Observations of TeV gamma rays from Markarian 501 at large zenith angles

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Abstract.
TeV gamma rays from the blazar Markarian 501 have been detected with the University of Durham Mark 6 atmospheric Čerenkov telescope using the imaging technique at large zenith angles. Observations were made at zenith angles in the range $70^\circ - 73^\circ$ during 1997 July and August when Markarian 501 was undergoing a prolonged and strong flare.

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1. Introduction

The use of atmospheric Čerenkov telescopes to make observations at large zenith angles was suggested by Sommers and Elbert [1] as a potentially efficient method of measuring gamma rays at the highest energy. The underlying principle is that at large zenith angles, the footprint of an air shower as seen in optical Čerenkov light (which is a penetrating component of the cascade) becomes large. This means that, although the threshold energy of a telescope will increase as the zenith angle increases, the accompanying increase in collecting area results in a useful gamma ray detection rate. Sommers and Elbert discussed this large zenith angle technique in the context of first-generation (non-imaging) gamma ray telescopes.

Markarian 501 (Mrk 501) is a relatively close BL Lac object (at a red shift $z$ of 0.034) which shows strong, variable, non-thermal emission from radio to X-ray wavelengths. Since its discovery as a VHE gamma ray source [2], Mrk 501 has been extensively monitored in the VHE waveband. In 1997, the object went into a prolonged active state at all wavebands. The VHE activity was detected by a number of Northern hemisphere facilities employing imaging techniques (e.g. [3, 4, 5, 6]). This state of high activity lasted from 1997 March – October and the source exhibited a complex time history with flaring activity on a time scale as short as a few hours [7]. Multiwave length studies of Mrk 501 during this time have been reported [3] and the energy spectrum at TeV energies has been established [7, 8, 9].

The upper bound to the TeV energy spectrum of an AGN is of considerable interest as it, together with the distance to the source, leads to a value for the density of intergalactic infrared photons (see e.g. [10, 11, 12]). The highest energy photons observed from this source to date have been detected by the HEGRA group and are in excess of 25 TeV [13].

We report here observations of Mrk 501 made from the Southern hemisphere at zenith angles in excess of 70° using the University of Durham Mark 6 imaging telescope. Our measurements of cascades which develop through three atmospheres demonstrate that imaging techniques may be applied at these large zenith angles with the prospect of improving the significance of the gamma ray signal at high energies.

2. Observations

2.1. The Mark 6 Telescope

The University of Durham Mark 6 telescope is located at Narrabri NSW Australia and has been described in detail [14]. It uses the established imaging technique to separate gamma rays from background cosmic rays and incorporates a robust, noise-free trigger involving signals from three parabolic flux collectors of diameter 7 m mounted on a single alt-azimuth platform. The imaging camera comprises 109 pixels (91 with 0.25° diameter and 18 with 0.5° diameter) and is mounted at the focus of the central flux detector. It combines with two low resolution cameras (19 pixels each of diameter 0.5°) which are
Table 1. Observing log for our observations of Markarian 501 during 1997.

| Date       | No. of scans ON source |
|------------|------------------------|
| 1997 July 4| 3                      |
| 1997 July 5| 5                      |
| 1997 July 7| 4                      |
| 1997 July 9| 3                      |
| 1997 July 23| 1                    |
| 1997 July 28| 5                      |
| 1997 July 30| 5                      |
| 1997 July 31| 3                      |
| 1997 August 1| 4                   |
| 1997 August 5| 4                    |

mounted at the foci of the left and right flux collectors to provide a trigger demanding a simultaneous temporal (10 ns gate) and spatial (0.5°) coincidence of the Čerenkov light detected in the three cameras. This trigger system allows the telescope to detect small light flashes, and hence low energy gamma rays, free of the triggers due to light produced by individual local muons. This is particularly important for observations at very large zenith angles when the background from local muons mimicking the signatures of gamma rays can become important.

2.2. Observations of Mrk 501

Mrk 501 was observed in 1997 July and August under clear and moonless skies during an interval of extreme activity when detection rates for gamma rays > 300 GeV (using conventional imaging telescopes) exceeded 10 photons per min (see e.g. Bradbury [15]).

Data were recorded at zenith angles of 70°–73° using the standard Mark 6 telescope procedure which involves recording data in 15 min segments. OFF source observations were taken by alternately observing regions of the sky which differ by ±15 min in right ascension from the position of Mrk 501 so ensuring that the ON and OFF segments possess identical azimuth and zenith profiles. This observing pattern, which involves reversal of the order of the ON and OFF source measurements, eliminates any first order changes in telescope performance due to residual secular changes in atmospheric clarity, temperature etc. An observing log is shown in table 1.

The background count rate of the telescope at 70° to the zenith was about 70 cpm, some 10% of that at the directions close to the zenith where the telescope would normally be operated. A preliminary estimate of the threshold for gamma ray detection with the Mark 6 telescope at 70° to the zenith is ~ 15 TeV which may be compared with the value of ~ 300 GeV for zenith angles ≤ 30°. We note that Sommers and Elbert [1] estimate a factor of ~ ×70 in threshold energy difference between zenith angles of 30° and 70° compared with the value of ~ ×50 from our estimate.

Data were accepted for analysis only if the sky was clear and stable according to
Table 2. The image parameter selections applied to the Markarian 501 data recorded at zenith angles between 70° and 73°.

| Parameter          | Ranges       | Ranges       | Ranges       | Ranges       |
|--------------------|--------------|--------------|--------------|--------------|
| SIZE (d.c.)        | 600 – 800    | 800 – 1200   | 1200 – 1500  | 1500 – 5000  |
| DISTANCE           | 0.35° – 0.85°| 0.35° – 0.85°| 0.35° – 0.85°| 0.35° – 0.85°|
| ECCENTRICITY       | 0.35 – 0.85  | 0.35 – 0.85  | 0.35 – 0.85  | 0.35 – 0.85  |
| WIDTH              | < 0.14°      | < 0.18°      | < 0.22°      | < 0.22°      |
| CONCENTRATION      | < 0.70       | < 0.70       | < 0.70       | < 0.30       |
| $D_{\text{dist}}$ | < 0.20°      | < 0.14°      | < 0.12°      | < 0.10°      |

the telescope background count rate and a boresighted FIR radiometer which provides a measure of sky clarity [16]. The gross counting rates in each pair of ON-OFF segments used were consistent at the 2.5σ level. A total of 9.25 hrs of data for ON-source observations and an equal amount OFF source meet these criteria.

3. Results

The reduction and analysis of accepted data follows a well established routine [17]. The gains and pedestals of all 147 PMTs and digitizer electronics are calibrated within each 15 min segment using embedded laser and false coincidence events. PMT noise is equalised for the ON and OFF source segments using the software padding technique [18] prior to identifying the accurate location of the source in the camera’s field of view using the axial CCD camera. Events confined to within 1.1° of the centre of the camera and which have in excess of 600 digital counts (to ensure reliable image reconstruction) are considered suitable for further analysis. Finally, the spatial moments of each image relative to the source position are evaluated and those events are rejected which are unlikely to have been initiated by gamma rays.

In addition to the background rejection based upon the image analysis, a measure of the fluctuations between the centroids of the samples recorded by the left and right collectors of the Mark 6 telescope ($D_{\text{dist}}$) provide an additional discriminant [19]. Gamma rays are identified on the basis of image shape and left/right fluctuation and then plotting the number of events as a function of the pointing parameter ALPHA. Gamma ray events from a point source appear as an excess at small values of ALPHA.

The selection criteria appropriate to observations at large zenith angles (> 70°) are summarised in table 2. Small changes have been allowed from the standard set of parameters identified for the analysis of data taken with the Mark 6 telescope at zenith angles < 45° to accommodate e.g. the narrower images of cascades propagated through three atmospheres.

The number of events in the ON and OFF samples after the application of the selections described above are summarised in table 3. The ALPHA plot of the differences of the ON and OFF distributions is shown in figure 1. The excess of events at small
Table 3. The results of various event selections for the Markarian 501 data.

|                               | On   | Off  | Difference | Significance |
|-------------------------------|------|------|------------|--------------|
| Number of events              | 40869| 41232| −363       | −1.3σ        |
| Number of size and distance   | 21570| 21286| 284        | 1.4σ         |
| selected events               |      |      |            |              |
| Number of shape selected      | 1935 | 1750 | 185        | 3.1σ         |
| events                        |      |      |            |              |
| Number of shape and ALPHA     | 647  | 475  | 172        | 5.6σ         |
| selected events               |      |      |            |              |

Figure 1. The difference in the distribution of values of ALPHA for the shape selected data recorded ON and OFF source from Mrk 501.

values of ALPHA suggest the detection of a source with an excess of events with ALPHA < 30° at a significance of 5.6σ. The width of the ALPHA distribution, with excess events with ALPHA of up to 30°, may be a consequence of the effects of magnetic field of 0.4 G, acting on the cascade over unusually large linear distances [24].

The ON and OFF source data have been re-analysed using a matrix of assumed source positions to provide a “false source” analysis. In figure 3 we show that the excess of gamma ray events originates from the source which is located in the right ascension, declination plot at a position consistent with Mrk 501. (The camera centre does not coincide with the source position.)
4. Conclusion

Observations of Mrk 501 during outburst made at zenith angles $> 70^\circ$ using a Southern hemisphere imaging telescope have demonstrated the efficacy of the large zenith angle ACT technique suggested by Sommers and Elbert [1].

The selection criteria used to reject background in observations with our imaging telescope at large zenith angles are similar to those employed for observations at small zenith angles. The main difference is in the maximum value of the width of images accepted, which are smaller than those in observations near the zenith due to the increased distance to cascade maximum.

In the absence of a network of gamma ray observatories giving full sky coverage, this detection of Mrk 501 has demonstrated that observations at large zenith angles may allow more continuous monitoring of strong TeV gamma ray sources.

Pending completion of a simulation study of the detailed response of the Mark 6 telescope at zenith angles of $\sim 70^\circ$ it is not possible to ascribe a reliable value to the
highest energy gamma rays detected in this short exposure observation. Thus it has
not yet been possible to extend the spectrum beyond the limiting energy available from
more extensive observations using atmospheric Čerenkov telescope techniques at smaller
zenith angles from Northern hemisphere observatories.

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