

Search for Pulsed VHE γ -ray Emission from Young Pulsars with H.E.S.S.

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Pulsars are commonly regarded as highly magnetized neutron stars, rotating up to several hundred times per second. Over 1,500 radio pulsars have been found so far, about 70 of which are X-ray pulsars, but only a handful have been observed in γ rays. This high-energy emission is believed to be produced by the electrons accelerated to TeV energies in the pulsar magnetosphere, resulting in cascades of secondary particles. The H.E.S.S. experiment is a system of four imaging atmospheric Cherenkov telescopes in Namibia, which is sensitive to γ rays above 100 GeV. Three young pulsars, Crab, Vela, and PSR B1706-44 have been observed with H.E.S.S. The results of the search for pulsed emission for these targets, and the constraints on the theories of pulsed very high energy γ -ray emission, are summarized here.

1. Introduction

The EGRET telescope on the Compton Gamma Ray Observatory (CGRO) identified at least six young spin-powered γ -ray pulsars [1] at energies up to 20 GeV. A search for pulsed emission above 20 GeV remains to be successful for ground-based Cherenkov instruments. Despite a reduction of the energy threshold down to 60 GeV [2], achieved with the the non-imaging telescopes, no evidence of a pulsed signal has been seen so far. It is widely accepted that this unexplored energy region is vital to address the long-standing question of how and where high energy emission emerges from the pulsar.

Polar cap models (for review of the models see [3]) assume that particles are accelerated right above the neutron star surface and that γ rays emanate from curvature radiation or inverse Compton induced pair cascades in a strong magnetic field. On the other hand *outer gap* models consider particle acceleration which occurs along null charge surfaces in the outer magnetosphere where γ -rays result from photon-photon pair production-induced cascades. These two types of basic models make rather different predictions, particularly of the spectral characteristics of pulsed γ -ray emission. Detection and study of this high energy emission, which is closely tied to the primary population of radiating particles, seems to be a good discriminant between pulsar models.

The *High Energy Stereoscopic System* (H.E.S.S.) of four imaging atmospheric Cherenkov telescopes with a low energy threshold of 100 GeV at zenith and below 1% Crab flux sensitivity for long exposures [4] was used for observations of three young pulsars: the Crab and Vela pulsars, and PSR B1706-44, characterized by their high-ranking position on a list of pulsars ordered by the parameter \dot{E}/d^2 , which ultimately determines pulsar luminosity at high energies for a given pulsar age. Here \dot{E} is the spin-down energy loss rate, and d is the distance determined from the dispersion measure to the object. The spectra of the EGRET-detected pulsars can be described quite well by simple power laws with spectral indices in the range 1.39-2.07 [6]. Some of the spectra show clear evidence for a drop in flux at high energy, above few GeV, whereas others have rather large uncertainties in the 4-10 GeV band, which prevent the clear identification of a similar cutoff.

Table 1. Summary of data samples

Source	Setup	Obs. period	t [hr]	E_{th} [GeV]	$\langle \Theta \rangle$ [deg]
Crab	3 Tel.	Oct'03	4.0	350	47
Vela	4 Tel.	Jan-March'04	12.6	235	33
PSR B1706-44	2 Tel. & 4 Tel.	May-July'03 & June-July'04	14.4 + 2.2	255	27

The measured Crab spectrum is a straight power law. Extrapolation of EGRET spectra into the dynamic range of H.E.S.S. suggested that high energy pulsed emission might be observable from these objects within a reasonable exposure time [7]. The outer gap model also supplements pulsed TeV emission via inverse Compton scattering by gap-accelerated particles. The most recent outer gap models [8] have TeV γ -ray fluxes for the Vela pulsar which should be detectable with H.E.S.S.

H.E.S.S. is an array of four atmospheric imaging Cherenkov telescopes, each with 107 m² of mirror area and equipped with a 960 photo-multiplier tube camera [4]. Telescopes are operated in a stereoscopic mode with a system trigger, requiring at least two telescopes to provide images of each individual atmospheric shower in Cherenkov light. H.E.S.S. has large field of view of 5° diameter. The angular resolution for individual γ rays is better than 0.1°. It allows a very good source localization accuracy of 30'' for relatively faint sources, which is important for point-like source (e.g. pulsars) identification.

2. Data Sample & Analysis

A substantial fraction of the data on young pulsars was taken during the construction phase of the H.E.S.S. array, when only two or three telescopes were available. Short summary of data is given in Table 1. The Crab pulsar, located in the northern sky, can be observed with H.E.S.S. only at a rather large average zenith angle ($\langle \Theta \rangle$) and consequently above rather a high energy threshold (E_{th}), whereas Vela and PSR B1706-44 can be seen with H.E.S.S. at much higher elevations. Most of the data were taken in so-called *wobble* source-tracking mode, which is optimal for observations of a point-like source. A few additional hours of observations of PSR B1706-44 have been extracted from the long scan of the galactic plane [5].

Prior to applying analysis cuts, data were selected for adequate recorded image quality, i.e. by applying the generic requirements of a minimum image amplitude (50 photoelectrons) and a maximum distance of the image's centroid from the camera center (35 mrad). Each accepted event was also required to comprise at least two images of adequate quality. The imaging analysis of the H.E.S.S. data is based on the reconstruction of the shower direction for each individual event, and joint parametrization of the shape of the Cherenkov light flash from an individual shower using multiple-telescope approach. Data were analyzed by the standard *directional* cut on θ^2 , where θ is the angular distance between the actual source position on sky and the reconstructed one. In addition data were analyzed by the image *shape* parameters of the mean scaled Width and Length [9] (see Table 2). The analysis cuts were optimized on the Monte Carlo simulated events for the zenith angle range covered in observations of a particular source, and the system configuration used (see Table 1). Details of the methods used to estimate the effective areas, the energy threshold, and the energy for each recorded event are given elsewhere [9]. The upper limits on pulsed γ -ray emission were calculated here using a *model-independent* approach [10], which exploits the energy information provided for each individual event.

The arrival times of the recorded events were registered by a Global Positioning System (GPS) clock with an absolute accuracy of about 1 μ s. The arrival times were recalculated to the solar system barycenter (SSB) by utilizing the JPL DE200 ephemeris [11]. The universal time as measured at the H.E.S.S. site was converted to the SSB arrival time (TDB). The corrected arrival times were transformed into phases of the radio pulse period

Table 2. The γ -ray selection criteria

	Crab	Vela	PSR B1706-44
θ^2 , deg ²	<0.055	<0.02	<0.02
mean scaled Width	<1.0	<0.9	<1.1
means scaled Length	<1.4	<1.3	<1.3

Table 3. The H.E.S.S. upper limits (99%) and parameters of the EGRET spectral fit for three young pulsars

	γ	E_c [GeV]	Phase region	Upper limit [$\text{cm}^{-2}\text{s}^{-1}$]
Crab	2.05	117	[0.32,0.42]&[0.94,0.04]	$F(> 350 \text{ GeV}) < 4.67 \times 10^{-12}$
Vela	1.62	26.5	[0,0.13]&[0.5,0.57]	$F(> 235 \text{ GeV}) < 7.17 \times 10^{-13}$
PSR B1706-44	2.25	71	[0.24,0.5]	$F(> 255 \text{ GeV}) < 1.06 \times 10^{-12}$

using publicly available contemporary pulsar ephemerides obtained from radio observatories, which monitor the pulsars observed with H.E.S.S. on a monthly basis. The resulting phasogram for each of observed pulsars was a subject to a number of statistical tests, i.e. χ^2 , Z_m^2 , H (for details see [12]), which allow the assessment of the significance of a pulsed signal for a variety of possible pulse profiles. A low chance probability of a uniform phasogram, i.e. less than 10^{-3} , derived from any of these tests might indicate a pulsed signal.

In order to verify the periodic analysis procedure, observations of the optical emission from Crab pulsar have been performed with a single stand-alone H.E.S.S. telescope. The optical data were folded to produce the phases using full chain of the H.E.S.S. periodic analysis tools. The distinct double-peaked optical light curve of the Crab pulsar at the correct phase was clearly resolved, which validates the periodic analysis [13].

3. Results & Discussion

Data taken with the H.E.S.S. system of four imaging atmospheric Cherenkov telescopes have been used to search for pulsed γ -ray emission from the Crab, Vela pulsars, and PSR B1706-44. No pulsed emission was found at the radio period for any of these pulsars, and corresponding upper limits on integral as well as on differential flux have been derived (see Table 3, Figure 1). The upper limits have been calculated for the phase regions selected according to the EGRET peak areas.

To extract the low energy events exclusively, we analyzed the data using a set of tightly adjusted cuts. In particular the total image amplitude must be less than 100 photoelectrons and maximum distance must not exceed 18 mrad. Such analysis resulted in differential upper limits (99%) of $dN/dE(232 \pm 51 \text{ GeV}) = 3.94 \times 10^{-11} \text{ cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$ for the Crab pulsar, and $dN/dE(75 \pm 12 \text{ GeV}) = 5.2 \times 10^{-10} \text{ cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$ for PSR B1706-44. Note that a disadvantage of this analysis is that it drastically suppresses the γ -ray acceptance at higher energies.

We modelled the pulsed γ -ray spectrum using the following form $dN/dE = CE^{-\gamma}e^{-E/E_c}$, where C is the EGRET measured normalization constant, γ is the index of the known EGRET power-law spectrum, and E_c is the maximal cutoff energy, which is consistent with the integral upper limit given in Table 3. The cutoff energy can be constrained as $\int_{E_{th}}^{\infty} (dN/dE)dE \leq F(> E_{th})$. Derived cutoff energies for three young pulsars observed with H.E.S.S. are given in Table 3. The stringent integral upper limits above 200-300 GeV reported here for three young pulsars after rather limited exposures with H.E.S.S. appear to be still above the predictions by the polar cap and outer gap models at these energies. Therefore, these upper limits cannot be used to discriminate between two competing models. However, they can severely restrain the luminosity of pulsed γ -ray emission. In addition, for the Vela pulsar the outer gap model predicts a rather flux emission via inverse Compton scattering at TeV energies [8], which is inconsistent with the model-independent H.E.S.S.

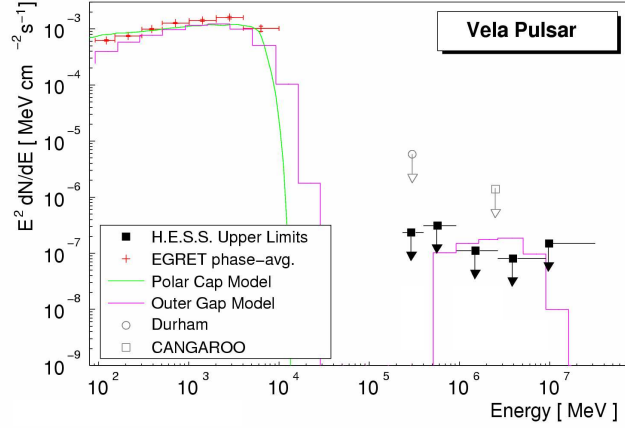


Figure 1. The energy spectrum of the pulsed emission from the Vela pulsar as measured by EGRET together with the H.E.S.S. upper limits. Predictions from the polar cap (solid curve) [3] and outer gap model (histogram) [8] are also shown. Other TeV upper limits are given for Durham [14] and CANGAROO [15] experiments.

upper limits reported here. The inverse Compton flux level depends on the emission spectrum mainly in the infra-red band, which is difficult to measure in most pulsars. Thus the H.E.S.S. upper limits in particular for Vela pulsar constrain the density of local soft photon field in the gap.

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