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# Energy spectra of TeV sources measured with the Durham Mark 6 telescope

**K.-M. Aye, P. M. Chadwick, M. K. Daniel, K. Lyons, T. J. L. McComb, J. M. McKenny, S. J. Nolan, K. J. Orford, J. L. Osborne, and S. M. Rayner**

Department of Physics, Rochester Building, Science Laboratories, University of Durham, Durham, DH1 3LE, UK

**Abstract.** Simulations have been made of the response of the Durham Mark 6 atmospheric Cherenkov telescope to air showers generated by ALTAI, CORSIKA and MOCCA codes. Comparisons are made between the simulations and real data. The effective collection area of gamma ray showers, including the retention factor is derived as a function of energy. On the basis of this work the flux of the AGN PKS 2155-304 above $1.5\mathrm{TeV}$ is derived to be $2.1 \pm 0.2_{\mathrm{syst}} \pm 0.5_{\mathrm{stat}} \times 10^{-7}$ $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$.

## 1 Introduction

The Durham Mark 6 atmospheric Cherenkov telescope operated in Narrabri, NSW (altitude=260m), from 1996 to 1999. In this time the telescope detected four sources of VHE gamma rays, including the most distant source of TeV gamma rays ever seen, the AGN PKS 2155-304 ($z = 0.117$) (Chadwick et al., 1999a). Due to the absence of any steady southern hemisphere TeV gamma ray source, the telescope's gain must be calibrated via a comparison of a simulated cosmic ray spectrum with off source data, thus allowing a refinement of the flux measurements of sources such as PKS 2155-304 to be made. A program of detailed simulations of the response of the telescope to gamma ray and cosmic ray initiated air showers has been completed.

## 2 Simulations

The Monte Carlo simulations are performed in two stages. In the first a version of the MOCCA95 code (Hillas, 1995) models the shower development in the atmosphere and generates the position, time and direction of arrival of the Cherenkov photons at the telescope mirrors. The version used includes wavelength dependent atmospheric absorption, mirror reflectivity and photomultiplier (PMT) quantum efficiency, thus Cherenkov photon data is expressed as potential photoelectrons at the PMT photocathodes. A US Standard Atmosphere derived from MODTRAN (Berk et al. (1999)) was used for the atmospheric profile as it was assumed to best approximate the conditions at the Narrabri site.

*Correspondence to:* Sam Nolan (s.j.nolan@dur.ac.uk)

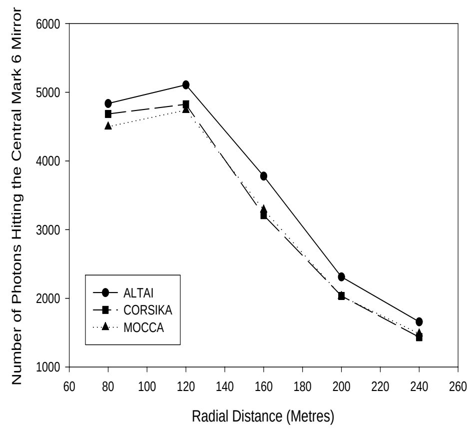


**Fig. 1.** Plot of Mean Number of Photons Hitting a Central Mark 6 Mirror, with atmospheric absorption, for a US Std Atmospheric Profile at an altitude of 1800 metres for a 1TeV Photon Primary for ALTAI, CORSIKA and MOCCA at fixed radial distances.

We investigated the effect of using two other popular shower simulation codes ALTAI (Konopelko, 2000) and CORSIKA (Heck et al., 1998) (see figure 1 and 2 for comparisons at 1TeV for Photon and Proton Primaries at $30^o$ zenith)). We find that after telescope simulation the MOCCA results for all image parameters are intermediate to the other two codes. MOCCA also has the advantage of appreciably shorter run times, which is important when simulating large numbers of showers for spectra.

The second stage models the majority of the telescope response. A detailed description of the Mark 6 telescope has been given elsewhere (Armstrong et al. , 1999). The physical sophistication of the code has also been outlined by Chadwick et al. (1999b), and will be outlined only briefly here.

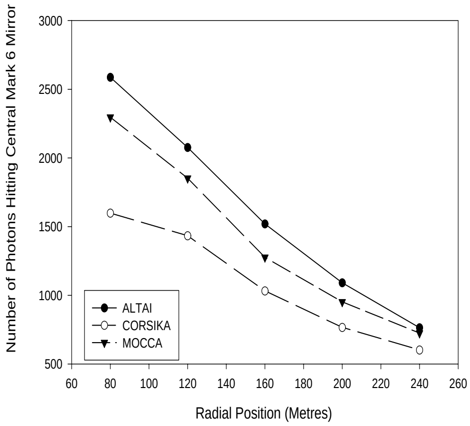


**Fig. 2.** Plot of Mean Number of Photons Hitting a Central Mark 6 Mirror, with atmospheric absorption, for a US Std Atmospheric Profile at an altitude of 1800 metres for a 1TeV Proton Primary for ALTAI, CORSIKA and MOCCA at fixed radial distances.

The Mark 6 telescope consisted of three 7 metre diameter parabolic mirrors, on a single alt-azimuth mount with a camera consisting of PMTs at each focus. The central camera consisted of 91 circular 2.5cm diameter Hamamatsu R1924 PMTs with a $0.25^o$ spacing (conical reflective light concentrators minimized the dead space between the tubes), surrounded by a guard ring of 18 circular 5cm Burle 8575 PMTs. The left and right cameras each had 19 Phillips XP3422 hexagonal PMTs covering the same field of view as the 91 central camera tubes. The three mirrors had reflective surfaces of Alanod 410G3 anodized aluminium with reflectivity $\geq 75\%$ in the wavelength range 700 to 350nm (falling off to $\approx 60\%$ at 280nm). The point spread function of the mirrors was measured by examining the response of the PMT cameras to bright stars. It may be represented as the sum of two Gaussians, a narrow component with an rms radius of $0.25^o$, and a 'skirt' with radius $0.45^o$, contributing $66\%$ of the total light intensity. The trigger requires (within an interval of 10ns) a signal from corresponding left and right mirror PMTs, and any two adjacent centre PMTs of the group of seven corresponding to the same region of sky as those in the left and right. This limits the effects of background sky noise. A direct measure of the gain of the system by means of a radioactive light pulser applied to each PMT gives a digital count to photoelectron ratio dc/pe $\approx 4$. These physical details and more are reproduced within the telescope simulation software (SOLMK), as detailed within previous ICRC proceedings (Chadwick et al., 1999b). However, since 1999 several improvements have been made to the code and random sky noise has been included within the telescope trigger to better simulate the actual response.

Showers have been simulated at various zenith angles ($20^o$, $30^o$, $40^o$) in the correct zenithal ratio to the reported PKS 2155-304 observations (Chadwick et al., 1999a). However once mirror blur and random sky noise have been applied, little zenith angle dependance is seen in the image shape or size for cosmic ray showers, thus for simplicity the majority of simulations were made at $30^o$ zenith. The effects on Cherenkov image shape (Chadwick et al., 1999c) of the perpendicular component of the geomagnetic field have been included.

## 3 Cosmic Ray Simulations

In order to calibrate the gain of the telescope 31,000 cosmic ray showers with energies between 0.3 and 30 TeV were generated, with values for composition and spectral index similar to those used by Mohanty et al. (1998). For each shower the telescope was placed at five random positions within a radius of 300m from the core location, and for cosmic rays only the shower direction took four random values out to a distance of $2^o$ from the centre of the field of view. The aim to match the 30 PKS 2155-304 off source segments of data taken between $25 - 35^o$ was met by adjustment of the discriminator level in the simulations to match the typical observed off source trigger rate at $30^o$ zenith, ($8.38$ events $\mathrm{s}^{-1}$). The $25 - 35^o$ region was chosen as this can be shown to be representative of the entire set of published data (Chadwick et al., 1999a) out to $45^o$ zenith angle. A value for the discriminator level was chosen which gave the best fit to the real off source image parameter distributions and most closely approximated the average count rate, however the simulated count rate still exceeded the real by $\approx 15\%$. The count rate could not be matched exactly as increasing the discriminator level lowers the number of smaller size events which trigger, thus causing the fit of image parameters to worsen. The cosmic ray fluxes used by Mohanty et al. are, however, about 15% higher than those of Wiebel (Karle et al., 1995) and this, to first order at least, may account for the discrepancy. Further investigation is required. A comparison of the size in digital counts of simulated and real data (see fig. 3), suggests a value of dc/pe $\approx 4.5$ which is in good agreement with the results of the measurements stated earlier. These remarks apply to MOCCA and ALTAI cosmic ray shower simulations. As illustrated in fig. 2 the CORSIKA simulations give a significantly lower Cherenkov photon density than the other two and it was not found possible to find a discriminator setting that could give a satisfactory fit to the images and come close to the observed trigger rate.

## 4 Results of Gamma Ray Simulations

A total of 150,000 gamma ray showers with energies between 0.1 and 30 TeV were generated in order to determine the triggering probability as a function of energy and the quality factor for gamma ray retention after the application of various selection criteria designed to enhance the gamma ray to cosmic-ray-background ratio. Again for each shower the telescope was placed randomly 5 times within a radius of 300m. A differential power law spectral index of -2.4 was used, however the exact value is unimportant as one needs the ratio of the number of showers generated to the number

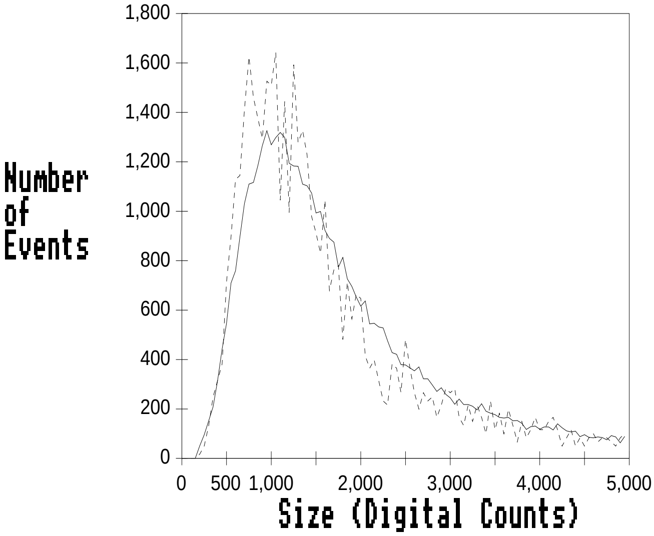


**Fig. 3.** Plot SIZE (in digital counts) versus number for real cosmic ray events (solid) and simulated cosmic ray events (dotted).

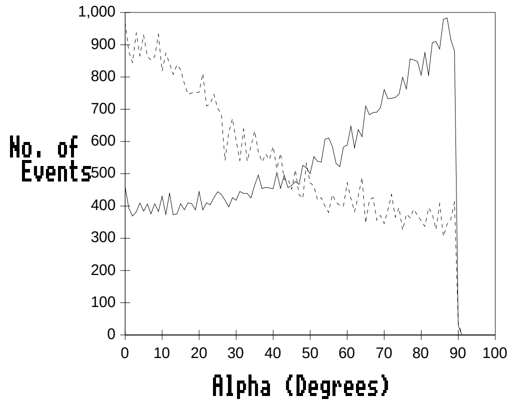


**Fig. 4.** Plot of ALPHA for real off source (cosmic ray) data (solid) versus simulated gamma data (dotted)

triggering at each energy. Using the discriminator level and dc/pe ratio set by the comparisons between real and simulated cosmic ray data, the total number of triggers after the removal of unconfined events was 20,938. The effective area for triggering as a function of energy is shown as the histogram in figure 5, this is obtained by multiplying the triggering probabilities by the 300m radius target area.

Any source energy spectrum may be multiplied into the effective area distribution and integrated to give the corresponding trigger rate. For example the curve in figure 5 is the smoothed effective area distribution multiplied by $E^{-2.6}$. It can be seen that the triggering starts at around $300\ \mathrm{GeV}$. However, a more usual definition of the energy threshold of a telescope is the energy of the peak of the triggering energy spectrum, which lies at $\approx\ 0.7\ \mathrm{TeV}$ for the Mark 6 Telescope. The effective area above threshold may be defined as that of a detector with $100\%$ triggering probability above the threshold energy and zero below it that has the same total triggering rate as the telescope. The value of this effective area is $1.38 \times 10^5\ \mathrm{m}^2$. The imaging atmospheric Cherenkov technique allows the separation of gamma ray and cosmic ray events by comparisons of image parameters (Hillas, 1985). Several cuts are placed on the data to maximise the removal of cosmic ray events, whilst minimising the removal of gamma-ray events. The first selection is based on SIZE, the sum of the digital counts in the tubes of the central camera (see figure 3). Images with SIZE below 200 dc are removed. 'Image' tubes are then defined, firstly as those with a digital count $>\ 37.5\%$ of the brightest tube and at least 4.25 times the rms sky noise and secondly those with $>\ 17.5\%$ and at least 2.25 times the rms sky noise that are adjacent to the first. Events with fewer than two image tubes are removed. A DISTANCE parameter is defined as the distance of the image centroid from the centre of the camera, and those events with DISTANCE $> 1.1^o$, or that have peak brightness within the guard ring are removed. These criteria result in the removal of $40\%$ of the cosmic ray events and $20\%$ of the gamma rays. By cutting data using WIDTH (the rms spread of the image along its minor axis), ECCENTRICITY (the ratio of image width/length), the CONCENTRATION (the fraction of dc in SIZE that are not in the image tubes), and $D_{dist}$ (the difference in position of the image centroids in the left and right cameras), we select a higher fraction of gamma-ray events from the data than cosmic-ray events. The final, and most crucial cut parameter is ALPHA (the angle between the image's long axis and the line from its centroid to the source position, i.e. the camera centre for simulations). A comparison of ALPHA distributions for simulated gamma-rays and observed cosmic rays is shown in figure 4. From knowledge of earlier simulations and a small amount of empirical optimisation, parameter cuts as detailed in Chadwick et al. (1999a) were chosen, including the requirement that ALPHA$< 22.5^o$, and applied to the PKS 2155-304 observations. The results of these cuts are shown in table 1. By applying the same cuts to the simulated gamma-ray events we obtain the variation of effective area with energy which can be applied to the excess (ON-OFF) counts in each size bin for an observed source to obtain the corresponding fluxes and therefore an indication of the source energy spectrum. We find, however that only the figures for the top two SIZE bins are sufficiently robust against refinements in the noise simulations and mirror blur parameters to be reliably applied.

## 5 Results

A signal from the close X-ray selected BL Lac PKS 2155-304 was observed during the observing seasons of 1996 and 1997. For zenith angle less than $45^o$ a total of 544 excess gamma-ray events were observed on source in 32.5 hours of observation. The two top size bins contain an excess of 358 events, with a significance of $4.1\sigma$.

| Parameter | Ranges | Ranges | Ranges | Ranges | Ranges |
|---|---|---|---|---|---|
| *SIZE* (d.c.) | $500-800$ | $800-1200$ | $1200-1500$ | $1500-2000$ | $2000-10000$ |
| *Excess on-source* | 29 | 74 | 83 | 138 | 220 |
| *Off-source Events* | 227 | 371 | 433 | 1546 | 2042 |

**Table 1.** The results of the application of the image parameter cuts (including ALPHA $< 22.5°$) to the PKS 2155-304 data.

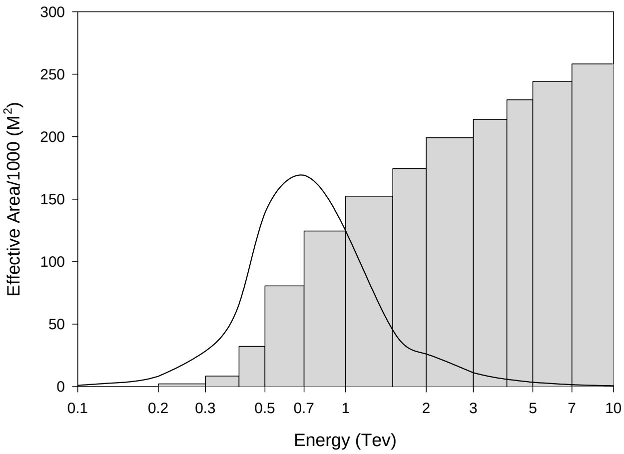


**Fig. 5.** The histogram gives the variation of the effective area of the telescope with energy for gamma ray showers. The curve, having a vertical scale in abitrary units, shows the form of the triggering spectrum for a power law differential source energy spectrum of index -2.6.

The derived integral flux above a thresold energy, $E_{\rm th}$, for an assumed differential spectral index, $\gamma$, is

$$S_\gamma(E_{\rm th}) = \frac{N}{T}\frac{E_{\rm th}^{-(\gamma-1)}}{\gamma-1}\left[A\int_0^\infty E^{-\gamma} f(E)\,dE\right]^{-1}$$

Where $N$ is the number of excess on-source events; $T$ is the time of observation; $A$ is the target area for the telescope, $\pi \times (300)^2 = 2.827 \times 10^5 {\rm m}^2$; and $f(E)$ is the fraction of gamma-ray showers of energy $E$ falling on the target area which trigger the telescope and whose Cherenkov images survive the cuts.

Assuming a differential spectral index of -2.6, approximating to that of Mkn 501, we find that the flux in gamma rays above $1.5$ TeV from AGN PKS 2155-304 is

$$2.1 \pm 0.2_{\rm syst} \pm 0.5_{\rm stat} \times 10^{-7} {\rm m}^{-2}{\rm s}^{-1}.$$

This is roughly twice the crab flux (Weekes et al., 1998).

Although the observations were all made under apparently clear and stable atmospheric conditions there were variations in the off source trigger rate of $\pm 7\%$ at a given zenith angle. These are most probably due to variations in atmospheric absorption due to aerosols (Bernlöhr (2000)). The effect of this on the factor $f(E)$ together with uncertainty in the optimum discriminator value in the simulations introduces a systematic error of $\approx 10\%$ into the inferred gamma ray flux.

The simulations show that about 80% of the excess in the two top size bins is produced by gamma-rays with energies between 1 and 4 TeV. Comparing the integral fluxes derived for the two top bins separately the indication is that the spectral index is somewhat higher than -2.6 but the statistics for bin 4 are not good enough to give a definitive value.

## 6 Conclusion

We have tested on the Mark 6 telescope our previous assumptions and have thus refined the telescope simulation code (SOLMK). This has led to an integral flux for PKS 2155-304 above 1.5 TeV. Its spectrum awaits determination by the next generation of southern hemisphere VHE telescopes (Hoffmann et al., 1999; Mori et al., 2000). We have shown that the ALTAI and CORSIKA simulation codes have only small output differences for gamma ray showers when compared to MOCCA. There is a significantly smaller Cherenkov signal predicted for hadronic showers by CORSIKA. ALTAI and CORSIKA have appreciably longer run times. This has significance for the next generation of Cherenkov Telescopes, which will require large databases of simulated events.

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