acceleration in, the pulsar wind nebula.

The upper limits imply a steep turnover of the pulsed high-energy spectrum at energies of a few tens of GeV. As the pulsar models differ significantly in their predictions of the exact shape and energy of the turnover, the search for pulsed

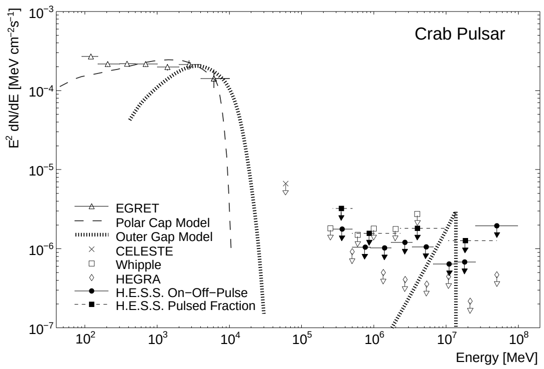

Figure 3: H.E.S.S. energy flux limits (99% c.l.) for pulsed emission of the Crab pulsar. The full circles and full squares correspond to the on-off-pulse and pulsed fraction limit determination methods, respectively. Below energies of 0.5 TeV the results were obtained with the low energy selection cuts, otherwise the standard cuts were used. The indicated polar cap curve was generated according to [11] and the outer gap model curve taken from [12]. Note that the southern location of H.E.S.S. allows only observations at rather high zenith angles for Crab, prohibiting a deep exposure especially at low energy thresholds.

γ-ray emission from pulsars provides interesting prospects for future satellite-based and ground-based γ-ray instruments.

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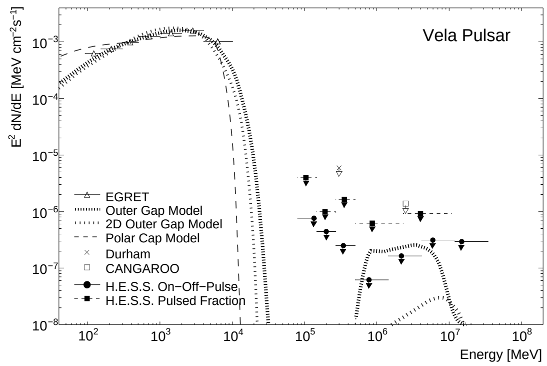

Figure 4: H.E.S.S. energy flux limits (99% c.l.) for pulsed emission of the Vela pulsar (see Fig. 3 for point descriptions). The polar cap (black dotted) and outer gap (dashed) model curves are generated according to the model of [11] and [6], respectively. The dotted grey outer gap model curve is taken from [7].

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