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Observations of the Crab Nebula and Pulsar with STACEE

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The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is an atmospheric Cherenkov detector that detects cosmic γ-rays using the showerfront-sampling technique. The 1 GS/s Flash ADCs used by STACEE provide both timing and pulse height information regarding the Cherenkov showerfront, and they allow for the reconstruction of the showerfront in off-line data analysis. We present STACEE's detection of the Crab Nebula using new γ/hadron separation parameters, along with the result of a search for the Crab Pulsar.

1. Introduction

The Crab Nebula is one of the most studied objects in astrophysics with observations extending over the complete detectable range of the electromagnetic spectrum, from radio waves to TeV γ-rays. Its broad spectral energy distribution is unique and is mainly attributed to non-thermal, synchrotron and inverse Compton, emission processes [1]. Of the confirmed sources of TeV γ-rays, the Crab Nebula is the only object with both steady and strong emission. Consequently, in addition to its use as an important astrophysical laboratory, it has become the *de facto* calibration source in TeV astrophysics. The Crab is regularly observed by all atmospheric Cherenkov telescopes, with the goal of refining the observing techniques.

Observations by the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) in 1998 and 1999 yielded a solid excess of 6.8 σ from the Crab Nebula in 43 hours of on-source exposure [2]. Since then the STACEE detector has undergone several important optical and electronic upgrades, including a doubling of the number of heliostats from 32 to 64 and installation of Flash Analog-to-Digital Convertors (FADCs). During the 2002-2003 and 2003-2004 observing seasons, the upgraded STACEE detector, known as STACEE-64, undertook observations of the Crab Nebula and Pulsar. The primary motivation for these observations was to aid in the characterization of the upgraded instrument, while simultaneously providing data for a pulsed emission analysis. We report here on a detection of the Crab Nebula using these data and on the result of our search for pulsed emission from the Crab Pulsar.

2. The STACEE Detector

STACEE is a showerfront-sampling atmospheric Cherenkov telescope that uses the facilities of the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico [3]. The NSTTF is a solar energy research facility incorporating a central receiver tower and an array of heliostats (solar mirrors). STACEE uses secondary mirrors, in the central receiver tower, to focus Cherenkov light reflected by the heliostats onto cameras having a total of 64 photomultiplier tubes. A one-to-one mapping between heliostats and PMTs allows the Cherenkov showerfront to be sampled independently at 64 different locations in the heliostat field.

STACEE uses a custom-built trigger system to select Cherenkov events from amongst the background of night-sky light fluctuations. In the event of a Cherenkov trigger, amplified and AC-coupled signals from the PMTs are recorded, together with a GPS timestamp, using 8-bit FADCs (one per PMT). The FADCs provide important temporal and intensity information, at a sampling rate of 1 GS/s, which is fully utilized in the offline data analysis procedure.

3. Crab Nebula Observations

STACEE observations of γ-ray sources are undertaken on clear moonless nights. Observations are conducted in ON/OFF mode. In this mode an observation of the source is followed by a coextensive observation of a control region of sky, at the same azimuth and elevation as the source. A γ-ray signal from the source manifests itself as an excess of ON over OFF events after data conditioning and γ/hadron separation.

The observations of the Crab Nebula, presented here, were undertaken on clear moonless nights during the Crab seasons of 2002-2003 and 2003-2004. Data were taken within $\sim$2 hours of source transit. A total of 30.3 hours of on-source data were obtained, comprising 10.9 hours in 2002-2003 and 19.4 hours in 2003-2004. Two different heliostat pointing configurations were employed during these observations. During the 2002-2003 season all heliostats were pointed toward the expected shower maximum location, at a distance 12.5 km/cosΘ a.s.l., upward from the center of the field, where Θ is the zenith angle of the source. This form of pointing, referred to as "monocanting", optimizes the Cherenkov light collection for intrinsically dim showers. For the 2003-2004 observations, a variant of monocanting, referred to as "paracanting", was employed whereby 48 heliostats were pointed toward the expected shower maximum position and 16 heliostats were pointed parallel to the Crab Nebula direction. The choice of paracanting over monocanting for the 2003-2004 season was motivated by simulation studies that suggested superior shower reconstruction for paracanted data [4].

4. Data Quality Selection

Before STACEE data are analyzed for the presence of a γ-ray signal, pairwise data quality selection is performed to remove sections of data flagged as unusable due to hardware malfunctions and/or unstable atmospheric conditions, see [5] for more details. Following removal of poor quality data from the Crab Nebula data set, a total of 21.2 hours of on-source data remained, comprising 7.2 hours in 2002-2003 and 14.0 hours in 2003-2004. Only these data were used in the analyses presented here.

5. Padding

Prior to shower reconstruction, any night-sky background brightness differences between the ON and OFF sky regions, which might otherwise introduce bias into the analysis, are accounted for through the use of software padding. In the padding procedure developed for STACEE data, [6], the quieter ON or OFF FADC trace for a particular channel is padded by the addition of an appropriate noise trace (taken from a library of measured FADC pulses) so that the ON and OFF traces have the same noise level. A software trigger requirement is then imposed on the padded data before event reconstruction algorithms are applied.

Table 1. Results from STACEE observations of the Crab Nebula. The numbers of events remaining (ON and OFF), the ON-OFF difference, the statistical significance, and the gamma-ray rate are tabulated for the 2002-2003 and 2003-2004 data after various cuts. The cuts are described in the text. "Re-trigger" refers to the imposition of a trigger in software after padding. Significances are calculated using the Li-Ma procedure [13] that accounts for the ON and OFF livetimes.

Cut	No. ON	No. OFF	ON–OFF	σ	γ Rate (min^{-1})
2002-2003					
Raw	165773	164341	1432	2.6	3.3 ± 1.30
Re-trigger	137923	136237	1686	3.4	3.9 ± 1.20
Re-trigger + Direction .	41440	40652	788	2.8	1.8 ± 0.67
Re-trigger + Grid Ratio	4452	3989	463	5.1	1.1 ± 0.21
2003-2004					
Raw	290770	288641	2129	2.4	2.5 ± 0.89
Re-trigger	231269	228932	2337	3.1	2.7 ± 0.79
Re-trigger + Direction .	75031	72818	2213	5.5	2.6 ± 0.45
Re-trigger + Grid Ratio	14331	13405	926	5.5	1.1 ± 0.19

6. Shower Reconstruction and Gamma/Hadron Separation

At present, the STACEE collaboration is experimenting with two main γ/hadron separation parameters in offline data analysis; the *shower direction* and the *grid ratio* (the *grid ratio* provides a measure of the smoothness of the showerfront). Both parameters are detailed in [7]. Given the small size of the STACEE Crab Nebula data sets for the 2002-2003 and 2003-2004 seasons, and the different heliostat pointing configurations employed, it was not possible to optimize γ/hadron selection criteria using a subset of the data. Accordingly, the selection cuts used were derived directly from γ-ray and proton air-shower simulations [7]. For both seasons a *shower direction* cut of $\theta < 0.3^o$ (θ is the angle between the reconstructed position and the source position) and a *grid ratio* cut of < 0.35 were used.

The response of STACEE to γ-ray and cosmic-ray air showers was studied using simulated data. To simulate electromagnetic and hadronic air-shower cascades, STACEE uses the CORSIKA package [8]. Custom ray-tracing and Monte-Carlo algorithms are used to simulate the telescope optics and electronics.

For a paracanted configuration, the sensitivity of STACEE to γ-rays of various energies, at a number of positions along the Crab Nebula's celestial trajectory, was calculated before and after γ/hadron separation. The energy threshold of the experiment, defined as the peak in the differential spectral response curve of the detector for the Crab Nebula TeV γ-ray spectrum (spectral index $\alpha = 2.4$, on an $E^{-\alpha}$ differential spectrum [9]), was determined to be $\sim$170 GeV.

7. Results

The significance and rate of excess events detected by STACEE from the direction of the Crab Nebula are listed in table 7. Results are provided for the *shower direction* and *grid ratio* parameters separately. The results indicate that the Crab Nebula was detected by STACEE in both seasons at the $\sim$5 σ level. The result from a combination of both parameters has not been calculated at this stage, pending a study of the degree of correlation between the two. The rather low excess obtained using the *shower direction* selection for the 2002-2003 data set is not unexpected given the poorer angular resolution expected for monocanted data as opposed to paracanted data, see [4] and [7] for more details.

An independent analysis for pulsed emission from the Crab Pulsar using a subset of 15 hours of data has been carried out [10]. No evidence of pulsed emission was found and an upper limit on the pulsed fraction of the STACEE signal was determined to be 16.4% at the 99.9% confidence level, for an energy threshold of 185 ± 35 GeV.

8. Summary

The Crab Nebula was detected by STACEE at a significance level above 5σ in each of the 2002-2003 and 2003-2004 observing seasons, at an energy threshold of around 170 GeV. In the most recent data, using paracanting, we find a significant improvement in the significance using the *shower direction* parameter when compared to the earlier monocanted data. A pulsed emission upper limit at 16.4% of the Crab Nebula signal was determined for the Crab Pulsar. Although consistent with measurements by other groups, the present upper limit cannot offer discrimination between the various Crab Pulsar emission models, for example [11] and [12].

Although the sensitivity of STACEE is not as good as that obtained by imaging Cherenkov telescopes, the results presented here do indicate the promise of the showerfront-sampling technique. It is noteworthy that these results were obtained using γ/hadron separation parameters taken directly from simulations without optimization. An optimization of STACEE's γ/hadron separation parameters on the Crab Nebula data set will provide useful selection criteria for application to other STACEE data sets.

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