

# Detection of the crab pulsar with MAGIC

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for the MAGIC collaboration

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**Abstract.** The MAGIC telescope has detected for the first time pulsed gamma-rays from the Crab pulsar in the VHE domain [1]. The observations were performed with a newly developed trigger system that allows us to lower the energy threshold of the telescope from 55 GeV to 25 GeV. We present a comparison of light curves measured by our experiment with the one measured by space detectors. A strong energy dependent decrease of the first peak with respect to the second peak P1/P2 could be observed. Finally, fitting our measured data and previous measurements from EGRET we determine a turnover of the energy spectrum at  $17.7 \pm 2.8$  (stat.)  $\pm 5.0$  (syst.) GeV, assuming an exponential cutoff. This rules out the scenario in which the gamma rays are produced in vicinity of the polar caps of the neutron star.

**Keywords:** Pulsars, Crab, IACTs

## I. INTRODUCTION

The mechanism of the pulsed electromagnetic emission in the Crab pulsar is still an open fundamental question. 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  $\gamma$ -ray pulsars and a few more likely candidates [3] (recently confirmed by the Fermi Gamma-ray Space Telescope [4]). In their turn, all the groups operating Cherenkov telescopes have been trying during the last 30 years to detect the Crab pulsar without success, being only the steady emission coming from its nebula visible at TeV energies. This suggested that the Crab pulsed spectrum should terminate at energies of tens of GeV. Although the existence of a sharp cutoff in the spectrum of pulsars is a common prediction of the different theoretical models, the energy at which this cutoff happens and its spectral features change from model to model. In the polar cap model (see e.g. [5]), electrons are accelerated above the polar cap radiating  $\gamma$ -rays via synchro-curvature radiation. Since these  $\gamma$ -rays are created in superstrong magnetic fields, magnetic pair production is unavoidable, and hence, only those secondary photons which survive pair creation (a few GeV for typical pulsars) escape to infinity as an observed pulsed emission (see Fig. 1). 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 [6]  $\gamma$ -ray production is expected to occur near the light cylinder of the pulsar, far away from the stellar surface. 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.

Thanks to its low energy threshold, MAGIC is the first ground-based  $\gamma$ -ray telescope able to overcome the sharp cutoffs expected near 10 GeV and detect pulsed  $\gamma$ -rays. This allows to measure the spectral shape of the pulsed emission in the relevant energy range, and therefore to discriminate between different emission models.

## II. 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  $\gamma$ -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  $\gamma$ -ray source emitting at a flux level of 1.6% of the Crab Nebula can be detected at a  $5\sigma$  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  $\gamma$ -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  $\gamma$ -rays, and the estimation of their energy.

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

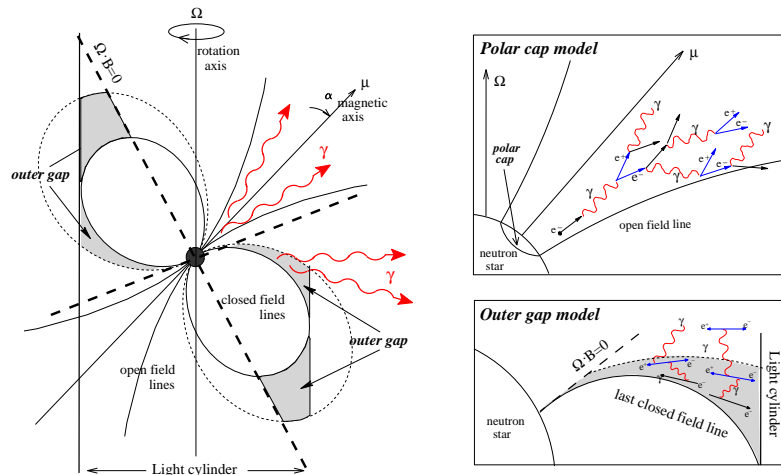


Fig. 1. A sketch of a pulsar's magnetosphere (left) and illustration of the most popular  $\gamma$ -ray emission mechanisms (right).

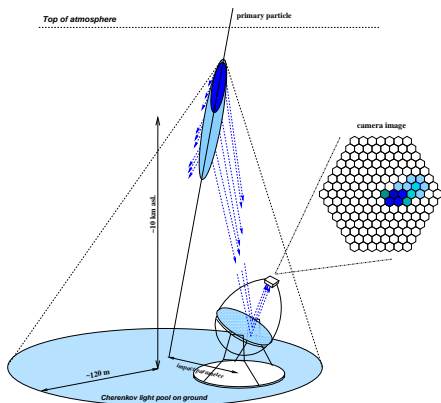


Fig. 2. The telescope 17 m MAGIC telescope detects  $\gamma$ -rays through short light flashes that are produced when  $\gamma$ -rays cross the atmosphere. An image of the shower is obtained in the telescope camera.

turned out to be too high to get a clear signal from the Crab pulsar [7]. This led 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 [8].

### III. OBSERVATIONS AND DATA ANALYSIS

The observations of the Crab pulsar with the new trigger system were performed between October 2007 and February 2008. Together with each event image we recorded the absolute arrival time of the corresponding cosmic-ray with a precision of better than  $1 \mu\text{s}$  from a GPS receiver, and we recorded simultaneously also the optical signal of the Crab pulsar with a special PMT located at the camera center [9]. After rejection of data taken under unfavorable weather conditions, 22.3 hours of observation remained for the 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  $\gamma$ -ray events. For the search of pulsed emission, the arrival time of each event was transformed to the barycenter of the solar system, and the corresponding rotational phase of the Crab pulsar was calculated using contemporaneous ephemeris provided by the Jodrell Bank Radio Telescope [10].

### IV. RESULTS AND DISCUSSION

In figure 3 we compare our pulse phase profiles in  $\gamma$ -rays above 25 GeV and in the optical waveband with the measurements from the EGRET instrument 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  $\gamma$ -ray data was evaluated by three different methods. The first method is a single hypothesis test and assumes that  $\gamma$ -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 [11]. The background is estimated from the remaining events outside of the intervals. In this way we obtain a significance of  $6.4 \sigma$ . The other two methods are uniformity tests: the H-Test [12] (a periodicity test that is commonly used for periodicity searches) and the well

known Pearson's  $\chi^2$  that tests the null hypothesis that the pulse profile follows a uniform distribution, both given a similar significance.

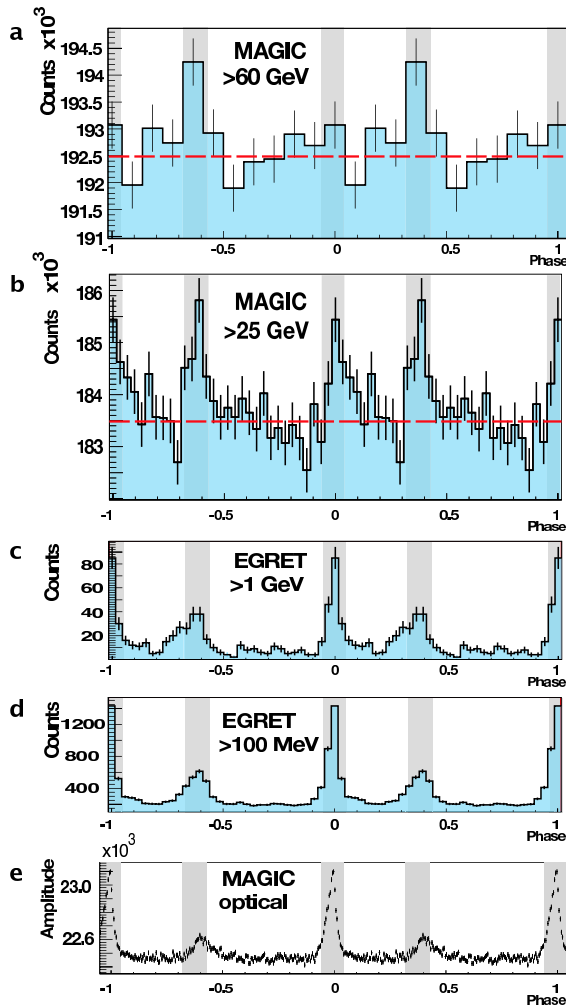


Fig. 3. Crab pulsed emission in different energy bands. The shaded areas show the signal regions for P1 and P2, as defined in [11]. The optical emission measured by MAGIC with its central pixel was recorded simultaneously with the  $\gamma$ -rays. P1 and P2 are in phase for all shown energies and the ratio of P2/P1 increases with energy from (D) to (A).

To evaluate the cutoff energy we extrapolate the energy spectrum measured by EGRET (between 100 MeV and 1 GeV) [11] to higher energies, assuming two different cutoff shapes. If we assume an exponential cutoff ( $\text{Flux} \times \exp(-E/E_0)$ ), the measured signal is compatible with a cutoff energy  $E_0$  of  $17.7 \pm 2.8_{\text{stat}} \pm 5.0_{\text{sys}}$  GeV. In case the cutoff is superexponential ( $\text{Flux} \times \exp(-E/E_0)^2$ ) we determine a cutoff energy of  $23.2 \pm 2.9_{\text{stat}} \pm 6.6_{\text{sys}}$  GeV. Figure 4 shows the Crab pulsar spectrum with the cutoffs obtained in this work, compared to different theoretical predictions. The values obtained for the cutoff energy are higher than expected, which allow us to draw important conclusions about the mechanism of  $\gamma$ -ray emission in the Crab pulsar. Using equation 1 of [13] that relates the location of the emission region,  $r$ , with the cutoff energy, one obtains

for the polar cap scenario  $r/R_0 > 6.2 \pm 0.2_{\text{stat}} \pm 0.4_{\text{sys}}$  (where  $R_0$  is the neutron star radius). This contradicts the basic picture of polar cap scenarios in which  $\gamma$ -rays are emitted very close to the pulsar surface.

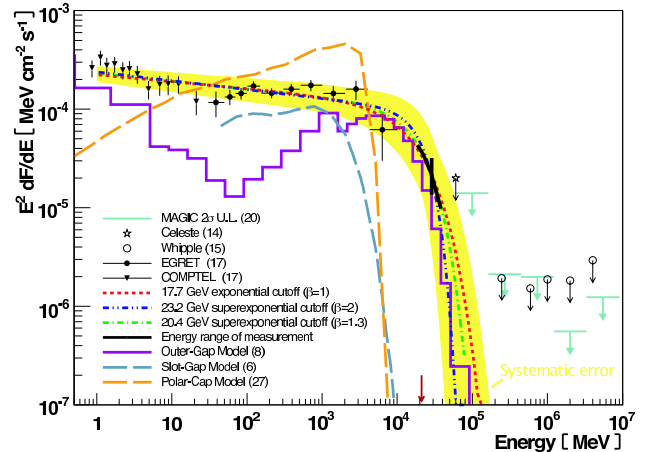


Fig. 4. Crab pulsar spectrum. The solid circles and triangles on the left represent flux measurements from EGRET, while the arrows on the right denote upper limits from various previous experiments. We performed a joint fit of a generalized function  $F(E) = AE^{-a} \exp[-(E/E_0)b]$  to the MAGIC and EGRET data. The figure shows all three fitted functions for  $b = 1$  (red line),  $b = 2$  (blue line), and the best-fit,  $b = 1.2$  (green line). The black line indicates the energy range, the flux, and the statistical error of our measurement. The yellow band illustrates the joint systematic error of all three solutions.

## V. SUMMARY

We succeeded in the detection of pulsed  $\gamma$ -rays from the Crab pulsar with the MAGIC Cherenkov telescope above 25 GeV. This ends a 30 year-long effort of ground based  $\gamma$ -ray instruments to detect a pulsar at VHE  $\gamma$ -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  $6.4 \sigma$ . We find that the main pulse and inter pulse in the pulse profile have about equal peak amplitudes in our energy range. We determine the cutoff in the energy spectrum at  $17.7 \pm 2.8_{\text{stat}} \pm 5.0_{\text{sys}}$  GeV assuming that the cutoff is exponential in shape. The cutoff energy shifts to  $23.2 \pm 2.9_{\text{stat}} \pm 6.6_{\text{sys}}$  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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