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# *EVIDENCE FOR RADIO PULSES FROM EXTENSIVE AIR SHOWERS AT LARGE ZENITH ANGLES*

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An experiment to detect radio pulses in coincidence with pulses of atmospheric Cherenkov light from cosmic ray extensive air showers at large zenith angles ($\sim 75°$) is described. A frequency $\nu = 44$ MHz and bandwidth $\delta\nu = 3$ MHz were employed, the field of view being 0.06 sr. The experimental evidence suggests that radio pulses caused by showers were observed at a rate $0.17 \text{ hr}^{-1}$, this being much higher than that found in previous observations near the zenith.

## INTRODUCTION

FOLLOWING the initial proposal [1] and subsequent demonstration [2] that radio pulses can be detected in association with extensive cosmic-ray air showers (EAS), interest has been expressed [3] in the possibility of exploiting the phenomenon to obtain information on showers of the highest energy (i.e. $> 10^{18}$ eV). The feasibility of this will depend largely on the absolute counting rates which can be obtained, and this in turn will be influenced, among other factors, by the effective collection area, and hence by the angular distribution of the radiation. It was early suggested [4], on various grounds, that some advantage should be gained by observing showers at large zenith angles. These tentative ideas have since been discussed in greater detail by Colgate [5], who has also pointed out the possible role of curvature in the shower front.

Showers viewed at large zenith angles develop at great altitudes and considerable distances from the detector. This implies (1) that the radiation from highly inclined showers will illuminate a much larger area of terrain, and (ii) that an antenna of given beam width will embrace a much larger volume of atmosphere where the showers attain their maximum development. On Colgate's model, to a first approximation, the frequency of detection of showers arising from primary particles having a given flux, varies inversely as the angle of elevation of the main beam of the antenna, when this angle is small.

Experiments reported so far [2,4,6,7,8,9], all of which have used antennas with their main lobes directed toward the zenith, have indicated rather a low rate of detection of radio pulses ($\sim 0.01$–$0.06 \text{ hr}^{-1}$), the exact figure depending on the values of the many parameters of the system. The results of Allan and Jones [9] suggest that for showers at moderate zenith angles ($\leq 60°$), the pool of radio emission on the ground is reasonably uniform up to distances 350 m from the core. Under these circumstances data on showers of the highest energy from the zenith is only collected at a rather low rate. Only small improvements can be expected here in detection efficiency, since such factors as frequency and bandwidth have probably already been optimised and are usually controlled by the interference situation, both local and distant.

This present paper describes a preliminary experiment to investigate the feasibility of detecting radio pulses from EAS at large zenith angles. Because, under these circumstances, the electronic component of the showers is negligible at sea-level, it is necessary to resort to the $\mu$-meson or optical Cherenkov component for trigger purposes1). In spite of its operational limitations, the Cherenkov technique was employed in the first instance, owing mainly to its simplicity and the availability of suitable equipment. The necessary restriction to the hours of darkness was not a severe limitation, since the radio interference was also minimal over this period.

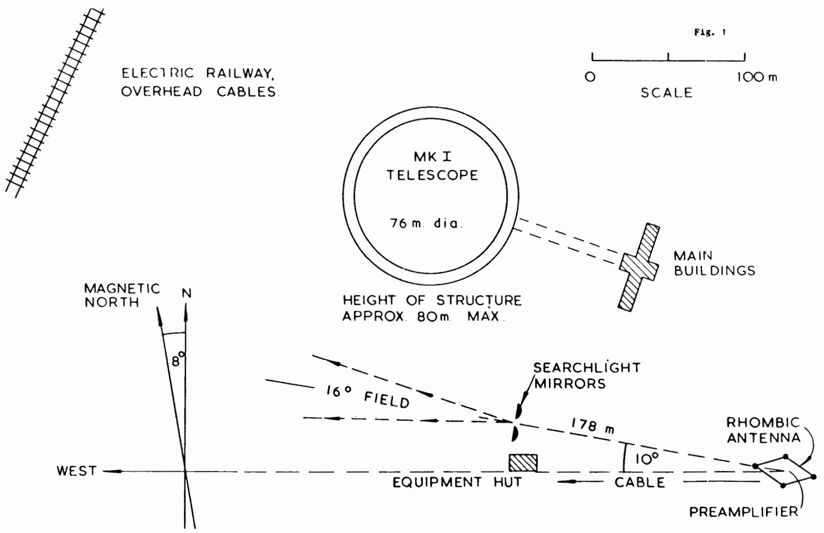

FIG. 1. The layout of the equipment in the present experiment, and relevant features of the site.

## Experimental Layout

The essential features of this are shown in Figure 1.

### (a) Light Receiver

This consisted of two units each having a 90 cm diameter f/0.46 parabolic searchlight mirror with a 12.5 cm diameter photomultiplier (EMI type 9530B) at the focus. These units, mounted with their optic axes parallel and 2 m apart, were attached to a boom on a Mk III Bofors gun mounting. The area for light collection was therefore $2 \times (6 \times 10^3)$ cm$^2$ and the geometrical full field of view of each mirror was 16° in diameter (0.061 sr). The experiment was carried out with the instrument pointing at an azimuth of about 280° (i.e. ~ WNW) and an elevation of 15°. This azimuth setting was primarily chosen because it lay approximately perpendicular to the Earth's magnetic field, while in addition it proved to be the darkest region of the sky at the Jodrell Bank site. The choice of elevation was dictated by the desire to work at the lowest angle above the horizon commensurate with stray lighting and low-level haze; with this arrangement the field of view constrained the reception of directed light to an elevation range from 7°—23° (see below, discussion).

The two light receivers were operated in time-coincidence; this was found to be essential because at this large zenith angle (75°) the counting-rate for light pulses from showers under clear-sky conditions for a single light-receiver was considerably lower than the detection rate of single particles passing through the phototube. The pulses from the two phototubes were amplified (30 MHz bandwith), selected by pulse-height discriminators and passed to a coincidence unit of resolving time $\tau = 0.085$ $\mu$sec.

The light receiver was fully automated and the phototube supplies were controlled by a servo operating on the single-channel counting rates at the coincidence unit inputs. In this way the single-channel rates were maintained at $30 \pm 2$ counts sec$^{-1}$ over the full range of variations of sky brightness encountered during the running periods. The chance rate was therefore constant and known. Under clear, moonless, night-sky conditions the system counted showers from the zenith at a rate ~40 min$^{-1}$, corresponding to an estimated threshold energy for zenith shower detection $E_0 \sim 10^{14}$ eV At a mean angular elevation of 15° under conditions of similar clarity the counting rate was ~0.2 min$^{-1}$, well above the chance-rate of $9 \times 10^{-3}$ min$^{-1}$. On nights with a uniform cloud-cover at an altitude ~1 KM, the rate of 15° elevation fell to $\leq 0.02$ min$^{-1}$ (i.e. close to chance rate); this suggested that under clear conditions the light receiver was genuinely detecting Cherenkov light from distant showers at high altitude, rather than such light either from Coulomb-scattered electrons of relatively nearby showers whose cores crossed the receiver beam[10], or from local $\mu$-mesons.

The phototube currents and the individual light-pulses were continuously monitored on chart recorders. The output of the light receiver was also displayed on one channel of a recording oscilloscope (bandwidth 30 MHz) with a 20 $\mu$.sec time-base, in order that the Cherenkov pulses could be distinguished by their sharply bandwidth-limited appearance, from flashes from the nearby electric railway.

### (b) Radio Antenna and Receiver

A large rhombic antenna of length 56.6 m, height 8.6 m and maximum width 19.4 m was used to provide broadband reception of horizontally polarized waves at low elevation. The centre of this antenna was sited 178 m to the east of the light receivers and the main lobe was approximately aligned with the light receiver axes. The antenna was designed to work at a mid-band frequency of 44 MHz. The main beam was calculated to have the following characteristics:- bandwidth in azimuth $16\frac{1}{2}^\circ$ to 3 db points, or 33° between nulls; and, in elevation, the main lobe was calculated to have its peak at $12\frac{1}{2}^\circ$ above the horizon with nulls approximately at 0° and 25°. The receiver consisted of a transistorised pre-amplifier sited at the antenna to which it was connected by a tapered open-wire feeder. The pre-amplifier was coupled to a vacuum-tube main amplifier which in turn was followed by a silicon diode detector operating in its linear mode. The overall bandwidth of the system was 3 MHz (to 3 db points), this including that of a filter inserted at the input to eliminate Channel 2 TV signals. The receiver noise temperature was $\sim$1000°K and the overall system temperature, during quiet periods at night in the absence of TV, was $\sim$5000°K.

The output of the detector of the radio receiver was displayed together with the output of the light receiver on the 20 $\mu$s timebases of a double-beam recording oscilloscope. The timebases were triggered by the reception of coincident optical pulses from the two light receivers; some delay was incorporated in both the radio and optical channels. The traces were recorded photographically with a continuously-moving-film camera. Artificially-triggered comparison traces were generated at 30 min intervals and a 2 MHz oscillator was available for calibration of the timebase. The expected times-of-arrival of both the optical and radio pulses were established with the aid of a pulsed light-source inside one of the light receivers; this triggered the receiver optically and also produced an electrical pulse which was detectable by the antenna.

## Observations and Results

The equipment was operated during a winter period of about three months. Observations were hampered by bad weather, but during this period approximately 500 light-receiver triggered recordings were obtained in 52 hrs of clear weather (mean rate $\sim .17\ \mathrm{min}^{-1}$) and 120 recordings in 93 hrs of cloudy weather (mean rate $\sim .02\ \mathrm{min}^{-1}$); 240 artificially-triggered recordings were also obtained. The weather was classified as 'clear' if the rate of coincident light pulses was $> 0.1\ \mathrm{min}^{-1}$; on almost all the remainder of the nights, which were classified as 'cloudy', the cloud cover was continuous at an altitude $\sim$1 Km during the observing period.

Several methods of analysis were applied to the recordings to determine whether the radio signal at the expected position on the timebase was significantly higher than elsewhere. For this purpose, the timebase was divided into intervals of 0.25 $\mu$s, only the first 12 $\mu$s of timebase normally being

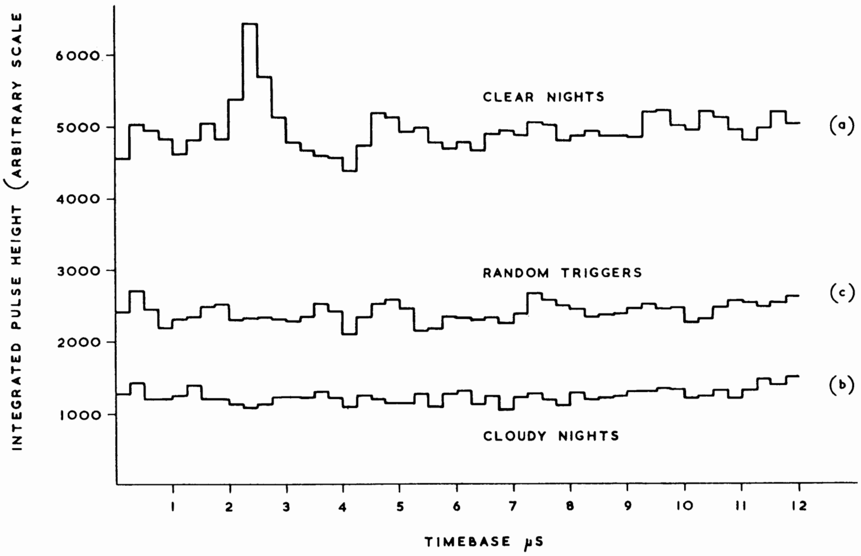

FIG. 2. Histograms showing the effect of integrating the pulse heights in each 0.25 s time interval for all radio recordings obtained under the following conditions. a) Light receiver triggering on clear nights (495 events); b) light receiver triggering on cloudy nights (123 events); c) artificial triggering at 30 min intervals (241 events). The pulse heights were normalized so that the average pulse height for each night's observation was the same (10 units). The expected delay of the radio signal is 2.25 s.

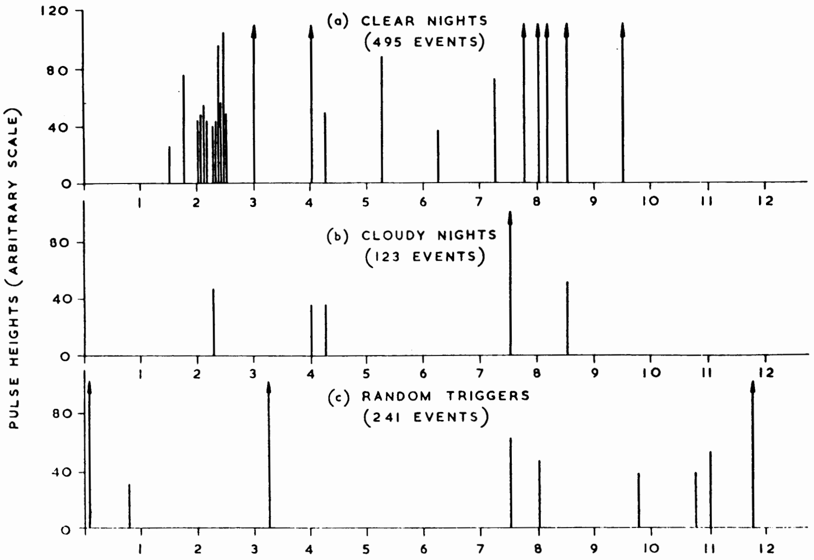

FIG. 3. Positions and heights of bandwidth-limited radio pulses whose heights exceeded 1.5 times those of any other pulses occurring on the same recording. The positions are correct to within each 0.25 s interval. The pulse heights have again been normalized to give the same mean level of background noise (10 units); an arrow denotes an off-scale pulse.

studied. Only those recordings where the optical channel showed a sharp, bandwidth-limited pulse at the appropriate delay were accepted for analysis. This was found to be a reliable criterion for eliminating flashes due to electric trains. The methods of analysis used were necessarily somewhat more searching than those used in the earlier experiments at Jodrell Bank[2,4] due to the less favorable interference situation associated with observation at low elevations in the present work, which led to the presence of many small interference pulses, superficially indistinguishable from the expected shower pulses, appearing apparently at random along the timebase. Two main methods were employed. i) The mean height of the radio signal in each 0.25 $\mu$s time channel was recorded for each radio trace and the height for all traces in each channel were integrated. Events with offscale signals were necessarily excluded.

ii) The position and height of any bandwith-limited pulse on each trace whose height exceeded 1.5 times the height of any other pulse on the trace were recorded.

Figure 2, shows the results of analysis (i) when applied to the records obtained for the various triggering conditions. Some night-to-night variation in the gain of the radio receiver occurred, so that the results for each nights observations have been normalized to give the same mean pulse height (10 units). A clear bias in favor of a larger signal in the 2.25—2.50 $\mu$S channel is evident in the results of fig. 2 or clear nights; this is the position expected on the basis of delay measurements and the peak is statistically significant. No similar peak occurs in either the results for cloudy nights or those for the artificially-triggered recordings.

Fig. 3 shows the heights and positions, within each 0.25 $\mu$S time interval, of the largest radio pulses as determined by analysis (ii). The clustering of a large number of pulses in the interval 2—2.5 $\mu$S on clear nights is obvious, in contrast to the relatively even distribution along the timebase of other pulses, frequently very large. These latter pulses are found under all conditions, including artificial-triggering, and their distribution appears to be compatible with their being pulses of external interference which, on average, may appear at any point on the timebase. No obvious source for these pulses was discovered although the electric railway was the most likely candidate; some night-to-night variation in the number and position of the pulses was observed. If we except the interval 2—2.5 $\mu$S on the clear nights, 28 of these large interference pulses were observed on ~860 timebases, each of 12 $\mu$S duration, suggesting a rate of interference pulses ~2800 $\sec^{-1}$. Clearly at this particular site, which is in close proximity to fairly intensively used roads, electric railway and airport, it would be difficult to obtain useful information on showers at this zenith angle from a radio system alone, having an exposed aerial of this type, at least in the absence of a coincidence system.

Considering the clear night data for the largest pulses, we find that in the first 12 $\mu$S of timebase, there are 23 large pulses, 9 of which lie in the interval 2—2.5 $\mu$S. The probability of the observed

9 pulses in the 2—2.5 μS interval being interference pulses is therefore $23!/14!\,9!(1/24)^9$ which is clearly negligible. If therefore, we accept as being genuine these 9 pulses, all of which are greater than 4 times the average pulse height, the rate of reception of large radio pulses in 52 hrs of clear-night observation is ~0.17 $\mathrm{hr}^{-1}$. This is significantly higher than the rate ( 0.008 $\mathrm{hr}^{-1}$ ) obtained in earlier observations at the zenith at Jodrell Bank (2, 4) using similar frequency (44 MHz) bandwidth (2.75 MHz) and field -of-view (.024 Sr). Only one large radio pulse at the correct delay was observed during 93 hrs of observation on cloudy nights. It therefore appears unlikely that the large radio pulses at the correct delay observed on clear nights were due to showers from angles outside the field of view whose cores fell very close to the light and radio receivers, since these would be equally effective whatever the cloud conditions, but rather that the bulk of the pulses originated from showers within the field of view which developed high in the atmosphere.

## Discussion

It appears, then, that bandwidth-limited pulses (duration $\lesssim$ 0.3 μS) have been observed from showers at zenith angles ~75° at a frequency of $\nu = 44$ MHz within $\delta\nu = 3$ MHz, even though this frequency is rather higher than that expected to be optimum. Using simple arguments based on Colgate's ideas [5], a shower developing in the earth's atmosphere at a zenith angle $\theta$ traverses a thickness to sea level which is greater by a factor sec $\theta$ than that traversed by a shower from the zenith. If a shower from the zenith caused by a primary of a particular energy reaches a certain age at an atmospheric pressure $P = P_1$, a shower caused by a primary of the same energy at a zenith angle $\theta$ will reach the same age when the atmospheric pressure $P = P_1 \cos\theta$. Since the thickness of the shower front $\alpha$ 1/p, for a zenith angle of 75°, the shower front will be four times thicker than that of a shower of the same age and energy from the zenith. At sea level the front of a shower from the zenith is typically ~2 m thick[11], so that at the same age a similar shower at a zenith angle of 75° would have a thickness ~8 m. Considerable decoherence might therefore be expected from such a shower at this zenith angle at a frequency $\nu = 44$ MHz (wavelength ~7m).

On the other hand, a zenith shower produced by a primary of energy $\sim 5 \times 10^{16}$ eV, which is thought to be near the threshold for producing detectable radio pulses at moderate zenith angles [4,9], only has an age S ~ 1.2 at 1000 gm $\mathrm{cm}^{-2}$ (sea-level). At a zenith angle of 75° the electronic component has not died out until the shower has passed through ~2800 gm $\mathrm{cm}^{-2}$, the atmospheric pressure at this point being ~0.7 atmospheres. As the shower propagates downwards it will contract in linear scale as the air pressure rises, leading to a corresponding increase in the frequency of the maximum of the coherent radio emission although the angular emission should remain unchanged. The intensity of the coherent radiation from each element of shower track will be proportional to the square of the number of particles at the point in question. A substantial amount of 44 MHz radiation may therefore be detectable from the later stages of shower development although probably over a smaller area than at lower frequencies, leading to a lower detection rate for radio pulses. One further factor helps to explain the detection of pulses at 44 MHz from these high zenith-angle showers. This is the occurrence of fluctuations in shower development, a factor which has already been cited by Allan and Jones [9] when discussing their results obtained at zenith angles between 0 and 60° at $\nu = 60$ MHz. Coherence depends critically on the thickness and curvature of the shower front in the region from which the radiation is received, and fluctuations in the properties of the secondary electron-photon cascades generated by the shower core can lead to quite wide variations in the shower thickness and curvature, and hence in the radio pulse amplitudes at any one frequency.

No very reliable estimate can be made of the energy of the showers which triggered the light receiver since at present no theoretical or experimental results for the lateral distribution of Cherenkov light from showers at high zenith angles are available. Many geometrical factors and the unknown degree of atmospheric absorption also preclude quantitative estimates. However, a number of properties of the light receiver which are relevant to the present experiments can be deduced qualitatively. If we accept the evidence obtained on cloudy nights, which suggests that a cloudbase at an altitude of ~1KM reduces the light-receiver counting rate by a factor $\gtrsim$ 10 x at a zenith angle of 75°, we must conclude that most of the light in showers detected on clear nights comes from distances > 4 KM from the receivers, since this is the slant distance to a 1 KM cloudbase. Now any shower whose core crosses the light receiver beam (angular diameter 16°) at a distance of 4 KM or greater must take at least

3.6 μS to cross the beam, so that any photons from Coulomb-scattered electrons which are emitted into the beam will straggle by this amount. A bandwidth-limited pulse (duration ≤ 30 ns for 30 MHz bandwidth) cannot therefore arise. Only when the arrival direction of the shower lies within the receiver beam will sharp light pulses as observed occur. The angular diameter of the Cherenkov light patch as observed against the sky background must be relatively small under these circumstances, since unlike the case of showers from the zenith, all the electrons producing the observed radiation are many kilometres away from the receiver. Using Greisen's approximate formula[12] for the number of particles in a shower, we find that the electron component of a shower induced by a primary of energy $10^{16}$ eV at a zenith angle of 75° has died out when the shower is ~15 KM from an observer on the line-of-sight. Thus even if the shower is still radiating over a disk ~200 M in radius immediately before this point, its angular diameter will be only ~1.6°, and this in fact represents an upper, rather than a lower limit. Thus we are led to conclude that the light receiver does in fact detect showers at high zenith angles with good directional fidelity.

An extremely crude estimate of the threshold energy of the showers necessary to trigger the light receiver at 75° zenith angle, and hence of the shower energy producing the radio pulses, can be made in the following way. The EAS produced by a $10^{16}$ eV primary at a zenith angle 75° reached an age $S = 1.0$, corresponding to the maximum number of particles, at a distance ~46 KM from a sea level observer on the line-of-sight of the shower, and its electronic component has died out ~15 KM from such an observer. If we assume that the bulk of the light detectable on the ground comes from the last 10 KM of track and that it is limited into a cone of half-angle ~0.1 radians, corresponding to the combined effects of the Cherenkov angle and Coulomb scattering of the electrons, the radius of the light pool in the plane perpendicular to the shower track and containing the observer will be ~2 KM. Using Greisen's figures[3] for the integral primary energy spectrum we thus find that the expected rate of observation of $10^{16}$ eV showers by the observer is ~0.14 $\text{min}^{-1}$, a figure agreeing quite well with the observed light receiver counting-rate for clear nights. Tentatively then, we put the threshold primary energy for detection by our light receiver at a zenith angle of 75° at ~$10^{16}$ eV. Since radio pulses were observed to occur in about 2% of the records obtained on clear nights, the minimum primary energy necessary to produce a detectable radio pulse with the equipment used is ~$10^{17}$ eV if we assume the lateral extents of the radio and optical emission to be about the same. While these figures are at best order-of-magnitude estimates only, they do indicate yet again the strong bias of radio techniques in favour of detecting showers of the highest energies.

We conclude that the evidence suggests that radio pulses have been observed from EAS at zenith angles ~75°, the energies of the primaries producing the showers probably exceeding $10^{17}$ eV. The rate at which pulses were observed (~0.17 $\text{hr}^{-1}$ under favorable conditions) substantially exceeds the rates obtained during observations near the zenith, with equipment of comparable sensitivity and field of view.

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Postscript (Sept 26, 1967). After submitting this paper but prior to its acceptance for publication in the Russian original, a similar experiment has been conducted by another group, and its results have been published elsewhere. Reference:—"Correlation between optical and radio emission from extensive air showers at large zenith angles." B. McBreen, E. P. O'Mongain, N. A. Porter and P. J. Slevin. Physics Letters **23**, No. 11, 677 (1966).

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