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The Spectrum of Markarian 421 above 100 GeV with STACEE

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Markarian 421 is a nearby blazar that is actively studied to constrain both physical blazar models and models of the extragalactic background light (EBL). The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE), a wavefront-sampling detector sensitive to gamma rays above 100 GeV, detected Mkn 421 during a multiwavelength campaign in early 2004. We measure an integral flux of $\sim 5 \times 10^{-10}$ photons cm^{-2} s^{-1} with an energy threshold of ∼175 GeV and a detection significance of 5.8σ. We also outline a new method for reconstructing gamma-ray energies from STACEE data. This technique was applied to the 2004 data, and we present a preliminary differential spectrum of Mkn 421 above 100 GeV. We measure a spectral index $\alpha = 1.65 \pm 0.20$, where the error is purely statistical and we do not yet report the systematic error. We discuss the STACEE spectrum in the context of the broader multiwavelength results from the same epoch.

1. Introduction

The bright, nearby (z = 0.03) blazar Markarian 421 was the first extragalactic object detected at TeV energies [16]. Since its discovery, it has been monitored by several multiwavelength campaigns (*cf.* [7, 11, 14, 1]). These measurements have contributed significantly to the physical understanding of the source. For instance, its radio – TeV spectral energy distribution has been successfully described in terms of Synchrotron Self-Compton (SSC) models [13, 6, 10, 2]. Also, the high-energy spectral energy distribution (SED) shows evidence of hardening with increased flux level, a feature that is attributed to an upward shift of the high-energy peak during flares [12, 1]. Recently, the TeV spectrum of Mkn 421 has been used in combination with three other TeV blazar spectra to constrain the infrared EBL [5].

Although extremely well-studied at all other energies, the flux of Mkn 421 between ∼100 and 300 GeV has only been measured twice [3, 15], and only one measurement has been made of its spectrum around 100 GeV [15]. Measurements in this waveband are of particular scientific interest, because the high-energy SED is expected to peak around 100 GeV. We report the detection of Mkn 421 above 100 GeV using STACEE [8] and present a preliminary measurement of the differential energy spectrum between 100 GeV and 1.6 TeV.

2. Observations and Integral Flux Results

STACEE is an atmospheric Cherenkov telescope that utilizes the wavefront sampling technique to measure gamma rays above ∼100 GeV. STACEE uses 64 heliostats at the National Solar Thermal Test Facility in Albuquerque, New Mexico, USA, to reflect Cherenkov light that is emitted in extensive air showers onto a camera of 64 photomultiplier tubes (PMTs). The PMT signals are digitized at a sampling rate of 1 GS/s, and the digitized pulses constitute the raw STACEE data product. STACEE employs an "on-off" observing strategy in which each on-source observation is paired with an equal-exposure off-source observation. We subtract the number of cosmic-ray events in the off observation from the number of on-source events to find the statistical excess of gamma-ray events.

STACEE observed Mkn 421 on 16 nights between January 29 and May 15 of 2004. After selection cuts to remove data marred by weather instabilities or equipment malfunction, STACEE detected Mkn 421 with a significance of 5.8σ in 9.1 hours of on-source observations. The mean significance per observation pair was 1.4σ in 28 minutes of on-source exposure time.

Table 1 lists the energy threshold E_{th} (defined as the peak of the differenial rate curve for gamma rays) and the integral flux Φ_{int} above E_{th}. These quantities depend on the assumed shape of the spetrum, which is typically expressed as a power law; the differential flux $\frac{dN}{dE} \propto E^{-\alpha}$. In Table 1, the spectral index α was varied between 1.7 and 2.5. The table also lists the systematic errors on E_{th} ($\sigma_{E_{th}}$) and on Φ_{int} ($\sigma_{\Phi_{int}}$); these arise from a $\sim 20\%$ uncertainty in STACEE's absolute energy scale [17].

3. Spectral Analysis

We have developed a technique [4] for reconstructing gamma-ray energies from the charges recorded on each of the 64 PMTs that constitute the STACEE camera. The method relies on two physical properties of gamma-ray showers: 1) the intensity of the Cherenkov light on the ground is approximately proportional to the energy of the initiating gamma ray; and 2) the light distribution on the ground is approximately uniform out to the edges of the shower. These properties, along with an independent method for finding the location of the shower core [9], allow us to convert PMT charges to the number of photons arriving at each heliostat. This reconstructed lateral photon distribution is then converted to a gamma-ray energy. The energy reconstruction method successfully reconstructs gamma-ray energies between 100 GeV and 1.6 TeV to an accuracy of better than 10% with an energy resolution of $\sim 30\%$.

This energy reconstruction method was applied to the 2004 Mkn 421 data. The reconstructed energies were binned into six energy bins: 100-150, 150-200 GeV, 200-300 GeV, 300-500 GeV, 500-1000 GeV, and > 1 TeV. For each bin, the number of events in the background observations was subtracted from the number of events in the on-source observation, and the gamma-ray excess in each energy bin was divided by the livetime for the observations and a time-averaged effective area curve. The preliminary differential spectrum $\frac{dN}{dE}$ (photons cm^{-2} s^{-1} GeV^{-1}) is shown in the left plot of Figure 1. We performed a weighted, χ^2 minimization fit to the binned spectrum assuming an exponential form with two degrees of freedom (solid line in the figure). We measure a spectral index $\alpha = 1.65 \pm 0.20$, where the error is purely statistical. In the right plot of Figure 1, the Mkn 421 spectrum is plotted using the standard convention, as $\nu F_\nu = E^2 \frac{dN}{dE}$ (ergs cm^{-2} s^{-1}) vs. frequency ν.

Table 1. The energy thresholds (E_{th}) in GeV and integral fluxes (Φ_{int}) for three different spectral indices α and their associated systematic errors. Φ_{int} and $\sigma_{\Phi_{int}}$ are given in units of 10^{-10} photons cm^{-2} s^{-1}.

α	E_{th}	$\sigma_{E_{th}}$	Φ_{int}	$\sigma_{\Phi_{int}}$
1.7	207	±41	4.08 ± 0.73	+0.86,-0.62
2.1	177	±35	5.06 ± 0.91	+1.50,-1.00
2.5	159	±32	6.27 ± 1.15	+2.48,-1.55

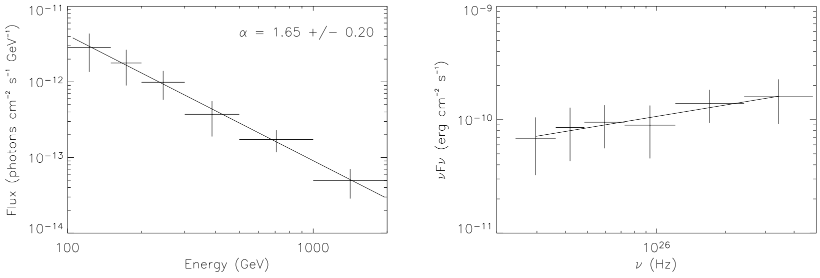

Figure 1. The Mkn 421 spectrum between 100 GeV and 1.6 TeV, as measured by STACEE in early 2004.

4. Discussion

The Mkn 421 spectrum is rising slightly in the STACEE band (right plot of Figure 1). The error bars on the differential flux measurements of STACEE are relatively large, reflecting the statistical uncertainty in the signal, and the spectrum is consistent with a flat (horizontal) SED at these energies. The STACEE measurement implies that the high-energy peak of the SED of Mkn 421 was at or above ∼300 GeV in early 2004. This is a higher energy for the peak than predicted by most SSC models. Such a shift of the high-energy peak is not unreasonable, however; Maraschi *et al.* (1999) suggested that the peak shifted to several hundred GeV during a flare in April 1998.

The STACEE observations of Mkn 421 coincided with an extensive multiwavelength campaign; during the first five months of 2004, the source was monitored by radio, optical, X-ray (*RXTE*), and TeV (Whipple) telescopes simultaneously [2]. These multiwavelength measurements are shown in the left plot of Figure 2. The data are divided into "medium" (squares) and "high" (circles) states of activity; the former covers the period from January 27 to March 26, and the latter covers April 16-20. These two sets of data are fit to Synchrotron Self-Compton models (solid lines). A power law fit to the medium- and high-state Whipple data assuming a high-energy cutoff of 4.96 TeV returned spectral indices of 2.40 ± 0.18 and 2.11 ± 0.14, respectively. STACEE observed Mkn 421 on about 40% of the nights represented in this plot, and ∼90% of the STACEE data was taken during these nights. Only ∼30% of the STACEE data were taken during the TeV flaring state in April.

The right plot of Figure 2 shows the Whipple data between 260 GeV and 1.7 TeV for the high (diamonds) and medium (squares) states. The STACEE spectrum is also shown. Notice that the first STACEE energy bin is at ∼140 GeV, 120 GeV lower than the first Whipple energy bin. Also, the STACEE flux levels are consistent with the medium-state TeV measurements, as expected. The STACEE spectral index is inconsistent with the spectral indices quoted by Whipple, but a direct comparison of the two spectral indices is misleading. The best comparison of the two data sets is restricted to the energy range where they overlap. Comparing only the low-energy TeV data to the STACEE spectrum (right plot of Figure 2), we find that the data below 1 TeV are consistent. Only the data between ∼1 TeV (log ν = 26.4) and 2 TeV are discrepant. The discrepancy may arise, at least in part, from the fact that the STACEE result combines data from the medium- and high-state time periods. The most consistent interpretation of the combined GeV and TeV data is that the peak of the SED is around 300-500 GeV (log $\nu \sim 25.8 - 26.1$). This peak energy is higher than that predicted by the SSC models shown in the left plot of Figure 2.

In summary, we have measured a preliminary spectrum of Mkn 421 above 100 GeV in six energy bins. This is only the second spectral measurement of Mkn 421 at these energies, and the lowest energy bin is ∼120 GeV lower than the Whipple data from the same epoch. The STACEE data suggest that we are detecting the high-

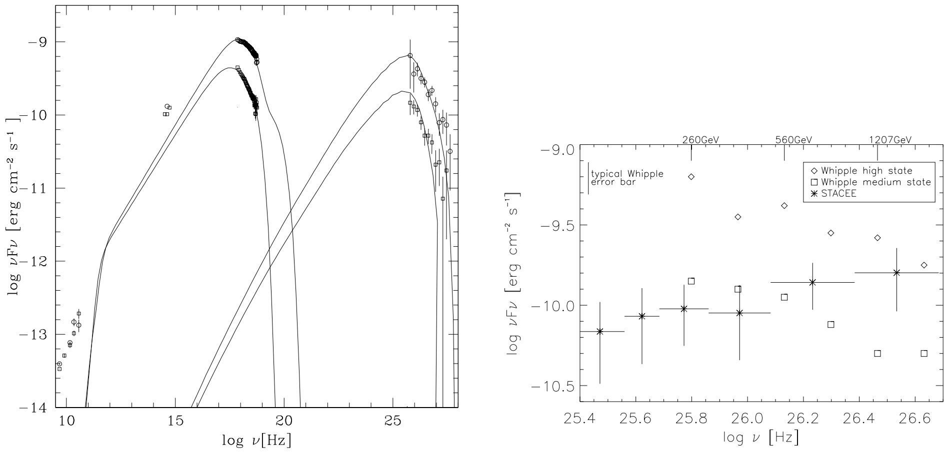

Figure 2. *left*: Data and models from a 2004 multiwavelength campaign on Mkn 421, from [2]. *right*: A close-up of the first six energy bins of the Whipple data, between ∼260 GeV and 1.7 TeV, for the high (diamonds) and medium (squares) data sets, and a typical Whipple error bar. The STACEE spectrum is also shown (stars).

energy peak of the SED for the first time with a ground-based instrument and that the peak is around 300-500 GeV.

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