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Observations of the Crab nebula with H.E.S.S.

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The H.E.S.S. stereoscopic Cherenkov telescope system observed the Crab nebula in January-February and October-November 2004 with the complete four telescope array. The data, taken at large zenith angles, show a clear signal with a significance in excess of 100 standard deviations and serve to verify the performance and calibration of the instrument. The energy spectrum of γ-ray emission from the Crab nebula is measured and is found to follow a straight power law, given by dN/dE $=$ $2.86 \pm 0.06(stat) \pm 0.57(sys) \times 10^{-11}$ $E^{-2.67\pm0.03(stat)\pm0.1(sys)} cm^{-2} s^{-1} TeV^{-1}$ between 440 GeV and 10 TeV. The position of the source is fitted and compared with X-ray observations.

1. Introduction

The Crab nebula was discovered at very high energies, (VHE, above 100 GeV) in 1989 [1] and the emission has been confirmed by a number of other experiments [2, 3]. Due to the high flux from the source, relative to other known VHE sources, and its expected flux stability, it is conventionally used as a standard reference source for VHE astronomy. Observations of the Crab region made with the High Energy Spectroscopic System (H.E.S.S.) are presented here. At the latitude of the H.E.S.S. experiment the Crab nebula culminates at 45°, so observations of this source must always be made at large zenith angles. This increases the energy threshold of the detector, whilst yielding a larger collection area.

The H.E.S.S. array is situated in the Khomas highlands of Namibia, at an elevation of 1800 metres above sea level. The four telescopes are placed in a square formation with a side length of 120 metres. The telescopes are of steel construction and have an effective mirror area of 107 m^2. The H.E.S.S. cameras each consist of a hexagonal array of 960 photo-multiplier tubes (PMTs). Each PMT covers an area of 0.16° in diameter projected onto the sky [4]. The total field of view on the sky is 5° in diameter. The integrated, modular camera design enables fast trigger and readout windows, minimising the night sky noise and enabling a low energy threshold. A central trigger system demands a minimum of two triggered telescopes within a 50 nanosecond window [5]. The experiment commenced operations in June 2002 with the first of four Cherenkov telescopes, and the array was completed with the fourth telescope in January 2004.

2. Observations

The Crab nebula was observed for a total of 27 hours between November 2004 and February 2005, with 11.3 hours remaining after selection of runs taken in good weather conditions. Note that this period in Namibia coincides with the local rainy season, when weather conditions are not optimal. The corresponding live time for this data set is 10.6 hours. The mean zenith angle for these observations is 48°, and the mean trigger rate is 150 Hz. All observations were taken in *wobble* mode whereby the source is alternately offset by a small distance within the field of view, alternating between 28 minute runs in the positive and negative declination (or right ascension) directions. This offset was varied from 0.0° to 1.5° for this data. The average energy threshold for these observations is 440 GeV.

In order to reject the overwhelming background of hadronic showers, two level image cleaning is used to remove pixels containing only background noise. Each image is then characterised using Hillas parameters.

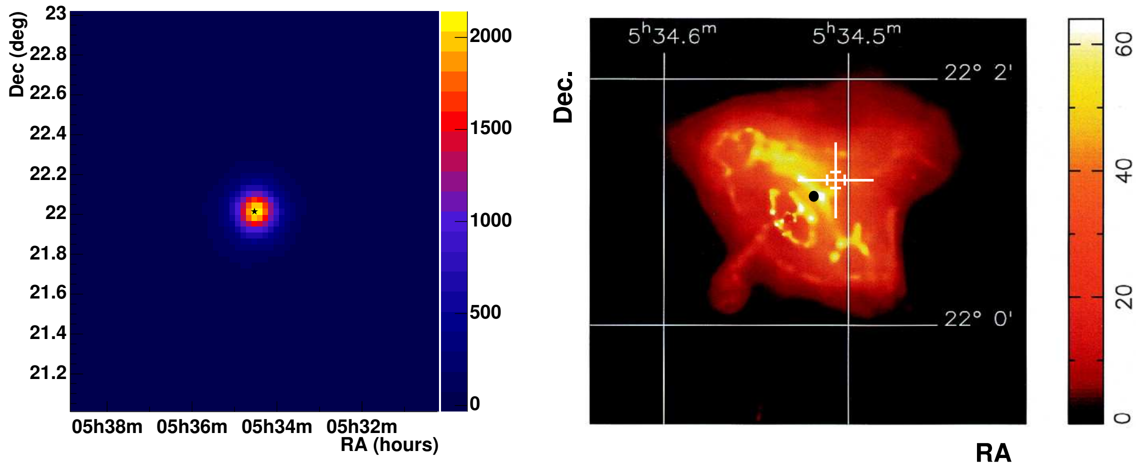

Figure 1. *Left* Two dimensional sky map of the region surrounding the Crab nebula (marked by a star), showing the γ-ray excess. *Right* Position of the centre of gravity of the VHE emission. The statistical errors are indicated by the partial box and the systematic errors by the cross. The black dot indicates the centre of gravity of the X-ray emission [10].

The source direction and shower impact parameter are calculated using standard geometric reconstruction. Mean reduced scaled width (MRSW) and length (MRSL) are calculated for each event by comparing the width and length of each telescope image with that expected for a given intensity and impact parameter. The average over the telescopes images passing selection cuts is then used for cosmic ray background rejection. Details of the calibration and data analysis procedures for H.E.S.S. data may be found in [6], [7] and [8].

An excess with a significance above $\sim 100\sigma$ after standard selection cuts is seen (according to the Li&Ma likelihood ratio formula [9]). The rate of excess γ-rays from the direction of the Crab pulsar is 6.49 ± 0.06 min^{-1}, within a radius of $0.11°$, which is optimised for the detection of a point source.

2.1 Position reconstruction

In order to study the precise position and extent of the VHE emission from the nebula surrounding the Crab pulsar, an uncorrelated map of the γ-ray excess from the sky in the region of the Crab was constructed. The two dimensional sky-map is shown in Figure 1 (left). A two dimensional Gaussian distribution was then fit to the image, and the resulting fit position of the excess (05h 34' 8", 22° 1' 11") is measured to be coincident with the Crab nebula. The statistical error on this fit is 5 arcseconds, while the systematic error is 20 arcseconds. Studies are under way to understand and reduce this systematic error.

This position is compared to the X-ray observations of the nebula from the Chandra satellite [10] in Figure 1 (right), and the extent of the statistical (partial box) and systematic errors (white lines) are shown. It can be seen that the position is consistent with the centre of the observed X-ray emission (black dot), while it is marginally consistent with the position of the Crab pulsar (centre of plot). The radius of the emission is consistent with a point source, given the H.E.S.S. point spread function for this analysis of 0.14°(68% containment radius).

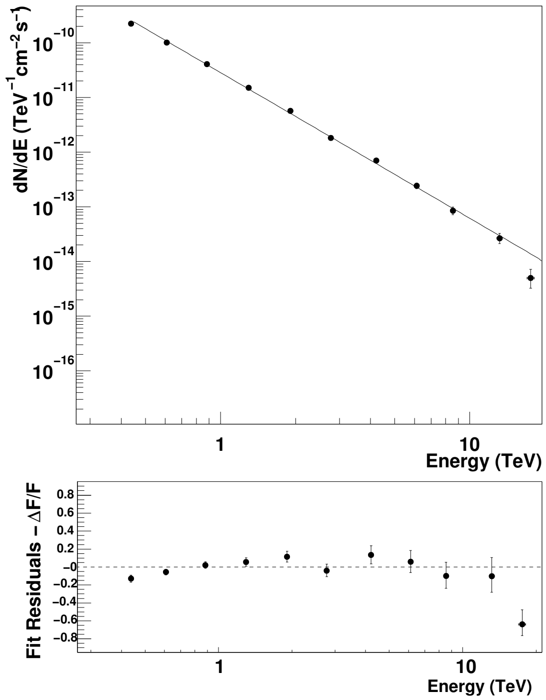

Figure 2. Reconstructed energy spectrum of VHE photons from the direction of the Crab nebula. Only the statistical error bars are shown.

2.2 Energy spectrum reconstruction

The energy of each event is estimated using a lookup table as a function of image intensity, impact parameter and zenith angle. The average estimated energy over telescope images passing selection cuts is then taken. The average energy resolution in the range used for spectral studies is 15%. The energy spectrum is then reconstructed using events passing standard cuts. The effective areas are estimated from Monte Carlo simulations as a function of energy, zenith angle and source position in the field of view. The reconstructed energy spectrum for these observations is well fitted by a straight power law from 440 GeV to 20 TeV, given by $dN/dE = 2.86 \pm 0.06(stat) \pm 0.57(sys) \times 10^{-11}\mathrm{E}^{-2.67\pm0.03(stat)\pm0.1(sys)}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. The estimation of systematic errors for this result is discussed further in [7]. The χ^2 from this fit is 25.0, with 8 degrees of freedom. A plot of the energy spectrum is shown in Figure 2. The flux and spectral slope agree well with previous measurements. There is marginal evidence for curvature in the spectrum from the Crab as measured by H.E.S.S.; this is the subject of further study.

3. Conclusion

A strong signal is seen from the Crab nebula, in large zenith angle observations by H.E.S.S.. The integral flux above 1 TeV is $1.71 \pm 0.04(stat) \pm 0.34(sys) \times 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The flux and energy spectrum are consistent with previous measurements of the source by H.E.S.S. [11] and other experiments. The observed excess is point-like, and the fit position is consistent with the centre of gravity of the X-ray pulsar wind nebula as seen by Chandra.

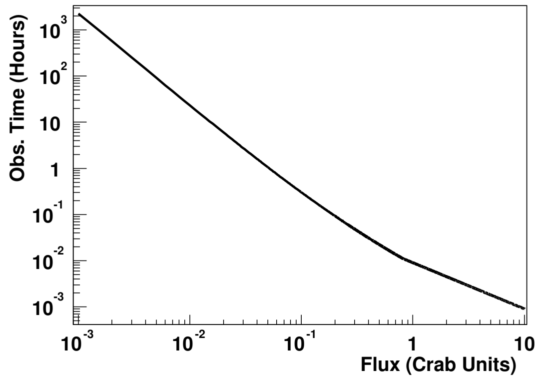

Figure 3. Sensitivity of the HESS array, expressed as the amount of time required to detect a signal at the 5σ level, vs. the flux of the source, for a source of similar spectral slope to the Crab nebula.

One can use Monte Carlo simulations to predict the time required to detect a source of a certain strength as a function of zenith angle. In Figure 3 the time as a function of signal strength required for a 5σ detection at 20° zenith angle is shown. The H.E.S.S. array is capable of detecting a source with a flux of 1% of the Crab nebula in 25 hours, or alternatively detecting a source of similar strength to the Crab in 30 seconds. This sensitivity is unprecedented in the field of VHE astrophysics and opens a new window for sensitive and precise measurements of VHE γ-ray sources.

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