Observations Of The Crab Nebula And Pulsar With The STACEE Detector

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Abstract

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a new ground-based detector presently under construction for γ-rays between 50 and 250 GeV. STACEE's low energy threshold gives it access to the unexplored energy regime between satellite and other existing ground-based telescopes. We present preliminary results from observations of the Crab Nebula and pulsar from November 1998 to February 1999 using the partially completed STACEE detector. Using thirty-two heliostat mirrors of what will eventually be a sixty-four mirror array, we detect γ-rays from the Crab Nebula at a significance of $+7\sigma$ for approximately 50 hours of on-source observations.

1 Introduction:

The Crab Nebula is one of the brightest sources in the γ-ray sky, and has been detected at energies from 1 MeV to 50 TeV. Its energy spectrum has been extensively studied by many detectors and a variety of techniques, and its unpulsed emission is well described by a synchrotron self-Compton (SSC) emission model. However, to date few observations have been made in the energy range between 10 and 200 GeV, which lies above the reach of current satellite detectors and below that of ground-based detectors. Observations of the Crab in this energy range are important for bridging satellite and ground-based observations. They can also test whether a simple SSC model is sufficient to explain the Crab's spectrum, or whether an additional component, perhaps due to bremsstrahlung or π^0-decay, is needed (Aharonian & Atoyan, 1998). In addition, outer-gap models of pulsar emission predict pulsed emission up to 100 GeV, whereas polar-cap models predict sharp cutoffs in pulsed emission at lower energies (Harding & de Jager, 1997). Observations of the Crab below 100 GeV could thus decide between competing models for pulsed emission. Because the Crab Nebula is such a bright source with an apparently constant flux, it also serves as a convenient "standard candle" with which to test new γ-ray detectors.

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a new ground-based γ-ray detector designed to probe the energy region from 50 to 250 GeV. STACEE is currently under construction, and is slated for completion in January 2000. During the winter of 1998-1999, we conducted observations of the Crab Nebula and pulsar with a subset of the STACEE detector. These measurements, along with observations by the CELESTE collaboration (Smith 1999), are the first by ground-based experiments to probe energies below 100 GeV. In this paper, we present preliminary results from Crab observations with the partially completed STACEE detector.

2 Description of the STACEE Detector:

STACEE is located at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories, Albuquerque, NM, USA (106.51°W, 34.96°N). The NSTTF comprises an array of 212 solar heliostat mirrors, each 37 m^2 in area. During the day these mirrors collect and focus sunlight onto a 200 foot tower for experiments in solar power generation. STACEE uses a subset of this array to reflect Cherenkov light from extensive air showers onto secondary optics located near the top of the tower. The secondary optics image this light onto a camera of photomultiplier tubes, with each phototube receiving light from a single heliostat. Phototube signals are discriminated, delayed, and combined in coincidence to form a trigger for the experiment. Multi-hit TDC's measure the shower front arrival time at each heliostat. Pulse heights, phototube rates and currents, and the GPS time are also recorded for each trigger.

Currently STACEE uses 32 heliostats, instrumented with integrating ADC's and multi-hit TDC's. A multi-level trigger divides the heliostats into four subclusters of eight channels each. We require at least 5 of 8 tubes to fire in each of three or more subclusters in order to trigger the experiment. STACEE will eventually use 48 heliostats (with plans to expand to 64), 1 GS/s flash ADC's, and improved trigger electronics, which should dramatically improve the detector's performance and energy threshold. The STACEE detector is described in more detail in Chantell (1998) and Covault (1999).

3 Observations:

STACEE conducted observations of the Crab Nebula and pulsar during the time period from November 15, 1998 to February 18, 1999. Observations were done on clear moonless nights when the source was within 45° of zenith. Substantial amounts of zenith (cosmic ray) data and calibration data were also acquired.

STACEE was operated in an ON-OFF observing mode. On-source runs of 28 minute length were alternated with off-source runs taken with the detector tracking a point $\pm 7.5°$ (one half hour) away from the Crab in right ascension. All runs pairs were matched to track the same trajectory in azimuth and elevation across the sky. After run cuts which removed pairs affected by poor weather, poor atmospheric clarity, or detector malfunctions, the data set for this analysis consisted of 113 ON-OFF pairs, with a total observing time on-source of ~ 3000 minutes.

4 Analysis and Results:

4.1 Analysis Technique: Unlike traditional imaging Cherenkov detectors, STACEE is a lateral Cherenkov array which samples the Cherenkov light pool across a wide area, on the order of the air shower size. The arrival direction of the shower is determined from the measured arrival times of the shower front at the heliostats. Calibrated ADC measurements can determine the shower energy and the lateral density profile of Cherenkov light in the shower.

The first step of event reconstruction is to reimpose the trigger in software using a short 12 ns coincidence window. Then the measured arrival times of the shower at the heliostats are fit to a spherical wave front with a fixed assumed core location to determine the arrival direction of the shower. See Figure 1.

Comprehensive run cuts are applied to each ON-OFF pair to ensure that both halves of the pair are matched closely with regards to their individual tube rates, subcluster rates, and other quantities. These run cuts remove any pairs which were affected by changing weather conditions or instrument malfunctions. The number of events after trigger reimposition is then tallied for the remaining ON-OFF pairs.

4.2 Results: Of 113 ON-OFF pairs, 82 pairs showed an excess of events after the trigger was reimposed, and 31 pairs showed a deficit. The significance of the total data set, after reimposing the trigger but before fitting the wave front, is $+7\sigma$. Table 1 shows a monthly breakdown of the significance values. Figure 2 shows the distribution of significances for each ON-OFF pair. The significances are normally distributed with a standard deviation of 1, as is expected for a γ-ray excess from a constant flux source like the Crab.

We are in the process of developing event cuts, derived from Monte Carlo simulation, to provide additional hadronic rejection, based upon such quantities as the reconstructed shower direction and the shower front shape. Preliminary results show that the overall significance of the signal increases when such cuts are applied.

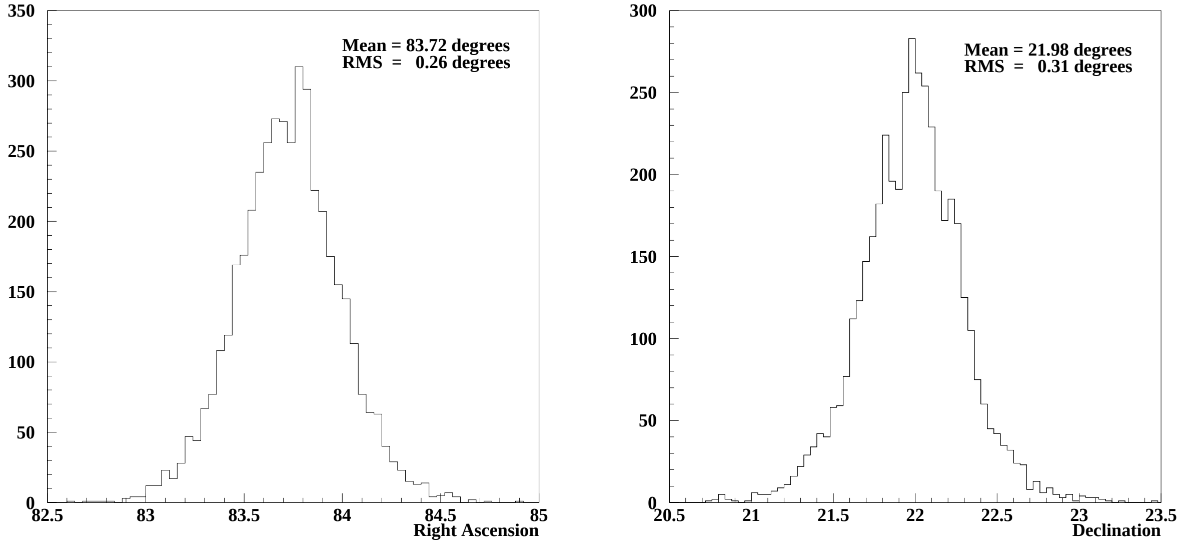

Figure 1: Reconstructed RA and DEC for a typical Crab on-source run. The displacement of the mean position is less than 0.09° from the expected Crab position of 83.64°, 22.01°.

Month(s)	Pairs With Excess	Pairs With Deficit	Monthly Significance
Nov ’98	28	10	$+5\sigma$
Dec ’98	29	13	$+4\sigma$
Jan-Feb ’99	25	8	$+4\sigma$
Total	82	31	$+7\sigma$

Table 1: Monthly significances for the Crab Nebula from the raw data. Data for the shorter observing periods in January and February have been combined. The monthly significances come from the total event counts after trigger reimposition.

The observed rate of excess events is ~ 2 events/minute. Monte Carlo simulations of STACEE’s effective area curve convolved with an assumed Crab spectrum imply that the detected γ-ray differential rate peaks near $\sim$75 GeV. Extraction of the integral flux and energy threshold from the data set is in progress.

5 Conclusions:

The partially completed STACEE detector has seen a $+7\sigma$ excess in the raw event rate for the Crab Nebula, compared to the off-source regions, in ~ 50 hours of on-source data. Preliminary Monte Carlo studies imply a trigger threshold of ~ 75 GeV. The observed γ-ray rate is ~ 2/minute, and the distribution of pairwise significances is normally distributed in accordance with expectations. We are in the process of developing event selection cuts to improve hadronic rejection. We are also currently modelling the effective area of the experiment in order to determine the integral flux. A pulsar analysis is planned.

Completion of the STACEE detector is anticipated in the fall of 1999. With the addition of more heliostats and new trigger electronics, we should significantly improve the energy threshold and sensitivity of the experiment.

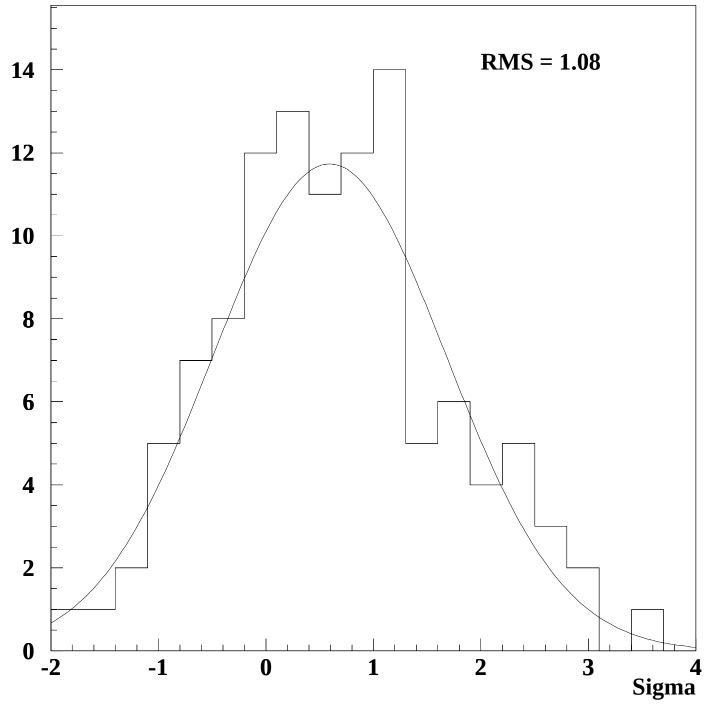

Figure 2: Distribution of the pair significances for all ON-OFF pairs from the raw data. The overall distribution is Gaussian with a standard deviation of 1, in accordance with expectations.

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References

Aharonian, F., Atoyan, A. 1998, Neutron Stars & Pulsars (Tokyo, University Acadmic Press), 439
Chantell, M.C. et al. 1998, Nucl. Instr. Meth. A 408, 468
Covault, C.E. et al. 1999, Proc. 26th ICRC (Salt Lake City, 1999) HE.6.1.01
Harding, A.K., de Jager, O.C. 1997, Towards a Major Atmospheric Cherenkov Detector-V, ed. O.C. de Jager (Kruger National Park, 1997), 64
Smith, D. et al. 1999, Proc. 26th ICRC (Salt Lake City, 1999) OG.2.2.06