STACEE Observations of Markarian 421 During the 2001 Flare

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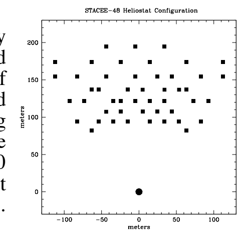
STACEE is a ground based gamma-ray observatory that uses a heliostat array, built for solar energy research, to detect atmospheric Cherenkov radiation from gamma-ray initiated extensive air showers. Its design allows STACEE to operate into the gamma-ray regime left unexplored by previous techniques. During the first half of 2001, a prototype detector, STACEE-48, was used to observe the blazar Markarian 421, which was in an extremely active state. The following is a discussion of these observations and the subsequent analysis.

STACEE-48 operated from 2000 to 2001 at the National Solar Thermal Test Facility (pictured left) in New Mexico, USA. This prototype employed 48 heliostats, distributed over approximately 2x10^4 square meters as illustrated to the right. Observations of Markarian 421 were conducted from March to May of 2001, constituting 26 nights and roughly 36 hours of exposure. Of this, 22 hours of source observations distributed among 26 nights were deemed good-quality data to be used for this analysis. Simulations of the detector performance indicate that the peak of the STACEE-48 response occurs at 140±20 GeV, which has been adopted as our energy threshold. Thus, these observations represent the lowest energy gamma-ray detection of the 2001 flare by a ground-based instrument.

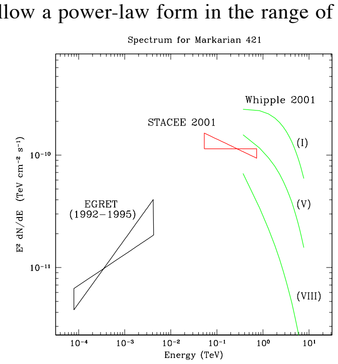


Spectral Results

The STACEE observations of Markarian 421 in 2001 yielded an average gamma-ray rate of $7.7 \pm 0.7 \pm 1.2$ min^{-1}. Included in this rate is a correction for false triggers due to the presence of a bright star (HD 95934, mag 6.16 in B band) within a few arcminutes of the source. The correction was determined by observing a star of comparable brightness (HIP 80460) with no known associated gamma-ray source. The excess rate from the HIP 80460 observations was attributed to a constant star effect, and thus subtracted from the Markarian 421 observations. The above rate corresponds to an average integral gamma-ray flux above 140 GeV of

$$\Phi(E>140\text{ GeV}) = (8.0 \pm 0.7_{stat} \pm 1.5_{sys}) \times 10^{-10}\text{ cm}^{-2}\text{ s}^{-1}.$$

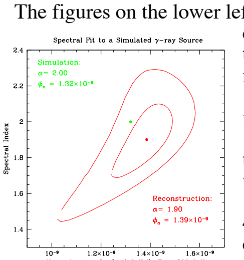
If the spectrum of Markarian 421 is assumed to follow a power-law form in the range of energies to which STACEE is sensitive, the normalization of the differential spectrum can be inferred from the measured rate, provided the spectral index is assumed. In the figure to the right (Boone et al. 2002), the range of possible power-law solutions to the STACEE rate for differential indices between 2.00 and 2.20 is given by the red butterfly. For comparison, Whipple observations around the same time are plotted in green for high (I), medium (V), and low (VIII) flux states (Krennrich et al. 2002). EGRET data from cycles 1 through 5 are also plotted for reference (Hartman et al. 1999).

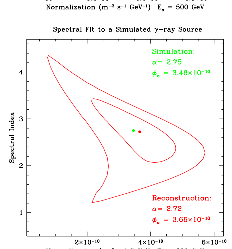


Since STACEE-48 did not record amplitude information for each event, an unbiased determination of the differential flux is difficult. However, because the STACEE response curve changes significantly as a function of the source elevation and the trigger configuration, it is possible to glean some information about the differential spectrum by using the forward-folding technique.

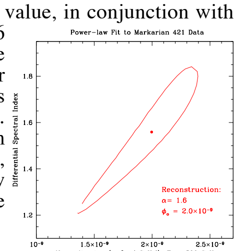
Under this prescription, the Markarian 421 data set was first divided into elevation bands. The simulated detector response to an assumed power-law spectrum at a given elevation was then compared to the appropriate subset of the Markarian 421 observations for several different reimposed trigger criteria. This process was repeated for a number of different elevation bands. The differential index (α) and normalization (ϕ_o) of the assumed spectrum were then adjusted to minimize the difference between the expected and observed responses over all considered combinations.

The figures on the lower left are simulated tests of this method (contours represent one sigma errors). Note that the normalization energy (E_o) has been adjusted to the nonstandard value of 500 GeV. This transformation was necessary to decrease the strong correlation in the two parameters. The success of the simulated tests indicates that the spectral information is in fact encoded into the detector response variation. However, due to potential systematic effects in the simulations themselves, these tests do not vouch for the validity of the technique when used on actual data.

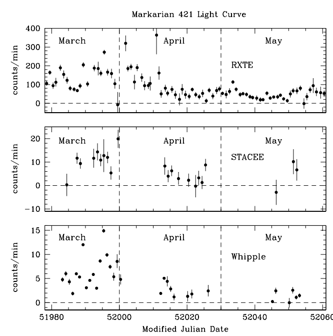




This is reflected in the application of the technique to the Markarian 421 data in the lower right-hand figure (contour is the one sigma error). In units of TeV, the reconstructed normalization translates to $(6.8 \pm 1.7)\times10^{-11}$ cm^{-2}s^{-1}TeV^{-1}. This value, in conjunction with the extremely hard spectral index of 1.6 does not agree with the average STACEE flux (red butterfly above) or the STACEE/Whipple flux ratios described in Boone et al. (2002). Whether these inconsistencies arise from inaccuracies in our detector simulations, the inappropriateness of a power-law postulate, or the high variability of the source remains to be seen.



Temporal Results



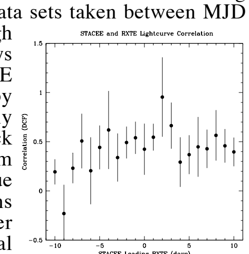
The plot to the left contains three light curves for Markarian 421 from March to May of 2001 (Boone et al. 2002). The upper panel, from the RXTE All Sky Monitor, is from the 2-10 keV energy band. The lower panel, from the Whipple detector (Holder et al. 2001), spans energies from 250 GeV to 8 TeV. The STACEE observations, depicted in the central panel, represent the photon flux between 50 and 300 GeV. Points are photon count rates, averaged on a day by day basis.

A correlation analysis was performed on the STACEE and RXTE data sets using the discrete correlation function (DCF) described in Edelson & Krolik (1998). Unbinned discrete correlation coefficients (UDCF) were formed for each pair of points in the respective data sets as follows:

$$UDCF_{ij} = \frac{(STACEE_i - \overline{STACEE})(RXTE_j - \overline{RXTE})}{(\sigma_{STACEE})(\sigma_{RXTE})}$$

These coefficients where then grouped by their associated time differences ($\Delta t = t_{RXTE} - t_{STACEE}$), and averaged to form the DCF.

The figure below is the correlation as a function of time lag for the STACEE and RXTE data sets taken between MJD 51990 and MJD 52050. Although there is a high point at two days (corresponding to the STACEE data leading the RXTE data by two days), it is not statistically significant. In addition, the lack of statistical power arising from the application of this technique to these particular observations precludes drawing any further conclusions regarding temporal correlations in the data.



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Boone, L. M., et al. 2002, to be published in ApJL
Edelson, R. A. & Krolik, J. H. 1988, ApJ, **333**, 646
Hartman, R. C., et al. 1999, ApJS, **123**, 79
Holder, J., et al. 2001, in Proc 27th ICRC (Hamburg), **1**, 2613
Krennrich, F., et al. 2002, ApJ, **575**, L9