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LETTER TO THE EDITOR

H.E.S.S. observations of the Crab during its March 2013 GeV gamma-ray flare


(Affiliations can be found after the references)

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ABSTRACT

Context. On March 4, 2013 the Fermi-LAT and AGILE reported a flare from the direction of the Crab nebula in which the high-energy (HE; \( E > 100 \text{ MeV} \)) flux was six times above its quiescent level. Simultaneous observations in other energy bands give us hints about the emission processes during the flare episode and the physics of pulsar wind nebulae in general.

Aims. We search for variability in the emission of the Crab nebula at very-high energies (VHE; \( E > 100 \text{ GeV} \)), using contemporaneous data taken with the H.E.S.S. array of Cherenkov telescopes.

Methods. Observational data taken with the H.E.S.S. instrument on five consecutive days during the flare were analysed for the flux and spectral shape of the emission from the Crab nebula. Night-wise light curves are presented with energy thresholds of 1 TeV and 5 TeV.

Results. The observations conducted with H.E.S.S. on March 6 to March 10, 2013 show no significant changes in the flux. They limit the variation in the integral flux above 1 TeV to less than 63% and the integral flux above 5 TeV to less than 78% at a 95% confidence level.

Key words. gamma rays: ISM – ISM: individual objects: Crab nebula – radiation mechanisms: non-thermal – relativistic processes

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1. Introduction

The Crab nebula (for an overview see Hester 2008) is a pulsar wind nebula (PWN) powered by the Crab pulsar (in the following, the name Crab is used synonymously for the system of the Crab pulsar and its nebula). The rotational energy of the pulsar is converted into kinetic energy of a relativistic pair-plasma flow terminating in a shock with subsequent particle acceleration (Rees & Gunn 1974). Unpulsed emission from the downstream flow (the nebula) covers all observable wavelengths. The electrons and positrons of the plasma emit synchrotron radiation from radio wavelengths up to several hundred MeV, and they Compton-upscatter ambient photons (see e.g. de Jager & Harding 1992; and Atoyan & Aharonian 1996) up to energies of at least 80 TeV (Aharonian et al. 2004).

These processes manifest themselves as clearly distinguishable peaks in the spectral energy distribution, which intersect in the energy band observed with Fermi-LAT (Abdo et al. 2010), AGILE (Tavani et al. 2009) and EGRET (Kuiper et al. 2001). While in the former, the flare component will largely remain unchanged, in the latter case, the inverse-Compton (IC) component shows a steepening of the spectrum in the HE part of the synchrotron energy range. The Crab nebula (for an overview see Hester 2008) is a pulsar 1. Introduction

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The apparent observed energy at a corresponding energy $E_{\text{IC}}$ of IC scattered ambient photons. The detection of variability in the raw data presented above indicates that the Crab nebula remains unsettled, pending independent confirmation with other instruments. The contemporaneous observations of the Crab nebula in March 2013 provide the opportunity to study the emission during a flaring state at multiple wavelengths, ranging from infrared to X-rays (Mayer et al. 2013) and VHE (Aliu et al. 2014 and H.E.S.S. observations reported in this paper). Spectral measurements at multi-TeV energies, which are most relevant in the search for an IC component, are required to complement our understanding of the flaring Crab nebula and facilitate broadband modelling. The highest sensitivity for multi-TeV $\gamma$ rays is reached with ground-based Cherenkov telescope observations at high zenith angles, since the inclination angle of the induced air showers results in large effective areas. Since the Crab nebula culminates at 45° for H.E.S.S., it provides the best observation conditions of all ground-based $\gamma$-ray telescopes.

2. Data set and analysis

The High Energy Stereoscopic System (H.E.S.S.) is an array of five Imaging Air Cherenkov telescopes situated in the Khomas Highland, Namibia, at 1800 m above sea level. Since 2004, four telescopes (H.E.S.S. Phase I) with mirror surfaces of $\sim 100 m^2$ each have been detecting air showers produced by $\gamma$ rays with energies higher than 100 GeV (Hinton 2004). This array forms a square of 120 m side length. It has a field of view of $5^\circ$ in diameter and a relative energy resolution of $\sim 14\%$ at 1 TeV (Aharonian et al. 2006). In September 2012, the fifth telescope placed in the middle of the original square was inaugurated, initiating H.E.S.S. Phase II. It has a mirror surface of $\sim 600 m^2$ and lowers the energy threshold of H.E.S.S. to tens of GeV.

Due to the flare, Fermi-LAT was switched to pointed target-of-opportunity observation mode of the Crab between MJD 56 355 and 56 359 (Mayer et al. 2013). The data presented here are ten observation runs taken in or shortly after this period, when the flux measured by Fermi-LAT was still about twice its average value. The data are comprised of runs with either three or four of the H.E.S.S. 1 telescopes, each lasting 28 min. Since it was the rainy season in Namibia, observations were possible only during a few nights. In this period of time, the Crab nebula was visible at large zenith angles for H.E.S.S. (see Table 1).

The data were analysed with the H.E.S.S. Analysis Package1 for shower reconstruction and a multivariate analysis (Ohm et al. 2009) applying $\zeta$ std-cuts for suppression of the hadronic background. To estimate the cosmic-ray background, the reflected region method (Berge et al. 2007) was used. Significances (in standard deviations, $\sigma$) were calculated using Eq. (17) in Li & Ma (1983). The analysis results for each night and for the whole data set can be found in Table 1. A cross-check with an independent analysis (de Naurois & Rolland 2009) and an independent data calibration indicates that the systematic error on the flux normalisation is 30% for this data set, which is taken into account in the calculation of flux upper limits shown below.

3. Results

Analysing the complete sample of ten runs taken in the nights from March 6 to March 10, 2013 (MJD 56 355–MJD 56 365), we obtained an acceptance-corrected live time of 4.4 h, yielding 754 excess events from the source region. A simple power law and an exponential cut-off power law were considered to

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1 HAP version hap-12-03-pl02.
model the energy distribution, motivated by previous publications (Aharonian et al. 2006). Low statistics for \(E > 10\) TeV, however, made it impossible to distinguish between an exponential cut-off and a simple power law model. This is not a characteristic of this specific data set: A sample of ten runs on the Crab nebula from another period with similar telescope participation did not allow any discrimination between a power law model and a power law model with an exponential cut-off, either. Therefore, the numerically more stable power law model was adopted for all spectra and fitted in the energy range \([0.681 - 46.46]\) TeV. The energy spectrum of the complete sample is shown in Fig. 2, together with the exponential cut-off power law spectrum taken from Aharonian et al. (2006) as a reference. Night-wise data were fitted with a power law model as well, and all results and their statistical errors are compiled in Table 1. The spectral analysis results of both night-wise and complete samples agree with Aharonian et al. (2006), where an exponential cut-off power law was the best-fitting spectral model with \(I_0(1\text{ TeV}) = (3.76 \pm 0.07) \times 10^{-11}\) cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\), \(\Gamma = 2.39 \pm 0.03\), and \(E_{\text{cutoff}} = (14.3 \pm 2.1)\) TeV.

To test for the compatibility of this spectrum with the spectrum of the flare data set presented here, a \(\chi^2\)-test was conducted. Under the optimistic assumption of cancelling systematics between both data sets, the spectrum from Aharonian et al. (2006) served as the null hypothesis for testing the photon spectrum above 1 TeV, 5 TeV, and 10 TeV, resulting in \(\chi^2/\text{ndf}\) values of 32.6/31, 15.7/14, and 5.0/7, respectively. These values indicate no significant difference in the spectra. Due to the low statistics in the last bin of the spectrum (four ON events, one OFF event) a likelihood profile was calculated as described in Rolke et al. (2005). With this method, a deviation of the last spectrum point from the expected flux according to Aharonian et al. (2006) is about \(2.5\sigma\), including neither systematic uncertainties nor the statistic uncertainties on the spectrum from Aharonian et al. (2006).

Since a flare in the MeV energy band is expected to be accompanied by an enhanced flux at tens of TeV (Lobanov et al. 2011), a search for variations in the flux above different energy thresholds was conducted. Integral fluxes above 1 TeV and 5 TeV were calculated for the night-wise samples (see Fig. 1), and higher energy thresholds were tested but are non-restrictive owing to low statistics. Fits of constants to the night-wise flux measurements give values of \((2.0 \pm 0.1) \times 10^{-11}\) cm\(^{-2}\) s\(^{-1}\) with \(\chi^2/\text{ndf} = 6.1/4\) and \((0.11 \pm 0.1) \times 10^{-11}\) cm\(^{-2}\) s\(^{-1}\) with \(\chi^2/\text{ndf} = 1.2/4\) for an energy threshold of 1 TeV and 5 TeV, respectively. For comparison, the integral fluxes of the spectrum published in Aharonian et al. (2006) above 1 TeV and above 5 TeV are 

\[
(2.26 \pm 0.08) \times 10^{-11}\text{ cm}^{-2}\text{ s}^{-1}\text{ and } (0.14 \pm 0.01) \times 10^{-11}\text{ cm}^{-2}\text{ s}^{-1},
\]

The first night of H.E.S.S. observations (MJD 56 358) is coincident with the highest flux level detected by Fermi-LAT in the March 2013 period of enhanced flux (Mayer et al. 2013). For that reason, upper limits on an enhancement of integral fluxes above 1 TeV and above 5 TeV were calculated for that night by comparison with the integral flux of the spectrum published in Aharonian et al. (2006). The spectrum in Aharonian et al. (2006) was produced with a different analysis and under different observation conditions; therefore, event-number based upper limit calculations as put forward in Rolke et al. (2005) cannot be applied. Instead, the two flux values \(F_{2006}\) and \(F_{2013}\), determined by integration of the fitted spectral functions, are compared, which automatically takes energy migrations and efficiencies correctly.
into account. Since no significant deviation of $F_{2006}$ and $F_{2013}$ is found, and $F_{2006} > F_{2013}$, a conservative 95% confidence level upper limit is determined as $F_{2006} + 2\sigma$, where $\sigma$ comprises the quadratically added statistical and systematic errors. With this method, the upper limit on an enhancement of the integrated flux above 1 TeV for the first night is $3.66 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ at a 95% confidence level, corresponding to an enhancement factor of 1.63 compared to the integrated flux published in Aharonian et al. (2006). For the integrated flux above 5 TeV, the upper limit on the flux enhancement factor relative to the integrated flux above 5 TeV as published in Aharonian et al. (2006) is 1.78 at a 95% confidence level.

4. Conclusions

The upper limits on the enhancement of the Crab flux are far above what is expected for the TeV energy range from some models, which predict enhancement factors of at most 1.01, as described above referring to Lobanov et al. (2011). In scenarios as in Bednarek & Idec (2011) or Kohri et al. (2012), however, enhancement factors of 2 or more are possible, exceeding the upper limits presented here. Besides this, experimental evidence does exist for such a high relative flux variability: During the flare discovered by AGILE in September 2010 (Tavani et al. 2010), three to four times the average Crab flux at a mean energy of 1 TeV was reported by ARGO-YBJ for ten days with an observation time of about 5.5 h each (Aielli et al. 2010). On July 3, 2012 ARGO-YBJ even observed an enhancement of eight times the average flux (Bartoli et al. 2012) for a flare reported by Fermi on that day (Ojha et al. 2012). Such an increase in flux clearly lies above the upper limits presented in this paper and could be observed by the H.E.S.S. instrument if it was present during the observations at hand, rendering it unlikely. More recently, the ARGO-YBJ group claimed a correlation of their Crab flux measurements with the varying Fermi-LAT flux and an average flux enhancement factor of $2.4 \pm 0.8$ during flares at GeV energies (Vernetto 2013). This value is compatible with the $2\sigma$ upper limits presented here only at the lower bound of its $1\sigma$ errors.

On the other hand, both the MAGIC and VERITAS imaging atmospheric Cherenkov telescopes did not detect any flaring activity at VHE either during previous flares or during the period investigated in this paper. These instruments use observation times in units of ~30 min, very similar to H.E.S.S. For the flare in September 2010, both MAGIC and VERITAS did not detect any flux enhancement in 58 min during one night and 120 min during four nights, respectively (Mariotti 2010; Ong 2010). For the flaring period discussed here, an integral flux above 1 TeV of $(2.05 \pm 0.07) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1}$ was reported by VERITAS for a period of ten days with 10.3 h of observations in total, compared to an integral flux of $(2.10 \pm 0.06) \times 10^{-11} \text{ cm}^{-2} \text{s}^{-1}$ for observations outside the flare time window (Aliu et al. 2014). Taking the 30% systematic error on flux measurements with VERITAS into account (Aliu et al. 2014), these numbers are in perfect agreement with the upper limits presented here and they give a very similar constraint on a possible flux enhancement.

The Fermi-LAT energy spectra of the flaring component extending to energies of a few hundred MeV favour at least a modest Doppler boosting. High angular resolution observations of moving features in the nebula, however, do not show direct evidence for bulk flow with $v > 0.5c$. It has been suggested that modest Doppler factors could be realised at the region close to the termination shock and that the optically resolved knot 0.6" displaced from the pulsar could be responsible for the $\gamma$-ray variability (Komissarov & Lyutikov 2011). In this scenario, the Doppler boost would lead to an apparent enhancement of the inverse-Compton component for the stationary observer. Not observing a transient feature at optical or X-ray frequencies Weisskopf et al. (2013) during the flare is consistent with this picture given that the extrapolation of the observed $\gamma$-ray spectrum to lower energies would render the X-ray/optical counterpart invisible against the bright nebula emission. Furthermore, a rather high value of the minimum energy of the radiating electrons would basically lead to no sizeable emission at lower energies.

Assuming that the specific flux of the flare follows a power law $f_{\gamma} \propto \nu^{-\alpha}$, the ratio of inverse-Compton and synchrotron emission at fixed frequencies scales with $f_{\nu}^{<\nu} / f_{\nu}^{\nu} \propto (\delta B)^{1 - \alpha}$ (Dermer et al. 1997; Georganopoulos et al. 2002), with $\delta$ the relativistic Doppler factor and $B$ the average magnetic field in the emission region. Therefore, the H.E.S.S. constraint combined with the contemporaneously measured Fermi-LAT (synchrotron) flux limits $\delta \lesssim 100/(B/122 \mu G)$.

Future multi-wavelength measurements, especially with instruments with larger collection areas for TeV $\gamma$ rays like the planned Cherenkov telescope array, will be able to constrain such models even further.

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References


Fig. 2. Crab photon spectrum. Black circles indicate the H.E.S.S. Crab nebula data taken in the nights from March 6 to March 10, 2013 with 1$\sigma$ error bars on the flux in the respective bin. The black line and the grey shaded area are the fitted power law model and the corresponding 1$\sigma$ error butterfly. The blue dashed line corresponds to the spectrum reported in Aharonian et al. (2006).