Detection of VHE Bridge emission from the Crab pulsar with the MAGIC Telescopes

T. Saito
Kyoto University, Kyoto, 606-8052 Japan
S. Bonnefoy
Universidad Complutense, Madrid, E-28040 Spain
K. Hirotani
Academia Sinica, Institute of Astronomy and Astrophysics (ASIAA), Taipei, P.O. Box: 23-141 Taiwan
R. Zanin on behalf of the MAGIC Collaboration
Universitat de Barcelona, ICC, IEEC-UB, Barcelona, E-08028 Spain

The Crab pulsar is the only astronomical pulsed source detected above 100 GeV. The emission mechanism of very high energy gamma-ray pulsation is not yet fully understood, although several theoretical models have been proposed. In order to test the new models, we measured the light curve and the spectra of the Crab pulsar with high precision by means of deep observations. We analyzed 135 hours of selected MAGIC data taken between 2009 and 2013 in stereoscopic mode. In order to discuss the spectral shape in connection with lower energies, 4.6 years of Fermi-LAT data were also analyzed. The known two pulses per period were detected with a significance of 8.0 $\sigma$ and 12.6 $\sigma$. In addition, significant bridge emission was found between the two pulses with 6.2 $\sigma$. This emission cannot be explained with the existing theories. These data can be used for testing new theoretical models.

1. Introduction

The Crab pulsar and the surrounding Crab nebula are the remnant of the supernova of AD 1054. Both the pulsar and the nebula are well studied in a very wide energy range starting from radio ($10^{-5}$ eV) to VHE energies (up to tens of TeV). It is one of the youngest pulsars known and its spin down luminosity ($4.6 \times 10^{38}$ erg/s) is the highest among Galactic neutron stars. To date, this pulsar is the only one for which pulsed emission has been detected above 100 GeV.

Gamma-ray pulsation from the Crab pulsar up to $\sim 10$ GeV had been known since the 1990s [Nolan et al. 1993]. In 2008, pulsations were detected by the MAGIC telescope at energies above 25 GeV [Aliu et al. 2008]. This result suggested that the emission originates in the outer magnetosphere. The simplest curvature radiation scenario in the outer magnetosphere predicts an exponential cutoff in the energy spectrum at GeV energies [e.g., Muslimov and Harding 2004, Takata et al. 2006, Tang et al. 2008]. Fermi-LAT observations from 100 MeV to a few tens of GeV, which started in August 2008, showed a clear break in the spectrum at $\sim 6$ GeV [Abdo et al. 2010] supporting this scenario. A few years later, however, MAGIC and VERITAS [Aleksić et al. 2011, 2012a, Aliu et al. 2011] found that the energy spectrum of the Crab pulsar extends up to 400 GeV following a power law. The emission above 100 GeV is difficult to explain only with the curvature radiation, and additional or different emission mechanisms are required. Several new models were recently proposed to explain the energy spectrum of the Crab pulsar [e.g., Aleksić et al. 2011, Aharonian et al. 2012].

Here we present new results from the continuing monitoring of the Crab pulsar with the MAGIC telescopes that will help to constrain any model for the emission. In order to discuss the Crab pulsar spectra at energies lower than those accessible to MAGIC, Fermi-LAT data were also analyzed.

2. Instruments, data sets, and analysis methods

2.1. The MAGIC Telescopes

The MAGIC telescopes are two Imaging Atmospheric Cherenkov Telescopes located on the island of La Palma (Spain) at 2200 m above sea level. Both telescopes consist of a 17 m diameter reflector and a fast imaging camera with a field of view of 3.5$^\circ$. The trigger threshold for regular observations at zenith angles below 35$^\circ$ is around 50 GeV and the sensitivity above 290 GeV (in 50 h) is 0.8% of the Crab nebula flux with an angular resolution better than 0.07$^\circ$ [Aleksić et al. 2012b].

For this study we used 135 hours of data taken at zenith angles below 35$^\circ$ during optimal technical and weather conditions between September 2009 and April 2013. Standard MAGIC analysis, as described in Moralejo et al. [2009] and Aleksić et al. [2012b], was applied to the data. The conversion from event arrival times to pulsar rotational phases used Tempo2 software [Hobbs et al. 2006] and a dedicated package inside MARS [López 2006]. The spin parameters of the Crab pulsar were taken from the monthly reports of
the Jodrell Bank Radio telescope\footnote{http://www.jb.man.ac.uk/~pulsar/crab.html} \cite{Lyne1993}.

\section*{2.2. Fermi-LAT}

The Large Area Telescope (LAT) is a pair conversion gamma-ray detector on board the Fermi satellite \cite{Atwood2009}. It can detect high-energy gamma rays from 20 MeV to more than 300 GeV. It has been operational since August 2008 and all the collected data are publicly available. In this work, we have used 5.5 years of Pass 7 reprocessed data\footnote{http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass7REP_usage.html} from 2008 August 4 to 2014 January 31. The region of interest was chosen to be 30\degree around the Crab pulsar.

Along with the public data, the LAT team provides the corresponding analysis software and instrument response functions (IRF) designed for the analysis of that particular dataset. We have used the version v9r32p5 of the Fermi-LAT ScienceTools\footnote{http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html} and the P7REP\textunderscore SOURCE\_V15 IRF. From the downloaded data we have discarded events taken at zenith angles above 100\degree to reduce the contamination of albedo gamma rays coming from the Earth’s limb. To compute the pulse phase, we used the same spin parameters as for the MAGIC analysis. The obtained fluxes were computed by maximizing the likelihood of a given source model using the gtlike tool. The binned likelihood method was adopted and a 40\degree bin width was used for the likelihood maximization. Apart from the Galactic (gal\_iem\_v05.fits) and extragalactic (iso\_source\_v05.txt) diffuse emission, we considered as background sources for the likelihood fits all sources listed in the second LAT source catalogue \cite{Nolan2012}. The data taken during the periods when the Crab nebula was flaring were not excluded from the analysis. These flares should not have any impact on the pulsed emission results because it is known that the pulsation component did not change during the flares \cite{Buehler2012}, and the average nebula flux including flare periods was subtracted when the pulsar signal was determined. Regarding the reported Fermi-LAT spectrum from the Crab nebula, the six Crab flares that lasted a few days might be responsible for a few percent of the photons below 1 GeV in the overall 5.5 year dataset. Given that the effect is expected to be small, and that this paper focusses on the emission from the pulsar, we did not correct for this effect.

\section*{3. Results}

\subsection*{3.1. Light curve above 50 GeV}

Figure\textsuperscript{1} shows the light curves of the Crab pulsar measured by MAGIC. Two peaks are clearly visible. Following our previous study \cite{Aleksic2012a}, we define phase ranges for the two peaks as P1\textsubscript{M} (phase $-0.017$ to $0.026$) and P2\textsubscript{M} ($0.377$ to $0.422$). The background level (hadrons and continuum gamma rays) is estimated using the phase range between $0.52$ and $0.87$ and it is then subtracted from the histograms\footnote{An estimation of the background using the off-peak interval from the LAT Second Pulsar Catalog, namely the phase range between $0.61$ and $0.89$, lead to very similar results.}. The number of excess events in P1\textsubscript{M} between 50 GeV and 400 GeV is $930\pm120$ $(8.0\sigma)$ and in P2\textsubscript{M} is $1510\pm120$ $(12.6\sigma)$.

In addition to the two main peaks, significant emission between them is also visible. The region between the peaks is generally called the Bridge. Defining the Bridge region as the gap between P1\textsubscript{M} and P2\textsubscript{M}, namely, between $0.026$ and $0.377$ (hereafter Bridge\textsubscript{B}), we obtain an excess of $2720\pm440$ $(6.2\sigma)$ events in this region. Adopting the definition used at lower energies for the Bridge as the region $0.14 - 0.25$ from \cite{Fierro1998} (hereafter Bridge\textsubscript{F}), then the number of excess events is $880\pm200$ $(4.4\sigma)$. This excess increases to $1940\pm370$ $(5.2\sigma)$ if we extend Bridge\textsubscript{F} with the so-called trailing wing of P1 and the leading wing of P2, namely to the interval of $0.04 - 0.32$ [see \cite{Fierro1998}. It should be noted that this detection confirms the hint of bridge emission already reported in \cite{Aleksic2012a}.

\subsection*{3.2. Comparison with lower energies}

Figure\textsuperscript{2} shows the light curves at optical, X-ray, and gamma-ray energies obtained with various instruments, together with the 50—400 GeV light curve from the bottom panel of Fig.\textsuperscript{1}. The background was subtracted in the same way as the MAGIC light curves (see Sect.\textsuperscript{3.1}). The intensity and morphology of the bridge emission varies considerably with energy. It is very weak at optical wavelengths and in the 100—300 MeV range, while there is an appreciable difference at X-rays and soft gamma rays. At the energies covered by MAGIC, the peaks become much sharper and a prominent bridge emission appears.

It is known that the flux ratio between the two peaks strongly depends on energy, as does the ratio between the first peak and the bridge [see, e.g., \cite{Kuiper2001}]. Fig.\textsuperscript{3} shows the flux ratio between P2\textsubscript{M} and P1\textsubscript{M} and that between Bridge\textsubscript{F} and P1\textsubscript{M} as a function of energy from optical ($\sim 2$ eV)
3.3. Spectral energy distribution

The spectral energy distributions (SEDs) of the P1M, P2M, BridgeM, and BridgeE between 100 MeV and 400 GeV are shown in Fig. 3 together with the Crab nebula SED obtained with a subset of the data used for the pulsar analysis. The SEDs were calculated using Fermi-LAT data below 50 GeV (below 200 GeV for the nebula), and MAGIC data above 50 GeV. The nebula SED is connected smoothly between the two instruments. The Fermi-LAT data were fit with a power law with an exponential cutoff, while the MAGIC data were fit with a simple power-law function. The obtained fit parameters are summarized in Table I. The power-law indices between 50 GeV and 400 GeV are about 3 and no significant difference is seen between different pulse phases. The uncertainty in the absolute energy scale is estimated as 17%, whereas the systematic error of the flux normalization is estimated to be 18%. We estimate the overall systematic uncertainty uncertainty on the spectral slope to be 0.3.

4. Discussion

In summary, the Crab pulsar above 50 GeV exhibits a light curve with a significant bridge emission between two sharp peaks (Fig. 1). The flux ratios P2M/P1M and BridgeE/P1M increase with increasing photon energy between 100 MeV and 400 GeV (Figs. 2 and 3). Between 30 GeV and 400 GeV, the fluence in the bridge phase is comparable to that in the P1 phase (Fig. 4). The SEDs in the 50 – 400 GeV range could be fit with power-law functions for the three phases.

There are several models which can explain the VHE emission of the Crab pulsar, such as Aleksić et al. [2011], Aharonian et al. [2012], Bednarek [2012], Arka and Dubus [2013], Chkheidze et al. [2013]. However, none of them can explain the VHE pulse profile and the spectrum consistently. Further theoretical studies and deeper observations of the Crab and other gamma-ray pulsars are needed to understand the VHE emission.
Table I Spectral Parameters

| phase     | $F_1$ a [$10^{-11}$ MeV$^{-1}$ cm$^{-2}$ s$^{-1}$] | $\Gamma_1^a$ | $E_c^a$ [GeV] | $F_{100}^b$ [$10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$] | $\Gamma_2^b$ |
|-----------|---------------------------------|-----------|-----------|---------------------------------|-----------|
| P1M       | 8.87 ± 0.14                     | 1.88 ± 0.01| 3.74 ± 0.15| 4.18 ± 0.59                     | 3.25 ± 0.39|
| P2M       | 3.14 ± 0.07                     | 1.97 ± 0.01| 7.24 ± 0.64| 8.48 ± 0.62                     | 3.27 ± 0.23|
| BridgeM   | 7.70 ± 0.11                     | 1.74 ± 0.01| 7.19 ± 0.39| 12.2 ± 3.3                      | 3.35 ± 0.79|
| BridgeP   | 0.95 ± 0.04                     | 1.44 ± 0.04| 6.94 ± 0.90| 3.7 ± 1.1                       | 3.51 ± 0.97|

Parameters obtained by fitting a function $F(E) = F_1(E/1\text{GeV})^{-\Gamma_1} \exp(E/E_c)$ to Fermi-LAT data between 100 MeV and 300 GeV.

Parameters obtained by fitting a function $F(E) = F_{100}(E/100\text{GeV})^{-\Gamma_2}$ to MAGIC data between 50 GeV and 400 GeV.

Figure 2: Light curve of the Crab pulsar at optical wavelength, 2.4 – 10 keV X-rays, 0.75 – 10 MeV, and 100 – 300 MeV gamma rays (from top to bottom). The light curve at 50 – 400 GeV is overlaid on each plot for comparison. The optical light curve was obtained with the MAGIC telescope using the central pixel of the camera [Lucarelli et al. 2008]. The keV and MeV light curves are from [Kuiper et al. 2001]. The 100 – 300 MeV light curve was produced using the Fermi-LAT data. All light curves are zero-suppressed by estimating the background using the events in the phase range from 0.52 to 0.87.

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Figure 4: Spectral energy distributions of the Crab nebula, P1M, P2M, BridgeEM, and Bridge measured with Fermi-LAT (below 50 GeV) and MAGIC (above 50 GeV). The flux values averaged over the rotation period are plotted.

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