CERENKOV LIGHT IMAGES OF EAS PRODUCED BY PRIMARY GAMMA RAYS AND BY NUCLEI

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ABSTRACT

It is shown that it should be possible to distinguish very effectively between background hadronic showers and TeV gamma-ray showers from a point source on the basis of the width, length and orientation of the Cerenkov light images of the shower, seen in the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins detector.

1. Detection of point sources of cosmic rays

Certain X-ray binaries, pulsars and active galaxies appear to be point sources of TeV cosmic rays — presumed to be gamma-rays. The sources have been detected by observing flashes of Cerenkov radiation from small showers in the upper atmosphere, but these do not stand out clearly against the intense isotropic background of ordinary proton (or nuclear) showers. If the appearance of the Cerenkov flashes differs for the two classes of shower, much of the background might be rejected. In another paper, Cawley et al. (1) describe the modification of the 10m reflector at the Whipple Observatory (Mt. Hopkins, Arizona) to record details of each Cerenkov image on a 0.5° grid, using 37 photomultipliers in the focal plane of the focusing mirror. (A central photomultiplier is surrounded by a ring of 6 others, then by a further ring of 12, and another of 18 — the whole forming a hexagonal grid pattern.) Predictions of the response of this system to air showers will be presented. Even though the r.m.s. widths of shower images are less than 0.5°, the image dimensions should be measured well enough to provide discrimination between types of shower, though the alignment of the short image with the source will be much less clear than with finer angular resolution.

2. Simulation of Cerenkov image patterns

A 3-dimensional Monte-Carlo calculation is used to simulate shower development. The computer program has been used previously for other investigations (2) and is much more detailed than is necessary for calculating Cerenkov processes, following particles down to an energy 0.05 MeV (far below the Cerenkov threshold), although "thin sampling" (3) is used to follow particles below 1/4000 of the primary energy to reduce computing time. The model atmosphere is not isothermal. Hadronic collisions have been simulated both by a radial scaling model with rising cross-sections and by a model with increased production of low-energy secondaries (relative to scaling) at high primary energies (though a less drastic change than proposed by Wdowczyk and Wolfendale, for example, as the important particles in the fragmentation region — high x — are largely retained). However, at TeV energies, there is little difference between the models, being constrained by accelerator data, so the simulation results have been combined together in the presentations below.

Although some loss of Cerenkov light by Rayleigh and aerosol scattering is allowed for (2), scattered light is assumed not to contribute to the spread of the image (size $<1^{\circ}$) in a clear mountain atmosphere. The

light is assumed to be received by a collector of 10m diameter (taken as 2/3 efficient) on the ground, and the directions of arrival of the rays recorded. The rays are traced to see whether they would reach a particular photomultiplier of the 37-tube array as used on Mt. Hopkins, assuming the mirror forms perfect images of stars. (About 50% of the light is lost in gaps between the tubes.) Fluctuations in conversion of photons were incorporated, but not the fluctuations in the electron multiplication process. The altitude (2300m) and geomagnetic field were taken to be the values appropriate for Mt. Hopkins.

All gamma-ray showers were taken to come from the direction of a source in the centre of the field of view, and were sampled from a spectrum $E^{-2.25}dE$ from 0.25 TeV upwards, and impact points were sampled randomly over an area of 250m radius. Showers for analysis had to give signals of at least 40 photoelectrons in at least 2 of the innermost 19 tubes. The proton background showers were sampled from a spectrum $E^{-2.65}dE$, and the images were displaced randomly over a sky area large enough to cover the field of view, to simulate an isotropic background. Some showers initiated by oxygen nuclei were also simulated, using a simplified nuclear breakup representation. As these are easier to distinguish from gamma showers, and as for a given intensity of flash a higher threshold energy is needed than for a proton shower, not so much attention was paid to such showers generated by heavy nuclei.

3. <u>Parameters used to describe Cerenkov images of showers</u>

A typical simulated image is shown alongside in Figure 1. The figures give numbers of photoelectrons in each photomultiplier. (2 TeV gamma-ray from source in centre of field. Impact parameter 60m, zenith angle 30°.) The image axis (dashed line) is determined: this line minimises the signal-weighted sum of squares of perpendicular angular distance of the detectors. (As small distant noise signals can distort the small r.m.s. dimensions, *any individual signal below 1% of the total in all 37 tubes is ignored*.)
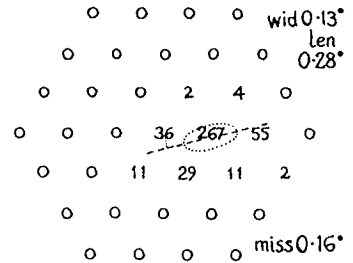
The r.m.s. spread of light in directions

Figure 1.

parallel and perpendicular to this axis are referred to as the *LENGTH* and *WIDTH* of the image. *FRAC(2)* (following a suggestion by Weekes) measures the general concentration of light: it is the fraction of light collected by all 37 tubes that is contained in the 2 largest signals. The orientation of the image relative to the (central) source is described by (a) *MISS*, the perpendicular distance of the centre of the field (the source) from the image axis, (b) the *AZIMUTHAL-WIDTH*, the r.m.s. image width relative to a new axis which joins the source to the centroid of the image, and (c) the *DISTANCE* (distance of image centroid from source), to be compared with the distance of the brightest point (tube with largest signal) from the source — thus related to the orientation of the skew images.

Showers aimed directly at the observer will not have distinctive shapes. (The maximum signal will occur in the central photomultiplier — referred to as *ZONE 0*.) Showers having impact parameters at some distance away are viewed partly from the side, and the width and length of the image reflect largely the width and length of the particle cascade. The geometry depends on the impact parameter, so it is important to classify separately shower images having the largest signal in one of the tubes in

the inner ring of 6 surrounding the centre (these are *ZONE 1* showers), showers with maximum signal in the next ring of 12 tubes (*ZONE 2*), etc.: the latter correspond to somewhat higher energies or impact parameters.

It is found that hadronic showers have longer and more fluctuating images (leading particle effect), and are wider (due largely to emission angles of pions), and are not systematically aligned with the source (if isotropic) — larger *MISS* and *AZIMUTHAL-WIDTH*, smaller *DISTANCE* of centroid for a given *ZONE* (position of peak signal).

4. Comparison of image parameters for different kinds of shower

Figure 2, below, shows the distribution of the widths, lengths, and other parameters of background proton showers, and for showers from oxygen
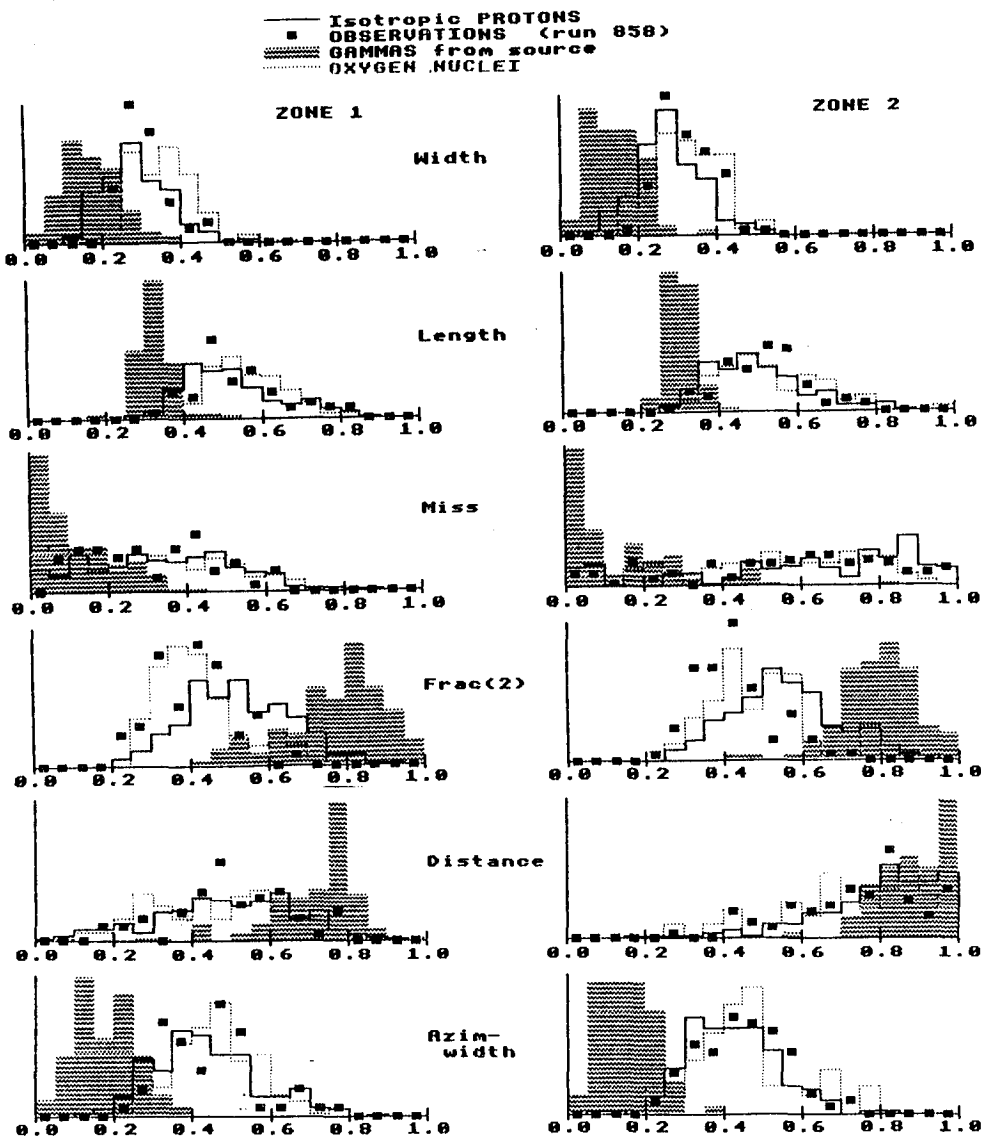

Figure 2: histograms of image characteristics. (vertical showers)

nuclei, compared with those for gamma-ray showers (shaded histogram) from a source placed in the centre of the field of view. Units: degrees — except for *FRAC(2)*, which is dimensionless. The triggering requirement is

as given above (2/19 at least 40 p.e.). Showers having the brightest signal on the inner ring of 6 tubes (zone 1) or the next ring of 12 (zone 2) are shown in the left and right column. The histograms demonstrate the more concentrated images of the gamma showers. Some real background showers observed in the zenith have been analysed in the same way (using data supplied by M.F.Cawley, D.J.Fegan and N.A.Porter). It seems that the simulations agree well with most features of the observed images, though some additional image spreading may be present in reality. Tests of the predicted image characteristics for gamma showers are not yet available.

5. Selection of gamma-ray showers from the general background

One can define, for each of the 6 image parameters, a boundary marking off the "gamma domain", containing most gamma images, but not many protons. If one then requires that 4 out of 6 parameters lie in the gamma domain, it is possible, in the case of the simulated images, to accept 60-70% of gamma showers, but only 1-2% of proton background showers. One would like to have the precise ranges of these parameters verified by experiment, but based on the simulations one might require, where $x = \sec\phi - 1$, ϕ being the zenith angle,
WIDTH < 0.21-0.17x, LENGTH < 0.35-0.13x, MISS < 0.17, FRAC(2) > 0.72+0.28x, DISTANCE > 0.65, AZIMWIDTH < 0.21-0.11x ...   for Zone 1 showers, and
Width < 0.19-0.2x,   Length < 0.33-0.13x, Miss < 0.22, Frac(2) > 0.72+0.31x, Distance > 0.83+0.04x, Azimwidth < 0.20-0.11x ... for Zone 2 showers.
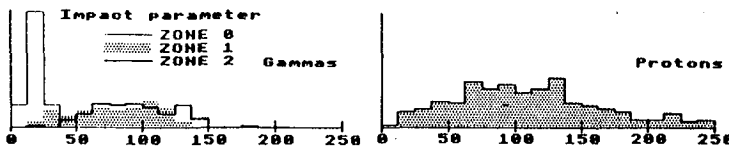
6. Miscellaneous features

Figure 3: distribution of impact parameter.

Figure 3 shows the distance to the shower axis when showers are selected by the (2/19) triggering criterion, and the images are classified into zones (by peak signal position).

Gamma showers (from a point source) peaking in the central tube have much smaller impact parameters than do other showers.

Energies and fluxes for vertical showers. With the above triggering requirement (and 10m diameter mirror, 2300m altitude, etc.), the effective threshold for gamma showers that peak in zone 1 (or 2) is 0.4 (0.7) TeV,* and the rate of showers in zone 1 (or 2) is equal to the flux of primary gammas above 0.4 (0.7) TeV within a radius of 88m (117m). A total of 550 (or 390) photoelectrons in all 37 tubes corresponds to $E_\gamma = 1$ TeV.

7. Higher energies   * (Median energy 0.7 (1.3) TeV)

Angular distance of image centroid from source as seen in ideal detector — i.e. large field of view and good resolution — is given quite well (for gamma showers) by the expression $\theta = 1.5 \times 10^{-5} (r + r_o)^2$ degrees, where at 1 TeV, $r_o = 150$m, at 40 TeV, $r_o = 195$m and at 1000 TeV $r_o = 230$m. This shows that at much higher energies the shower images are further from the source: at 40 TeV and typical impact parameter 110m the centroid would be at 1.5° — but the image would still have only 0.5° lengthways spread about this, so a bigger field of view would be needed: detection would be harder.

References
(1) Cawley, M.F., et al., paper OG 9..
(2) Hillas, A.M. (1982) J. Phys. G **8**, 1475-92; **8**, 1461-73.
(3) Hillas, A.M. (1981) 17th Int. Cosmic Ray Conf., Paris, **2**, 193-6.