VHE gamma-ray measurements of the Crab Nebula and Pulsar by MAGIC

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Abstract. In the last two years 2010 and 2011 the Crab nebula and its pulsar have surprised the gamma-ray astrophysics community at least twice: the former with GeV flares detected by AGILE and Fermi-LAT, the latter with very high energy (VHE, $E > 100$ GeV) pulsed emission extending up to 400 GeV detected by MAGIC and VERITAS. These exciting results show that there is still much left to understand about this object. We report here the results of the MAGIC stereoscopic observations of the Crab nebula and pulsar carried on between October 2009 and April 2011. For the nebula, the analysis of these data yields a differential energy spectrum with an unprecedented precision spanning from 50 GeV to 45 TeV, a precise determination of its inverse Compton (IC) peak, and the measurement of the VHE emission during the GeV flare of April 2011. Implications on the modeling of the Crab nebula, especially regarding the strength of the magnetic field, are discussed. For the pulsar, a phase-resolved energy spectrum and a lightcurve in the range 50-400 GeV are obtained. Together with previous MAGIC monoscopic results above 25 GeV they allow for a detailed study of the pulsed VHE emission, which can be interpreted as an additional component due to IC emission from secondary and tertiary pairs on IR-UV photons in the outer magnetosphere.

Keywords: Gamma-rays,PWN,pulsars,VHE,Crab Nebula,M1

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MAGIC OBSERVATIONS OF THE CRAB NEBULA

The Crab pulsar and its pulsar wind nebula (PWN) are the remnants of the historical supernova SN 1054[1]. Due to its apparent steady emission, the nebula has been used as “standard candle” for ground-based VHE astronomy since its discovery [2], and it is arguably one of the best studied pulsar – PWN complex in across the whole accessible electromagnetic spectrum.

The MAGIC telescopes situated on the island of La Palma (28.8° N, 17.8° W, 2220 m a.s.l.) use the imaging atmospheric Cherenkov technique to detect gamma rays above a few tens of GeV. The two 17m telescopes operate in stereoscopic mode, i.e. in coin-

cidence, achieving a sensitivity¹ of 0.8% Crab nebula units above 250 GeV and a lower energy threshold of 50 GeV [3].

We considered 48.7 hours of optimal quality wobble data at zenith angles between 5° and 50°. The analysis of the data was performed by using the standard tools of the MAGIC analysis software MARS [4]. For the image cleaning a new algorithm (dubbed “sum cleaning”) was employed to improve the analysis sensitivity at energies below 100 GeV [5, 6].

The spectrum we obtained spans three decades in energy, from 50 GeV to 45 TeV, and 8 decades in flux (see figure 1). It can be fitted to a log-parabola function: $\frac{dN}{dE dA dt} = f_0 \left(\frac{E}{1 \text{ TeV}} \right)^{\alpha + \beta \log_{10} \left(\frac{E}{1 \text{ TeV}} \right)} \frac{\text{photons}}{\text{TeV cm}^2}$, with $f_0 = 3.20 \pm 0.5 \times 10^{11}$, $\alpha = -2.40 \pm 0.01$ and $\beta = -0.13 \pm 0.02$. The errors on the fit parameters are statistical only, and are quite small ($\sim 5\%$) below 100 GeV. The systematic errors dominate this measurement, affecting the flux normalization f_0 and the energy scale by about 15% and the photon index by ± 0.15 . If we combine this data with that of Fermi-LAT [7], it is possible to map most of the inverse Compton (IC) bump, and measure its peak position to be $59 \pm 6_{\text{stat}} \pm 10_{\text{sys}}$ GeV.

To model gamma-ray emission of the Crab Nebula, two possibilities were taken into consideration, following [8] (figure 1 B): a phenomenological constant magnetic field model, as in [11], and a magnetohydrodynamic (MHD) flow model, as outlined in [12, 13]. The free parameters for these models (average B-field and magnetization of the flow at the shock, σ) were fitted to the data points obtaining $B = 124 \pm 6 \mu\text{G}$ and $\sigma = 0.0045 \pm 0.0003$ (statistical errors only). Taking systematic uncertainties into account, both models can reproduce the observation: they can only be disentangled by more precise measurements of the Crab and of other young PWN with smaller systematic errors, to be carried on in the future.

During the September 2010 flare above 100 MeV [14, 15] the gamma-ray flux above 300 GeV from the Crab nebula has been found to be constant within a systematic uncertainty of 13%, to a CL of 95%. Additionally, we observed the nebula during the April 2011 flare [16], under strong moonlight conditions, for a total of about 140 minutes. Also in this dataset we found no evidence of change in the flux between 0.7 and 10 TeV during the first peak of the flare, between April 12 and 14.

MAGIC OBSERVATIONS OF THE CRAB PULSAR

The Crab pulsar, despite numerous efforts, was never detected above 10 GeV until 2008 [17], because its spectrum shows a steepening at these energies. In fact, the origin of the gamma-ray emission in the “classic” Outer Gap (OG) [18] and Slot Gap (SG) [19] models is curvature radiation, which implies an exponential cutoff at a few GeV. However, during the last year, both operating Cherenkov Telescopes in the northern hemisphere, VERITAS and MAGIC, reported the detection of pulsed gamma-ray emission from the Crab Pulsar, from 25 up to 400 GeV [10, 20], inconsistent with such a cutoff shape. We focus here on the MAGIC stereoscopic results only. Of the above-mentioned ob-

¹ Defined as the source strength needed to achieve $N_{\text{ex}}/\sqrt{N b k g} = 5$ in 50 h effective on-time

FIGURE 1. A) Spectral energy distribution of the Crab Nebula. B) Models from [8] overlayed to the data in A): constant B-field (red line) and MHD (black line) C) Folded light curve of the Crab pulsar for the total range in estimated energy. D) Compilation of spectral measurements of the Crab pulsar and nebula for both peaks. E) Spectra for P1 only F) Spectra for P2 only. The phase interval definitions are E =EGRET[9] M =MAGIC (this work) V =VERITAS[10].

servations, we selected 73 hours of data between both in “on” and “wobble” mode, with zenith angle between 5° and 35° . The data analysis was performed in the same way as for the nebula, however the cuts used to extract the signal were loosened, and only the energy range 46 - 416 GeV was considered. The data was timed using the Jodrell Bank ephemeris and the TEMPO2 timing package[21]; it showed a pulsation whose significance was tested with the Z_{10} , H and χ^2 tests, obtaining 8.6, 6.4 and 7.7 σ , respectively. The folded lightcurve (figure 1 C) shows two prominent peaks, P1 and P2: they were fitted with two Gaussians, the resulting peak positions in phase were 0.005 ± 0.003 and 0.3996 ± 0.0014 , while the corresponding FWHMs were 0.025 ± 0.007 and 0.026 ± 0.004 .

To extract the spectra we considered two definitions for the phase intervals of the two peaks: one based on the EGRET data [9] (therefore a-priori); another, much narrower, defined a-posteriori as the Gaussian peak positions $\pm 2\sigma$. The resulting phase-resolved spectra were found to be compatible with power-laws, as can be seen from figure 1 D), E) and F). More detailed information about this measurement can be found in [20].

Our spectra, together with the Fermi-LAT measurements in [7] comprise the first

phase-resolved measurements of the gamma-ray emission from the Crab Pulsar between 100 MeV and 400 GeV. We put forward a theoretical explanation for this emission, in the framework of the outer-gap model [22], that has the gamma-rays emitted by inverse Compton scattering of secondary and tertiary electron/positron pairs on IR/UV photons. These higher-order magnetospheric cascades were not taken into account in previous pulsar modeling and can produce a power-law gamma-ray spectrum extending at TeV energies, shown as a blue line in figure 1 D). To test this model it will be important in the future to measure the pulsar at those energies.

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