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Astrophysics around 100 GeV with STACEE

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Abstract

STACEE is an atmospheric Cherenkov detector using the large mirror area of a solar research facility to obtain an energy threshold around 100 GeV. STACEE has been used to study the Crab and several AGN: Markarian 421, W Comae, H 1426 + 428. The STACEE observing program is coordinated with the high-energy astrophysics community both by participation in multiwavelength campaigns and by follow-up observations of γ-ray burst alerts. Analysis methods under development using pulse height information from flash ADCs installed on each channel are expected to substantially improve the experiment's sensitivity. A summary of the performance is given.

Keywords: BL Lacertae objects: individual (H1426 + 428, Markarian 421, W Comae); Galaxies: active; γ-rays: observations; Instrumentation: detectors; ISM: individual (Crab Nebula); Pulsars: individual (Crab Pulsar)

1. Introduction

Imaging atmospheric Cherenkov telescopes (IACTs) have achieved great success operating above 300 GeV, with the next generation of detectors (H.E.S.S. (Hinton, 2004), CANGAROO III (Kubo, 2004), VERITAS (Krennrich, 2004), and MAGIC (Lorenz, 2004)) anticipating substantial sensitivity below 100 GeV. They will be able to study this energy range because they have significantly larger mirror area than present generation IACTs. STACEE has been able to start pioneering the 100 GeV energy region by using the large installed mirror area at an existing solar research facility. A schematic view is

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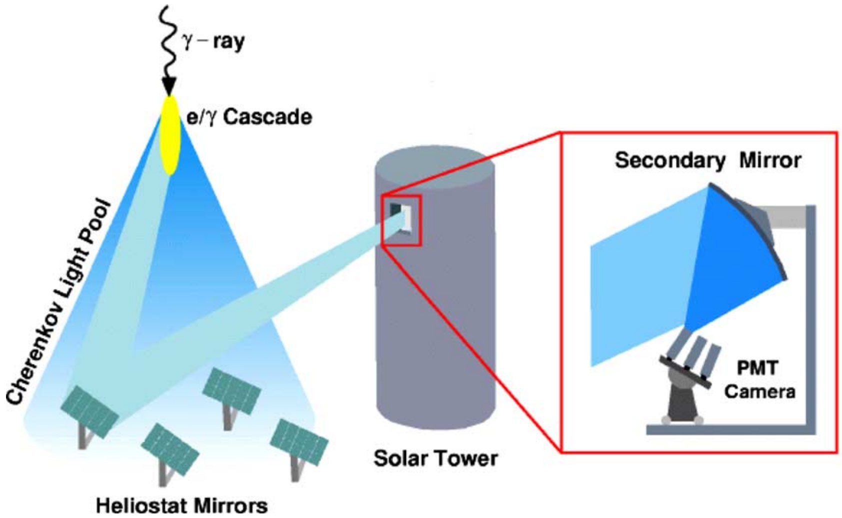

Fig. 1. Design of the STACEE detector. Cherenkov light produced by showers in the atmosphere is reflected by heliostat mirrors on the ground onto a secondary mirror on the solar tower. The secondary focuses light from each heliostat onto a separate PMT.

shown in Fig. 1. CELESTE (Bussons-Gordo, 2004) and Solar-2 (Tripathi, 2004) employ a similar technique.

STACEE uses the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories outside Albuquerque, New Mexico, USA. The NSTTF is located at 34.96° N, 106.51° W and is 1700 m above sea level. The facility has 220 heliostat mirrors designed to track the sun across the sky, each with 37 m^2 area. STACEE uses 64 of these heliostats.

STACEE employs five secondary mirrors on the solar tower to focus the Cherenkov light onto photomultiplier tube (PMT) cameras. Three 2-m diameter secondaries 50 m above ground level each receive light reflected from 16 heliostats. Two 1.1-m diameter secondaries 39 m above ground level receive light from 8 heliostats each. As STACEE was being constructed, data were taken in two configurations with fewer than 64 heliostats. STACEE-32 used two 2-m secondaries and 32 heliostats (Hanna et al., 2002) and operated from 1998 to 1999. STACEE-48 operated with all three 2-m secondaries and 48 heliostats from 2000 to 2001. STACEE-32 and STACEE-48 data analysis relied primarily on timing information, because pulse height information was not recorded for all channels. As part of the completion of the full STACEE experiment, 1 gigasample per second flash ADCs (FADCs) were connected to all channels in September 2001. The FADC information (Zweerink et al., 2003) allows much more sophisticated data analysis to be performed, and brings additional ability to distinguish γ-ray showers from hadronic showers, reducing the cosmic-ray background.

The STACEE observing program is designed to study a number of the key topics in high-energy γ-ray astronomy. Studies of the Crab have been used to search for pulsed emission and to benchmark experimental performance. Data have been taken on a number of active galaxies, to elucidate the emission mechanism(s). In many cases, the data have been part of multiwavelength campaigns involving other TeV γ-ray instruments and X-ray satellites. An additional motivation for the study of these extragalactic sources is to seek evidence of absorption of γ-rays by the extragalactic infrared background light. An exciting possibility for STACEE is to follow up γ-ray burst alerts from satellites. The sections which follow elaborate on STACEE results and plans for several of these sources.

An important part of the STACEE observing program is participation in multiwavelength campaigns, especially those including X-ray data. The contemporaneous data collected across many energy bands of the electromagnetic spectrum by these campaigns are especially valuable in testing models of particle acceleration and γ-ray production. Current information about STACEE participation in these campaigns is posted on the web site http://www.astro.columbia.edu/~stacee/multi.html. In addition to several campaigns for particular sources discussed in the following sections, there are two Target of Opportunity (ToO) proposals with RXTE, both lead by Krawczynski, which STACEE is part of. Indeed, a ToO was declared in May 2003 for the AGN 1ES 1959+650, during which STACEE acquired as much data as possible.

2. The Crab

γ-ray emission from the Crab Nebula was detected (Oser et al., 2001) between November 1998 and February 1999 using STACEE-32. The energy threshold for the observations, defined as the peak of the detected γ-ray spectrum, was $E_{\mathrm{th}} = 190 \pm 60$ GeV, and the integral flux was $I(E > E_{\mathrm{th}}) = (2.2 \pm 0.6 \pm 0.2) \times 10^{-10}$ photons cm^{-2} s^{-1}. This flux is consistent with IACT results at higher energies, for a differential power law spectrum of $E^{-2.4}$. To search for pulsed emission from the Crab pulsar, the recorded event times were transformed to the solar system barycenter, folded modulo the Jodrell Bank radio ephemeris (Lyne et al., 1999), and the resulting phase histogram was examined for excess emission in the "on pulse" region seen by EGRET (Nolan et al., 1993; Ramanamurthy et al., 1995; Fierro et al., 1998). The phase histogram is consistent with being flat, and the pulsed fraction of the emission is found to be less than 5.5%.

Data for the Crab have been taken in Winter 2002–2003 with the complete STACEE instrument, although limited by the conjunction of the Crab with Saturn. Analysis of the data is still under way. The preliminary γ-ray rate of ~5 per minute compares quite favorably to the rate of 1.6 min^{-1} measured with STACEE-32, a detector with less acceptance. In conjunction with the γ-ray data, three heliostats were used to collect data on the optical pulsar, as a check of the ephemeris and barycentering code, as well as the data acquisition system timing. Preliminary analysis of the optical data, including digital filtering to remove 120 Hz signals from artificial lighting, shows the expected pulsed signal.

3. Markarian 421

Markarian 421 was the first AGN detected at TeV energies (Punch et al., 1992), and also the first AGN detected by STACEE (Boone et al., 2002). It has been a highly variable source for the last several years (Gaidos et al., 1996), and the spectrum has been observed to change as the flux changes (Krennrich et al., 2002). Based on the existing data above 100 MeV, the high energy peak of the spectral energy distribution (SED) is apparently near the energy region covered by STACEE. In an effort to understand the emission mechanisms of this source, it has been the target of many multiwavelength campaigns.

Markarian 421 had a strong outburst in Spring 2001, during which data were obtained with STACEE-48. The integral flux observed above 140 GeV was $(8.0 \pm 0.7 \pm 1.5) \times 10^{-10}$ cm^{-2} s^{-1}, consistent with a continuation to lower energies of the TeV spectrum. As shown in Boone et al. (2002), the light curve obtained by STACEE covering 50–300 GeV appears correlated with light curves from both RXTE and Whipple observations.

The STACEE collaboration participated in the recent Mrk 421 multiwavelength campaigns lead by Krawczynski (December 2002 and January 2003) and Edelson (February–March 2003). Unfortunately, very little data was obtained during either campaign because of bad weather. Since the source had been active, observations continued even after the campaigns ended, with 0.5–1 h allocated each night to Mrk 421, for so long as its position in the sky, the weather, and the moon allowed. The analysis of these data continues and will be the topic of a future publication.

4. W Comae (ON + 231)

W Comae, also known as ON + 231, is an AGN at a moderate redshift of $z = 0.102$. From both an observational and a theoretical point of view, it is a good candidate for emission around 100 GeV, but has not yet been detected above EGRET energies. It was one of the few AGN detected by EGRET above 10 GeV, including one photon of 27 GeV (Dingus and Bertsch, 2001), and has a hard (differential) spectral index of -1.73. It was also predicted to be a strong TeV source by Mannheim (Mannheim, 1996). X-ray data constrain the SEDs for leptonic models to cutoff sharply above 100 GeV (Böttcher et al., 2002). Hence, emission above 100 GeV could be a smoking gun for hadronic emission processes.

Observations of W Comae with STACEE were conducted in 1999 (with STACEE-32), 2002, and 2003. Fig. 2 shows the upper limits obtained from the 1999 and 2002 data sets, compared to the EGRET data and extrapolated power law. The preliminary upper limit from the 2002 data for the flux above 140 GeV is 1.41×10^{-10} cm^{-2} s^{-1}. The 1999 limit is reported in Théoret (2001). The STACEE limits are not yet quite strong enough to conclusively show a cutoff in the EGRET power law, whereas the Whipple limit (Buckley, 1999) clearly shows a cutoff by 350 GeV.

5. H 1426 + 428

The highest redshift TeV blazar detected so far is H 1426 + 428, having $z = 0.129$. It is a weak TeV source as seen by Whipple (Horan et al., 2002), HEGRA (Aharonian et al., 2002), and CAT (Djannati-Atai et al., 2002), with a flux about 3% of the Crab and a very soft $E^{-3.5}$ spectrum. H 1426 is an "extreme" X-ray BL Lac, with a synchrotron peak near 100 keV. It is one of the best TeV candidates in SSC models.

STACEE data were taken in 2002 for H 1426 as part of a multiwavelength campaign, yielding a preliminary upper limit for the differential flux at 120 GeV of 2.0×10^{-9} cm^{-2} s^{-1} TeV^{-1}. As shown in Fig. 3, this limit is below the power law extrapolation of the higher energy measurements, perhaps indicating a roll over of the spectrum below a few hundred GeV. Additional observations of this source have been taken in 2003; the analysis of those data is underway.

6. 3C 66A

A promising AGN for future detection above 100 GeV is 3C 66A (0219+428). There is a re-

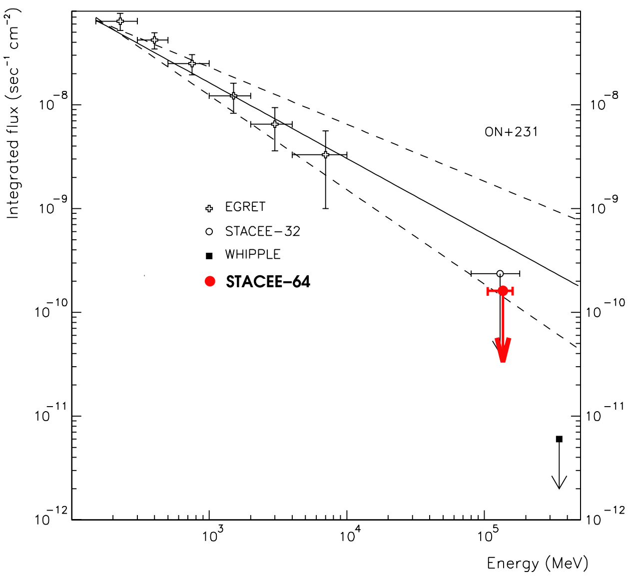

Fig. 2. High-energy γ-ray results for W Com (ON+231). The STACEE-64 upper limit is from 2002 and is preliminary.

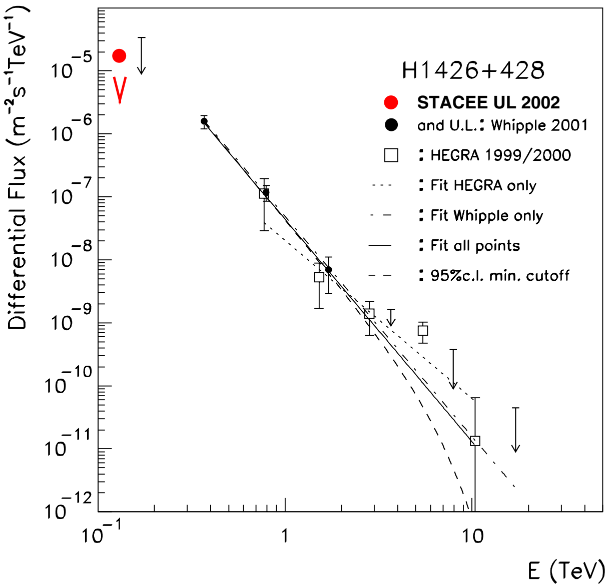

Fig. 3. High-energy spectrum of H 1426 + 428. The STACEE upper limit (UL) from 2002 is preliminary. Figure adapted from Aharonian et al. (2002).

ported TeV detection in 1996 (Neshpor et al., 1998), but no other experiment has yet confirmed it as a TeV source. Also, Costamante and Ghisellini identify 3C 66A as a good TeV candidate (Costamante and Ghisellini, 2002). It is a BL Lac object intermediate between the high- and low-frequency peaked subclasses. Hence a detection above 100 GeV would open the door to a new class of sources. It was detected by EGRET several times, and X-ray observations indicate that its synchrotron component extends into the X-ray regime. In addition, its relatively high redshift of 0.44 makes it a good candidate for observation of IR absorption features. The STACEE Collaboration plans to participate in the recently awarded RXTE campaign to be lead by Böttcher in winter 2003–2004.

7. γ-ray bursts

Several GRBs were detected by EGRET in the energy range from 100 MeV to 1 GeV (Hurley et al., 1996), and at least one was detected with emission up to 18 GeV (Hurley et al., 1994). The possibility of detecting GRBs at energies between 50 and 250 GeV by an experiment such as STACEE is exciting for several reasons. First, a general picture of the high energy (>1 GeV) emission has not been established. For example, it is unknown whether GeV emission is a typical feature of most bursts, or whether it appears only in special cases. Second, the low energy threshold of STACEE makes it sensitive to γ-rays out to larger redshifts than other ground-based experiments. This is particularly important now that the redshifts of many bursts are known to be ∼1 or greater. Only an experiment with STACEE's energy threshold has even a chance to detect very high-energy emission from most bursts.

Observing γ-ray bursts is a high priority for STACEE. The GCN (Gamma-Ray Burst Coordinates Network) burst alerts are monitored with a computer program which alerts the STACEE operators if one is visible from the STACEE site. The STACEE instrument can be re-targeted to the position of a GRB within about 2 min to search for emission above 50 GeV. We also search for afterglow emission from bursts that have occurred within the previous 24 h. STACEE is already making observations of several bursts per year. Once NASA's SWIFT satellite (Gehrels, 2004) is launched in May 2004, we expect to have prompt observations for ~6 bursts per year, and afterglow observations within the first 24 h for ~30 additional bursts per year.

The ability of STACEE to observe the GRB source position within minutes of the first emission is very significant. EGRET detected GeV emission, including an 18 GeV photon from GRB940217, 90 min after the start of the burst (Hurley et al., 1994), so there is still a very good chance of detecting a burst after the STACEE response time. γ-ray bursts are by far the brightest high-energy objects in the sky when they occur, and STACEE would easily detect the flux estimated by power-law extrapolation of the EGRET data. We estimate that the STACEE sensitivity (5σ in a 30 min observation) to a GRB is about 2×10^{-9} cm^{-2} s^{-1} above 70 GeV. The flux from GRB940217 extrapolated to STACEE energies is ~50 times higher than this sensitivity.

8. Sensitivity gains using FADC data

The results discussed so far have not yet made use of the new information available from the FADCs. There are several ways in which that information is expected to improve performance. The first of these has to do with the effects of night sky background (NSB) light. STACEE observations are taken in On–Off mode, comparing the rate of events when tracking the source to the rate when tracking a comparable off-source region of sky. Brightness differences between the on-source and off-source fields can cause apparent differences in the background rate because NSB fluctuations in the brighter field promote small cosmic ray showers over the trigger threshold at a higher rate. The analysis of the STACEE-48 data for Mrk 421 corrected for this effect using data taken tracking an ordinary star as if it were a γ-ray source. Having FADC information, a more direct way to account for differences is to pad the FADC traces in software with extra NSB photons so that the on- and off-source data have equivalent NSB rates. The CELESTE group has used this method (de Naurois et al., 2002). Data taken on several stars are now being used to test various padding schemes.

The second area in which FADC information will improve STACEE performance is event reconstruction. The pulse height information measured by the FADCs improves the energy and angular resolution. The angular resolution is improved, as shown in Fig. 4, because the shower core can be found and used in the fit to the shower direction.

The FADC information should also enable γ-ray showers to be distinguished from the background cosmic ray showers to a large degree. In γ-ray showers, the energy of the primary particle is distributed among hundreds of relativistic electrons and positrons, which are produced with small transverse momentum relative to the incident primary. The result is a pool of Cherenkov light reaching the ground which illuminates the heliostats relatively uniformly. On the other hand, hadronic showers from cosmic rays have fewer particles, generally with a higher fraction of the primary energy and larger transverse momentum with respect to the primary particle. The Cherenkov light from such showers has much larger variations in the intensity from one heliostat to the next. Preliminary Monte Carlo studies using these differences to reject background showers have achieved gains in sensitivity (quality factors) of 2.5–3.5.

9. Summary

Construction of the STACEE experiment is complete. Analysis methods are still being developed to take full advantage of FADC information. A summary of the anticipated performance characteristics is given in Tables 1 and 2.

The science done with STACEE so far has concentrated on AGN and the Crab. The results illustrate the role STACEE data plays in illuminating the "low energy" part of the high energy γ-ray spectrum. Plans for future observations with STACEE include the full range of potential sources, such as supernova remnants, pulsars, and EGRET unidentified sources.

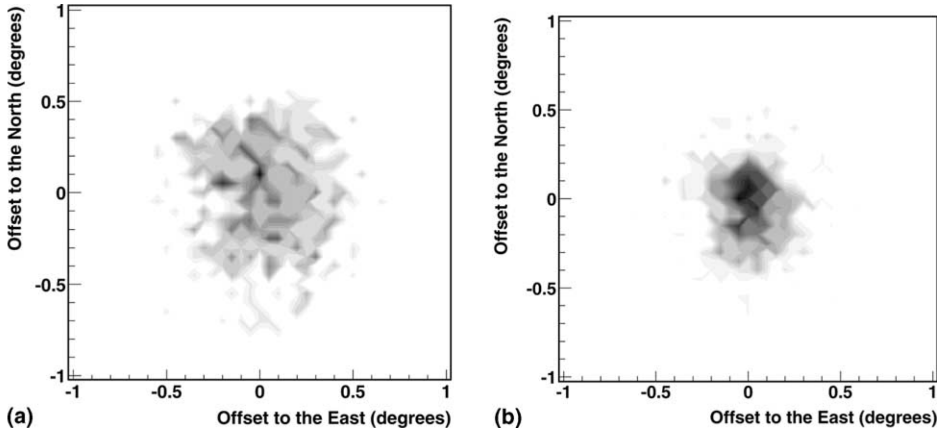

Fig. 4. The arrival directions reconstructed by STACEE for simulated vertical γ-rays. (a) The direction is reconstructed without knowledge of the core location of each event, and the RMS is 0.26° in the east–west direction and 0.31° along the north–south direction. (b) A maximum likelihood fit is used with the pulse height information to constrain the core position, improving the RMS values to 0.19° and 0.22°, respectively.

Table 1
Summary of anticipated STACEE performance parameters, incorporating FADC-based reconstruction, which are energy independent

64-channel trigger rate	~8 Hz
Discriminator threshold	4 p.e. ≃ 50 GeV
Crab 10σ detection	25 h
Crab 10σ w/hadron rejection	4 h

Table 2
Summary of anticipated STACEE performance parameters, incorporating FADC-based reconstruction, which are energy dependent

	100 GeV	250 GeV
Angular resolution	0.18°	0.15°
Energy resolution	30%	25%
Effective area	4000 m^2	15,000 m^2

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