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Observations of Markarian 421 with the STACEE-48 instrument

J. A. Hinton[1], L. M. Boone[2], D. Bramel[3], E. Chae[1], C. E. Covault[4], P. Fortin[5], D. M. Gingrich[6,7], D. S. Hanna[5], R. Mukherjee[3], C. Mueller[5], R. A. Ong[8], K. Ragan[5], R. A. Scalzo[1], D. R. Schuette[8], C. Theoret[5], and D. A. Williams[2]

[1]Enrico Fermi Institute, University of Chicago, 5640 Ellis Av., Chicago, IL 60637, USA
[2]Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA
[3]Columbia University & Barnard College, New York, NY 10027, USA
[4]Department of Physics, Case Western Reserve University, 10900 Euclid Av., Cleveland, OH 44106, USA
[5]Department of Physics, McGill University, Montreal, Quebec H3A 2T8, Canada
[6]Centre for Subatomic Research, University of Alberta, Edmonton, Alberta T6G 2N5, Canada
[7]TRIUMF, Vancouver, British Columbia V6T 2A3, Canada
[8]Department of Physics & Astronomy, University of California, Los Angeles, CA 90095, USA

Abstract. Several experiments have reported the detection of high fluxes of TeV γ-rays from Markarian 421 (Mrk 421) in early 2001. We describe preliminary results from observations of Mrk 421 during the period February to May 2001 using the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE). STACEE is sensitive to γ-rays in the energy range from about 50 to 500 GeV. The low energy threshold of STACEE should allow us to extend the γ-ray spectrum of this source, thereby placing additional constraints on emission models during outburst.

1 Introduction

During the period January to May 2001 enhanced X-ray and TeV γ-ray emission has been observed from the blazar Mrk 421 (Boerst, 2001). Since February 2001, the newly completed STACEE-48 detector has been used to search for ~100 GeV γ-ray emission from this object.

STACEE is an experiment which uses the atmospheric-Cherenkov technique to study sources of 50-500 GeV γ-rays (Covault, 2001). Observations with low energy threshold detectors such as STACEE should provide new data on the spectral energy distribution (SED) of Mrk 421 and its variation during flaring episodes. Extension of the measured SED to lower energies should in turn provide tighter constraints on models of γ-ray production in blazars.

The STACEE-48 instrument represents an intermediate stage between the STACEE-32 detector as described in (Oser, 2001) and the final, 64 channel, STACEE observatory which is due for completion in the summer of 2001. The current detector utilizes 48 heliostat mirrors (each 37 m^2) distributed over an approximately circular area of diameter ~200 m. Cherenkov light striking each heliostat is focussed onto a separate photomultiplier tube (PMT) via one of three 2 m diameter secondary mirrors.

Correspondence to: J. A. Hinton (jah@hep.uchicago.edu)

2 Observations

The STACEE observations of Mrk 421 so far consist of 42 hours of on-source data taken between the 16th February and the 25th May 2001. Each of the ninety 28 minute on-source runs is accompanied by an off-source run tracking an identical path in horizon coordinates. Given stable conditions in both runs of a pair, an excess of triggers on-source can be interpreted as a γ-ray signal on top of the cosmic-ray background. Target sources are tracked on clear moonless nights while they lie within $45°$ of zenith. The trigger rate of the array due to cosmic ray initiated showers varies from 3-4 Hz depending on the zenith angle of the target.

Careful monitoring of all components of the system is essential to the reliability of the on/off technique. The active optical elements of STACEE are the heliostat mirrors. The pointing direction of these mirrors is checked every 10 seconds and any heliostats deviating by more than $0.1°$ from their assigned directions are removed from the on/off pair off-line. The stability of the electronic detector system is also carefully monitored. Photomultiplier (PMT) currents and discriminator rates are read out every 0.5 seconds. Runs with excessive PMT currents and/or variable currents are rejected. The dead-time of the system is monitored in every run using vetoed and unvetoed 10 kHz clock signals.

Period of observations	**Feb 16 - May 25**
Total on/off pairs	**90**
Number of pairs after cuts	**58**
Days with observations after cuts	**25**
Total on-source time after cuts	**26 hours**

Table 1. Summary of STACEE observations of Mrk 421 in 2001.

STACEE has a two level coincidence trigger; the first level trigger (L1) requires a multiplicity N from the 8 heliostats in a cluster. The second level trigger requires L1 signals from M of the 6 clusters. For the observations described here $N = 5$ and $M = 4$ were used. The discriminator thresh-

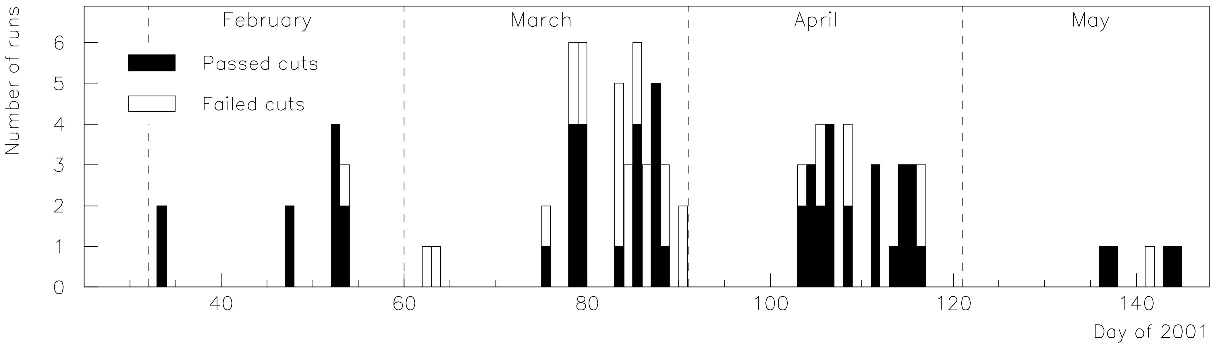

Fig. 1. The distribution of STACEE Mrk 421 observations in time.

old for an individual PMT was 145 mV (corresponding to $\approx$ 6 photoelectrons) for the majority of the data considered here.

The rate of L1 triggers in individual clusters (dominated by night sky background (NSB) fluctuations) is monitored and used to calculate the expected rate of NSB level 2 triggers. In test data triggering only on the NSB, our calculations of L1 rates from PMT rates and the trigger rate from L1 cluster rates agree with observations to within 10% and 20% respectively. The NSB trigger rate calculation is used to impose a further cut: the expected rate of NSB triggers in a run must be < 0.2 per minute. This cut ensures minimal contamination of a γ-ray signal by NSB fluctuations.

A final run cut is applied based on an estimate of sky conditions by the observer. After all cuts, 58 pairs (a total of 26 hours on-source) remain. Figure 1 and Table 1 provide a summary of the Mrk 421 observations.

3 Discussion

Taking all data together we observe an on-source excess in our raw trigger rate with very high statistical significance. In addition to this overall excess there is also strong evidence for variability in our data with the greatest activity observed between the 17th and 24th of March.

Off-line data cuts based on reconstruction of the shower front should further enhance this signal. Our preliminary analysis applies the following procedure:

- the trigger condition is re-applied in software to remove any mis-triggered events. Less than 1% of events fail the trigger reimposition.
- the arrival time of photons at each heliostat is calculated from TDC data and the known time-of-flight through the detector.
- a minimization process is used to find the best fit values of the arrival direction. A spherical wavefront with an impact point at the centre of the array is assumed in the fit. The radius of curvature is fixed for a given zenith angle and is 9 km for vertical showers.
- the χ^2 of this fit is typically smaller for γ-ray initiated showers than cosmic-ray showers. A cut on χ^2 can therefore be used to reject part of the cosmic-ray background.

Figure 2 shows the distribution of directions reconstructed using this method for a sample on/off pair.

The presence of a 6th magnitude star in the Mrk 421 field of view means additional care must be taken to ensure a correct estimate of γ-ray flux from an on/off pair. Observations of a field containing a similar star (and no γ-ray source) are underway and will allow us to fully quantify the effects of increased on-source currents in the Mrk 421 data.

A program of simulations has been performed to establish the energy threshold and effective area of the array and to test reconstruction algorithms. These simulations consist of the following stages:

- Air-shower development, Cherenkov light production and atmospheric attenuation are modeled using CORSIKA (Heck, 1998).
- Cherenkov photons reaching ground level are propagated through the STACEE optics using a three dimensional ray trace.
- Night sky background photoelectrons are added to the signal photoelectrons generated in the PMTs and a waveform generated for each STACEE channel. These waveforms are then passed through a model of the STACEE trigger electronics.
- Information from showers deemed to trigger the array is written out in the format of our raw data and passed through our standard analysis.

Preliminary results from this analysis suggest an energy threshold of 120 ± 25 GeV for a source with an E^{-2} spectrum at zenith (Covault, 2001).

4 Conclusions

We have observed the BL Lac object Markarian 421 during February-May 2001 with the STACEE telescope. During this

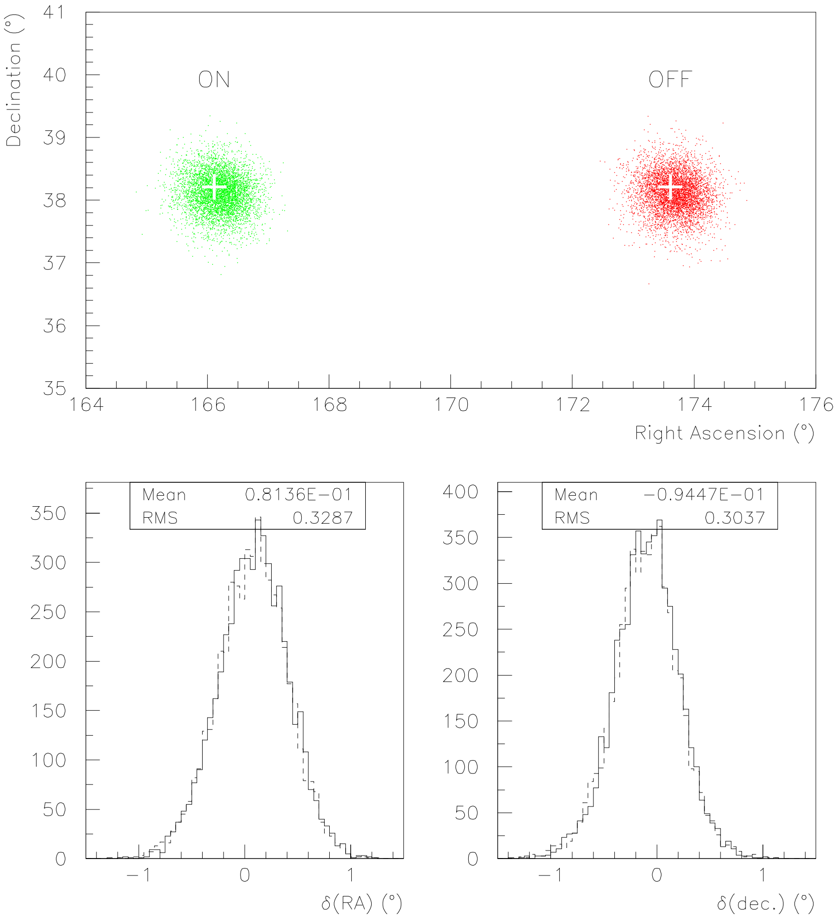

Fig. 2. The upper plot shows reconstructed directions for an on/off pair. The target positions are marked with a white cross. The lower plots show the difference between reconstructed and pointing directions in RA and δ. The distribution from the off-source run is shown as a dashed line.

time, an integrated total of more than 40 hours of on-source observations were recorded. Quality cuts reduce this total to 26 hours on-source.

Our initial analysis of the data reveals both strong significance for the detection of the source and evidence for variability. Refinements to this analysis are underway, and complete details on the energy threshold of STACEE and the flux deduced from these observations will be presented at the conference.

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