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VHE γ-ray observations of the pulsar PSR B1951+32 and its associated nebula CTB 80 with the MAGIC Telescope

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Abstract: Observations of pulsars and pulsar wind nebulae have been conducted during the last two years using the MAGIC Imaging Cerenkov Telescope. In addition to the study of the nebula emission, the low energy threshold of MAGIC offers the opportunity to search for the pulsed emission with very high sensitivity. The selection of the objects was based on their spin-down luminosity and the probability of emission given by various models of VHE γ-ray production above 100 GeV. We present the results of these observations and their implications for models of VHE emission.

Introduction

The observations of pulsars and their SNR in the HE and VHE γ-ray domain allows one to study particle acceleration in these objects and how they contribute to the ultra relativistic charged cosmic rays population in our Galaxy. The selection of pulsars as candidates for observation with MAGIC is guided by theoretical predictions and observational constraints, e.g. by a high spin-down luminosity. From these considerations the other best candidate besides the Crab pulsar is PSR B1951+32, one of the three rotation-powered high energy pulsars detected by EGRET in the northern hemisphere. PSR B1951+32 is the only source observed in γ-rays by EGRET up to 20 GeV with no evidence of a cutoff in the differential spectrum.

PSR B1951+32 was first detected in radio (Kulkarni et al., 1988). In γ-rays the system was studied with EGRET (Ramanamurthy et al., 1995). Between 100 MeV and 20 GeV the spectral index of the pulsar was found to be -1.8. From the low magnetic field strength ($\sim 0.1 B_{Crab}$) one expects a cutoff in the γ-ray spectrum at a few tens of GeV.

The pulsar is associated with the core of the radio nebula CTB 80. The nebula has a cometary shape in X-rays [13] produced by the pulsar's high proper motion (240$\pm$40 km/s) [15]. Bednarek and Bartosik [4] predict a γ-ray flux above 200 GeV of ~ 4% of the Crab flux.

In previous studies at GeV-TeV energies by the Whipple collaboration [17] an upper limit on the spectral cutoff energy of 75 GeV and an upper limit of $\leq 1.95 \times 10^{-11}$ cm^{-2}s^{-1} on the steady emission above 260 GeV have been determined.

Observation and analysis

Observation of pulsars and their nebulae presented here have been performed with the MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescope [14], located on the Canary Island La Palma (2200 m asl, 28.45°N,17.54°W). The data were collected between July 4^{th} and September 17^{th} of 2006 for a total of 31 hours in the so-called ON/OFF observation mode. The observations was restricted to a zenith angle range (5°-25°), result-

E_{th} (GeV)	Excess evts.	Significance (σ)	Flux U.L. (cm^2s^{-1})
140	-64	-0.2	1.5×10^{-11}

Table 1: Results of the analysis in search for steady γ-ray emission.

ing in the lowest possible energy threshold of ~ 60 GeV. A point source with a γ-ray flux of $\sim$ 3% of the Crab nebula and the same spectrum can be detected by MAGIC on a significance level of $5\,\sigma$ within 30 hours [2].

Following calibration of the data [8] and some image cleaning a Hillas parameterization of the shower images was applied [10]. We required a minimum pixel content of 6 photoelectrons (phe) for core pixels and 4 phe for boundary pixels with the additional condition of a time coincidence of less than 7 nsec between adjacent pixels. We used the Random Forest procedure for background suppression [5]. The Random Forest method is also used to estimate the event energy. Typical energy resolutions are 30% at low energies (< 150 GeV) and 20% at higher energies.

Results

In our analysis we have searched for steady γ-ray emission from a point source (a), as well as from an extended source (b) and also for pulsed γ-ray emission (c).

a The search for steady γ-ray emission from the position of the pulsar yielded no significant excess. Hence upper limits were calculated using the method of Rolke. The integral upper limits were calculated assuming a spectral index of 2.6. Table 1 lists the upper flux limit for steady emission above 140 GeV. In Figure 1 upper limits are shown as function of energy are together with the Whipple upper limits, the Crab flux (100%, 10%, 1%) and the predictions from Bednarek and Bartosik [3].

b Similar to the steady emission analysis from a point-like source we have searched for extended or displaced γ-ray emission within a

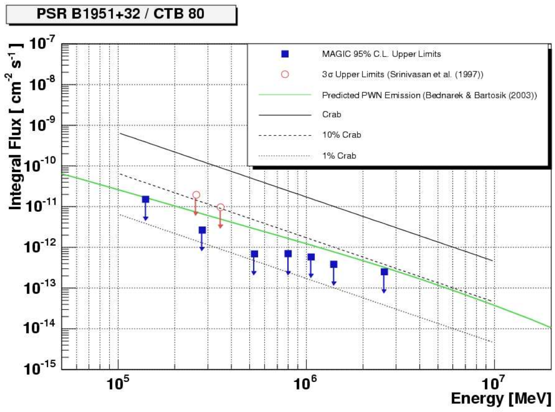

Figure 1: Integral upper limits (95% C.L.) on the steady γ-ray emission from the direction of PSR B1951+32/ CTB 80. For comparison, the Crab nebula γ-ray flux (Otte et al. ICRC, these proc.)(black line) and Whipple u.l. (red circles) are also indicated.

FoV of $\sim 0.6^o$ radius. Using the so-called DISP-method [7] we reconstructed the γ-ray arrival direction with an accuracy of $\sim 0.1\,^o$. Figure 2 shows the γ-ray excess significance in a sky map around PSR B1951+32 for E$\gtrsim$ 200 GeV.

c The analysis chain for the γ-ray pulsed emission was tested on Crab optical emission data (Lucarelli et al., 2007, ICRC, these proc.). The event arrival times, derived from a GPS-controlled Rubidium clock with a precision of $\sim$ 200 ns, were transformed to the solar system barycentre by using the TEMPO timing package. The corrected arrival times were folded to the pulsar period using contemporary ephemeris provided by Lyne (2006).

Periodicity was searched for in the folded arrival times with the H-Test [6] and the Pearson's χ^2-Test. No signature of pulsed emission was found in four independent energy bins. The corresponding 95% c.l. upper limits on the pulsed γ-ray flux, derived from the H-Test, are shown in Figure 3. For our calculation we assume a pulsar duty cycle of 36%, which is motivated by observations

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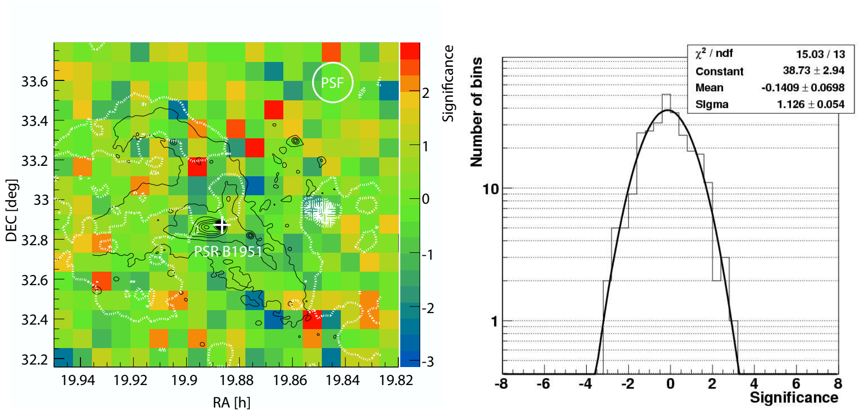

Figure 2: Significance of VHE γ-ray emission from a binned region of (0.1×0.1) deg^2 (E $\gtrsim$ 200 GeV). Left: Sky map centered at PSR B1951+32 coordinates. Right: Significance distribution.

with EGRET. An independent analysis for events with energies above 75 GeV also gave no hint of pulsed emission, numbers shown in Table 2. From the upper limit of pulsed excess event, derived from the H-Test, we determine a new upper limit on the cutoff energy. For this calculation we assume a continuation of the EGRET measured power-law spectrum (Fierro, 1996, PhD Thesis) attenuated by an exponential cutoff and convoluted with the effective collection area of the telescope. By varying the cutoff energy until the expected number of excess events agrees with our derived upper limit on the excess events we find a new cutoff energy of 32 GeV. Figure 3 shows the extrapolated EGRET spectrum assuming a cutoff energy equivalent to our newly determined upper limit. Also shown in the figure are predictions of the polar cap [9] and outer gap model [11].

Conclusions

Despite favorable theoretical predictions no γ-ray emission has been detected from the pulsar or the associated nebula.

The upper limits on steady emission constrain the predictions by ?. Although their model takes into account the temporal evolution of the nebula (but not the spatial evolution), the acceleration of leptons and therefore also the equilibrium spectrum of leptons inside the nebula still depends on a few free parameters. These parameters, e.g. the density of the medium surrounding the PWN, the acceleration efficiency of leptons, or the magnetization parameter of the pulsar wind at the shock region, are not well constrained by observations.

Another aspect is that the model of [4] deals with PWNe which are well confined by the external medium, and pulsars which are, at most, moving slowly through the interstellar medium (the prototype of such a nebula is the Crab nebula). Only in such a scenario a well localized γ-ray source should be expected, whereas, when the pulsar is moving very fast, the γ-ray emission will be distributed over a larger volume. In the case of PSR B1951+32, which is moving with an apparent velocity $v_{\rm PSR} = 240 \pm 40$ km s^{-1} [15], the γ-ray flux estimated by [4] will be smeared over an area with a diameter d of at least $d = v_{\rm PSR} \cdot \tau_{\rm PSR} \approx 0.5^\circ$, assuming an age of the pulsar of $\tau_{\rm PSR} = 7 \times 10^4$ years and a distance of the pulsar of 2 kpc.

Considering the pulsed γ-ray emission, we constrain the cutoff of the pulsed emission to $<$ 32 GeV, if the cutoff is an exponential, which is appropriate when the γ-rays are emitted above a few neutron-star radii from the surface. Regarding further that large uncertainties govern the last spectral point measured by EGRET it follows that the allowed energy region where the cutoff resides can

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E_{th}	H-Test			χ^2
(GeV)	Result	(σ)	Flux U.L. (2σ)($cm^2 s^{-1}$)	Result
75	1.4	0.3	4.3×10^{-11}	7.2

Table 2: Results of the analysis in search for pulsed γ-ray emission.

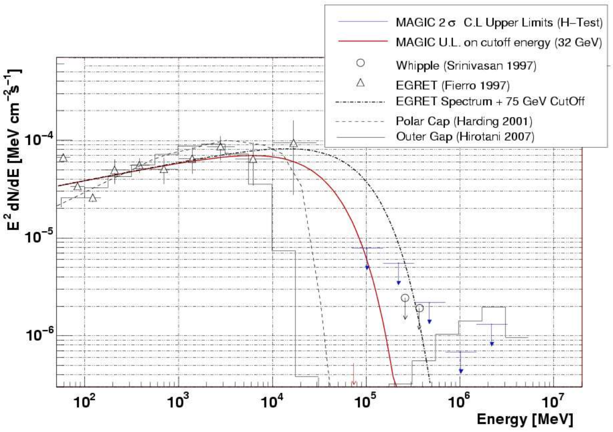

Figure 3: Results of the pulsed emission analysis from PSR B1951+32.

be constrained to be somewhere between 10 and 30 GeV.

Therefore, more sensitive measurements spanning the critical energy range are needed. This will likely be achieved in the future by the next generation of HE observatories (MAGIC-II, HESS-II, GLAST and CTA).

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