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STACEE Observations of 1ES 1218+304

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Abstract: We present the analysis and results of recent high-energy gamma-ray observations of the high energy-peaked BL Lac (HBL) object 1ES 1218+304 with the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE). 1ES 1218+304 is an X-ray bright HBL at a redshift z=0.182. It has been predicted to be a gamma-ray emitter above 100 GeV, detectable by ground-based Cherenkov telescopes. Recently, this source has been detected by MAGIC and VERITAS, confirming these predictions. STACEE's sensitivity to astrophysical sources at energies above 100 GeV allows it to explore high energy sources such as X-ray bright active galaxies and gamma-ray bursts. We present results from STACEE observations of 1ES 1218+304 in the 2006 and 2007 observing seasons.

Introduction

Active galaxies of the "blazar" class include BL Lac objects and flat-spectrum radio quasars (FSRQs), and are characterized by non-thermal continuum emission that extends from radio to high energy gamma rays. The spectral energy distributions (SEDs) of these sources typically have two broad peaks, one at low energies (radio to X-ray) and the other at higher energies (keV to TeV). In the framework of relativistic jet models, these objects are highly beamed sources, emitting plasma in relativistic motion (e.g. [1]). In blazar SEDs, the low energy peak is explained as synchrotron emission from high energy electrons in the jet, while the high energy peak is probably due to inverse Compton emission. Several competing "leptonic" and "hadronic" jet model explanations exist for the high energy emission (e.g. see [2] & [3] for reviews), and further broadband observation of blazars are needed to distinguish between these models.

Since the discovery of blazars as high energy gamma-ray sources by the Energetic Gamma-Ray Experiment Telescope (EGRET) on board the *Compton Gamma Ray Observatory* (CGRO) [4] and the first detection of a TeV (10^{12} eV) blazar by the Whipple Observatory (Mrk 421 [5]), the search has been on for more TeV blazars. The number count of TeV blazars is growing, with the advent of new generation atmospheric Cherenkov telescopes (ACTs) [6]. To date, almost all confirmed blazars detected at TeV energies are high-frequency-peaked BL Lac objects (HBLs), as opposed to quasars that constitute the majority of the EGRET detections. HBLs are a sub-class of BL Lac objects, characterized by lower luminosity than FSRQs and a synchrotron peak in the X-ray band [1]. Blazars are categorized into different sub-classes based on the peak frequencies and the relative power in the low and high energy peaks of their SEDs [7]. Given the high synchrotron peak frequencies of HBLs, indicating the presence of high energy electrons, these sources have been predicted to be good candidates for TeV emission, based on synchrotron self-Compton (SSC) emission models [8] as well as hadronic models [9]. Several of the "extreme" synchrotron BL Lacs [10] have been detected at TeV energies, confirming these predictions.

1ES 1218+304 is an X-ray bright (flux at 1 keV $>$ 2 μJy) HBL, categorized as an "extreme" BL Lac, and predicted to be a TeV source. The source was recently detected by both MAGIC [11] and VERITAS [12], at energies > 100 GeV. At a redshift of $z = 0.182$, 1ES 1218+304 is one of the most distant blazars detected to date. The source was never detected by EGRET, indicating that ACTs are sensitive to a different population of gamma-ray blazars than EGRET.

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a ground-based experiment that is sensitive to gamma rays above 100 GeV. STACEE observations of AGN are motivated by the need to understand particle acceleration and emission mechanisms in blazars, as well as their interaction with the extragalactic background light (EBL). Despite what is already known, a great deal remains to be discovered regarding the physics of blazars. STACEE's extragalactic observing program has included both HBLs, as well as LBLs [13, 14]. Recent observations of 1ES 1218+304 with STACEE were motivated by the detection of TeV emission from the source by MAGIC, providing further evidence that X-ray bright HBLs tend to be strong VHE sources. STACEE observations of 1ES 1218+304 were carried out in the 2006 and 2007 observing seasons. In this paper we present a summary of STACEE observations of the HBL 1ES 1218+304.

The STACEE Detector

STACEE is a shower-front sampling Cherenkov detector that operates with an energy threshold of about 100 GeV. It uses 64 large, steerable mirrors (heliostats) at the National Solar Thermal Test Facility (NSTTF) near Albuquerque, NM, USA to collect Cherenkov light from extensive air showers. The large light-collection area ($\sim 2400\ \mathrm{m}^2$) gives it a lower energy threshold than all but the newest imaging Cherenkov detectors. STACEE uses secondary mirrors, in the central receiver tower to focus Cherenkov light reflected by the heliostats onto photomultiplier tubes (PMTs), with a one-to-one mapping between the heliostats and the PMTs (Figure 1 shows a schematic diagram). The 64 channels are grouped into eight clusters of eight channels each for triggering, and the two level trigger requires that all events trigger at least five tubes in each of at least 5 clusters. STACEE has been operating as a complete detector since 2001 and has observed numerous astrophysical sources [15, 16]. Details of the STACEE detector and operations are given elsewhere [17].

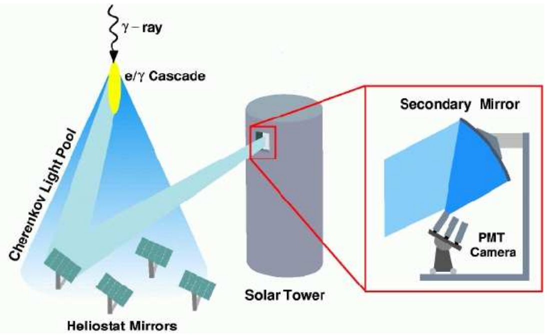

Figure 1: The shower-front sampling technique as employed by STACEE. Cherenkov light from air shower cascades is reflected by the heliostat mirrors onto secondary mirrors in the receiver tower, which in turn concentrate the light onto a bank of photomultiplier tubes.

Observations & Data Analysis

STACEE observed 1ES 1218+304 from February to June, 2006 and February to May, 2007. Data taken with STACEE consist of 28-minute paired ON-source and OFF-source observations, the latter taken to determine the background. Table 1 summarizes the STACEE data and the total livetime on 1ES 1218+304.

The STACEE data set was analyzed off line to remove data taken in unfavorable weather conditions or with detector malfunctions (e.g. malfunctioning heliostats, high voltage trips, etc.), eliminate biases in the trigger rates and increase the sensitivity of the instrument. STACEE data cleaning criteria or *cuts* are described elsewhere [18]. In addition, cosmic ray background suppression techniques were applied to the data, as described in [19, 20].

During the 2006 and 2007 observing seasons, a total of 152 ON-OFF pairs (70.9 hr) were taken on 1ES 1218+304. After several standard data quality cuts, the total number of hours on source was reduced to 28.3 hr in the combined 2006-07 seasons. The difference in the field brightness between the ON and the OFF field was also taken into account using a technique called *library padding* [21]. After cuts and padding, a net ON-source excess of 236 events was seen against a background of 5547 events. At a significance of 2.3σ, this excess is insufficient to claim a detection of 1ES 1218+304 but is used to establish flux upper limits for the source. There were no significant transient events in the data, as shown by the histogram of significances for each of the 152 pairs in Figure 2.

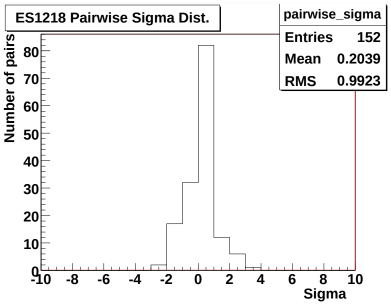

Figure 2: Pair-wise sigma distribution for the 1ES 1218+304 data set.

Table 1: STACEE Data on 1ES 1218+304

Year	Live-^{a} time	ON-Source Excess Events	Detection Sig.
2006	12.0	236	2.3σ
2007	16.3		

Note. – a Total hours remaining after quality cuts.

Detector Simulations

In order to understand the results of the observations of 1ES 1218+304, Monte Carlo simulations were carried out to determine the effective area of the STACEE detector, as described in [18]. The effective area was calculated as a function of energy at several hour angles, for gamma-ray and proton primaries. Figure 3 shows the net effective area of STACEE for the 1ES 1218+304 observations. The simulated effective area was then used to calculate the detector energy threshold and fluxes. The energy threshold E_{th} is defined as the peak of the response curve obtained by multiplying the detector effective area with the source spectrum. A spectral index of -3.0 was assumed for 1ES 1218+304, based on the measurement of the gamma-ray spectrum by MAGIC [11]. For 1ES 1218+304 we get $E_{th} \sim 150 \pm 45_{\text{sys}}$ GeV.

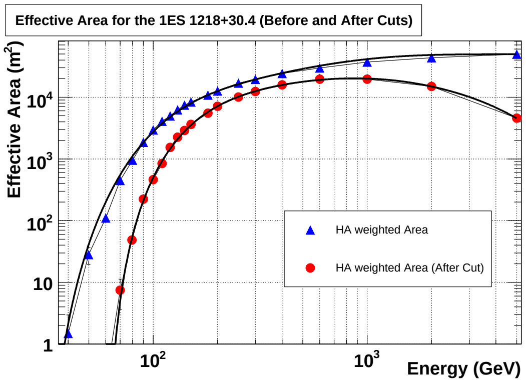

Figure 3: Hour-angle weighted effective area of the STACEE detector for the 1ES 1218+304 observations. The lower plot shows the effective area after quality cuts.

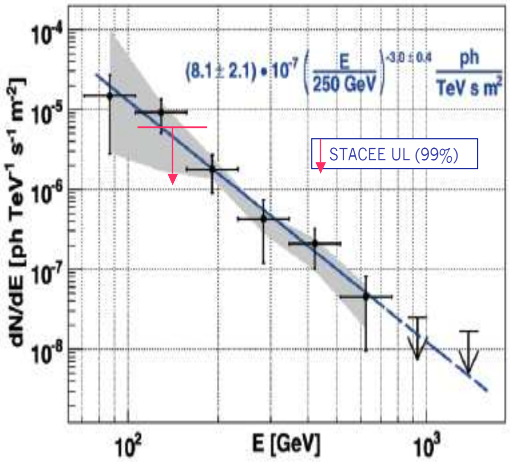

Figure 4: Gamma-ray spectrum of 1ES 1218+304, as measured by MAGIC (figure from [11]). The STACEE 99% flux upper limit is overlaid on the plot at 150 GeV, the energy threshold of STACEE, as obtained from detector simulations. The upper limit was calculated assuming the power-law spectral index of -3.0 measured by MAGIC.

Summary & Discussions

STACEE observed the high frequency-peaked BL Lac object 1ES 1218+304 in 2006 and 2007. After all cuts and padding 28.3 hr of data yielded an ON-source excess with a significance of 2.3σ consistent with no detected flux. Simulated effective areas (Figure 3) were used to derive flux upper limits. For the combined 2006 and 2007 data sets the differential flux upper limit at the 99% confidence level was derived to be $< 5.2 \times 10^{-6}$ m^{-2} s^{-1} TeV^{-1} at 150 GeV, the energy threshold of STACEE. The upper limit was calculated assuming that the differential flux of photons follows a power law with an index of -3.0, as measured by MAGIC [11]. The STACEE upper-limit is shown overlaid on the MAGIC spectrum in Figure 4. These numbers are consistent with the spectrum measured by MAGIC [11], and with the recent VERITAS results indicating a weak gamma-ray source at ~ 5% of the Crab flux [12].

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