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STACEE Observation of Low-Frequency Peaked BL Lac Objects

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We present the analysis and results of recent high-energy gamma-ray observations of two low frequency-peaked BL Lac objects, 3C 66A and W Comae, made with Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE). The 3C 66A observations were part of an extensive multiwavelength campaign in 2003-2004. STACEE's sensitivity to astrophysical sources at a lower energy range (100 - 500 GeV) allows it to explore LBLs, with their synchrotron peaks at lower energies than HBLs. Detection of $>$ 100 GeV emission from LBLs is potentially interesting as it would open the door to a new class of objects for TeV astronomy.

1. Introduction

BL Lac objects and flat-spectrum radio quasars (FSRQs) are active galactic nuclei belonging to the "blazar" class, whose emission at most wavebands are dominated by violent, non-thermal continuum emission. These objects are characterized by bright radio emission and high variability at most frequencies, and have been seen to emit a significant portion of their bolometric flux in high energy gamma rays, at least during flares. The spectral energy distributions (SEDs) of these sources typically have two broad peaks, one at lower energies (radio to X-ray) and the other at higher energies (keV to TeV). In the framework of relativistic jet models (e.g. [1]), the low energy emission is explained as synchrotron emission from high energy electrons in the jet. The details of particle acceleration and the production of high energy gamma-rays responsible for the second peak in the SED are still under debate and several competing "leptonic" and "hadronic" jet models exist (e.g. see [2] & [3] for reviews).

To date, all confirmed blazars detected at TeV (10^{12} eV) energies by ground-based atmospheric Cherenkov telescopes (ACTs) have been low-redshift, high-frequency-peaked BL Lac objects (HBLs) [4]. The advent of new generation ACTs, with lower energy thresholds and steadily improving sensitivities [5], now allows the possibility of extending the list of very high energy (VHE) blazars to include intermediate- and low-frequency-peaked BL Lac (LBLs) objects, with lower peak frequencies in their broadband SEDs. The study of a new class of blazars with ground-based detectors is now possible at gamma-ray energies.

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a wavefront sampling Cherenkov detector that currently operates above an energy threshold of about 100 GeV [6]. 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 and concentrate it onto an array of photomultiplier tubes. The large light-collection area gives it a lower energy threshold than all but the newest imaging Cherenkov detectors. STACEE observed two LBLs, W Comae and 3C 66A several times during the 2002 - 2005 observing seasons. As potential gamma-ray sources, 3C 66A ($z = 0.444$[1]) and W Comae ($z = 0.102$), are attractive targets for the study of the optical and infrared extragalactic background light (EBL). The relatively large redshifts of these sources makes them accessible only to detectors operating at low energy threshods, at or below 100 GeV. 3C 66A was considered an interesting target for STACEE because of its detection at EGRET energies, its synchrotron peak at a higher energy than for typical LBLs, and an unconfirmed previous TeV detection [4]. During the 2003-2004 observing season, the STACEE observations of 3C 66A were part of an extensive multiwavelength campaign during which the source was found to be in an historically high X-ray (3-10 keV) state [7]. The second LBL observed by STACEE was W Comae, a source also detected by EGRET with a hard photon spectral index and an X-ray spectrum that shows clear evidence for the onset of the high energy emission component beyond ~ 4 keV [8]. W Comae was recently predicted to be an excellent test case for distinguishing between leptonic and hadronic blazar jet models [9], making it an attractive source for coordinated VHE gamma-ray and broadband observations. STACEE observations of W Comae during the spring of 2003 and the implication of the results in the context of hadronic and leptonic jet models were discussed by Scalzo et al. (2004) [10]. In this article we summarize the recent STACEE observations of 3C 66A and W Comae.

2. 3C 66A

During the 2003-2004 observing season, STACEE observed 3C 66A for a total of 33.7 hours, plus an equivalent number of "off-source" hours for background observations. These observations were part of an extensive multiwavelength campaign that included radio, optical and infrared monitoring, X-ray observations with RXTE, and VHE observations with STACEE and VERITAS [11].

The STACEE data were analyzed by applying several data-quality "cuts," or data-cleaning criteria, that removed data taken in unfavorable weather conditions or known detector malfunctions (e.g. inoperational heliostats, high voltage trips, etc.) [7]. In addition, the effect of the difference in the night sky background (NSB) rate between the source region and the off-source region was taken into account using a technique called *library padding* that has been shown to effectively eliminate field brightness differences in the STACEE data [10]. After cuts and padding, 16.3 hours of live on-source data remained which yielded an on-source excess significance of 2.2σ.

In order to calculate the spectral limits of 3C 66A, Monte Carlo simulations of the STACEE detector were done and the effective area of the detector was determined. These are described in detail by Bramel et al. (2005) [7]. We report here estimates of integrated flux which results from a convolution of the source spectrum with the acceptance of the STACEE detector. The interpretation of our results depend on the assumed source spectrum. Unfortunately, the spectral properties of 3C 66A are essentially unknown above 10 GeV, the EGRET energy limit. The spectrum of 3C 66A is likely to be cut off either due to intrinsic softening or absorption by the EBL. Figure 1a shows the post-cut energy response curve of the STACEE detector for an assumed power-law photon spectrum with differential spectral index of -2.5. Table 1 shows the energy thresholds and flux upper limits derived from the STACEE observations.

Figure 1b shows the SED of 3C 66A at various epochs of the core multiwavelength campaign for this source in 2003 [11], as well as archival measurements. The STACEE upper limits at $E_{th} > 200$ GeV from Table 1 are also shown in the figure. The RXTE data indicate that the X-ray spectrum is very soft, and that the low frequency component of the SED extends beyond 10 keV. From the shape of the time-averaged spectrum

[1]Note, however, the uncertainty associated with the redshift of 3C 66A, as discussed by Bramel et al. (2005)[7].

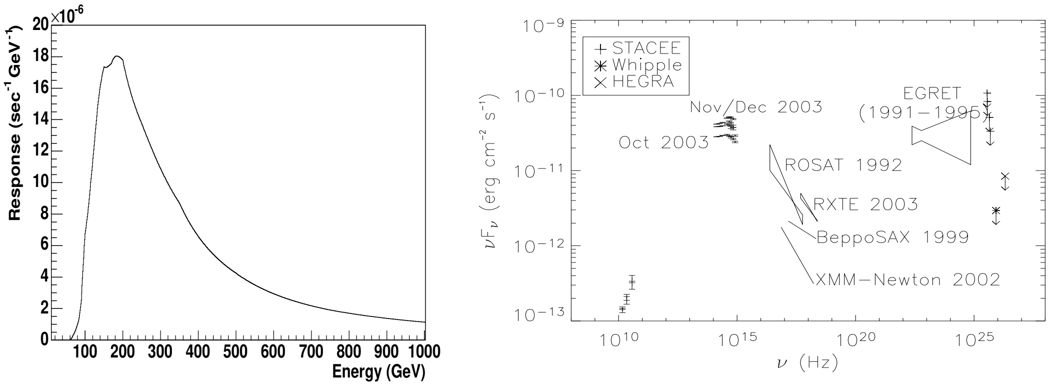

Figure 1. (a) Net response of STACEE during the 3C 66A observations, for an example power-law photon spectrum with a differential spectral index of -2.5. The peak in the curve indicates the detector energy threshold. **(b)** SED of 3C 66A showing contemporaneous STACEE, RXTE and radio/optical/UV data. Note the variability seen in the optical data during the 2003 campaign. Historical X-ray, gamma-ray (EGRET) and TeV data are also included. (See [7, 11] for references).

in the optical/UV band, it is apparent that the peak of the synchrotron component of the SED is located in the optical range. If the historical EGRET spectrum is representative of the gamma-ray flux during the 2003 campaign, then the total energy output in the synchrotron and high energy peaks of the SED are comparable, as is generally seen in LBLs. The STACEE upper limits are consistent with this picture. The data shown in Figure 1b represents the first simultaneous set of broadband spectral data on 3C 66A from optical to gamma-ray energies; they will be useful in various modelling studies of AGN, e.g. leptonic jet models [2] or hadronic synchrotron-proton blazar models [3]. Further work in this area is anticipated in the future.

3. W Comae

W Comae was observed by STACEE during three different epochs: Spring 2003, 2004 and 2005. Observations carried out in the spring of 2003 did not find any significant emission in a data set comprising 10.5 hours of ON-source observing time [10] (13.5 hours before quality cuts). These observations were made at a lower energy threshold than any other ACT and were used to place constraints on certain hadronic (synchrotron proton blazar - SPB) models for W Comae [9]. Upper limits on the flux at the 95% confidence limit were derived: $(1.5 - 3.5) \times 10^{-10}$ cm^{-2} s^{-1} above 100 GeV for the leptonic models, or $(0.5 - 1.1) \times 10^{-10}$ cm^{-2} s^{-1} above 150 GeV for the hadronic models [10]. The STACEE limits for the hadronic models were found to be quite close to the sensitivity necessary to begin to distinguish between the different hadronic models.

To increase the W Comae data set, STACEE observed the source again in 2004 and 2005. These observations are summarized in Table 2, which shows the total number of hours taken ON-source. As in the case of the 3C 66A analysis, the data were subject to several standard data quality cuts that reduced the total numbers of hours on source to 4.6 hours in 2004 and 5.1 hours in 2005. Library padding was also included to remove the effects of a brighter ON-field. No significant emission was detected from W Comae in either epoch. In comparison to the earlier 2003 data set, the combined data of 2004-2005 has a shorter integrated livetime available after quality cuts. Work is in progress to combine the data sets from all three years and derive a 99% confidence level flux upper limit.

Table 1. STACEE Integral Flux Upper Limits for 3C 66A

	$\Gamma = \infty$		$\Gamma = 200$	
α	E_{th}	99%CL	E_{th}	99%CL
-2.0	200	< 1.0	150	< 1.9
-2.5	184	< 1.2	150	< 1.9
-3.0	150	< 1.7	142	< 2.1
-3.5	147	< 1.8	137	< 2.3

Note. – 99% confidence limits (CL) on the 3C 66A photon flux (units of $10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) derived assuming an EBL-absorbed power-law spectrum with photon index α and exponential EBL cutoff energy Γ (GeV). E_{th} is the STACEE energy threshold, in GeV.

Table 2. 2003 - 2005 STACEE Data on W Comae

Year	Hours^a (Total)	Hours^b After cuts	σ^c
2003	13.5	10.5	0.67^d
2004	9.7	4.6	0.2
2005	9.4	5.1	-1.5

Note. – a Total hours ON-source taken each year. b Total hours remaining after quality cuts. c Significance of detection. d Field brightness correction for the 2003 data set was applied using the technique called "dynamic thresholds." See [10] for more details.

4. Summary

STACEE observed two LBLs, W Comae and 3C 66A, during the 2002-2005 observing seasons. Although the observations did not result in positive detections, STACEE upper limits are useful in understanding the properties of blazars through AGN modelling studies of the broadband spectra of these objects. Leptonic and hadronic jet models of LBLs such as BL Lac and W Comae have yielded different flux predictions at VHE energies [10, 12], making these objects promising targets for ground-based experiments. Hadronic models for blazar jets predict significantly greater TeV fluxes than leptonic jet models. Detection of > 100 GeV photons from sources in the class of LBLs like W Comae, 3C 66A or BL Lac, would be a very interesting result for VHE astronomy and should motivate future observations with VERITAS, MAGIC and GLAST.

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