TeV pulsed emission from the Crab detected by MAGIC

David Fidalgo[*1], Roberta Zanin[2], Emma de Oña Wilhelmi[3], Daniel Galindo[2], Daniel Garrido Terrats[4], Wojciech Idec[5], Thomas Schweizer[6], Woldek Bednarek[5], Diego F. Torres[7], Markus Gaug[4], Marcos López[1], Takayuki Saito[8] *for the MAGIC*[†] *collaboration* and Kouichi Hirotani[9]

[1]Universidad Complutense, GAE, Madrid, Spain; [2]Universitat de Barcelona, ICC, IEEC-UB, Barcelona, Spain; [3]Institute of Space Sciences, Barcelona, Sapin; [4]Universitat Autnoma de Barcelona, CERES-IEEC, Barcelona, Spain; [5]University of Łódź, Łódź, Poland; [6]Max-Planck-Institut fr Physik, München, Germany; [7]ICREA and Institute of Space Sciences, Barcelona, Spain; [8]Kyoto University, Kyoto, Japan; [9]Academia Sinica, Institute of Astronomy and Astrophysics, Taipei, Taiwan

[*]dfidalgo@gae.ucm.es

[†]https://magic.mpp.mpg.de/

Introduction

The Crab pulsar is one of the few pulsars detected across the whole electromagnetic spectrum, from radio up to γ-rays. The exceptionality of this source was recently underlined by the discovery of pulsed emission at energies up to 400 GeV [1, 2], a range where no other pulsar has been detected yet. The high-energy (HE, E > 100 MeV) gamma-ray emission from pulsars is believed to be produced via synchro-curvature radiation by electron-positron pairs moving along curved paths at high-altitude zones inside the open magnetosphere [3]. However, to explain the very-high-energy (VHE, E > 100 GeV) tail of the Crab pulsar one has to push this model to extreme values [4] or propose a new mechanism to be at work, e.g. inverse Compton scattering either in the vicinity of the light cylinder [2] or in the wind zone extending from the light cylinder to the wind shock [5].

The goal of this work is to investigate the maximum energy reached in the Crab pulsar spectrum by reanalyzing most of the Crab data recorded by MAGIC.

Observation and analysis

The two MAGIC telescopes
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MAGIC is an array of two imaging atmospheric Cherenkov telescopes (IACTs) designed for the detection of γ-rays in the energy band between few tens of GeV and few tens of TeV. It is located on the Canary island of La Palma (Spain) and started its operation in 2004 with only one telescope (*MAGIC-I*). Since then it underwent several upgrades, involving the addition of a second telescope (*MAGIC-II*) in 2009 and the exchange of the *MAGIC-I* camera in 2012. At zenith angles below 30° the current instrument has an energy threshold of ~70 GeV, an energy resolution of 0.15-0.17% at ~1 TeV and an integral sensitivity above 220 GeV of 0.66% of the Crab nebula flux in 50 hours of observation [6].

For this work we reanalyzed Crab data recorded by MAGIC since 2007, both in stand-alone and stereoscopic mode, resulting in more than 300 hours of excellent quality observation. For IACTs the energy reconstruction and calculation of the effective area is done by means of Monte Carlo (MC) simulations. Given that the considered data sample spreads over seven years, with different instrument performance and different observation modes, we divided it into 19 sub-samples each with its corresponding MC production.

The pulsar rotational phase of each event was defined by using the TEMPO2 package [7] and the monthly ephemerides publicly provided by the Jodrell Bank Observatory [8].

The Crab pulsar (optical/X-rays)
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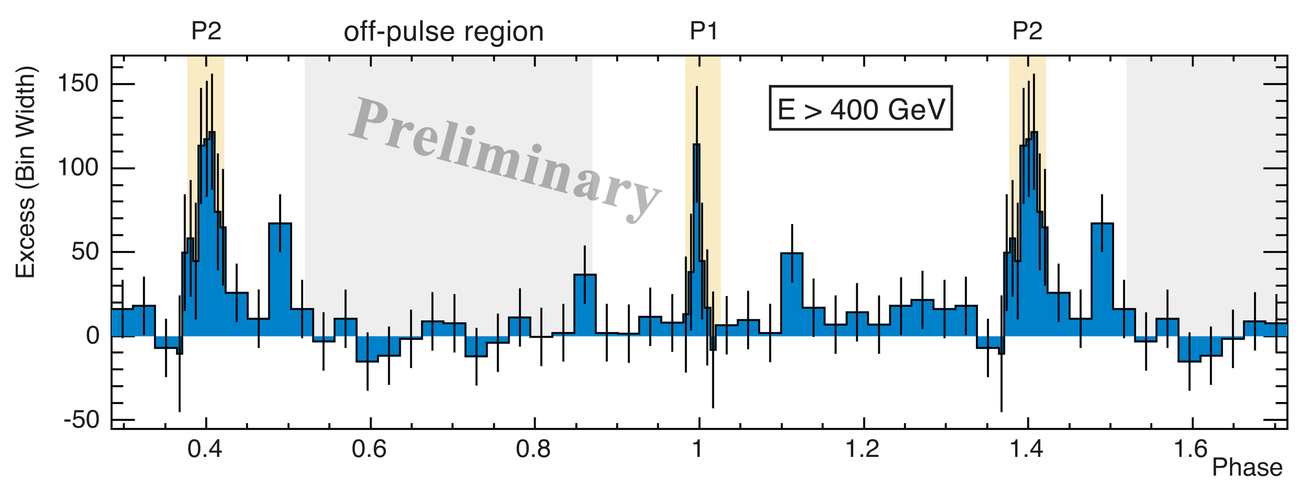
Results

The pulsar light curve



With 318 hours of observation time the folded pulse profile above 400 GeV shows a detection (6.0σ) of the so-called *interpulse* (P2), while a hint of the *main pulse* (P1) is seen at a significance level of 2.2σ. To obtain the exact location and width of the two peaks we fitted a finer binned light curve with two symmetric Lorentz functions, see Table 1.

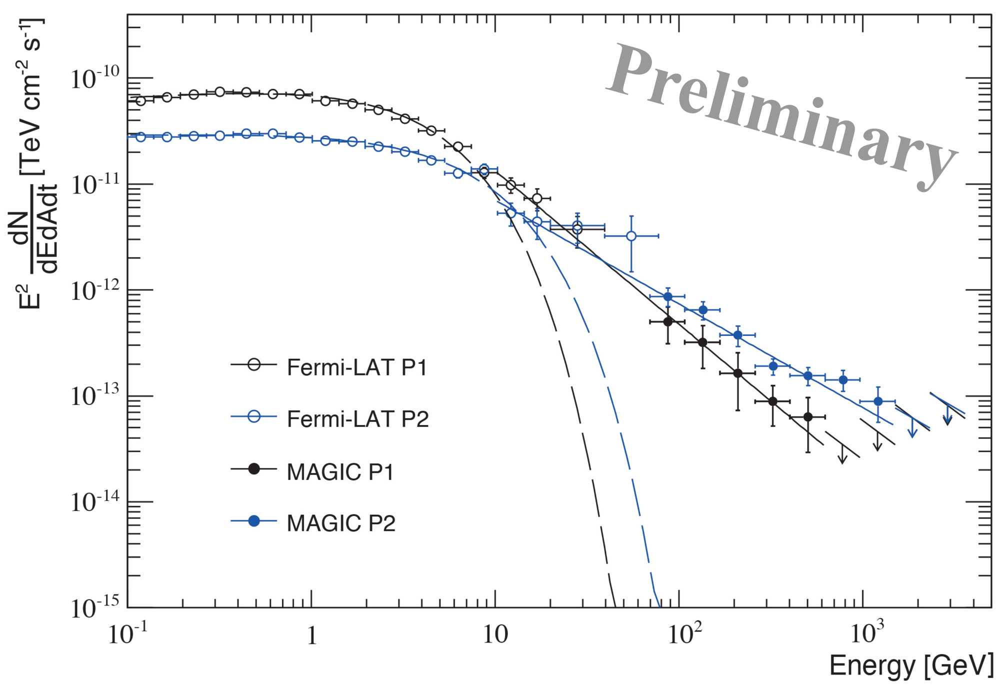
peak	position	full width at half maximum (FWHM)
P1	$0.997 \pm 0.001_{\text{stat}} \pm 0.004_{\text{sys}}$	$0.005 \pm 0.002_{\text{stat}} \pm 0.002_{\text{sys}}$
P2	$0.403 \pm 0.003_{\text{stat}} \pm 0.004_{\text{sys}}$	$0.022 \pm 0.008_{\text{stat}} \pm 0.002_{\text{sys}}$

Table 1: Fit results for the pulsar light curve with two symmetric Lorentz functions

	peak	r [GeV]	f [TeV^{-1} cm^{-2} s^{-1}]	α	χ^2/dof
Fermi-LAT	P1	50	$(5.3 \pm 0.8) \times 10^{-10}$	3.5 ± 0.1	$1.5/6$
+ MAGIC	P2	50	$(5.7 \pm 0.6) \times 10^{-10}$	3.0 ± 0.1	$8.4/9$

Table 2: Fit results for the spectra with the power-law $f(E/r)^{-\alpha}$

The energy spectra



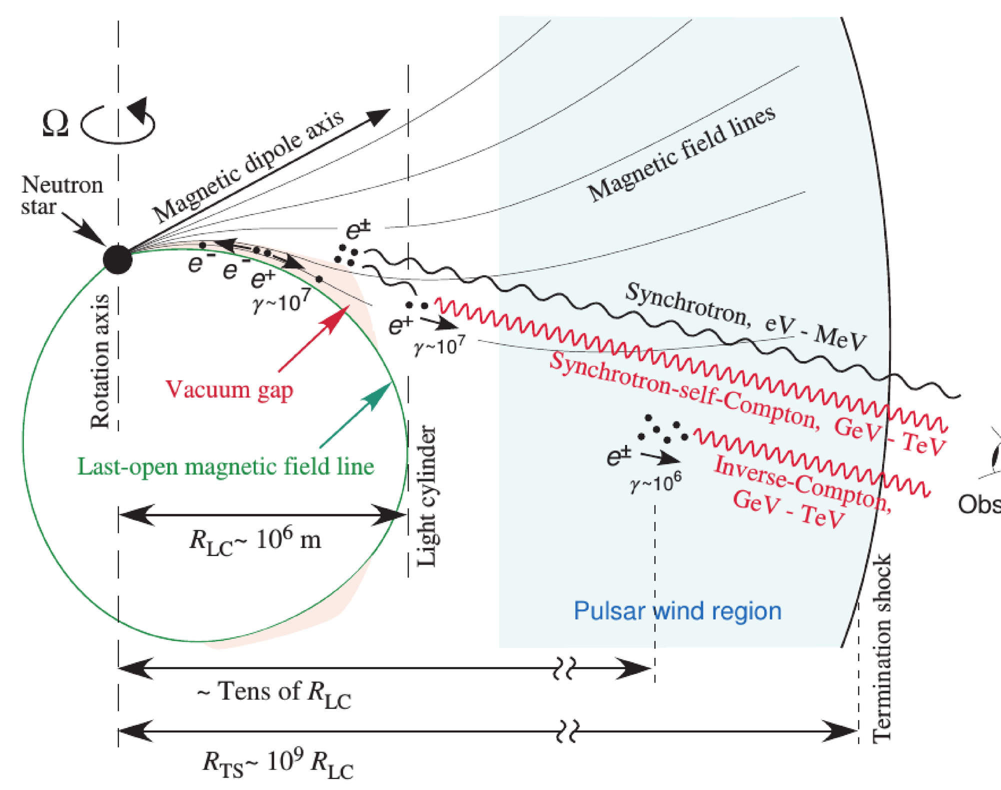
Both peaks, P1 and P2, exhibit a power-law like spectrum from ~90 GeV up to ~500 GeV and ~1.2 TeV, respectively. The obtained spectra naturally connect to the last spectral points measured by the Fermi-*LAT* [9, 10]. When performing a joint fit with spectral points above 10 GeV, the difference between the two spectral slopes becomes significant by more than 3σ revealing a softer spectrum for P1 compared to P2 (see Table 2).

Discussion

The TeV pulsed emission cannot be produced with synchro-curvature radiation, since the required curvature radius would be at least one order of magnitude larger than what is generally considered [11]. Therefore, the measurement of pulsed emission extending up to TeV energies implies that the inverse Compton (IC) process is at work in the Crab pulsar. The underlying electron population should have Lorentz factors greater than 2×10^6. Furthermore, the simple power-law function obtained by a joint fit of Fermi-*LAT* and MAGIC data from ~10 GeV to ~1 TeV suggests a single mechanism (e.i. IC scattering) dominating the whole VHE range of the Crab pulsar spectrum.

Concerning IC scattering, two scenarios which were previously proposed to explain the VHE emission below 400 GeV can be considered:

- the **magnetospheric synchrotron-self-Compton model** [2] assumes acceleration gaps in the outer magnetosphere where primary positrons produce curvature radiation. A part of it escapes the gap and gets absorbed by magnetospheric infrared photons to materialize as secondary electron-positron pairs. The synchrotron-self-Compton component of those secondaries can reach us below several TeV.



- in the **wind zone scenario** [5] the conversion from an electromagnetic energy to a kinetic energy dominated pulsar wind takes place in a narrow zone tens of light cylinder radii away from the pulsar. In this zone the synchrotron UV-X rays are upscattered by abruptly accelerated electron-positron pairs to TeV pulsed photons.

Conclusions

- MAGIC detected **TeV pulsed emission** from the Crab pulsar. The emission above 400 GeV mainly stems from **P2, the interpulse**.
- The spectrum can be described by a **simple power-law from ~10 GeV to ~1 TeV** which suggests a single mechanism being responsible for the VHE emission.
- Curvature radiation is not able to explain our results. Therefore **inverse Compton scattering by electrons/positrons with Lorentz factors above 2×10^6** is needed.

Acknowledgements

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References

[1] VERITAS Collaboration, E. Aliu, et al. *Science*, 334(6052):69–72, 2011.
[2] MAGIC Collaboration, J. Aleksić, et al. *A&A*, 540:A69, 2012.
[3] R.W. Romani. *Science*, 344(6180):159–160, 2014.
[4] W. Bednarek. *Monthly Notices of the Royal Astronomical Society*, 424(3):2079–2085, 2012.
[5] F.A. Aharonian, S.V. Bogovalov, and D. Khangulyan. *Nature*, 482(7386):507–509, 2012.
[6] MAGIC Collaboration, J. Aleksić, et al. *Astroparticle Physics*, 2015. http://dx.doi.org/10.1016/j.astropartphys.2015.02.005 (in press).
[7] G.B. Hobbs, R.T. Edwards, and R.N. Manchester. *Monthly Notices of the Royal Astronomical Society*, 369(2):655–672, 2006.
[8] A.G. Lyne, R.S. Pritchard, and F.G. Smith. *Monthly Notices of the Royal Astronomical Society*, 265(4):1003–1012, 1993.
[9] MAGIC Collaboration, J. Aleksić, et al. *A&A*, 565:L12, May 2014.
[10] Fermi-LAT Collaboration, W.B. Atwood, et al. *The Astrophysical Journal*, 697(2):1071–1102, 2009.
[11] D. Viganò, D.F. Torres, K. Hirotani, and M.E. Pessah. *Monthly Notices of the Royal Astronomical Society*, 447(3):2631–2648, 2015.