Optical Cerenkov emission from large cosmic ray air showers (computer simulation)

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LETTER TO THE EDITOR

Optical Čerenkov emission from large cosmic ray air showers

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Abstract. Computer simulations of the optical Čerenkov emission from large cosmic ray showers indicate that the form of the lateral distribution of photons is sensitive to the longitudinal development of the electron cascade and so to the nature of the primary particle. The breadth of the computed distribution of photons, confirmed by measurements made at the Haverah Park air shower array, suggest the possibility of detection of the largest air showers using widely separated, simple detectors.

1. Introduction

Following the pioneer work of Galbraith and Jelley (1953) and Chudakov and co-workers (Chudakov *et al* 1960) on the detection of the optical Čerenkov radiation emitted by extensive air showers (EAS) initiated by low energy primary particles ($\sim 10^{15}$ eV), the studies by Kreiger and Bradt (1969), and Diminstein *et al* (1972, private communication), comprise the only work to date on the larger EAS arising from primary particles of energy greater than 10^{17} eV.

This letter gives an account of computer simulations of the Čerenkov radiation to be expected in the largest air showers (corresponding to primary energies as high as 10^{18} eV) together with preliminary data from measurements made in such large showers at the Haverah Park array.

Our present interest in the optical Čerenkov radiation from large showers arises for three reasons.

(i) The lateral spread of the optical Čerenkov radiation is considered to be an indication of the depth of maximum development of the shower and studies of the fluctuation in this quantity may provide a source of information on the important problem of the nature of the primary particles.

(ii) The optical Čerenkov radiation at certain lateral distances in EAS relates well to the energy of the primary particle, an effect recently utilized by Diminstein *et al* in deriving the energy spectrum of primary cosmic rays. We consider that the optical Čerenkov radiation is a quantity that may be measured using simple, portable detectors and may form the basis for reliable intercalibration of the energy responses of the large EAS arrays which employ different types of shower detectors.

(iii) It is possible that the largest showers (primary energy $> 10^{20}$ eV) may be economically and effectively detected with arrays of sensitive area greater than 1000 km^2 comprising widely spread Čerenkov radiation detectors located in regions of satisfactory climate and night sky clarity.

The experimental work described here was undertaken to obtain experience of the techniques of detection of Čerenkov emission, to identify the cheapest and simplest detector suitable for use in large showers and to investigate the duty cycle of an automated device in an unfavourable climate.

2. Computer simulations of optical Čerenkov emission

The simulations have formed part of a larger program of work involving many aspects of EAS, the results of which have been described by Dixon *et al* (1973). The electrons giving rise to the majority of the Čerenkov radiation have been derived from the number of neutral pions of various energies produced at various heights in the atmosphere in proton initiated showers, according to the preferred model of high energy interactions employed by Dixon *et al.* The development of the electron–photon cascade has been followed by using cascade theory under approximation A to consider the development of showers of energetic particles (energies > 50 GeV) and subsequently the three-dimensional calculations of Messel and Crawford (1969) to evaluate the number of electrons of given energy at various heights and lateral distances. From this cascade, the electron track length can be calculated and hence the number of optical Čerenkov photons in the shower as a function of core distance at a prescribed observation level may be computed. This procedure requires that the angles made by the electrons with the core be known and these have been obtained from the work of Nishimura and Kamata (1958).

The fluxes of photons in the wavelength range 350–500 nm have been computed for distances 100–1000 m from the cores of showers initiated by primary protons of energy 10^{15}–10^{18} eV incident from the zenith. The data of figure 1 represent the lateral distribution of photon densities in showers of energy in the range 10^{15}–10^{18} eV together with the predictions from models for photon and proton induced showers derived by Diminstein *et al* (1972, private communication). We show also the effects of increasing the assumed angular distribution of the electrons and considering photons of wavelengths 300–800 nm which are detected at the Yakutsk array.

The data of figure 2 represent the radiation in vertical showers initiated by primary protons of energy 10^{17} eV which, as a result of the normal fluctuation effects in points of interaction and inelasticity of the nucleons, reach their maximum development at different depths in the atmosphere. These showers were chosen from a sequence of about 100 simulations to have depths of maximum cascade development which increase in equal intervals from about 550 to 1000 g cm^2 or more. It is clear from figure 2 that the lateral distributions of the radiation in these showers indicate a region of core distance of about 300 m at which the photon density relates well to the primary particle energy, independent of the shower development. There exist other regions at distances less than 200 m and greater than 600 m from the core where the photon flux changes as the depth of shower maximum increases. Correlations between the ratio of the photon densities at 100 and 600 m and the depth of cascade maximum development, are given by the data shown inset in figure 2. The measurement of the ratio of the photon densities at 100 m and 600 m should therefore provide a useful indication of the presence of primary protons from the large fluctuations which they produce.

We note that the fluctuations in simulated showers, based upon fragmentation data for silicon and iron nuclei suggested by Waddington (private communication)

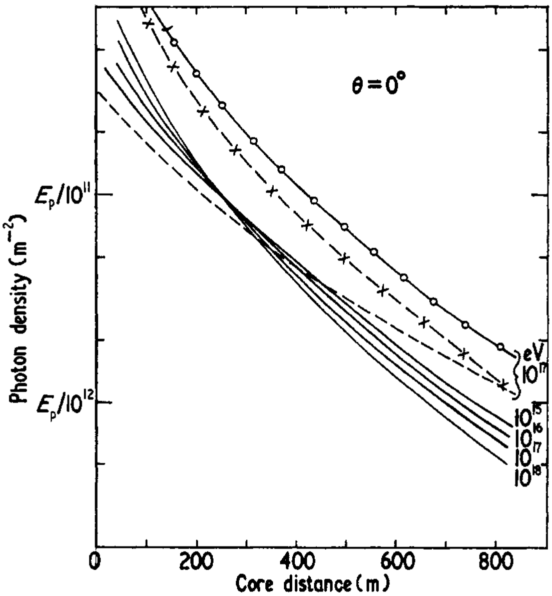

Figure 1. The computed average lateral distribution of optical photons. Full curves: present work, proton primary, 350 nm $< \lambda <$ 500 nm; broken curve: present work, increased dispersion; broken curve with crosses: Diminstein *et al* (1972, private communication), photon or proton primary, 300 nm $< \lambda <$ 800 nm; full curve with open circles: present work, proton primary, 300 nm $< \lambda <$ 800 nm.

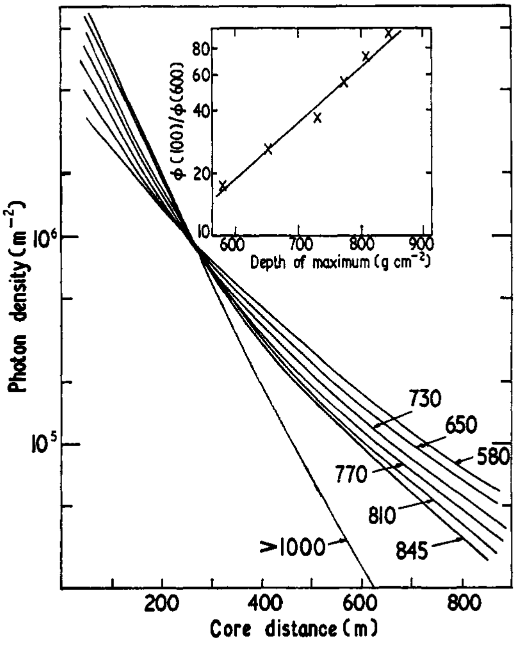

Figure 2. The computed lateral distributions of photons in 10^{17} eV vertical showers having their maxima of development at different depths in the atmosphere (shown on the figure in units of g cm^{-2}); the ratio of the flux ϕ at 100 m to that at 600 m as a function of depth of maximum is shown inset.

are small, such that about 95% of events have depths of maximum development between 600 and 660 g cm^2; such heavy primaries should not produce showers with maximum development at significantly greater depths.

3. Comparison of simulation data with experimental measurements

Measurements were made during the UK winter of 1972/73 using a simple sensor comprising a single 7 in photomultiplier without any optical system. Data were obtained in about 100 showers of energy of the order of 3×10^{17} eV, incident at zenith angles less than 60° (according to the Haverah Park particle detector array).

For showers incident at zenith angles less than 30° we find that the photon density at a core distance of 300 m increases linearly with the Haverah Park ground parameter ρ_{500}. On the basis of this relationship we find the lateral distribution of photons in a shower specified by $\rho_{500} = 0{\cdot}5\ \mathrm{m}^{-2}$, corresponding to a primary energy of about $2{\cdot}5\text{–}3 \times 10^{17}$ eV, to be shown in figure 3 and in agreement with the predictions of the computer simulations. (In the absence of an absolute calibration of the photon detector in this preliminary work, our experimental data are normalized to the simulation results at a core distance of 300 m.)

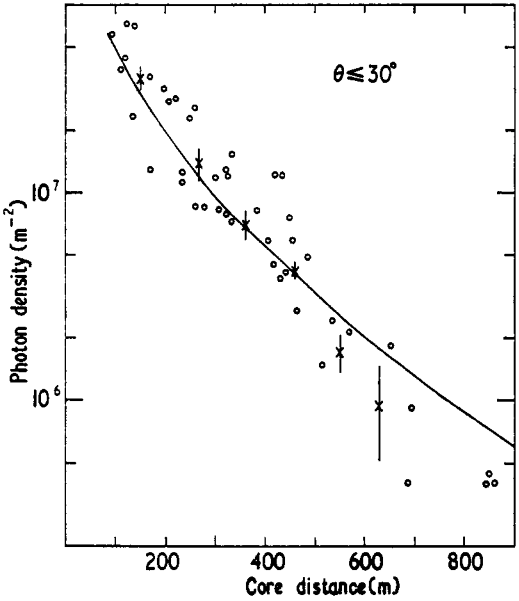

Figure 3. The measured lateral distribution of optical photons in large air showers. Full curve: present work, 5×10^{17} eV energy, 300 nm $< \lambda <$ 800 nm; crosses with error bars: Diminstein *et al* (1972, private communication); open circles: present experiment, individual measurements.

The data from many showers of energy of the order of 5×10^{17} eV incident at zenith angles less than 30° obtained at the Yakutsk array and reported by Diminstein *et al* (1972, private communication) are shown in figure 3 (these data are the quoted absolute densities and have not been normalized). They are in agreement with simulation data and preliminary measurements.

4. The detection of large air showers

The main requirements for an array capable of detecting large showers effectively are a low unit detector cost and the ability to locate detectors at widely separated locations such that sufficient detectors will sample the showers to ensure reliable primary particle energy estimation. We estimate that the unit detector cost for a simple detector of atmospheric Čerenkov photons could be about £1000 and that such detectors could be located on, for example, a square matrix with detector separations of 3 km or more, so that 100 such detectors will enclose a sensitive area of greater than 1000 km^2. The possibility of the use of such wide detector separations is based upon both the experimental and simulation data reported here; recent measurements at Haverah Park have shown that measurements at distances of 1·5 km in showers of energy of about 10^{18} eV are possible in which the signal is measured to be greater than the 'noise' using a simple detector. Computer simulations indicate that the measurements of signals of amplitude greater than 3 times the 'noise' would be possible at core distances of about 2 km in showers of primary energy of the order of 5×10^{19} eV. Showers of such energy would, on the basis of existing measurements of the energy spectrum at Haverah Park (Edge *et al* 1973) be detected at a rate of about ten per year on an array of area 1000 km^2, assuming a duty cycle for the optical detectors of 25%.

5. Conclusions

(i) It has been shown that, using an automated sensor, useful measurements may be made on a worthwhile sample of showers in climatic conditions as poor as those which occur at Haverah Park; measurement in large showers has been possible under conditions of limited moonlight.

(ii) Computer simulations and experiment confirm the existence of a measurement of optical radiation, the photon density of about 300 m, which varies little with the stage of development for a 10^{17} eV proton initiated shower and reflects accurately the primary particle energy. The measurement of the photon density at about 300 m may readily be undertaken with simple equipment at all current large EAS arrays and may form a reliable low-cost method of intercalibration of their energy responses.

(iii) Computer simulations suggest that measurement of the ratio of the photon density at large and small core distances may indicate the stage of development of the shower and hence, assuming that there exist late developing showers, the presence of protons in the high energy primary flux.

(iv) Measurements have been made at core distances of 1·5 km in showers detected and analysed using the Haverah Park array (showers falling outside the array at distances >2 km, for which analyses are not available, have also given signals). This evidence, together with that from computer simulations suggests that widely spaced, cheap optical detectors may form a useful method for detecting the largest showers; further considerations of detector optimization, array design and site surveys would seem worthwhile in view of the present limited possibilities of detection of large EAS using other techniques.

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