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First detection of the Crab pulsar above 25 GeV with the MAGIC Telescope

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For the first time, pulsed γ-rays above 25 GeV from the Crab pulsar have been detected with the MAGIC telescope [1]. All Crab pulsar emission models predict that the energy spectrum of the pulsed emission drops off sharply somewhere between a few GeV and a few tens of GeV. The lack of experimental data at the relevant energies prevented so far the discrimination between the different theoretical scenarios of γ-ray emission in pulsars. The MAGIC measurements reveal that the drop-off in the emitted radiation occurs at relatively high energies, which indicates that the emission must occur far out in the Crab pulsar's magnetosphere. All models in which the emitting region is located close to the Crab pulsar's surface (e.g., the so-called polar cap model) are ruled out by the MAGIC results.

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1. Introduction

Observations with the EGRET instrument on-board *Compton Gamma-Ray Observatory* [2] led to the detection of the Crab pulsar up to energies of $\sim$ 10 GeV, in addition to other six γ-ray pulsars and a few more likely candidates [3]. Whereas some of these pulsars are amongst the brightest sources in the GeV sky, only their plerions appear to be visible at TeV energies. The non-detection by the previous generations of Cherenkov telescopes of pulsed sub-TeV γ-rays from EGRET pulsars, suggested that their pulsed spectra should terminate at energies below a few hundred GeV. This is not unexpected, since both *polar cap* [4] and *outer gap* [5] models predict that the spectra of γ-ray pulsars should cut off at energies between a few GeV and a few tens of GeV. In the polar cap model, electrons are accelerated above the polar cap radiating γ-rays via synchro-curvature radiation. Since these γ-rays are created in superstrong magnetic fields, magnetic pair production is unavoidable. This produces electron-positron pairs which in turn radiate more γ-rays, and a γ-ray/$e^{+/-}$ cascade develops (see Fig. 1). Only those secondary photons which survive pair creation (a few GeV for typical pulsars) escape to infinity as an observed pulsed emission. A natural consequence of the polar cap process is a superexponential cutoff of the spectrum above a characteristic energy E_0. In the outer gap model γ-ray production is expected to occur near the light cylinder of the pulsar. In this case the cutoff is determined by photon-photon pair production, which has a weaker energy dependence compared to magnetic pair production, and therefore a higher energy cutoff may be observable.

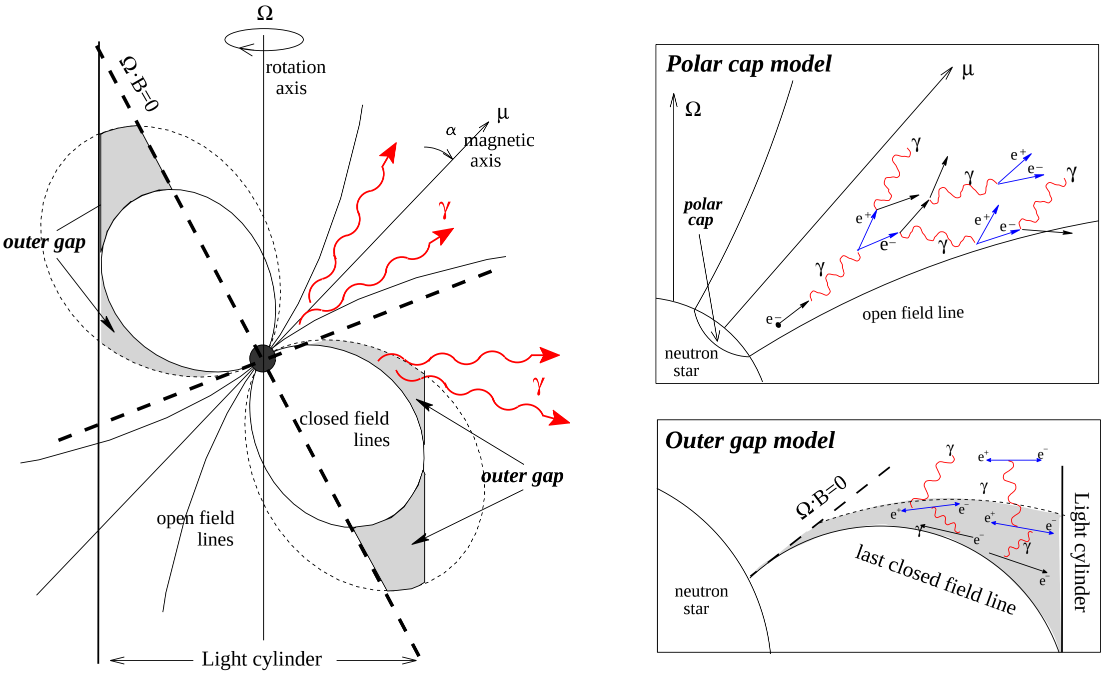

Figure 1: A sketch of a pulsar's magnetosphere (left) and illustration of the most populars γ-ray emission mechanisms (right).

A low-energy threshold ground-based γ-ray telescope, as MAGIC, should be able to overcome the superexponential cutoffs expected near 10 GeV and detect pulsed γ-rays. This would allow to measure the spectral shape of the pulsed emission in the relevant energy range, and therefore to discriminate between polar cap and outer gap models.

2. The MAGIC Telescope

The 17 m diameter MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescope is a state of the art instrument for exploring the very high energy γ-ray Universe. It is located on the Roque de los Muchachos Observatory, at La Palma island (Spain). MAGIC was built and is operated by a large international collaboration, including about 150 researchers. A γ-ray source emitting at a flux level of 1.6% of the Crab Nebula can be detected at a 5 σ significance level in 50 hours of observations. The relative energy resolution above 100 GeV is better than 30% and the angular resolution is $\sim 0.1^\circ$. The construction of a second telescope is now in its final stage and MAGIC will start stereoscopic observations in the coming months.

MAGIC works by detecting the faint flashes of Cherenkov light produced when γ-rays (or cosmic-rays) plunge into the earth atmosphere and initiate showers of secondary particles. The Cherenkov light emitted by the charged secondary particles is reflected by the telescope mirror and an image of the shower is obtained in the telescope camera (see Fig. 2). An offline analysis of the shower images allows the rejection of the hadronic cosmic ray background, the measurement of the incoming direction of the γ-rays, and the estimation of their energy.

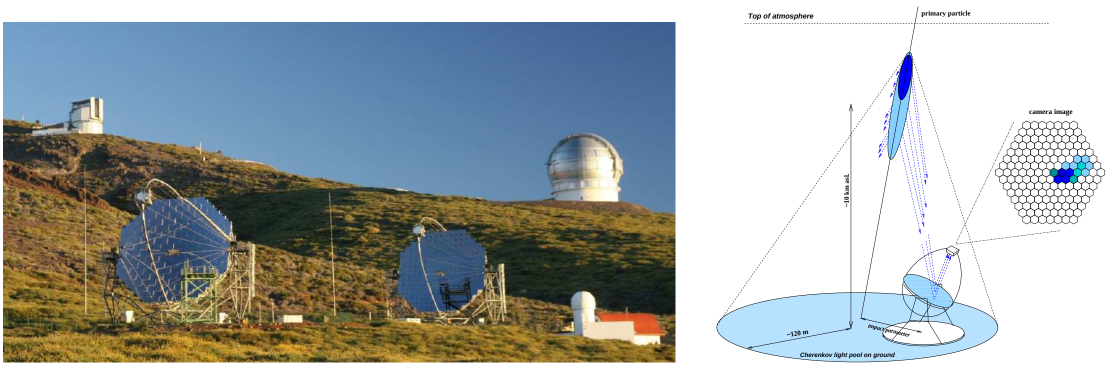

Figure 2: Left: The two 17 m diameter MAGIC telescopes atop Roque de los Muchachos on the Canary Island of La Palma. Right: The telescopes detect γ-rays through short light flashes that are produced when γ-rays cross the atmosphere. An image of the shower is obtained in the telescope camera.

The MAGIC telescope was built with the aim of achieving the lowest possible energy threshold, and since 2004 it operates with the lowest threshold worldwide, namely $\sim$ 50 GeV. However, even this low threshold turned out to be too high to get a clear signal from the Crab pulsar [6]. This lead the MAGIC collaboration to build an innovative trigger concept aimed at lowering the threshold by a factor of 2. This new trigger is based on the analogue summation of the signals coming from clusters of 18 pixels, instead of discriminating single PMT signals (as it is done in the MAGIC standard trigger). At low energies, this approach provides a better discrimination of the faint flashes of Cherenkov photons from the night sky background [7].

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3. Observations and data analysis

After having installed and commissioned the new trigger system in October 2007, we started to observe the Crab pulsar. The observations were performed between October 2007 and February 2008 at zenith angles below 20°, i.e. in a range where the energy threshold of MAGIC is lowest. Together with each event image we recorded the absolute arrival time of the corresponding cosmic ray with a precision of better than 1 μs from a GPS receiver, and we recorded simultaneously also the optical signal of the Crab pulsar with a PMT in the center of the camera [8]. The detection of the Crab pulsar in the optical wavelength range is a cross-check for the correctness of our timing analysis.

After rejection of data taken under unfavorable weather conditions, 22.3 hours of observation remained for analysis. We processed the data with three independent analysis chains, which all gave consistent results. In the analysis, each shower image is cleaned to remove the influence of the night sky background, and parameterized to describe its main features. One image parameter is the brightness of the image (SIZE) in photoelectrons, which is a good estimator of the energy of the primary particle. Other parameters are the orientation of the image with respect to the source position in the camera (angle ALPHA), and several additional parameters, which describe the shape of the image. We apply soft hadron rejection cuts, consisting basically in a cut in SIZE to select only low energy showers, and a SIZE dependent cut in ALPHA optimized on simulated Monte Carlo γ-ray events.

For the search of pulsed emission, the arrival time of each event was transformed to the barycenter of the solar system with the TEMPO pulsar timing package [9], and in a second analysis with our own code [10]. After transformation to the barycenter, we calculated for each event the corresponding rotational phase of the Crab pulsar using contemporaneous measurements of the rotation frequency, phase and its derivative in radio wavelengths, provided by the Jodrell Bank Radio Telescope [11].

4. Results and discussion

Figure 3 compares our pulse phase profiles for the γ-ray data above 25 GeV and in the optical waveband with measurements from the EGRET satellite above 100 MeV. In all profiles a pronounced signal is visible at the position of the main pulse (at phase 0) and at the position of the inter pulse. The significance of the pulsed signal in the γ-ray data was evaluated by three different methods. The first method is a single hypothesis test and assumes that γ-ray emission is expected in two phase intervals around the main pulse and inter pulse, respectively. For the selection of the two signal intervals we adopt the definition of the main pulse (phase -0.06 to 0.04) and inter pulse (phase 0.32 to 0.43) given by [12]. The background is estimated from the remaining events outside of the intervals. In this way we obtain a significance of 6.4 σ. The other tho methods are uniformity tests: the H-Test [13] (a periodicity test that is commonly used for periodicity searches) and the well known Pearson's χ^2 that tests the null hypothesis that the pulse profile follows a uniform distribution, both given also a significance close to 6 σ.

With the present detection one can for the first time determine the cutoff energy in the spectrum of the Crab pulsar and thus put a stringent constraint for models of high energy γ-ray emis-

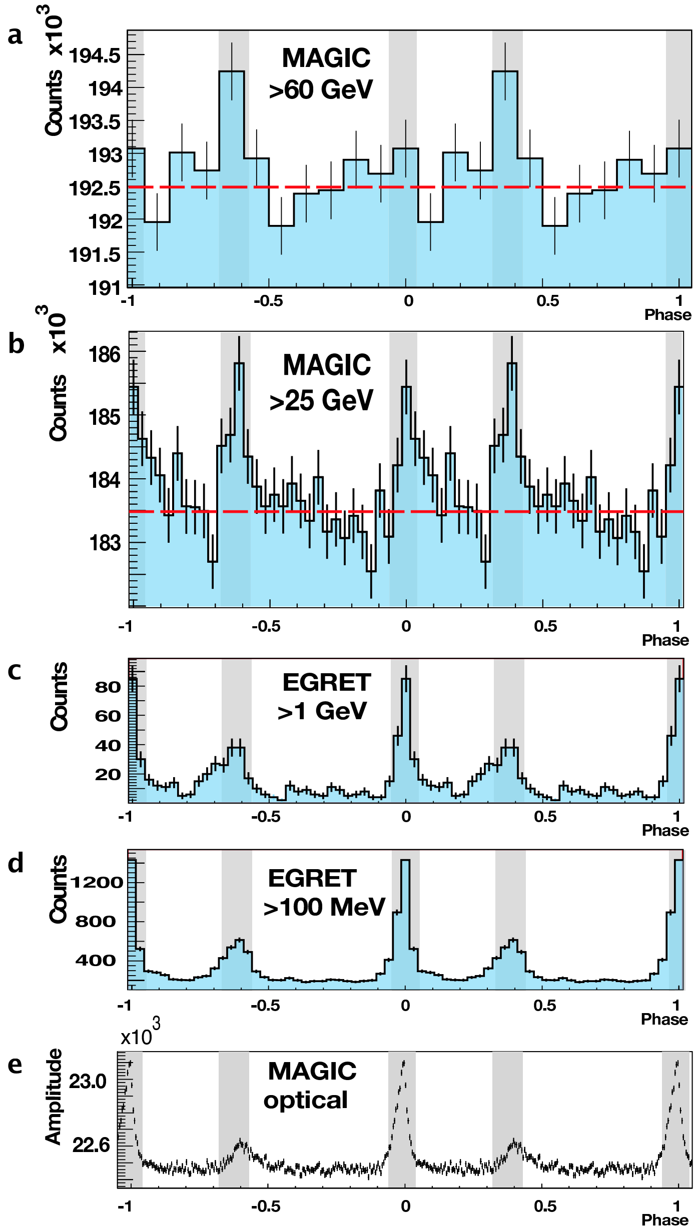

Figure 3: Crab pulsed emission in different energy bands. The shaded areas show the signal regions for the two peaks P1 and P2, as defined in [12]. Optical emission measured by MAGIC with its central pixel [8]. The optical signal has been recorded simultaneously with the γ-rays. Both peaks are in phase for all energies. The ratio of P2/P1 increases with energy from (D) to (A).

sions. We evaluated the cutoff energy by extrapolating the energy spectrum measured by EGRET (between 100 MeV and 1 GeV) [12] to higher energies, and by assuming two different cutoff shapes. If we assume an exponential cutoff (Flux$\times \exp(-E/E_0)$), the measured signal is compatible with a cutoff energy E_0 of $17.7 \pm 2.8_{\mathrm{stat}} \pm 5.0_{\mathrm{sys}}$ GeV. Assuming a superexponential cutoff (Flux$\times \exp(-E/E_0)^2$), we determine a cutoff energy of $23.2 \pm 2.9_{\mathrm{stat}} \pm 6.6_{\mathrm{sys}}$ GeV. The values obtained for the cutoff energy are higher than expected, which allow us to draw important conclusions about the mechanism of γ-ray emission in the Crab pulsar. Using equation 1 of [14] that relates the location of the emission region, r, with the cutoff energy, one obtains for the polar cap scenario $r/R_0 > 6.2 \pm 0.2_{\rm stat} \pm 0.4_{\rm sys}$ (where R_0 is the neutron star radius). This contradicts the basic picture of polar cap scenarios in which γ-rays are emitted very close to the pulsar surface.

5. Summary

We succeeded in the detection of pulsed γ-rays from the Crab pulsar with the MAGIC Cherenkov telescope above 25 GeV. This ends a 30 year-long effort of ground based γ-ray instruments to detect a pulsar at VHE γ-rays. The detection was made possible by the upgrading of the trigger system, which reduced substantially the trigger threshold from about 50 GeV to about 25 GeV. The significance of the pulsed signal is 6.4 σ. We determine the cutoff in the energy spectrum at $17.7 \pm 2.8_{\rm stat} \pm 5.0_{\rm sys}$ GeV assuming that the cutoff is exponential in shape. The cutoff energy shifts to $23.2 \pm 2.9_{\rm stat} \pm 6.6_{\rm sys}$ GeV if the cutoff is superexponential. The high value of the cutoff, and a marginally better fit with a simple exponential point to an acceleration region located at high altitude in the magnetosphere.

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