RADIO EMISSION
FROM
EXTENSIVE AIR SHOWERS

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by

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ABSTRACT

The phenomenon of radio emission from Extensive Air Showers is a recent discovery, and as yet its nature is not well understood. Chapter 1 indicates that the observation of the radio emission from showers may be one of the more promising methods of detecting very high energy showers, to which considerable astrophysical importance is attached.

Various theoretical models have been put forward to predict the expected nature of the radio emission; these are presented and discussed in Chapter 2. Since the subject is less than 4 years old experimentally, a review is presented in Chapter 3 of all the main experiments carried out in this field up to the commencement of the present experiment.

The author took part in the radio-detecting experiment operated with the Haverah Park Extensive Air Shower Array. The apparatus used, and the installation procedure, are described in Chapter 4.

The results of this experimental work are described in Chapter 5. The main aim of the analysis is to determine the radiation mechanism from the polarisation of the radiation, and also correlation is sought between the radio emission and the large-scale features of showers.

In Chapter 6, the results are discussed and comparisons made with the results of other experiments. The feasibility of using the radio method in place of particle detectors for high energy showers is then discussed. It is also indicated that the study of the radio emission may yield information on the longitudinal development of showers. Finally the possible future development of the radio work at Haverah Park is given.

RADIO EMISSION FROM EXTENSIVE AIR SHOWERS

CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 High Energy Cosmic Rays

The primary cosmic radiation is made up of high energy particles which continuously reach the top of the earth's atmosphere from outer space. This radiation reaches the earth after travelling vast distances through space, and a study of its composition, energy spectrum, arrival directions and time variations, should reveal information on the source of the radiation, and also on the fields and matter through which it has passed.

There are many general questions about cosmic rays which we would like to answer. For instance: where do these particles originate, and what sort of acceleration mechanism is responsible for their very high energies? Are they confined to our own galaxy, or are they of extra-galactic origin and so pervade the whole of space?

One particularly important aspect of high energy cosmic rays, which is closely associated with the above questions, and on which much attention has been focused, is the primary energy spectrum. The flux of particles falls off steeply with increasing energy. Closely linked to the primary energy spectrum is the study of the composition of the primary radiation. Up to about 10^{15}eV, the composition is well established: about 90% of all the particles are protons, rather less than 10% are alpha-particles, and less than 1% are heavier nuclei up to iron. (Ginzburg and Syrovatsky, 1964). The exponent of the integral primary energy spectrum has a slope of -1.6 up to 10^{15}eV, where a well-established 'kink' occurs, the slope steepening to about -2.4. This steepening is believed to be due to the inability of the galactic magnetic field to contain protons inside the galaxy above this energy. Heavier primaries can be contained at higher energies, the factor depending upon the atomic number Z of the particular nucleus. Between 10^{17}eV and 10^{18}eV, another 'kink' is thought to exist, the slope flattening again to about -1.7. This may be due to the presence of protons of extra-galactic origin. Very few measurements are at present available at such high energies, due to the extremely low flux and consequent difficulty of observation.

A fairly recent cosmological discovery which could have an important effect on the cosmic ray energy spectrum at very high energies is the isotropic black-body radiation at 2.7°K., first observed by Penzias and Wilson (1965). Greisen (1966) suggests that this radiation should effectively act as a barrier to prevent the acceleration of cosmic ray protons beyond 10^{20}eV. Thus the measurements at the extremely high end of the primary energy spectrum take on an added significance. The existence of a cut-off in the cosmic ray flux would indicate that the radiation is probably universal. Any theories of the evolution of the universe must be able to account for the existence of this radiation, and therefore the confirmation of its existence is of great cosmological importance.

Thus the features of high energy cosmic rays which we wish to study experimentally are the flux, energy spectrum and composition of the primaries. Before going on to describe the techniques employed in making these measurements, a description is given of the processes which occur when a high energy primary particle enters the atmosphere.

1.2 Extensive Air Showers.

When a cosmic ray nucleus penetrates the atmosphere, it soon interacts with an atmospheric nucleus, and as a result, secondary particles, normally positive, negative and neutral pions, are produced. The incident nucleon, or nucleons, lose only a fraction of their energy, and carry on to make further interactions, while the particles produced either decay or themselves interact. The decay of neutral pions into two high energy photons initiates an electron-photon cascade carried on by the processes of pair production and bremsstrahlung, while muons are produced by the decay of the charged pions. For primary energies of above 10^{13}eV, this cascade can penetrate down to sea level, where the lateral spread of the particles may be considerable: Hence the name Extensive Air Shower, usually shortened to E.A.S..

The nucleonic cascade plays the main role in determining the development and structure of a shower. A primary cosmic ray proton entering the earth's atmosphere interacts after traversing, on average, a mean free path of about 80 gms./cm.^{2} For heavy primaries the mean free path is shorter, and fluctuations in the height of the first interaction are less than for protons.

The primary nucleon will lose a fraction of its energy in the first interaction, and together with any other highly energetic nucleons and pions produced, will continue along the original direction of the primary, forming a sharply collimated beam. After a further 80 gms./cm^2. the particles will again interact: for a vertically falling shower, the atmosphere presents about 12 or 13 interaction mean free paths, and the most energetic secondary nucleons will produce the nuclear-active component observed at sea level. The lower energy nucleons will be absorbed through ionisation loss in the atmosphere.

On average, equal numbers of positive, negative and neutral pions are produced in the nuclear interactions. The neutral pions, which have a mean lifetime of less than 10^{-15} sec., decay very rapidly into two high energy photons. These initiate electron-photon cascades which develop by the repeated processes of pair production by photons, and bremsstrahlung radiation by the electrons and positrons. These cascades would die out well before sea-level is reached, for the initial energy becomes shared between so many particles that ionisation loss becomes dominant and the cascade is absorbed. However, the further interactions in the nucleon cascade create additional neutral pions which initiate new electron-photon cascades. Thus the electron-photon component at sea level is produced mainly in the last one or two interaction lengths. The electron-photon component spreads laterally away from the core over a wide area mainly because of Coulomb scattering.

Charged pions produced near the top of the atmosphere with energy less than about 10 GeV are more likely to decay than to interact, the decay products being muons and neutrinos. The large lateral spread of the muons is due mainly to the emission angle of the parent pions, although Coulomb scattering and deflections in the earth's magnetic field play a small part. In contrast to the electron-photon component, the majority of muons produced in the atmosphere, even in the first interaction, reach sea-level because of their relatively long lifetimes and their low cross-section for all interactions apart from ionisation loss.

It will be useful to give the typical distances and dimensions associated with a 10^{17}eV shower, which is close to the mean primary energy observed at Haverah Park. The electron-photon component may extend laterally over an area of radius a few hundred metres. The muon component, which comprises only about 10% of all the particles at sea level, is much more isotropic, and extends out well beyond 1 Km. In a vertical shower the number of particles builds up to a maximum at an altitude of about 6 Km., and then decays so that at sea level only a fraction remains. Showers of higher energy will reach maximum development lower in the atmosphere, while the maximum of inclined showers will be higher.

1.3 Techniques for Observing Extensive Air Showers

The features of the primary cosmic radiation which the observation of extensive air showers can reveal, are the flux, energy and composition of the particles.

The cascades initiated by the primary cosmic rays of energy below 10^{13}eV do not generally extend down to sea level. However, the flux of these particles is relatively high, and so detectors carried by balloons to the top of the atmosphere can record the primary radiation. In the energy range 10^{13}eV - 10^{15}eV, observation of the optical Cerenkov radiation, generated by the passage of the shower particles through the atmosphere, has proved to be a fairly reliable method of counting showers. (Jelley, 1958). At energies above this, the only way to record the primaries is to observe at sea level the secondary particles of the extensive air showers. This is done by the operation in coincidence of two or more particle detectors. The larger the showers one hopes to detect, the larger must be the area covered by the array of particle detectors.

In view of the considerable astrophysical interest in the upper reaches of the primary energy spectrum ($E_p \gtrsim 10^{18}$eV), very large arrays have been constructed in various parts of the world. These include the arrays at Volcano Ranch (Linsley, 1963), Sydney (Browmlee et al., 1967), Haverah Park (Earnshaw et al. 1967) and the proposed Russian array at Yakutsk. The considerable expense and man-power involved in the construction and operating of these arrays has prompted several workers to look into the possibility of using alternative methods for the observing of large showers.

Among these alternative possibilities is one suggested by Greisen, who is setting up a complex system of photo-multipliers to look at the atmospheric fluorescence produced by a shower (Bunner et al., 1967). Also Suga has recently revived the idea of detecting by radar the ionisation produced by the shower particles on passage through the atmosphere. (Matano et al., 1967).

The detection of radio emission from showers has for some years been mentioned as a possible method for observing large showers: this idea was first suggested by Jelley (1958). Since then several experiments have been performed with the ultimate aim of detecting showers by radio methods alone: these are described in Chapter 3. Recently Colgate has designed a system for detecting showers due to primaries of energies of 10^{19} eV and above, by the simultaneous observation of the radio emission and the optical Cerenkov radiation. The theoretical basis for this experiment is the model described in Chapter 2 (Colgate 1967).

The advantage of detecting showers by radio methods alone, if it proves feasible, is that a radio system is much easier and cheaper to install than a large particle-detecting array. Before the method can be used, it is necessary to find out the mechanism by which the radio emission is generated in showers. Also it would seem advisable to obtain some correlation between data from particle-detecting arrays and radio detectors before hoping to obtain shower data from radio detectors alone.

Another property of cosmic rays which is of considerable astrophysical interest is the primary composition, and how it varies with primary energy. From a knowledge of the primary composition, conclusions can be drawn about the sources, acceleration mechanisms, and the nature of the motion of cosmic rays in interstellar space. Of particular interest is the way in which the composition changes with primary energy at energies of above 10^{17}eV.

Various methods have been suggested for attempting to determine the charge of an incident primary nucleus. Wolfendale has pointed out that changes in composition should be reflected in the fraction of muons observed in showers (Adcock et al., 1967). The number of muons in a proton-initiated shower is known to vary as Ep^{a}, where Ep is the primary energy and a is between 0.7 and 0.8. For a heavy primary with A nucleons, the number of muons produced should be proportional to $A(\frac{Ep}{A})^{a}$ which gives an apparently higher value for a. Thus a plot of a against Ep should indicate any change in composition with primary energy.

Vernov and Khristiansen (1967) suggest that the simultaneous recording of the Cerenkov light and the muon flux from showers, should indicate the nature of the primary composition. The total Cerenkov light from a shower is believed to be closely proportional to Ep, whereas the number of muons depends on both E_p and on A, the mass number of the primary.

Another method is that suggested by Orford and Turver (1968). The use of a muon detector in conjunction with the Haverah Park array, revealed that certain events gave muons with high transverse momentum at large distances from the core. They calculate that these can only be explained on the basis that they are produced in the interaction of a heavy primary nucleus, and that this is therefore a method of identifying heavy primaries.

It is expected that the study of the radio emission from showers should yield information on the charges of the primary nuclei. The amplitude and time profile of the radio pulse are expected to depend upon the longitudinal development of the shower, and in particular upon the height of the first interaction, which is essentially determined by the charge of the primary.

The radio experiment at Haverah Park was therefore set up with the main aims of discovering the nature of the radiation mechanism, and of establishing a functional relationship between the radio emission and the gross features of showers. From this it was hoped that a decision could be made as to the feasibility of using the radio method for the detection of very high energy showers, and the charges of the primary particles initiating them.

CHAPTER TWO

THEORIES OF RADIO EMISSION FROM EXTENSIVE AIR SHOWERS

2.1 Introduction.

In chapter 1 it was indicated that information about the energy and charge of primary cosmic ray nuclei might be obtained from the observation of radio emission from showers. Several theoreticians have set up models with the aim of determining the nature of the radio emission expected, and their work is summarised in this chapter.

As early as 1941, Blackett and Lovell (1941) suggested the possibility of the radar detection of the ionisation produced by a shower. However, owing to the short time for electron attachment in air at normal pressures, the reflecting power is much smaller than that estimated by Blackett and Lovell. Nevertheless, the idea has recently been revived by Suga, and an attempt is being made to detect very large showers of about 10^{20} eV by this method, using low frequency, high power radar pulses. (Matano et al., 1967).

Some time elapsed after the original proposal before Jelley (1958) suggested the possibility of the passive detection of the microwave Cerenkov radiation from showers. He estimated that to obtain an adequate sensitivity with this method, a parabolic aerial of diameter about 3 metres would be required. In a more detailed analysis, Lerche (1965) calculated that with a wavelength of 3 cms., and a 10% bandwidth, for a shower of size 10^6 particles, a receiver of diameter at least 80 metres would be required to give a signal to noise ratio of 3 to 1. However, in either case the beamwidth of the aerial would only be a few minutes of arc, and the counting rate would be very low.

At longer wavelengths in the radio region, it seemed that the intensity would be still further reduced, since the Cerenkov radiation is proportional to frequency. However, the wavelength then becomes comparable with the dimensions of the shower, and this led Askaryan (1962, 1965) to suggest that the normal Cerenkov radiation might be enhanced. This prompted the start of experimental work in the field.

2.2 The Charge Excess Model of Askaryan.

In his first paper, Askaryan pointed out that a fractional excess of negative charge in a shower would, at these longer wavelengths, give rise to a considerable enhancement of the normal Cerenkov radiation, because of mutual coherence. He suggested that such an excess of electrons over positrons would exist in an electron-photon cascade, mainly due to the annihilation of positrons in flight. There would also be contributions to this excess from delta-rays and from Compton electrons, though these would be of lower energy and less important.

Askaryan ignored the contributions from delta-rays and Compton electrons: the fractional excess of electrons over positrons is then given by the cross-section for positron annihilation, divided by the cross-section for bremsstrahlung radiation. For air showers, Askaryan took a value of 100 MeV for the mean particle energy at shower maximum, which leads to an excess ε of the order of 7%. For a shower of N particles, the rate of production of the mutually coherent Cerenkov radiation will depend on $(\varepsilon N)^2$. For N particles radiating incoherently, this factor would be replaced by N. Thus the enhancement factor due to mutual coherence is $\varepsilon^2 N$. A typical value at Haverah Park for N, the number of particles at shower maximum, is 5.10^7, and this gives an enhancement factor of about 2.5×10^5. Thus by choosing a suitable frequency for the detection system, the energy flux increases by a factor of about 10^5.

The intensity of this enhanced Cerenkov radiation should increase with increasing frequency, as long as the conditions for mutual coherence hold. For full coherence these conditions, as elaborated by Jelley (1965), are:-

(a) The wavelength of the radiation must be much greater than the thickness of the shower front.

(b) The effective lateral spread of the shower must be within one Fresnel zone as seen from the aerial.

(c) The area of the receiving aerial must lie within one Fresnel zone as seen by the shower front.

Askaryan's first paper made no mention of these coherence conditions. However, in a second paper (1965), in order to take into account the lateral extent of the shower, he obtained an interference factor by integrating the retardation of the radio pulse over the cross-sectional area of the shower, and using a value of 30m. for the effective radius of the shower disc, found a maximum frequency for coherence of 60 MHz.. Since this analysis takes no account of the lateral distribution of the shower particles, Askaryan then calculated the frequency dependence of the interference factor using an empirical expression for the lateral distribution. In this case the decrease in the interference factor was less marked and even over-compensated by the normal Cerenkov increase in signal intensity with frequency. However, Askaryan does not consider the effect of the finite shower front thickness. Whatever the radiation mechanism, for full coherence the shower thickness should not exceed one half wavelength. The accepted value for the thickness near the axis is 2m. (e.g. Bassi et al., 1953), so this gives an upper frequency limit of 75 MHz..

It should be mentioned, however, that the characteristic shower dimensions (diameter and thickness) are related to the radiation length (the typical distance travelled by a high-energy electron before it radiates a photon by a scattering process). The radiation length in air is about 37gm.cm.$^{-2}$, but this will obviously give a variable distance depending on the altitude. At sea level the radiation length is about 300m., but at 6km., a typical height of maximum development, the value will be nearer to 600m., and the dimensions of the shower disc may also be doubled. The estimates given above for coherence are therefore optimistic.

2.3 The Theory of Kahn and Lerche.

The Cerenkov radiation described in the previous section arises as a result of the longitudinal motion of the shower particles through the medium. Kahn and Lerche (1966) were the first to show that the transverse motion of the particles would be at least as important. Taking a more fundamental approach to the problem, they considered the properties of the shower as a whole, and its surroundings, and then set up Maxwell's equations to determine the electric field components due to different effects.

A highly idealised model of a shower is used. They consider an annular ring of charge, thin compared with the wavelength of emission, and moving relativistically with velocity greater than the phase velocity of radiation in the medium. The medium is taken to be infinite and with a constant refractive index, and thus the analysis has some similarity with that for Cerenkov radiation.

Kahn and Lerche realised that the systematic separation of the oppositely charged electrons and positrons in the earth's magnetic field would make an important contribution to the radiation due to two effects. A current would be caused by this charge separation, and an electrostatic dipole would be maintained by this current. The excess charge mechanism as suggested by Askaryan was also considered. For distances from the shower axis greater than the annular radius, it was found that the radiation due to the current term dominated, while the dipole term became important near the shower core. These two effects would each give radiation polarised at right angles to both the shower direction and the magnetic field direction. For vertical showers this leads to mainly East-West polariaation, but for inclined showers the polarisation direction depends on the shower arrival direction. This is discussed more fully in section 2.7.

To make the model more realistic, an exponential decay was incorporated into the analysis, representing the decay of the shower from maximum. This did not appreciably change the overall picture, but revealed that the emission angle would generally be larger than the Cerenkov angle, and for a fast decaying shower, independent of the refractive index of the medium. Thus the radiation could not be regarded in any way as Cerenkov radiation, the lateral spread being much more isotropic. However, the intensity of the radiation would be expected to show roughly the same increase with increasing frequency.

The Kahn and Lerche model applies to showers of small zenith angles falling fairly close to the receiving aerial. One should not expect it to apply to showers of large zenith angles, which reach maximum development at greater height and distance, so that the approximation of infinite length is unrealistic. Other criticisms of the model are that it does not consider either the variation of refractive index with height, or the growth of the shower up to maximum development. This may be important in determining the lateral spread of the radiation, and also the frequency spectrum.

However, although the shower model used by Kahn and Lerche is a highly idealised one, the analysis was extremely important, if only for stressing the role played by the geomagnetic field in producing the radio emission.

2.4 The Colgate Model.

Another very different approach to the problem was made by Colgate (1967). As in the Kahn and Lerche model, the radiation is produced as a result of the deflection of the electrons and positrons in the geomagnetic field. Colgate shows that this deflection gives rise to a perturbation of the magnetic field in the form of a forward travelling pulse whose momentum corresponds to that removed by the deflection of the charged particles. If no magnetic deflection occurs, then the momentum of the primary initiating the shower is finally all dissipated by collision losses of the secondaries in the atmosphere and in the ground. However, if the electrons and positrons are separated by the earth's field before giving up their momentum, then one would expect part of this momentum to appear as a disturbance of the field.

The efficiency of conversion of relativistic momentum to radio frequency electromagnetic radiation increases with altitude. Colgate therefore confines his analysis to showers which arrive almost tangential to the earth's surface, and which therefore reach maximum development at high altitudes. In this respect the model is applicable to just the type of shower which does not fit the Kahn and Lerche analysis. In many ways the Colgate model is more realistic, since it takes into account the growth and decay characteristics of the shower, and also the thickness and curvature of the shower front.

The important results which Colgate arrives at are that for this type of shower, the radiation spectrum will show a maximum as low as 2 MHz.. This value is dependent on the disc thickness, and therefore on the atmospheric density, at the position of maximum development. For vertical showers, Colgate finds that the optimum frequency may be close to the 44 MHz. first used by Jelley et al. (1966). The angular spread of the radiation is found to be about 0.2 radian, depending on (front thickness/front radius of curvature). By contrast, Colgate shows that the Kahn and Lerche model predicts an angular spread given by (front thickness/attenuation length)$^{\frac{1}{2}}$ which leads to a value of 0.03 radian (Smith et al. 1965).

2.5 The Theory of Allan.

Another approach to the subject of radio emission from E.A.S. has been made by Allan (1967A), which in some ways is similar to that of Colgate. He sets out to calculate the actual electric field E(t) as a function of time, rather than the magnitude of the Fourier components, as do Kahn and Lerche. He shows that E(t) depends upon the position of the receiving aerial relative to the shower, and also upon the way in which the shower builds up to maximum and then decays.

The method used to calculate the electric field at a given point from the motions of the shower particles, is one suggested by Feynman (1963). For relativistic energies, the electric field is found to be dependent mainly on the angular acceleration of the charge as seen from the point at which the field is required.

The analysis takes the form of a series of steps, commencing with a single charged particle moving along an infinite track, and reaching a model which incorporates most of the important features of a real shower. In the course of the analysis, several interesting points emerge. When considering the longitudinal motion of the shower particles, the radiation due to particles with energies above, or less than the Cerenkov threshold is found to be not greatly different. Thus the Compton electrons, ignored in the Askaryan analysis, may in fact be important in contributing to the enhanced Cerenkov radiation due to the charge excess ε. The scattering of electrons is not found to affect the radiation appreciably, but a considerable enhancement takes place as a result of the transverse deflection of electrons and positrons in the geomagnetic field, and the radio emission is principally associated with this effect.

The radio pulse waveform is expected to consist of an initial sharp pulse not less than 0.01 μsec. in duration, followed by a long tail of low amplitude. The frequency spectrum is expected to be fairly flat up to 20 MHz.. These values are typical but they can be expected to vary depending upon the distance from the shower axis and the zenith angle. Even at large zenith angles, there can be an appreciable high frequency component, though, in agreement with Colgate, the dominant frequency is expected to be less than 10 MHz..

2.6 Charman's Two Models and Other Theories.

Charman has suggested that the earth's electric field may be responsible for radio emission from showers in two different ways. Under normal fine-weather conditions, the electric field is vertical and has typical values of about 100 V/m at sea level and 10 V/m at an altitude of 10 Km.. Under disturbed weather conditions, much higher values may occur, up to 10^4 V/m in thunderstorms: the field may then have considerable horizontal components and may even reverse in sign.

Charman firstly (1967) points out that the shower electrons and positrons will be systematically separated by the electric field. This will result in the formation of a dipole and a transverse current exactly analogous to those caused by charge separation in the earth's magnetic field. However, for this transverse separation to be comparable with that due to the magnetic field, Charman finds that electric fields of about 6.10^3 V/m are required, which only occur during thundery conditions. He also considers the charge separation produced along the direction of the shower motion by the component of the potential gradient parallel to this direction, and finds that the enhancement factor produced over the normal Cerenkov yield is negligible compared with the Askaryan charge excess enhancement factor.

In a second paper (Private communication) Charman suggests that the acceleration of slow ionisation electrons in the electric field may yield observable effects at radio frequencies. A similar model was suggested by R.R. Wilson (1957) some years before the discovery of radio emission from showers. Charman pictures slow ionisation electrons produced in the atmosphere by the passage of a shower, as being fairly rapidly accelerated up to a constant drift velocity before suffering a rapid retardation on capture by an oxygen molecule. As a result the positive accelerations will add up within a time of about 0.03 μsec., while the negative accelerations will be spread over about 1 μsec.. An estimate of the energy of the pulse at 10 MHz due to this mechanism finds it to be comparable with that due to the charge excess model of Askaryan.

The radiation from this mechanism should be polarised in a direction at right angles to, and in the vertical plane containing, the shower axis. No systematic variation with azimuth angle would therefore be expected.

A study of the polarisation properties of radio pulses should indicate how much importance should be attached to this mechanism. However, it is also necessary to take into account the local climatic conditions which can affect the earth's electric field.

Another theory which deserves some attention is that of Rosenthal and Filchenkov (1966). In searching for a mechanism which gives radiation more isotropic than the Askaryan mechanism they consider the bremsstrahlung from delta-rays resulting from ionisation by the shower electrons. They estimate that detectable pulses should be produced by showers of primary energy greater than 10^{17}eV.

However, Jelley (1967) points out some deficiencies in the theory. He suggests that incorrect values for cross-sections were used in the calculation, and also that since the path length of the delta-rays is much smaller than the radiation wavelength, the radiation fields from the beginning and end of each track will tend to cancel. Jelley also considers the possibility of direct bremsstrahlung by the shower particles themselves, and finds that the expected radiation is negligible. He concludes that both these bremsstrahlung mechanisms will yield incoherent radiation which will be negligible compared with the other mechanisms proposed.

2.7 Predictions from the Theories.

Various features of the radio emission predicted by the different theories can be compared: the polarisation, lateral spread and frequency dependence.

The polarisation of the radiation should indicate which type of mechanism is responsible. For the Askaryan excess charge mechanism, the radiation should be radially polarised, as for all Cerenkov radiation. Thus an aerial which is sensitive only to the electric field component in a particular direction should show a clustering of showers at positions along the aerial axis. For instance, an aerial sensitive to the East-West component would receive the maximum signal from showers falling to the East and West of the aerial.

Both the Charman mechanisms which depend on the earth's electric field will give the same polarisation. Although the radiation is isotropic with azimuth, an aerial of particular orientation will not record the same signal from showers from any direction. An aerial orientated East-West will record more from showers arriving from the East or West, rather than from the North or South. On the other hand, unpolarised radiation, although again isotropic with azimuth, should give a larger pulse on an East-West orientated aerial, for showers arriving from the North or South.

The Kahn and Lerche, Colgate, and Allan theories, all suggest that the geomagnetic field is mainly responsible for the radio emission, and this radiation should be polarised at right angles to both the shower axis and the magnetic field. Fig.2.1 shows for which shower arrival directions the East-West component is greater than the North-South, and vice versa. It will be noticed that on average the East-West component is more likely to be the larger, but to state the radiation is predominantly polarised East-West is not true.

The frequency dependence of the radiation should also help to distinguish between the different models. Both the Askaryan, and the Kahn and Lerche theories, predict a Cerenkov-type of dependence: i.e. the intensity increases with increasing frequency up to an expected maximum due to the onset of

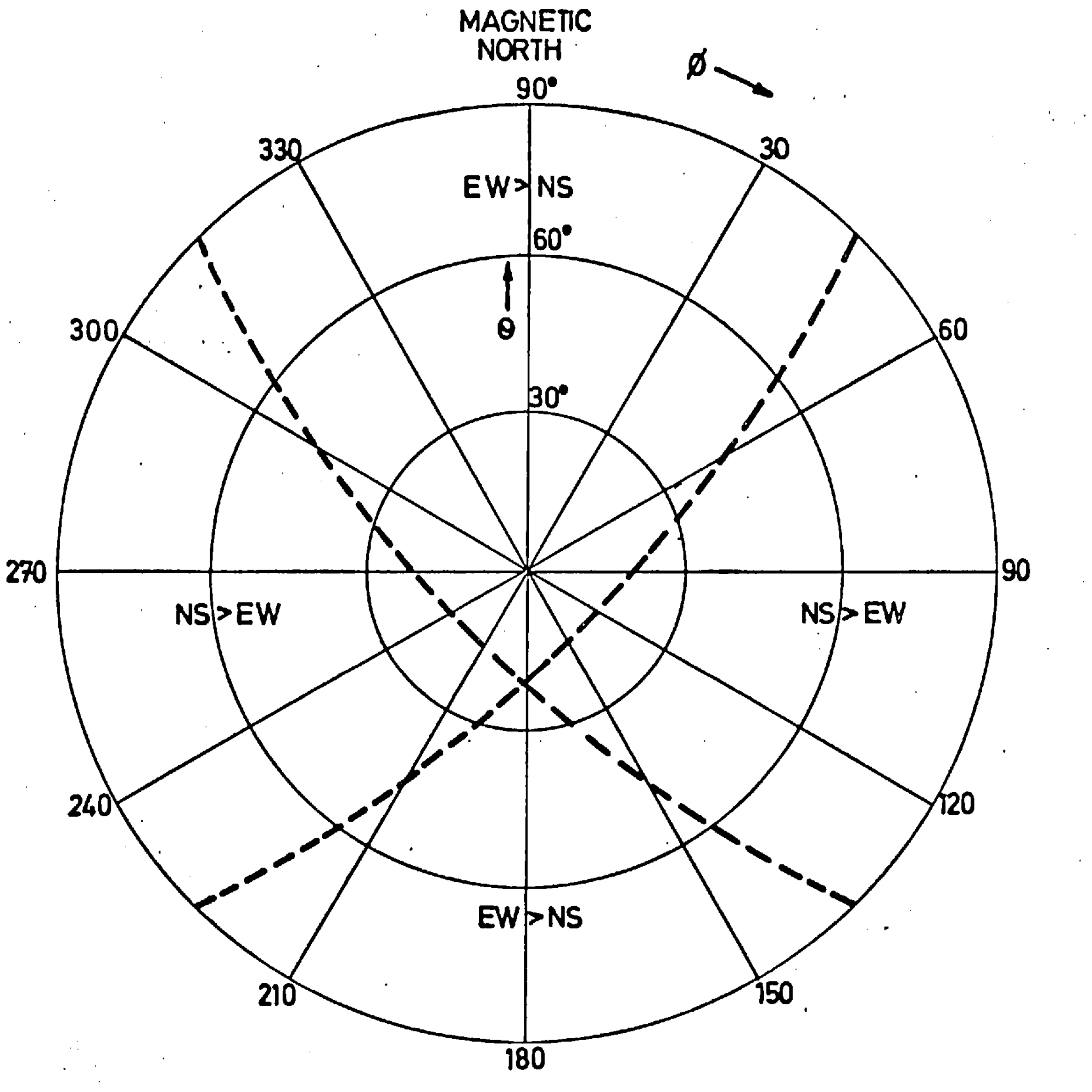


FIG. 2.1 TO ILLUSTRATE WHICH POLARISATION COMPONENT IS EXPECTED TO BE LARGER UNDER THE GEOMAGNETIC CHARGE SEPARATION MODEL FOR ANY ARRIVAL DIRECTION.

decoherence. On the other hand, the theories of Colgate and Allan predict a maximum intensity at frequencies of the order of 10 MHz., with only residual components of the pulse at higher frequencies.

Whereas the Kahn and Lerche theory predicts an angular spread of the radiation of about 0.03 radian, the value worked out by Colgate, who takes account of the shower front curvature, is about 0.2 radian. Allan makes the important suggestion that as one moves away from the shower axis, the pulse observed becomes flatter and the optimum frequency becomes lower.

Most of the theories predict that roughly the same electric field strength will be observed, within an order of magnitude. Allan (1967 B) has shown that the calculation of this field for an Askaryan type of mechanism is relatively straightforward. He suggests that the frequency spectrum will be fairly flat up to an optimum frequency of about 20 MHz. where decoherence sets in. At any frequency below this, the electric field is found to be given approximately by:

$$E = 10^{-12} N \text{ volts/metre/MHz.}$$

Thus if the receiver bandwidth is 1 MHz., and the shower contains 10^7 coherently radiating particles, the field strength is

$$E = 10 \,\mu\text{volts/metre.}$$

A short mention should be made here of the expected contribution of muons to the radio emission from showers: none of the theories considers this in detail, although Allan (1967A) does point out that the mean energy of muons in showers is close to the Cerenkov threshold. About 10% of all shower particles are muons. The ratio of positive to negative muons is close to unity, from which we can conclude that the coherent Cerenkov radiation from muons will be negligible compared with that from electrons.

However, the deflection of muons in the geomagnetic field will be greater than for electrons since their path lengths are longer, and the effects of scattering are less. On the other hand, the lateral spread of the muons is much greater than that of the electrons. In a shower of size 10^7 particles, about 50% of the electrons lie within a radius of 80m. from the shower axis, whereas the corresponding radius for muons is 360m. (Greisen, 1960). This suggests that the number of muons which will radiate coherently will be very small, and that it is probably reasonable to ignore the contribution to the radio emission from muons.

CHAPTER THREE

REVIEW OF OTHER EXPERIMENTAL WORK

3.1 Introduction.

The pioneer experiment in the detection of radio emission associated with E.A.S. was performed at Jodrell Bank by Dr. Jelley and his colleagues during the latter part of 1964. The existence of the phenomenon was definitely established, and many other workers were encouraged to make further investigations. There have been three main objectives in the succeeding experiments: to find out how the radio energy varies with frequency, and with distance from the core, (lateral distribution), and most important, to measure the polarisation of the radiation and hence deduce the radiation mechanism.

The various experiments can be assigned into three categories: (a) those in which attempts were made to trigger on radio pulses alone, (b) those in which the radio system was triggered by a simple particle array, or optical Cerenkov detector, and (c) those in which an extensive particle array was available, not only to provide a trigger pulse, but also to give detailed information on each shower.

Experiments of type (a) tend to be plagued with severe pick-up problems, and it is arguable that one should not attempt to detect showers in this way, before correlating radio data with particle detector information. Experiments of type (b) do ensure that events recorded are associated with E.A.S., but it seems that most will be learned about the phenomenon from experiments of type (c) in which polarisation and other measurements can be made on individual showers.

In this chapter a review is presented of all the experimental work performed by the various groups. It has been found more convenient to consider the development of the work at each centre in turn, rather than attempt to present the experiments in chronological order.

3.2 Various Experiments at Jodrell Bank.

Most of these experiments are described by Jelley et al. (1966) and by Porter (1967).

In the very first experiment, a small geiger array was used to trigger the oscilloscope which displayed the output from a 44 MHz. receiver, of bandwidth 2.8 MHz.. The aerial used was a broadband array, $6\lambda \times 6\lambda$, polarised East-West, with maximum response at the zenith, and with a 3db beamwidth of 10^{o}.

Out of a total of 4500 showers recorded, 11 showers gave a radio pulse at the expected time. In addition, histograms of the integral amplitude, and frequency of maximum fluctuation, showed statistically significant peaks at the expected time. Although hodoscope information was available, this was unreliable, but the shower size was known to be between 10^5 and 10^6 particles at sea level.

During the early months of 1965 the geiger array was replaced by an optical Cerenkov detector, whose response was also directed towards the zenith. Out of about 10^4 events, no significantly correlated pulses were observed, and the conclusion was that the threshold primary energy of the light receiver was too low. The null result was consistent with a primary energy threshold of above 10^{16}eV for the production of a detectable radio pulse.

In a further experiment, radio observations were made at 150 MHz., where the wavelength should be less than the shower thickness. During six weeks of operation, 5 large pulses were observed at 44 MHz., but none at 150 MHz. which was consistent with a shower thickness of not less than 1m. causing decoherence. However, the receiver used may have been in faulty adjustment (Private communication R.A. Porter), and this result should therefore probably be disregarded.

Following this, one half of the 44 MHz. aerial array was rotated to be orientated North-South, so that polarisation measurements could be made. Fifty days of observations revealed no significant difference between the pulses from the two arrays. However, it was decided that the geiger array selected showers whose cores fell very close to the aerial array and that these would not be suitable for distinguishing between the geomagnetic and excess charge mechanisms.

In the mid-winter months of 1965-66 an attempt was made to correlate optical Cerenkov and radio frequency impulses from showers at high zenith angles. The experiment was a collaborative effort between the groups from Jodrell Bank and Harwell. The radio channel consisted of a rhombic aerial of centre frequency 48.5 MHz. whose main lobe was at an angle of about 12.5° to the horizon. The amplified output from this aerial was photographed every time a coincident pulse was received from a pair of optical Cerenkov detectors whose field of view was similar to that of the rhombic aerial.

Although the conditions in Britain are obviously far from ideal for this type of experiment, some 500 events were recorded during 52 hours of clear sky conditions. Two methods of analysis were adopted. In the first, each trace was divided into 48 channels, and the mean pulse height in each integrated over all the events. A strong peak occurred at the time expected for shower-associated pulses. In the second method, the amplitude and position of every pulse greater than 1.5 times any other pulse on the same trace were recorded. Again an obvious cluster around the expected position was observed. From the recorded rate of optical events, and assuming the height of production of the Cerenkov radiation, an estimate of 10^{16}eV for the threshold energy was obtained. Since about 2% of events gave detectable radio pulses, the threshold primary energy for detectable radio pulse production was assumed to be about 10^{17}eV.

The most important experiment carried out at Jodrell Bank was a North-South asymmetry experiment, designed to observe the suggested charge separation mechanism of Kahn and Lerche. (Porter R.A. et al. 1967). The aerials used were two 90° corner reflectors, back to back, with beamwidths of 45°, and directed at 45° to the zenith. An extended array of geiger counters, forming altogether seven equilateral triangles along an East-West line 175 m. long, detected the showers, a coincidence being registered whenever the three counters of any one triangle were simultaneously struck. The estimated threshold energy was 5.10^{15}eV.

Assuming the shower arrival direction to vary as $(\cos\theta)^7$, and the radio pulses to arise wholly from geomagnetic charge separation, the expected North to South ratio was calculated to be 7:1. In fact no significant difference was observed between the North and South channels, and the conclusion drawn was that at 44 MHz., the effects of charge separation did not dominate as the Kahn and Lerche theory suggested.

Recently an attempt has been made by Jodrell Bank workers to trigger on radio pulses alone at Hafren Forest, a quiet site in Mid-Wales. The system consists of four vertical unipoles centered on 50 MHz. with bandwidth 20 MHz. and operated in 4-fold coincidence. No news of any results has yet been published.

3.3 Experiments by the Dublin Group.

A group from University College, Dublin, has been active in this field, and apart from collaborating with the Jodrell Bank group in the original experiment, has itself performed several interesting experiments. A sheltered valley site with relatively low noise background has made wide-band operation feasible.

In the first experiment, (Porter N.A. et al. 1965), the video output from a helical aerial, centered on 70 MHz. and with bandwidth 20 MHz., was triggered by a plastic Cerenkov particle detector situated 70m. away, which was adjusted to give about 20 events per hour, many of which were probably due to local showers or muon-induced events. Out of 12,000 traces recorded, five pulses at least five times the average noise fluctuation were observed at the expected time. In a more detailed analysis a short interval of 250 nsecs. about the expected position was compared with an arbitrary interval of similar length: 23 pulses, larger than any in the comparison channels, and greater than twice the background noise, could then be distinguished. Pulses associated with E.A.S. had thus been observed.

Following this, a correlation between optical and radio emission from showers at large zenith angles was established. (McBreen et al. 1966). The results were compatible with those from the similar experiment at Jodrell Bank : probably due to the higher working frequency (75 MHz., bandwidth 20 MHz.), no large pulses were observed, but the familiar technique of recording the amplitude and position of the highest peak in each trace and integrating for a number of channels, revealed statistically significant peaks at the expected position.

The Dublin group have also carried out a long-distance coincidence experiment, triggering on radio pulses alone.(Fegan et al. 1967). Apparently the main source of interference pulses below 100 MHz. is vehicle ignition, and to eliminate false coincidences due to this the receivers have to be separated by several kms., and so three sites at relative spacings of 10 kms., 12 kms., and 20 kms. were selected. In order to reduce the effective separation of the detectors, it was necessary to work at large zenith angles, which also had the advantage that the lateral spread of the coherent signal would be increased. However, one disadvantage of operation near the horizon is that it means detecting the vertical polarisation component, since, (unless the antenna is raised well above the ground), the ground image cancels the antenna pattern at the horizon for the horizontal polarisation component. As was mentioned in chapter 2, under the charge separation mechanism, the vertically polarised component is always smaller than the North-South component by a factor of about 0.4 at British latitudes, and for most arrival directions is also much smaller than the East-West component.

Another difficulty encountered was that of correlating events at the three stations, since it was obviously not feasible to connect them by underground cable. Initially a clock was photographed for each event, but this was later improved upon by photographing at each site the audio waveform from a commercial radio station, followed by comparing the three sets of waveforms, giving an effective resolving time of 0.05 sec.

Twenty-three probable coincidences were recorded for the pair of stations at 10 kms. separation, but none for the other two pairs. A variety of antennae, with different frequencies and bandwidths, were employed at the three sites, so perhaps comparisons are not very meaningful. The estimated threshold energy for showers giving coincidences was about 10^{18}eV. It seems that purely radio selection of showers may be feasible under these conditions, but not much can be learned this way either about the radiation mechanism or about the showers themselves.

The latest experiment to be reported from Dublin is an investigation at a very high frequency, to test the theoretical expectation that the radio power falls off above about 75 MHz. due to decoherence. (Fegan and Slevin, 1968). A master radio pulse from two 44 MHz. receivers was used to investigate the outputs from both a 520 MHz. receiver, bandwidth 2 MHz., and a scintillation detector. A coincidence between the master radio pulse and a particle in the scintillation detector was assumed to be due to a shower.

Sixty-three analysable events were recorded, of which eleven gave pulses at the expected time at least 1.5 times the average noise fluctuation. Subsidiary experiments were carried out and eliminated the possibility of the events being due to pick-up, or to random coincidences. Thus it seems that evidence has definitely been established for ultra-high radio frequency emission from E.A.S., whereas most of the theoreticians predict little radio power above 100 MHz.. A value of 2.0 ± 0.6 for the exponent of the integral pulse height spectrum was measured, (even though the amplitudes only varied from 1.5 to 3 times the noise fluctuation on each trace), which, since a square law detector was used, implied incoherent radiation. Thus the effect postulated by Rosenthal and Filchenkov, that of radio bremsstrahlung from delta-ray electrons, may be responsible, while also possible, but not worked out in detail, are isotropic recombination radiation from atmospheric atoms and molecules, or radiative Coulomb scattering of low energy shower electrons.

3. 4 The Harwell Experiment.

Members of the Harwell group have participated in many of the experiments at Jodrell Bank. Recently they have set up an independent experiment for detecting E.A.S. at low elevations by wholly radio methods. (Charman et al. 1967). Two sites, at Grove and Harwell, have been selected. They are 9 kms. apart which should make local interference negligible, and the arrangement should be suitable for detecting showers with zenith angle about 80°, and incident along the Harwell-Grove bearing.

At each site the main apparatus consists of a pair of corner reflectors about 100m. apart at frequency 55 MHz. and bandwidth 30 MHz.. The main beams are along the Harwell-Grove bearing, and a coincidence unit for each pair gives an effective beamwidth of about 30°. The two sites are linked by pulse radio giving a time association of about 1 μsec. Also available at

Harwell are some tanks of liquid scintillator, a large Cerenkov night sky detector, and low frequency equipment at 15 MHz..

Preliminary results from the Harwell site only are reported. A large number of coincident pulses are believed to be due to distant electrical storms. Of the remaining pulses it is believed that some are associated with E.A.S., and to distinguish between these and man-made pulses, it is intended to use the scintillators to provide information on the presence of shower particles.

3.5 The Experiments at Kharkov and Moscow.

The first E.A.S. radio experiment in the U.S.S.R. took place at the Kharkov State University. (Borshkovsky et al. 1966). Two separate arrays, of six dipoles each, at frequency 20 MHz. and bandwidth 1.4 MHz., one orientated North-South, and the other East-West, were each triggered by a separate array of three groups of geiger counters. Visual recording was not used. and an 'event' consisted of a coincidence between pulses from the three appropriate geiger counters and a pulse from the aerial system. The discrimination level in the radio channel was not mentioned.

Four four-fold coincidences were reported during 60 hours recording on the East-West channel, and one during 38 hours recording on the North-South channel. This was claimed as distinct evidence for the geomagnetic charge separation mechanism. However, the numbers involved are very small, and also, as was pointed out at the end of chapter 2, charge separation does not necessarily imply East-West polarisation for a particular shower, even though on average more showers will give radiation polarised in this direction than North-South Before drawing conclusions from such a small number of showers, one must have detailed information about the showers from a particle array.

The second experiment to be reported was from the Moscow State University where an extensive particle detecting system of geiger counters and scintillators was available. (Vernov et al. 1967). Two half-wave dipoles, both orientated East-West, were erected at distances of 60m. and 140m. from the centre of the particle array. The resonant frequency for both was 30.2 MHz. and the bandwidths, including amplifiers, were 3.7 MHz. and 2.2 MHz. respectively.

The oscilloscopes displaying the outputs from the dipoles were triggered by a coincidence pulse from the particle detecting system, and for 1100 hours of operation, an incomplete analysis revealed 17 pulses during 700 hours, with power flux greater than 25 times cosmic noise: there were also 27 pulses with power greater than 5 times cosmic noise, during the other 400 hours.

Good correlation was observed between the radio power and the square of the total number of muons in the shower. Since Nμ was taken to be a good measure of the primary energy

Ep, it was deduced that the radio power was approximately proportional to Ep^2.

The lateral distribution function exponent for the radio power was calculated from data on the two antennae. A mean value of -1.09 was obtained, but this was later stated to be incorrect due to errors in the calibration of one of the antennae.

The experimental set-up was later extended to include altogether nine dipoles at various locations in the particle array. Of these, seven were orientated East-West, while there was one pair of crossed dipoles with directions both East-West and North-South. Thus it was hoped to obtain information on the polarisation of the radiation as well as the lateral distribution function. A first report of the experiment gave rather indecisive results as far as polarisation was concerned, but this was apparently due to some error in the calculation of the response of the half-wave dipoles. A second report was published (Vernov et al. 1968) together with a full explanation of the calculation of the polar diagram (Abrosimov et al. 1968); this will be taken as correct.

The results presented included ten events for which a pulse was observed on at least one of the two crossed dipoles. These events were analysed in terms of the two models, geomagnetic charge separation and charge excess. The conclusions were that in nine of the events the ratio observed 'did not contradict' the geomagnetic theory. For the charge excess mechanism, only three 'did not contradict', and these were all showers in which the angle between the shower axis and the geomagnetic field was less than 30°. One or other of the mechanisms was considered to be invalid if the measured power ratio differed from the calculated value by more than 2.5 times the standard deviation. While the measurements do not agree in any way exactly with the charge separation model, this is found to be the most likely mechanism at 30 MHz..

In order to obtain information on the lateral distribution function, five individual showers, for which pulses were observed on at least three aerials, were used. Graphs of radio power against distance from the shower core were plotted assuming that the geomagnetic mechanism was dominant, and also that the radio power varied as R^{-n}. The values obtained for n varied from 1.3 to 3.2 with a mean of 1.9.

Good correlation was also obtained between the radio power and N_μ^2, (but not with Ne^2, where Ne is the total number of electrons in the shower), after normalizing to 150m. and assuming a geomagnetic mechanism. It is predicted in the paper that it should be possible to observe radio emission from large showers at distances of the order of kilometres, even though the observations so far extend only as far as 400m.. With this in mind an aerial has now been erected about 1.5 km. from the centre of the array, but no news of results is yet available.

3.6 Observations from Mount Chacaltaya.

When the workers at B.A.S.J.E. (altitude 5200m) began looking for radio emission from air showers, they were understandably sceptical of obtaining useful results, as working at high altitudes has two disadvantages: there is a shorter shower path for producing radiation, and Cerenkov effects are reduced by the lower air density. However, Chacaltaya is favourably situated in being very close to the geomagnetic equator (5° South) so that charge separation in the earth's field is maximum for vertical showers: also there are few sources of man-made interference in Bolivia so that broadband reception is possible at all times.

Observations were made with various antennae of different bandwidth ranges (Barker et al. 1967). Plots were made of the arrival directions of showers with which a radio pulse was observed, and good correlation was obtained with the antenna pattern for each aerial system, showing that the pulses were definitely an effect of the showers. A comparison of the rates of detection of pulses with the different antennae revealed that for the two whose bandwidth extended down to 40 MHz., rates of 0.06 and 0.08 per hour were recorded, while for one whose bandwidth extended down to only 50 MHz., the rate was only 0.01 per hour. Thus useful evidence was obtained for the variation of the radio emission with frequency. A systematic experiment is planned to explore this more fully.

3.7 The First Experiment at Calgary.

An important experiment, as far as the polarisation question is concerned, is reported from the University of

Calgary. (Prescott et al. 1967). The actual experiment took place at the Radio Observatory near Penticton, where use was made of a $4\lambda \times 4\lambda$ array of wide-band, full-wave dipoles, polarised East-West, centered on frequency 22.25 MHz., and with bandwidth, including receiver, of 4 MHz.. A phasing network allowed the use of the single antenna system to make simultaneous measurements with antenna lobes directed 30° N. and 30° S. of the zenith. Assuming a fixed shower size, and a $(\cos\theta)^7$ zenith angle dependence of showers, it was calculated that on average, the North facing antenna should be favoured by a factor of three over the South facing, for radio emission resulting from charge separation in the earth's magnetic field.

A coincidence between two plastic scintillators 30m. apart, each set at a discrimination level of 300 particles m^{-2}, was used to trigger the dual beam oscilloscope on which the detected outputs were displayed, giving a lower limit to the shower size of about 2.10^6, and a most probable value of 8.10^6.

The output from the North channel was on average about two times that from the South channel, thus suggesting that while the effect of the geomagnetic field is obviously important, it is not so completely dominant over other effects, such as the charge excess, as most theories have predicted.

3.8 The First Experiment at Haverah Park.

The frequency chosen for the first radio experiment at Haverah Park was 60 MHz. (Allan and Jones, 1966; Jones 1967).

Some details of the particle detecting array are given in the next chapter. The antenna used was a broadband array of eight full-wave dipoles, with effective area 2 λ x 2 λ. The signal was amplified by a preamplifier, and then by a main amplifier including a detector stage. Before displaying the output on an oscilloscope, in order to allow for the delay in the generating of the master trigger pulse from the particle detecting array, the signal was delayed by a 7.1 usec. length of Hackenthal HH 1500A delay cable, whose poor frequency response, however, reduced the effective bandwidth of the system from 6 MHz. to 2 MHz.. Although this delay cable was later replaced by lengths of UR67, no useful results were obtained with the improved apparatus.

During 390 hours of operation, about 600 showers were recorded, from which a radio pulse was observed in 29 events. Correlation was sought between the presence of a radio pulse and some parameter of the shower. The majority of radio showers fell less than 350m. from the aerial, and there was also a preference for showers of size above 10^7 particles. Perhaps the most significant result was that the fractions of radio showers with zenith angle greater than and less than 30° were more or less equal. Since the antenna response had a null at 30° and a side lobe beyond this of maximum gain only 1/5 of the value of the main lobe at the zenith, this suggests that the number of radio pulses increased with increasing zenith angle. An analysis of the radio showers with respect to the azimuth angle, showed that showers from the South quadrant had an average zenith angle of 48°, compared with 29° for the North quadrant. This was the kind of variation expected for geomagnetically-induced radio pulses, but the number of showers in each group was very small, making any firm predictions dangerous. Jones also observes that there is a grouping of the showers to the East and West of the aerial, possibly indicating some degree of radial polarisation.

An integral plot of the number of pulses against pulse amplitude gave an exponent of -3 ± 0.8, which was consistent with the radiation being partially coherent.

3.9 Comparison of Experimental Results

The experiments described above have been carried out at various frequencies, mainly in the range 20 MHz. to 100 MHz.. It is significant that at all these frequencies, it was possible to observe radio emission from E.A.S., though more evidence about its polarisation and other features was available from the experiments at the lower frequencies. The Jodrell Bank experiment failed to detect any radiation at 150 MHz., but as was indicated, this result may not be reliable. On the other hand, the Dublin group have observed radio pulses at 520 MHz., a very surprising result.

From several of the experiments, deductions concerning the radiation mechanism have been made, and they are here compared in order of decreasing frequency. The 60 MHz. Haverah Park experiment with a single East-West orientated antenna showed some weak evidence for both the geomagnetic charge separation, and the excess charge mechanisms. Two Jodrell Bank experiments at 44 MHz. designed to observe the charge separation mechanism, both gave inconclusive results. The 30 MHz. experiment at Moscow, with crossed dipoles, favoured the charge separation model, rather than the charge excess, in the majority of showers. In the 22 MHz. Calgary experiment, the charge separation effect was certainly found to be present, but was evidently not the only cause of the radiation. In the 20 MHz. experiment at Kharkov, the slight statistics were in favour of geomagnetically polarised radiation. The overall picture is that at the lower frequencies, geomagnetic charge separation seems to be the dominant mechanism, but at the higher frequencies, the mechanism is not clear.

Only at Moscow were results on the lateral distribution of the radiation available. These will be compared in the concluding chapter with the results from the present Haverah Park experiment.

Other comparisons of the experimental results are very difficult. It would be extremely useful to be able to compare the rates of detection of radio pulses in the various experiments at different frequencies. Unfortunately, this is made almost impossible by the variety of antennae employed, with different bandwidths and angular sensitivities, and by the different particle-detecting systems used to provide the trigger pulses.

CHAPTER FOUR

THE HAVERAH PARK EXPERIMENTS AT 32 MHz. AND 44 MHz.

4.1 Introduction : Choice of Frequency.

In the original experiment at Haverah Park, described in the previous chapter, receiving equipment centered on 60 MHz. was used. This frequency was selected after considering several factors. The pioneer experiment at Jodrell Bank had shown that pulses were observable at 44 MHz.. If the radiation was indeed Cerenkov in character, (Askaryan's ideas were still important at that time), then the radio power, and also the rate of detection of events, would be expected to increase with increasing frequency. Also the galactic noise background is known to decrease with increasing frequency. On the other hand, the finite shower front thickness, usually taken to be about 2m., would cause decoherence above a maximum frequency of about 75 MHz.. A search with rather insensitive equipment revealed that 24-hour operation should have been possible using a centre frequency of 60 MHz. with a bandwidth of up to 10 MHz.. However this depended on filtering out a B.B.C. television signal at 56.75 MHz., which later proved to be impracticable, and operation was only feasible for 8 hours per day.

At first sight, the results from the 60 MHz. work were not especially encouraging. Pulses were observed with only 5% of all showers, and the pulses themselves were never larger than a few times the galactic background noise. On the other hand, 50% of the pulses had come from showers with zenith angle greater than 30^{o}, whereas the aerial polar diagram showed a null at 30^{o}, and only a small side lobe beyond this. This suggested that more pulses should be observed with an aerial whose polar diagram did not fall off so quickly from the zenith. The ideal aerial would be one with an angular sensitivity isotropic with both zenith and azimuth directions.

Accordingly, the design and construction of a new detecting system were undertaken. The 60 MHz. experiment had not provided any information on the polarisation of the pulses observed. The lateral distribution of the radio emission was another property of interest, and so the system planned was the three 'boxing-ring' sites, described in detail in section 4.3.

Initially it was decided to continue recording at 60 MHz.. During the time that the new apparatus was being set up, however, theoretical suggestions indicated that lower frequencies would be more important in the radio emission from showers. (Colgate 1967, Allan 1967A). Also the results from Moscow, in which a considerable number of showers gave pulses at 30 MHz., convinced us that the time lost in changing the frequency of our equipment would be more than compensated by the increased detecting rate. Below 30 MHz., man-made interference makes recording impossible, but a scan with an audio-receiver revealed minimum interference around 32 MHz.. However, when a new system was set up at this frequency, the background noise was found to be in fact many times that expected for the galactic emission, and also it fluctuated wildly. It was evidently hopeless to attempt to record pulses above this noise, and so the frequency of two channels was changed to 44 MHz., the choice in the first experiment at Jodrell Bank. It was realised that recording would only be possible for eight hours during the night, due to B.B.C. television interference during the day, but at least the night background seemed reasonably quiet and uniform. Since recording at 30 MHz. had evidently been possible at Moscow, a 32 MHz. channel was retained in order to study the noise problem.

4.2 The Haverah Park Particle Detector Array.

The present experiment was carried out at the site of the Haverah Park E.A.S. Array (Tennent 1967). Before going on to give the details of the radio receiving equipment, the main features of the array will be described. A plan of the array is given in fig. 4.1, and also indicated are the aerial sites eventually chosen (see section 4.3). The main array detectors are arranged in a Y-shape, the outer detectors being 500m. from the central detector. This simple layout has the advantage that, for showers in which the response in the central detector is the largest, the collecting area is well defined and is the triangle in fig. 4.1. In each hut are situated water Cerenkov tanks, of total area 34m.^{2}, and depth 120 cms..

The array triggers whenever the central detector and two of the outer detectors, each record, in coincidence, a pulse

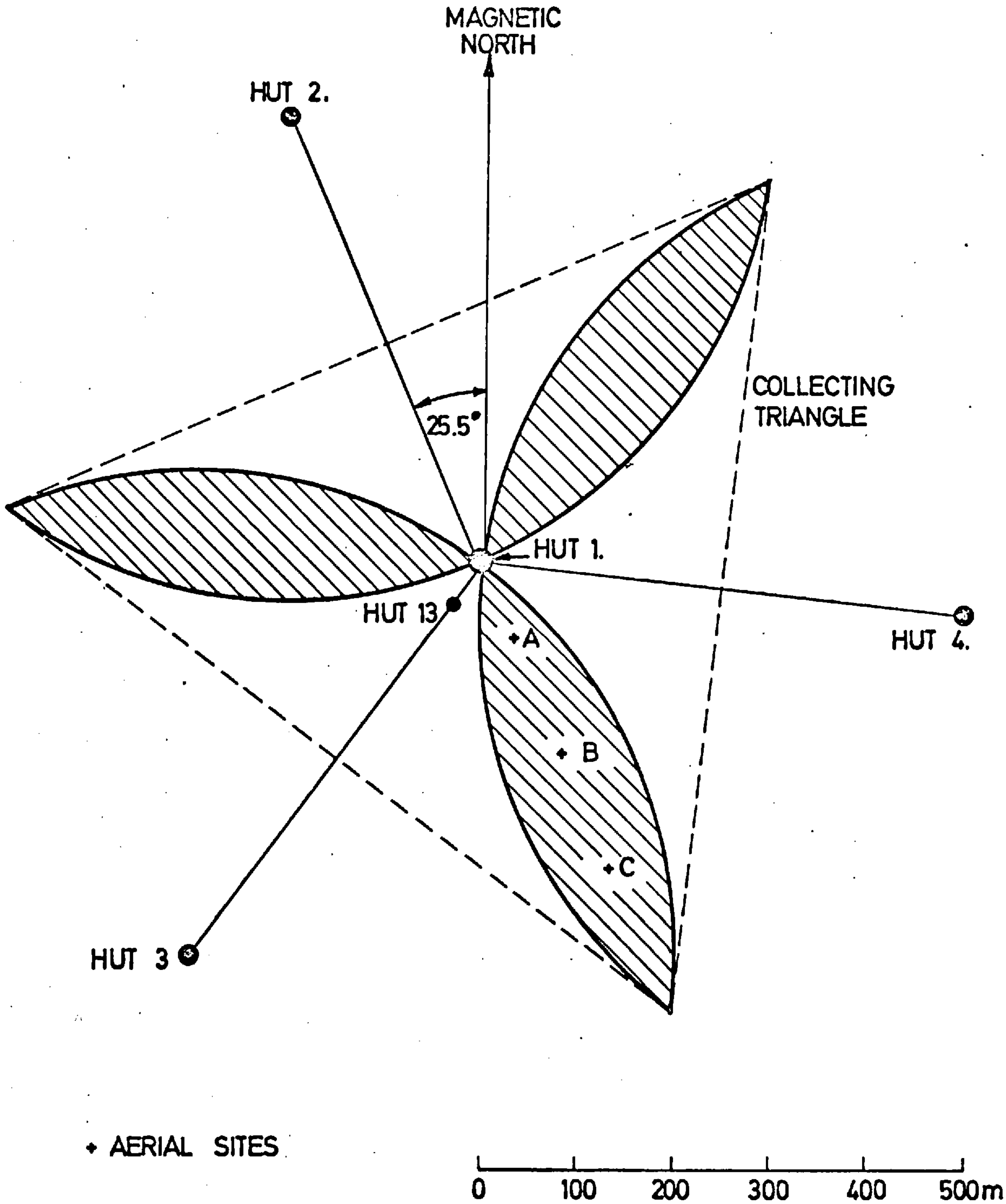


FIG. 4.1 THE HAVERAH PARK MAIN ARRAY.

produced by an energy loss in the detector of not less than 2.2 GeV (equivalent to the passage of about 10 relativistic muons). A trigger pulse is available for subsidiary experiments, such as the radio experiment, whose observations can thus be correlated with the main array data. About 40 events are recorded per day, and they are analysed by the Leeds University Cosmic Ray Group. Parameters evaluated for each shower include the zenith and azimuth arrival directions of the shower axis, the position on the ground of the axis with respect to the array co-ordinates, and the so-called E_{100}, the estimated energy which would be lost by the shower in traversing an annular ring of water 120 cms. deep extending from 100m. to 1000m. from the core.

The principal merit of E_{100} is that it is a quantity which is close to what is actually measured in the detectors. However, it is thought that the radio emission originates close to the shower maximum, and so it is the primary energy E_p, which effectively determines the maximum shower size, which is expected to be related to the amount of radio emission. An estimate of E_p can be made using the method of Reid and Watson (1967). A vertical equivalent size V_{100} is assigned to the shower, defined as the value of E_{100} which would have been measured had the shower arrived vertically, the correcting factor depending only on the zenith angle. Then the primary energy is given roughly by 140 V_{100}, though the value of 140 is open to some doubt, and probably slowly changes with E_{100} as $E_{100}^{0.2}$. Also the energy loss observed at sea level can vary greatly depending on fluctuations in the development of the shower, and so it is unwise to place too much reliance on individual values of Ep.

A consequence of the array triggering requirements is that there are three areas, around the vertices of the collecting triangle, where relatively small showers can fall and trigger the array. In fact, about 80% of all showers triggering the array fall in these three 'clover leaves' (see fig.4.1): this high percentage is a consequence of the steep primary energy spectrum. This was an important factor to take into account when choosing the sites for the aerials.

4.3 The Aerial Sites.

It was mentioned in section 4.1 that three aerial sites were originally planned. The positions which were eventually decided upon are shown in fig.4.1. Again several factors had to be taken into account when choosing these sites.

The previous experiment at 60 MHz. had revealed that the majority of radio showers fell closer than 350m. from the aerial. Thus since we hoped to measure the lateral distribution of the radio emission with the new system, it seemed sensible to position the aerials close to one of the 'clover-leaf' areas, so that a sizeable fraction of the showers triggering the array would be falling close to all three aerials. The actual sites chosen were preferred to the two other possibilities, as they were close to the tarmac road leading to the centre hut, thus making installation and maintenance easier: also they were fairly remote from the overhead mains cables which lead to the central hut. The distances of these sites from the central hut, (they lay along the hut 2—hut 1 line) were respectively 80m., 210m., and 340m..

A ring of steel poles was erected at each site, from which the aerials were supported, and three cables were laid underground from each site to hut 13 where most of the recording equipment was to be installed. (Hut 13 was one of the huts housing the detectors of a 50m. array, which has now been dismantled). Two of the cables were lengths of UR67 to carry the radio signal, while the other was UR39 to take L.T. out to preamplifiers which were to amplify the signals from the aerials.

Two pairs of dipoles were set up at each site, arranged in a 'boxing-ring' fashion so that one pair was aligned in the (magnetic) North-South direction, and the other East-West. The original intention was to amplify the signal from each pair of dipoles, delay one signal relative to the other by 0.5 μsec. by having different lengths of UR67 to hut 13, and then mix the two signals before final amplification and display on an oscilloscope. Thus we would have available, on three separate oscilloscopes, three pairs of signals, which would provide information on both the polarisation, and the lateral distribution, of the radio emission.

However, as was explained in section 4.1, difficulties in choosing a suitable frequency eventually led to our using equipment at two frequencies, 32 MHz. and 44 MHz.. It now seemed that the most important measurement we could make was to determine the polarisation of the radiation at 44 MHz.. So two independent 44 MHz. channels were set up from the two pairs of aerials at site A. The East-West pair of 32 MHz. aerials at site B constituted the third channel, and for the time being the remote site C was not used.

4.4 Aerial Design.

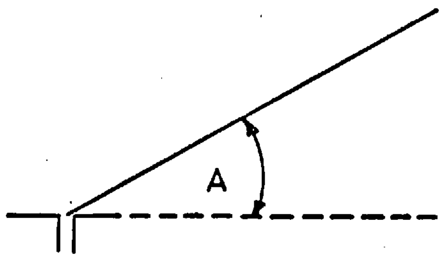
From the original Haverah Park experiment it was clear that an aerial system with a relatively isotropic response was desirable in order to increase the possibility of detecting pulses from showers at large zenith angles. Also however the gain of the aerial should be as high as possible for maximum sensitivity. The compromise we decided upon was two folded half-wave dipoles separated by half a wavelength and coupled in phase to give maximum sensitivity at the zenith. The dipoles were supported one quarter of a wavelength above the ground, and the calculation of the polar diagram is now described.

The performance of a receiving aerial system is related to its performance in transmission. For a given direction, only that component of the incoming radiation with the same polarisation as is produced in transmission can be detected. The relative efficiency of detection of this component is given by the aerial polar diagram. A full calculation for the aerials used in the experiment would be somewhat lengthy, and so the following approximate method was used.

Each folded half-wave dipole was treated as an infinitesimal Hertzian dipole: thus its sensitivity in free space for reception was assumed to be proportional to the component of the incident electric vector parallel to the dipole. In this way one arrives at the well-known sinA expression (see fig.4.2). The true polar diagram for a half-wave dipole in free space is in fact given by $\cos(\frac{\pi}{2}\cos A)/\sin A$ but as is shown in fig.4.2 this does not differ by more than 10% from the sinA dependence for any angle.

Now we must take account of the presence of the second aerial, and also the effect of the conducting ground. Using the well-known method of images, the calculation is done in two stages. Consider first a single short dipole at height h above a perfectly conducting ground (see fig.4.3). We can replace the effect of reflection from the ground by an image dipole with current equal in magnitude but of opposite phase: this condition is necessary in order to satisfy the boundary condition that the tangential component of the electric field should vanish along the surface of the perfect conductor. Then the path time difference between a plane wave front reaching the two dipoles is $2h\cos\theta$, which, since the dipoles are out of phase, gives a phase factor of $\sin(2\pi h\cos\theta/\lambda)$ and since $h = \lambda/4$, this becomes $\sin(\frac{\pi}{2}\cos\theta)$.

Now to find the effect of the second dipole at distance d, we must work out the phase relationship between the two real dipoles. If the dipoles are orientated East-West, then one is situated North with respect to the other. The time difference between a plane wave front reaching the two is then



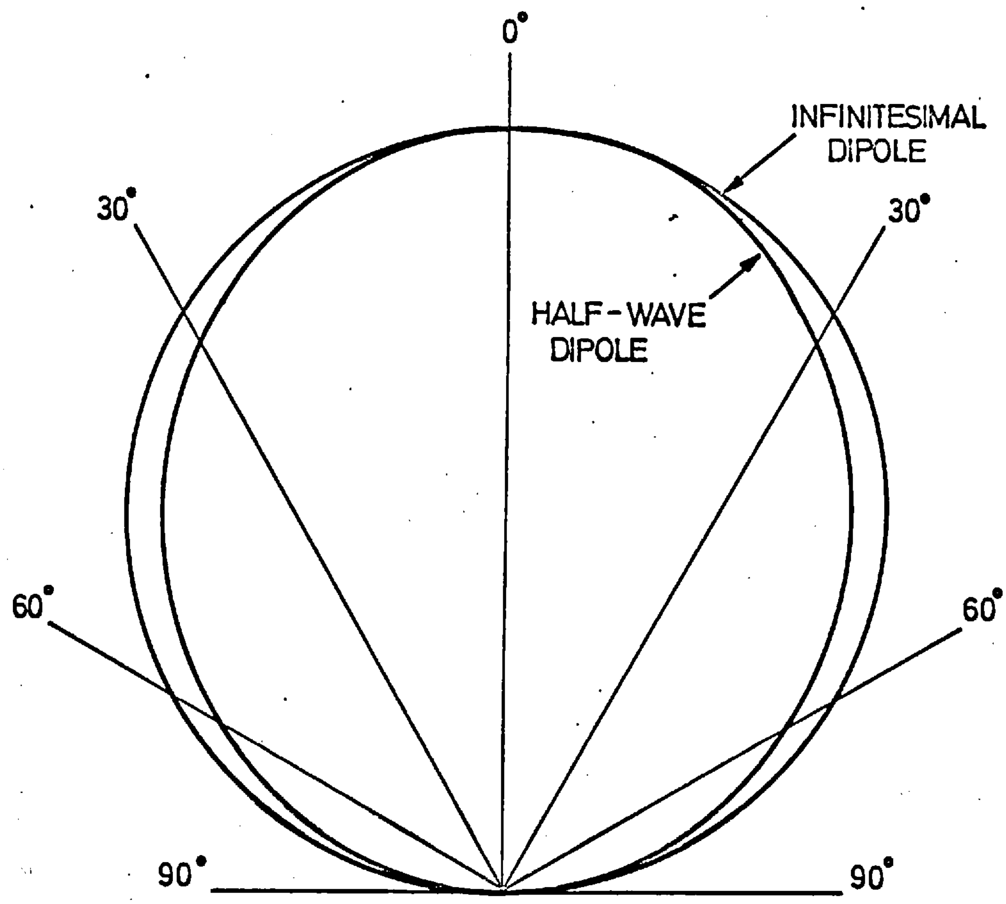


FIG. 4.2 COMPARISON OF THE FREE-SPACE POLAR DIAGRAMS OF AN INFINITESIMAL DIPOLE AND A HALF-WAVE DIPOLE.

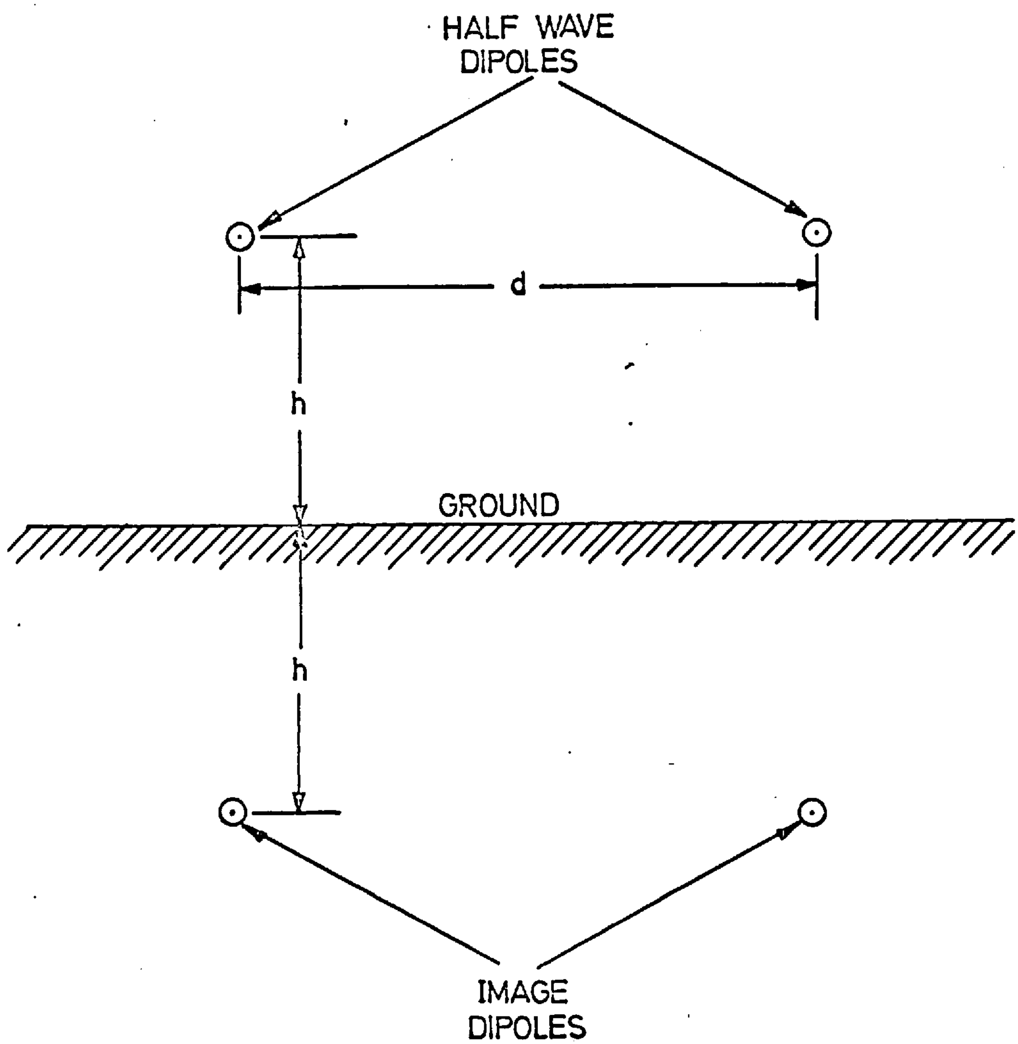


FIG. 4.3 THE AERIAL SYSTEM USED IN THE EXPERIMENTS

given by ($d \cos \emptyset \sin\Theta$), and the phase factor, since the two are in phase, is given by: $\cos(\pi d \cos\emptyset \sin\Theta/\lambda)$ and since $d = \lambda/2$ this becomes: $\cos(\frac{\pi}{2}\cos\emptyset \sin\Theta)$.

Thus the complete expression which takes account of the phase differences between two infinitesimal dipoles above a perfectly conducting earth is, for an East-West orientated aerial

$$\cos(\frac{\pi}{2}\cos\emptyset \sin\Theta) . \sin(\frac{\pi}{2}\cos\Theta).$$

The polar diagram for transmission for the aerial system as a whole will be this expression multiplied by $\sin A$, which in terms of Θ and $\emptyset$ is given by $(1 - \sin^2\emptyset \sin^2\Theta)^{\frac{1}{2}}$. Thus the approximate transmission polar diagram is given by

$$\cos(\frac{\pi}{2}\cos\emptyset \sin\Theta) . \sin(\frac{\pi}{2}\cos\Theta) . (1 - \sin^2\emptyset \sin^2\Theta)^{\frac{1}{2}}.$$

This expression is shown in fig.4.4. The plot with the azimuth angle shows that the response is almost isotropic for this variable. The response falls off with zenith angle so that at 45° the sensitivity is about 0.5 of its value at the zenith. On the other hand, the response does not change rapidly with zenith angle, so that an error in the calculated arrival direction of the shower will not lead to a large error in the assumed aerial sensitivity.

Another arrangement which we considered was to couple the two dipoles out of phase. At first sight this was an attractive idea, since, as is seen in fig.4.5, the variation with zenith for a fixed azimuth shows a maximum at 45°. This sensitivity variation is not markedly different from that of the particle detecting array, which has a maximum at 34°. However,

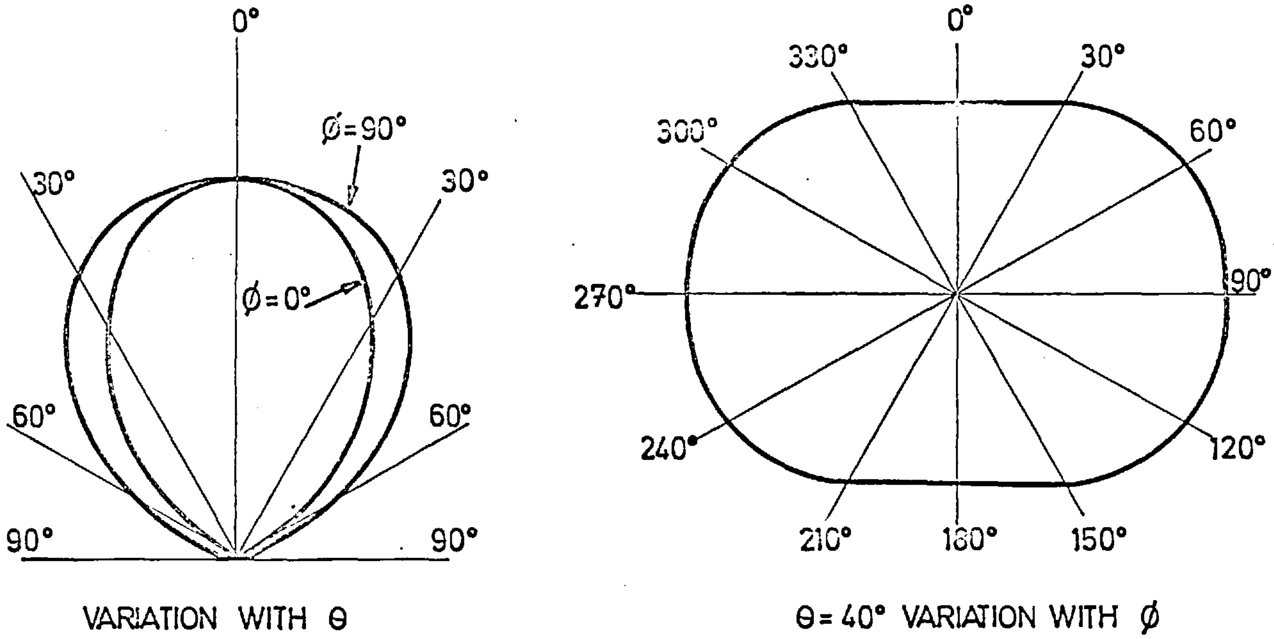


FIG. 4.4 POLAR DIAGRAM OF TWO HALF-WAVE E-W DIPOLES CONNECTED IN PHASE

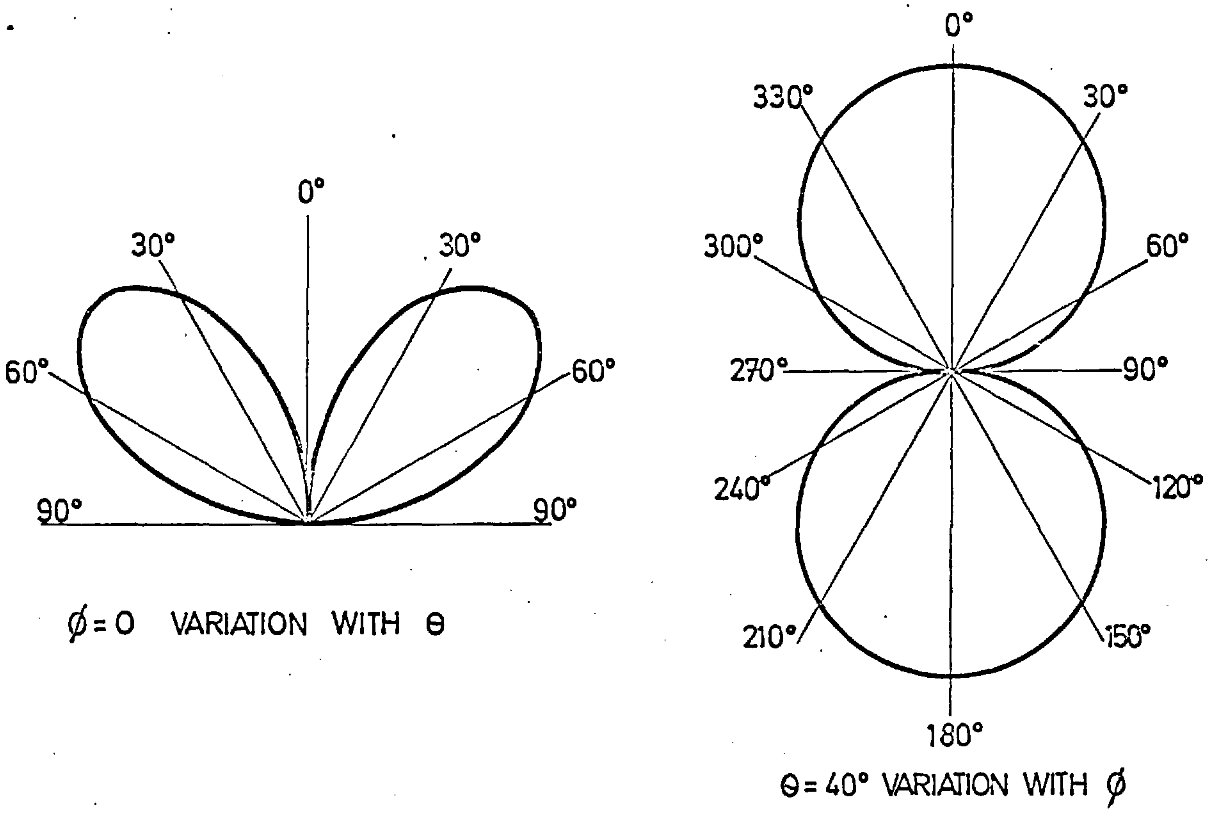


FIG. 4.5 POLAR DIAGRAM OF TWO HALF-WAVE E-W DIPOLES CONNECTED OUT OF PHASE

the variation with zenith angle is fairly rapid, so that any error in the calculated arrival direction could lead to a large error in the aerial response. Also, the response with azimuth is extremely non-isotropic. There was also a practical difficulty which ruled out the possibility of using this arrangement. This was the considerable cross-talk which would occur between the two pairs of dipoles in the 'boxing ring'. Using one pair of dipoles as a transmitter, it was found that 20% of the signal strength was picked up by the other pair. The same experiment repeated with each pair connected in phase showed a factor of less than 2%.

In deriving the above formulae, we have approximated the ground to being a perfectly conducting surface. The moor over which the aerials were supported was generally wet, and even when water was not actually lying on the surface, the soil beneath was always very damp. Since water is a good conductor at radio frequencies, it is reasonable to assume that the conducting properties of the ground did not change much from day to day or from season to season.

The physical dimensions of the aerials were calculated using radio engineering tables (Jasik, 1961). The resonant frequencies of the erected dipoles were measured using a radio frequency bridge, and found to be almost exactly the values expected for the given dimensions. The impedance was found to vary by not more than 20% over the frequency range equal to the bandwidth of the receiving system.

4.5 The Receiving System.

The theoretical impedance of a folded half-wave dipole is about 300 ohms, and so in order to match into a feeder cable of characteristic impedance 70 ohms, a Balun 4:1 step-down transformer was connected across the aerial terminals. Equal lengths of UR43 from each dipole led to a preamplifier which was placed underneath an upturned plastic bucket at the centre of the 'boxing-ring'. The two cables in parallel presented an effective impedance of 35 ohms, which was a reasonable match to the preamplifier input of 50 ohms.

A block diagram of the complete recording system is shown in fig.4.6. For the two 44 MHz. channels, preamplifiers of different gains were used to compensate for the difference in attenuation between the two lengths of cable leading to the recording hut. These different lengths were to introduce a time delay of 0.5 μsec. had we decided to mix the two channels as originally planned.

The master trigger pulse from the main array may be generated by the coincidence circuit up to 4 μsecs. after the passing of the shower front through the central particle detector. Because of this it was necessary to introduce a dela in each radio channel to ensure that the pulse would always be on the oscilloscope time-base. It had been found in the original Haverah Park experiment that the poor frequency response of the Hackenthal HH 1500A delay cable used had severely cut down the bandwidth of the system. So it was

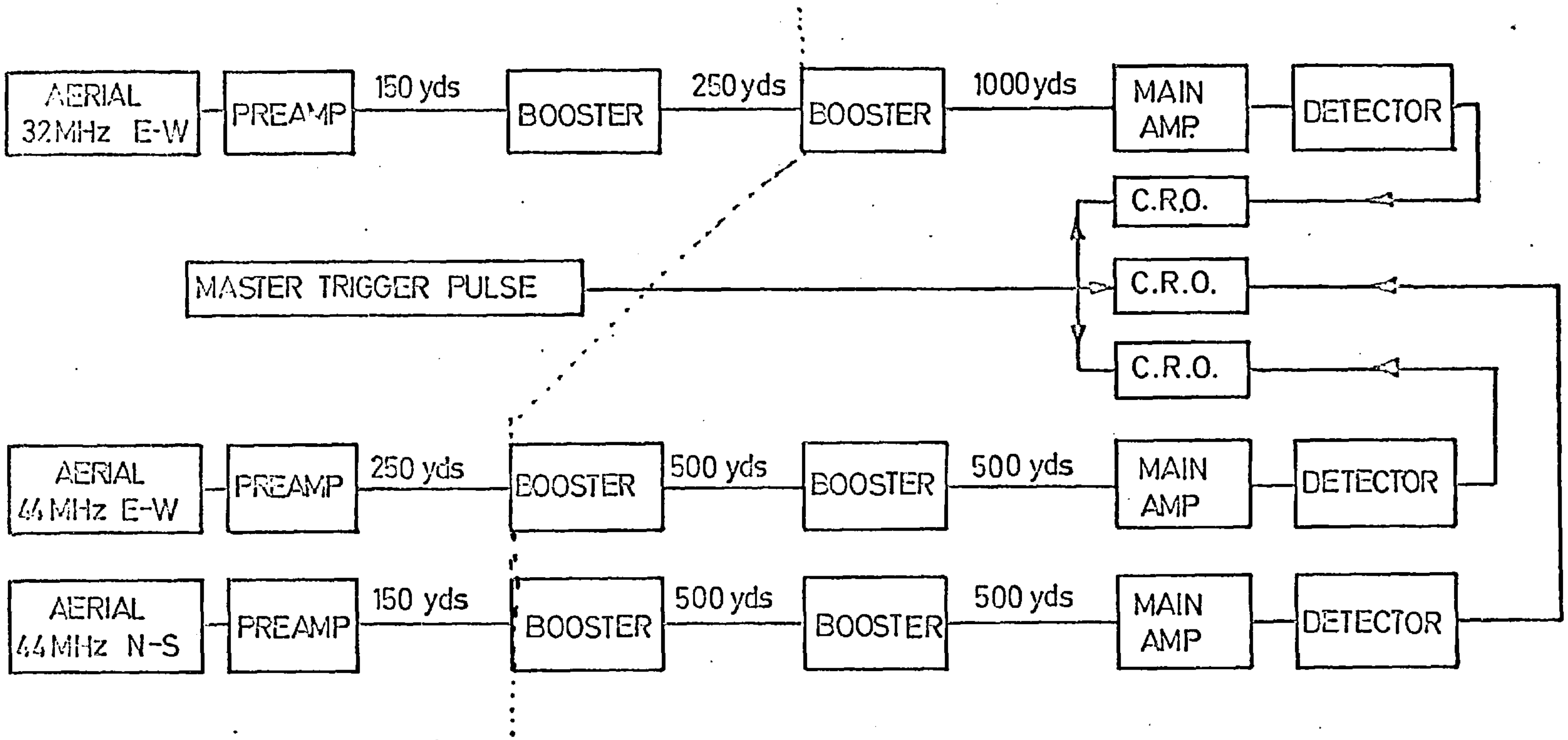


FIG. 4.6 BLOCK DIAGRAM OF RECORDING CIRCUITRY

decided to use instead UR67 cable, and in order to obtain the 4.5 μsec. delay thought necessary, 1000 yds. for each channel were installed in hut 13. Since the attenuation of this cable at radio frequencies was considerable (about 35 db. for the 1000 yds. at 44 MHz.) it was necessary to include in each channel one or more booster amplifiers in order to keep the signal above noise. The main amplifier in each channel had a variable gain of up to 75 db., and included a detector stage before the final output, which was fed to a Tektronix oscilloscope.

The amplifiers were made by Decca Radar Ltd., standard models retuned to our required frequencies. The detector stage was linear over only a small voltage range, so that the gain adjustment in each channel was highly critical. As it turned out, the 44 MHz. channels were quite well adjusted, so that most of the pulses corresponded to the linear range, but the 32 MHz. channel proved to be well off the linear range, making pulse amplitude comparisons impossible.

The three oscilloscopes displaying the signals from the three channels were viewed simultaneously by a single camera using a mirror device. Whenever a master trigger pulse arrived from the central hut, the oscilloscopes were triggered, and lights illuminating the number register were flashed. Some three seconds later, the camera, which was used without a shutter, was automatically wound on ready for the next event. The number register, which was used to correlate radio events with those of the main array, was moved on once every half minute by a pulse from a master clock in the central hut.

A second detector stage made possible the measuring of the d.c. current in each main amplifier. The outputs from the 32 MHz. channel, and one of the 44 MHz. channels, were continuously monitored using a dual-trace Rustrak chart recorder. This was found to be very useful in determining the source of the noise at 32 MHz..

4.6 Calibration Procedure.

In order to find out the correspondence between the voltage of a pulse across the aerial, and the amplitude actually recorded on the oscilloscope, the following calibration procedure was carried out for each channel. A pulse modulated signal at the resonant radio frequency was applied to the appropriate preamplifier input. After passing through all the normal cables and amplifiers, the output from the main amplifier was measured on an oscilloscope. Thus we measured the gain of the channel from the preamplifier input to the final output, whereas we would have liked to know the effect of a pulse of a certain amplitude across the aerial. However, this was impossible to simulate, so it was necessary to make the approximation that the input voltage at the preamplifier was equal to the voltage across the aerial.

Using this arrangement we were able to measure the variation of gain with input voltage by varying the voltage output of the signal generator. Also by varying the radio frequency, the bandwidth pf the system was measured. The bandwidths of the two 44 MHz. channels were both 4 MHz., and that of the 32 MHz. channel was 3 MHz.. The theoretical bandwidths of the aerials used were greater than these, and were confirmed by measurements with the radio frequency impedance bridge.

4.7 The Timing System.

In order to facilitate the identifaction of genuine, shower-associated radio pulses, an accurate timing system was used. A block diagram of the so-called 'Z-modulation unit' is shown in fig.4.7.

Whenever a master trigger pulse arrived, a negative 40V. pulse about 100 usecs. long was generated. An output was also available direct from 4 of the 16 tanks in the central hut, and this was fed through a discriminator. Whenever a pulse large enough to overcome the discrimination level occurred, a blocking oscillator was fired, causing a 40V. positive spike about 1 µsec. long to be produced with a very sharp leading edge. After being delayed for about 7 µsecs. this was superimposed on the 100 µsec. negative pulse. The brightness control on the oscilloscope was turned down, and the output from the 'Z-modulation unit' applied to the cathode. The result was that each time the oscilloscope was triggered, the trace brightened up along its whole length, except for a 1 usec. blanking pulse at a position related to the arrival time of the particles into the hut 1 detector.

Since the particles in the shower travel at almost the

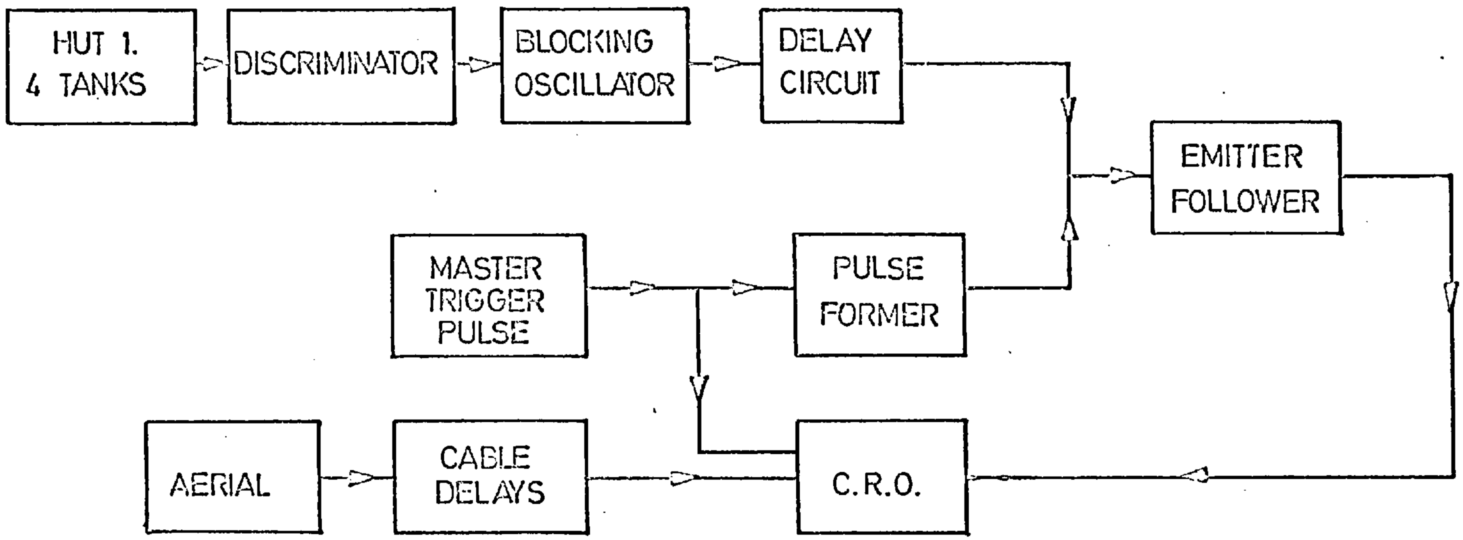


FIG. 4.7 BLOCK DIAGRAM OF THE TIMING SYSTEM (Z - MODULATION UNIT)

speed of light, for a shower arriving vertically, the shower front and the radio emission should arrive almost simultaneously. Thus for a vertical shower the blanking pulse should always occur at a definite time after the radio pulse, the time difference depending on the relative cable and electronic delays in the two channels. This difference was measured for each channel by simultaneously injecting signals into the cable carrying the output from the four hut 1 tanks, and the cable leading from the preamplifier. It was necessary to remove the amplifiers in the radio channel while this was being done, but it was assumed that the delay in them would be negligible.

Having in effect measured the expected time difference between the radio pulse and the blanking pulse for a vertical shower, it was easy to apply a correction for an inclined shower. If r is the distance of the aerial from hut 1, and θ and ϕ the zenith and azimuth angles of the shower axis, then the correction is: $dt = -r \sin\theta \cos(\phi + a) / 300$ usecs.
where a is the angle between the hut 1 - hut 2 line, and the direction from which ϕ is measured. For high zenith angle showers this can give a correction of up to 0.7 μsec. for the 32 MHz. aerial site.

The above calculation assumes that the shower front is a plane, whereas in fact it is known to be convex. However, the error introduced is less than the smallest time difference which could be resolved on the oscilloscope (about 0.1 μsec. for a 10 μsecs. time base), and so it was ignored.

The pulse from the central particle detector was taken from only 4 of the 16 Cerenkov tanks. As a result, due to fluctuations in the distribution of particles in the 16 tanks, about 20% of showers did not produce a hut 1 pulse large enough to overcome our discriminator, and these were therefore not suitable for analysis. However, in the other 80%, a reliable time marker was available so that genuine events could with confidence be distinguished from spurious pulses.

4.8 Pulse Identification.

At 44 MHz., recording between 08.00 hours and midnight was impossible due to the proximity of a B.B.C. television transmitter. During the eight quiet hours of the night, the background against which pulses were observed consisted typically of an occasional small spike superimposed on a lower noise level, which corresponded to a voltage at the preamplifier input of about 20 μV.. No pulse was accepted as a genuine, shower associated event, unless it occurred at the predicted time, within a maximum error of 100 μsecs.. Also the pulse was discarded if a larger pulse occurred elsewhere on the trace. Occasionally, large pulses were observed at other points on the time base, and there is obviously a chance that some of the pulses occurring at the expected time were not genuine events. Considering the number of pulses observed, and the precision of the timing system, it is estimated that the number of such events is less than 5%.

At 32 MHz., the noise problem was somewhat different. When recording commenced, in the summer of 1967, the noise was excessive for most of the 24 hours. Only for two or three hours during the night did the noise level fall and remain constant. However, the shortening of the days corresponded to a lengthening in this quiet period, until in December and January, the background was quiet for more than 12 hours per day. It certainly appeared that the length of the noisy period depended on the number of hours of daylight: this was probably some effect connected with the ionosphere. Had this been realised beforehand, we would almost certainly have operated a second 32 MHz. channel throughout the winter. During the quiet period, the background noise consisted of a series of small pulses, exactly the appearance one would expect for random noise. This background imposed a threshold for detection of pulses at about 35 µV..

Whereas the radio pulses observed at 44 MHz. varied in amplitude up to about 100 µV., it became evident on analysis that the 32 MHz. system was saturating at an input voltage only two or three times the background noise, despite the precautions taken. However, we were fortunately still able to measure fairly accurately the background noise voltage which imposed the threshold for detection. Thus no useful information could be gained about the 32 MHz. pulse amplitudes: only the presence or absence of a radio pulse above a known threshold could be established.

	32MHz	144 MHz	
B.W.	3	4	MHz
Threshold (v)	35	20	μV
Threshold (v/m)	385	220	

CHAPTER FIVE

EXPERIMENTAL RESULTS

5.1 Introduction

First of all, a few facts and figures are presented. Observations were made during the winter of 1967-8 at two frequencies: at 44 MHz. two channels were available, with aerials orientated both East-West and North-South, while at 32 MHz. there was, unfortunately, only one channel, with the aerial orientated East-West. Altogether 725 showers were eventually found suitable for analysis with the 44 MHz. data, and with 95 of these an associated radio pulse was observed on one or both of the channels. The numbers on the two channels were very nearly equal; 60 on the East-West, and 64 on the North-South. At 32 MHz., out of 1010 observed showers, 100 had an associated radio pulse, on the single East-West channel.

Since, as was mentioned in the previous chapter, the pulse amplitudes measured are not too reliable, whereas the thresholds for detection are known with confidence, the method of analysis has been to divide showers into two categories; those that give a radio pulse, and those that do not. The two categories have then been compared to find out any correlations with other parameters of the showers as measured by the particle detecting array. From the particle array data, deductions can also be made concerning the polarisation mechanism. It is very useful to be able to compare the results at the two frequencies, particularly with regard to the rate of detection of radio events, and the polarisation of the radiation.

5.2 Dependence on the Perpendicular Distance R Between the Aerial and the Shower Core.

For each shower the perpendicular distance R between the shower core and the aerial was calculated for each of the two aerial sites. If L is the horizontal distance on the ground between the position of the core and the aerial, then the required distance in the plane of the shower front is given by:

$$R = L(1-\sin^2\theta \cos^2(\phi-\psi))^{\frac{1}{2}} \quad \text{(see Appendix)}$$

Fig. 5.1 shows the distributions in R for all showers for the two aerial sites: also indicated are the distributions of showers with which a radio pulse was observed on the East-West aerial at either frequency. It will be noticed that the distributions for all showers are very different for the two aerial sites. In particular, the number of showers falling within 100m. of the 32 MHz. aerial was 140 compared with only 37 for the 44 MHz. aerial. This was a consequence of the triggering bias of the particle-detecting array: the 32 MHz. aerial was situated close to the centre of one of the "clover leaves", while the 44 MHz. aerial was rather nearer to the centre of the array. Thus most of the showers falling within 100m. of the 32 MHz. aerial were probably small showers just large enough to meet the array triggering requirements, but perhaps not large enough to produce a detectable radio pulse. It is only for the highest energy showers that this triggering

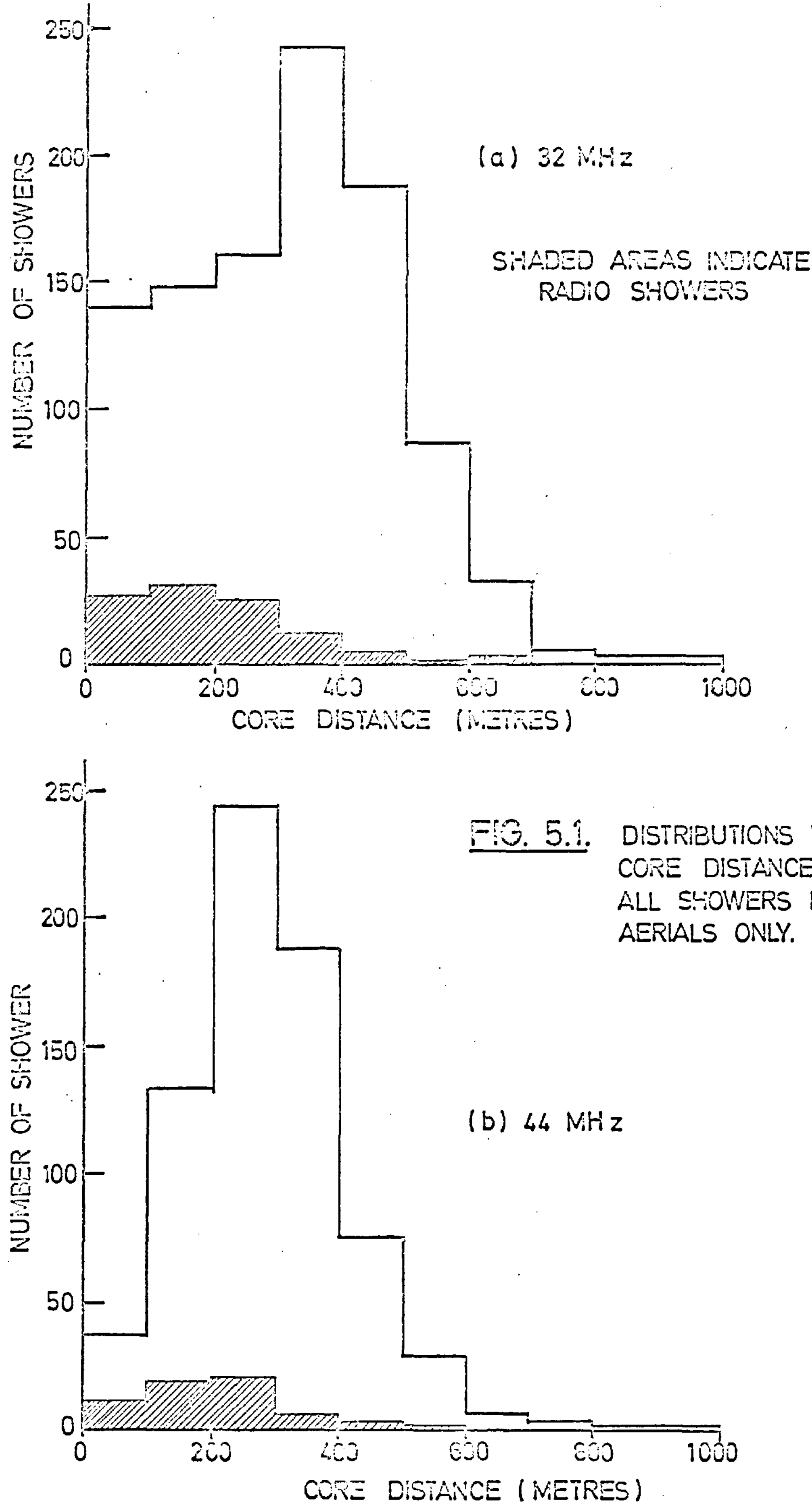


FIG. 5.1. DISTRIBUTIONS WITH CORE DISTANCE FOR ALL SHOWERS E-W AERIALS ONLY.

bias does not exist. Thus in order to compare the distributions with R of radio showers at the two frequencies, only the 10% of showers with the highest energies should be considered. In fig. 5.2 the distributions with R are given for all showers, and for radio showers, with Ep greater than 5.10^{17}eV.

It will be noticed from fig.5.1 that the distributions of radio showers for showers of all energies are very similar at the two frequencies, the majority of radio showers falling within 300m. of the aerial. However, as was stated above, a comparison between the two frequencies is only really meaningful for the highest energy showers. From fig. 5.2 it is found that at both frequencies about 25% of the high energy showers have an associated radio pulse. However, since the threshold for detection of radio pulses was higher at 32 MHz. than at 44 MHz., it can be concluded that the radiation falls off slightly at the higher frequency. A more detailed discussion of the relative radio emission at the two frequencies is given at the end of this chapter. The overall distributions in fig.5.2 show that the average shower distance is the same to each aerial site, about 450m.. However, the radio events at 32 MHz. are recorded at rather larger distances, up to 650m., than are the 44 MHz. events for which 450m. is the maximum observed distance. Although the statistics are poor, this is some evidence for the lower frequency component extending further out from the shower core.

It is of interest to know which showers produced a detectable radio pulse at 32 MHz. at large distances from the

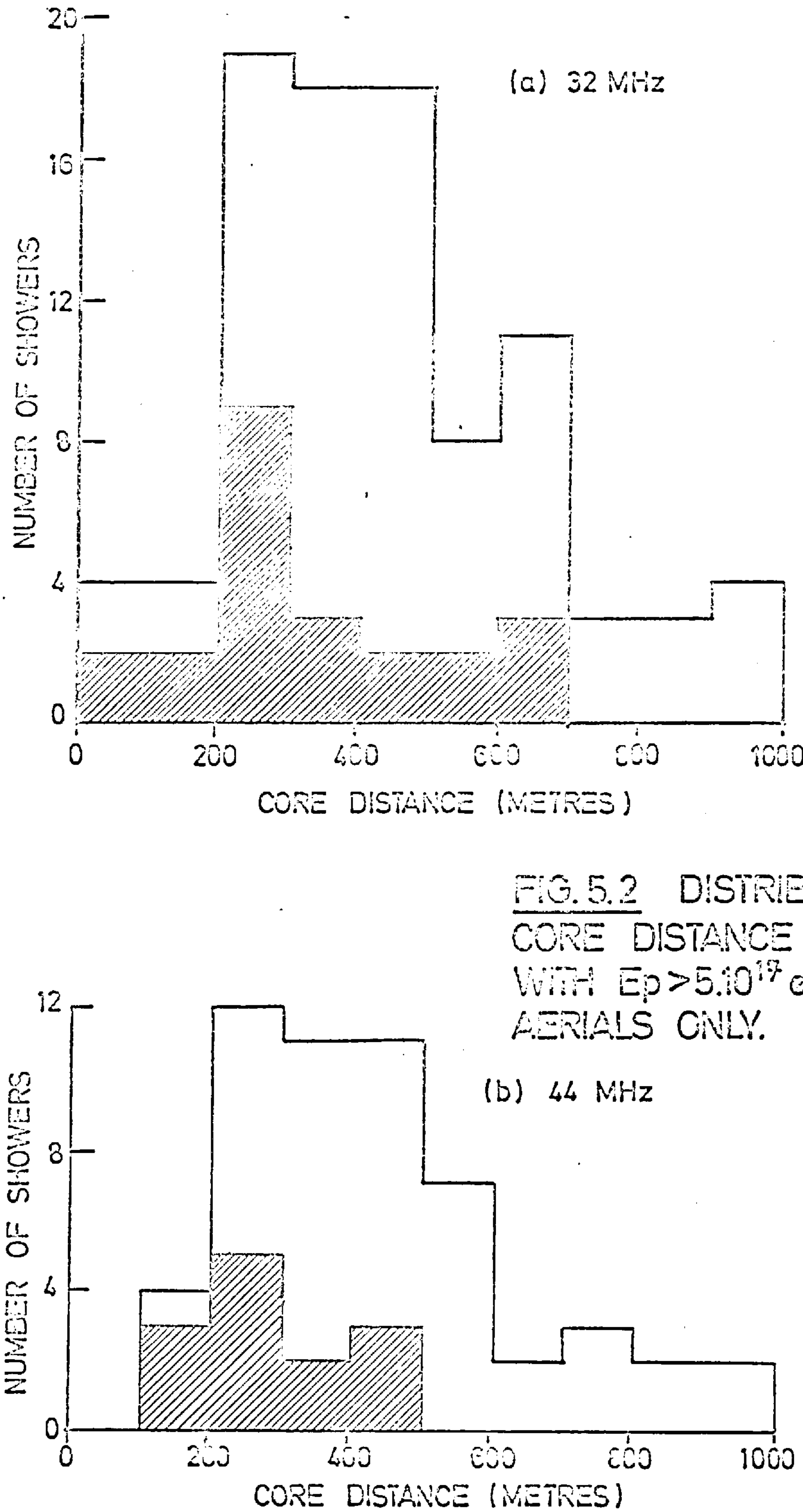


FIG. 5.2 DISTRIBUTION WITH CORE DISTANCE FOR SHOWERS WITH Ep > 5.10^{17} eV E-W AERIALS ONLY.

greater distance of [illegible] max ;
cause. pulse to [illegible]

shower core. It was noticed, on casual inspection of the data, that these showers tended to arrive at large zenith angles. A more systematic approach was adopted, in which the radio showers were separated into four zenith angle ranges. It was assumed that the radio amplitude should depend on the shower size, and therefore the primary energy, and so to make allowance for the fact that the response of the aerial falls off with increasing zenith angle, correspondingly higher ranges of Ep were taken. The variation in the mean level of R in the four zenith angle ranges is given in fig. 5.3, and it is seen that showers producing radio pulses at large distances from the core also have, on average, larger zenith angles. This can be interpreted in the following way: showers which are highly inclined to the zenith will reach their maximum development at greater distances from the aerial, than will vertical showers, and thus one might expect, from simple geometric considerations, that their radio emission would have a greater lateral spread on the ground

5.3 Dependence on the Primary Energy Ep.

Since, on average, the larger showers detected by the Haverah Park array tend to fall further from the aerials, than do the smaller ones, one must choose a definite range of R in order to make meaningful any comparison with the primary energy. In fig. 5.4 only those showers falling closer than 200m. to the aerial are considered in determining the distribution of radio showers as a function of Ep.

It is immediately noticeable that at both frequencies, the

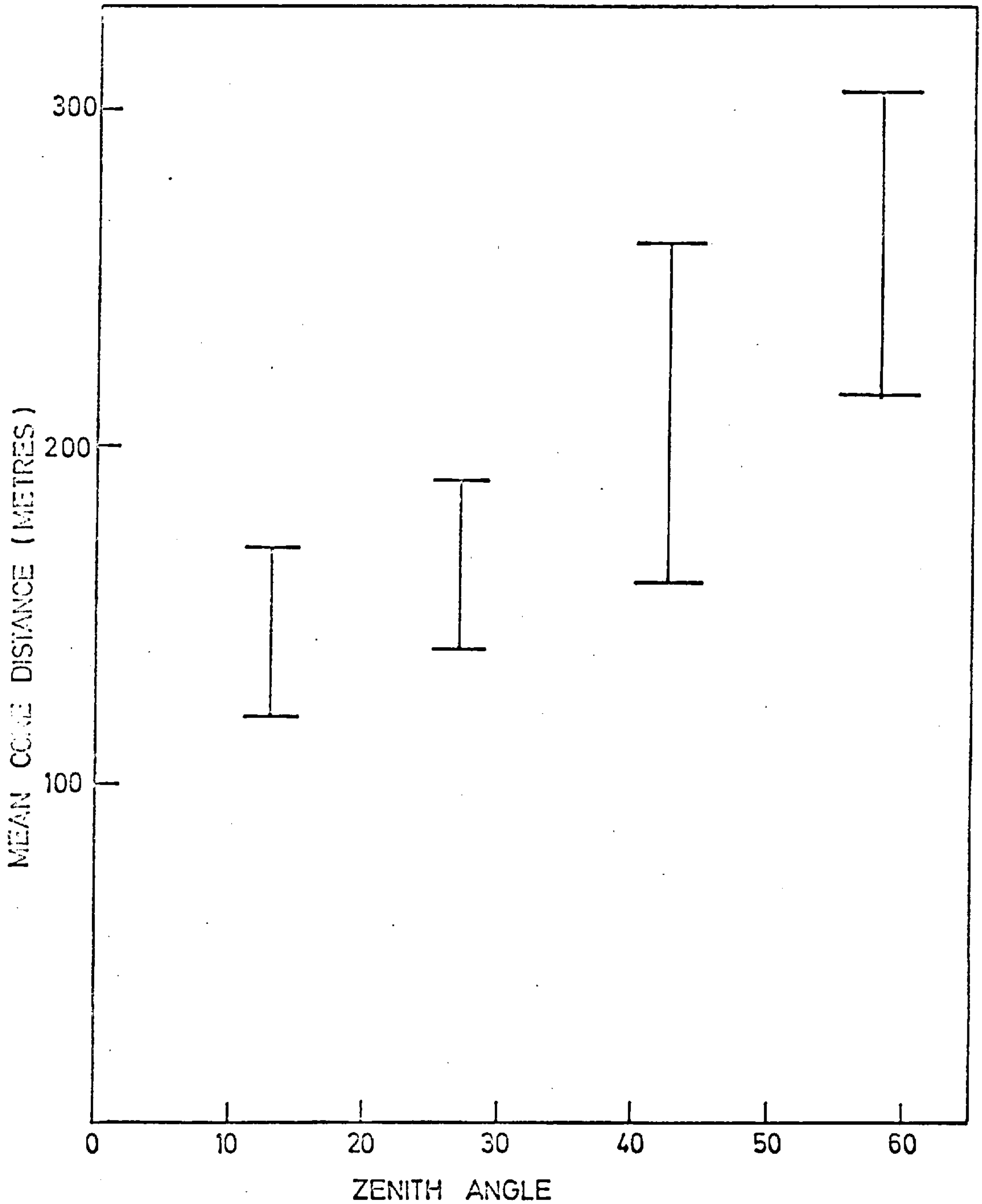


FIG. 5.3. VARIATION OF MEAN VALUE OF CORE DISTANCE WITH ZENITH ANGLE FOR 32 MHz RADIO SHOWERS

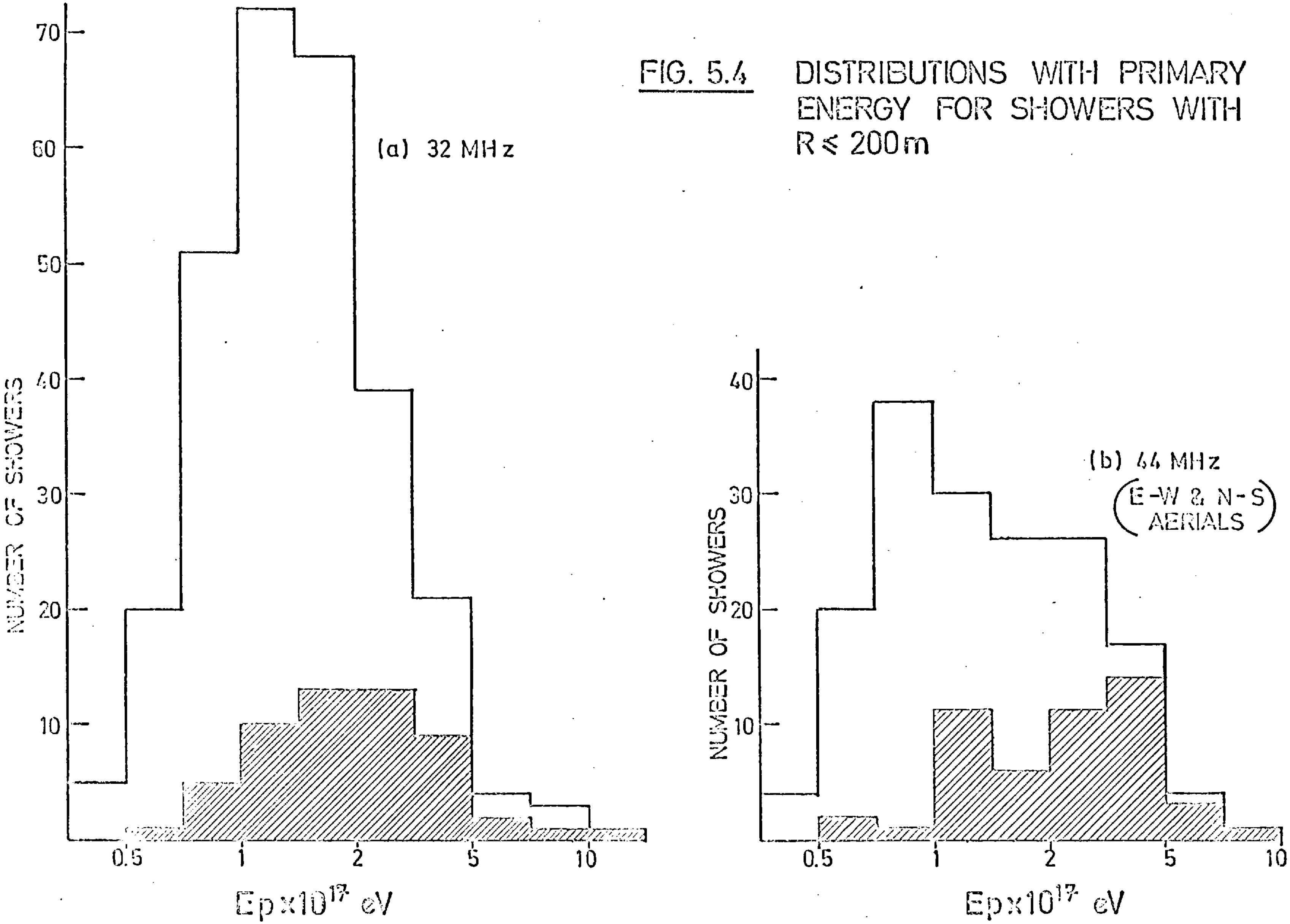


FIG. 5.4 DISTRIBUTIONS WITH PRIMARY ENERGY FOR SHOWERS WITH $R \leqslant 200$m

radio showers tend to be those with high primary energy. There are very few radio showers with Ep less than 10^{17}eV. From the 32 MHz. data, for showers with Ep greater than 2.10^{17}eV., some 40% have an associated radio pulse. It would be interesting to find out the reason for a radio pulse not being observed with the other 60%. In fig. 5.5, these 68 showers, with Ep greater than 2.10^{17}eV. and R less than 200m., are plotted to show their zenith angle distribution. Most of the showers which do not produce a radio pulse originate at high zenith angles, and this is consistent with the explanation that the polar diagram of the aerial is falling off with increasing zenith angle. However, even for the 40 showers in this category which have θ less than 50^o, only 50% have an associated radio pulse. A plot of these 40 showers with their azimuth angles (fig. 5.6) reveals that the radio showers have a definite tendency to come from the North rather than the South. As will be discussed in a later section, 5.5, this North-South asymmetry is of great importance in establishing the radiation mechanism.

At 44 MHz., a radio pulse was observed on either or both channels, with 60% of the 48 showers having Ep greater than 2.10^{17}eV. and falling within 200m. of the aerial. They were analysed in a similar way to the 32 MHz. events, and again it was found that those showers without an associated radio pulse arrived mainly at high zenith angles. However, no pronounced asymmetry in the azimuth distribution, as at 32 MHz., was observed, even when the radio events were split up into

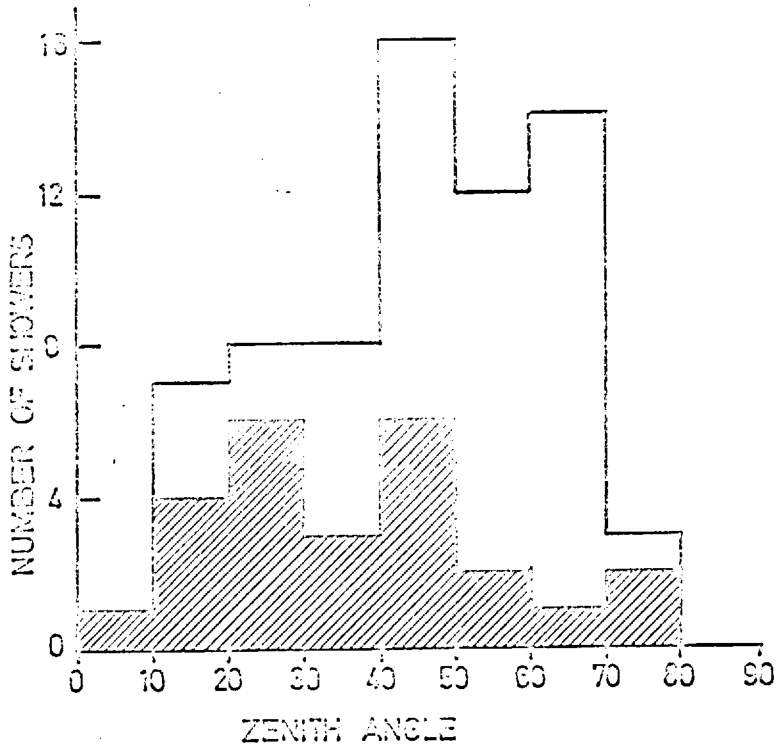


FIG. 5.5 DISTRIBUTION WITH ZENITH ANGLE FOR 32 MHz SHOWERS WITH $E_p > 2.10^{17}$ eV AND $R \leqslant 200$ m

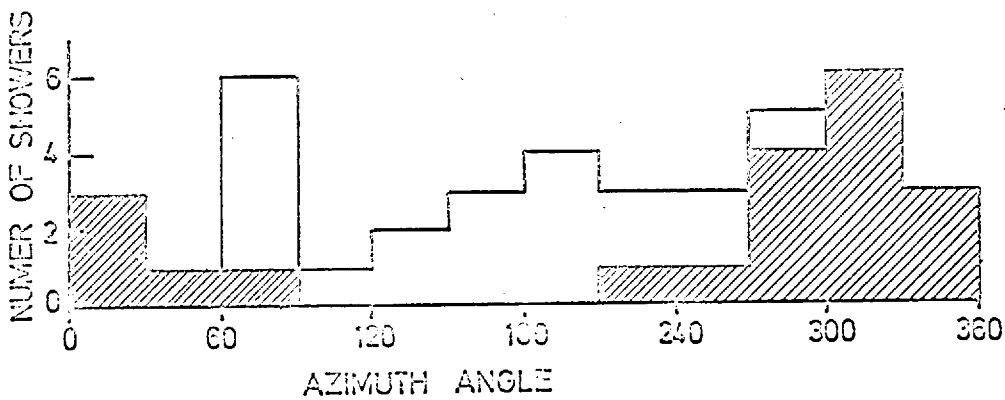


FIG. 5.6 DISTRIBUTION WITH AZIMUTH ANGLE FOR SHOWERS IN FIG. 5.5 WITH $\theta \leqslant 50°$

those on the East-West aerial, and those on the North-South.

One curious feature of the 44 MHz. results for this class of showers was that the number of radio events recorded on each channel was appreciably different: 27 were observed on the North-South channel, but only 18 on the East-West, whereas for all showers the numbers of events on the two channels were equal. The probability that this was a random fluctuation is only about 17%, and I am unable to explain the result.

5.4 Dependence on Zenith Angle.

Any dependence on primary energy should also show up in a zenith angle distribution, since for the same E_{100} at sea level, a shower of higher zenith angle will have been caused by a primary of higher E_p. However, other factors are likely to affect the zenith angle distribution. For instance, if charge separation is indeed the dominant mechanism, then one would expect more radio emission from showers making large angles with the geomagnetic field, and since the field is nearly vertical, this means showers with large zenith angles. On the other hand, there is also the polar diagram to take into account: for observing the radio emission, low zenith angles will be preferred.

In fig. 5.7 are plotted the distributions with zenith angle for the two frequencies. The radio showers at 44 MHz. include those with pulses on either or both channels. There is a definite tendency for the 44MHz. radio showers to be at high zenith angles, but at 32 MHz. the distribution for the radio

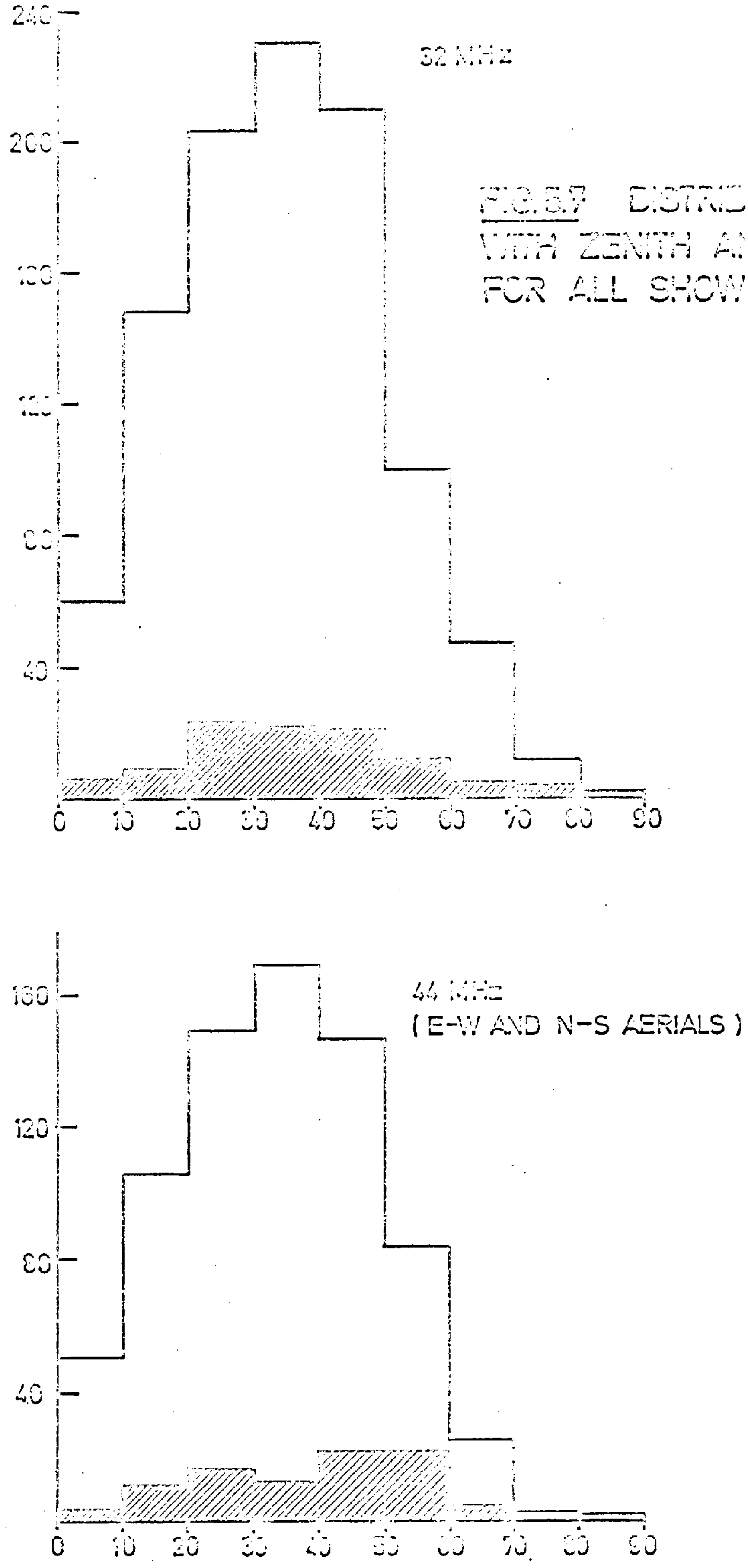


FIG. 5.7 DISTRIBUTIONS WITH ZENITH ANGLE FOR ALL SHOWERS

showers is not very different from the overall distribution. In fact; a chi - square test to decide the probability of the radio distribution being a random sample of the overall distribution, above and below 40°, gives a chance of less than 0.1% at 44 MHz., but about 30% at 32 MHz. Taking the 44MHz. distribution for the East-West channel only, still gives a probability of 0.1%.

Considering that the polar diagram response of the aerial at a zenith angle of 40° is about 0.6 of its value at the zenith, it may be concluded that for all showers, there is more radio emission from high zenith angle showers, especially at 44 MHz. This may seem to contradict the conclusion of section 5.3, where it was observed that for showers of energy greater than 2.10^{17}eV., and falling within 200m. of the aerial, high zenith angle showers tended not to give a detectable radio pulse. The most probable explanation is that, in general, high zenith angle showers give more radio emission, as they tend to originate from higher energy primaries. For showers in a certain energy range, however, the aerial is more effective for detecting radio emission from showers which arrive from directions close to the zenith.

5.5 Dependence on Azimuth Angle.

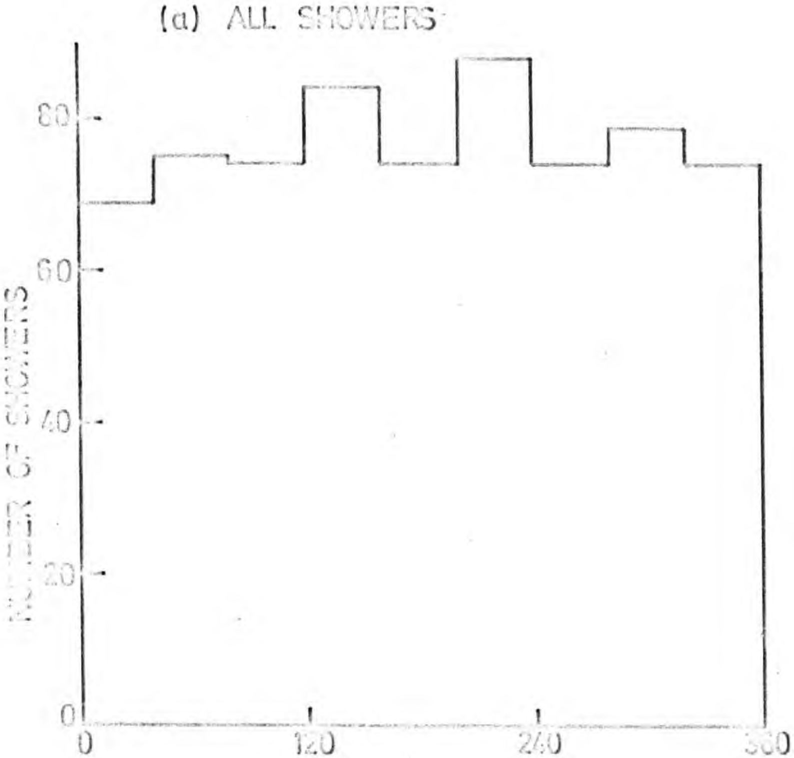
The distribution of radio showers with azimuth angle, should show up, on an aerial of a particular orientation, any dominant process in the mechanism of radiation. In particular, for an aerial orientated East-West, for "vertical" polarisation,

	E-W aerial	N-S aerial
Vert. :	from E or W	from N or S
Unpol	from N or S	from E or W
GM :	N	" E or W
Radial	?	?

we should observe a preponderance of showers from the East and West: for unpolarised radiation, there should be more from the North and South, while for geomagnetic deflection, there should be a strong preponderance from the North only. On the other hand, for an aerial orientated North-South, the "vertical" polarisation would give more radio showers from the North and South, while for both unpolarised, and geomagnetically induced radiation, more would be expected from the East and West. It is more difficult to make predictions for radial polarisation, as this also depends on the bearing, from the aerial, of the point of impact of the shower on the ground.

The Haverah Park 500m. array particle detectors lie in a plane which is not quite horizontal, but is tilted about 2° roughly towards the North. This is sufficient to cause a slight excess of showers recorded from the South over the North. As is shown in fig. 5.8, the minimum in the overall distribution occurs at about 20° East of magnetic North. The distributions in azimuth for the three channels are also given in fig. 5.8. Taking the 32 MHz. channel first, there is a pronounced tendency for the radio showers to come from the North; comparing the numbers from the Northern half of the sky to those from the Southern half, the ratio is 73 : 27. This extreme anisotropy can only be caused by one mechanism, namely geomagnetic charge separation.

Now consider the 44 MHz. results; the azimuth distributions are given in fig. 5.[illegible] for the two aerial



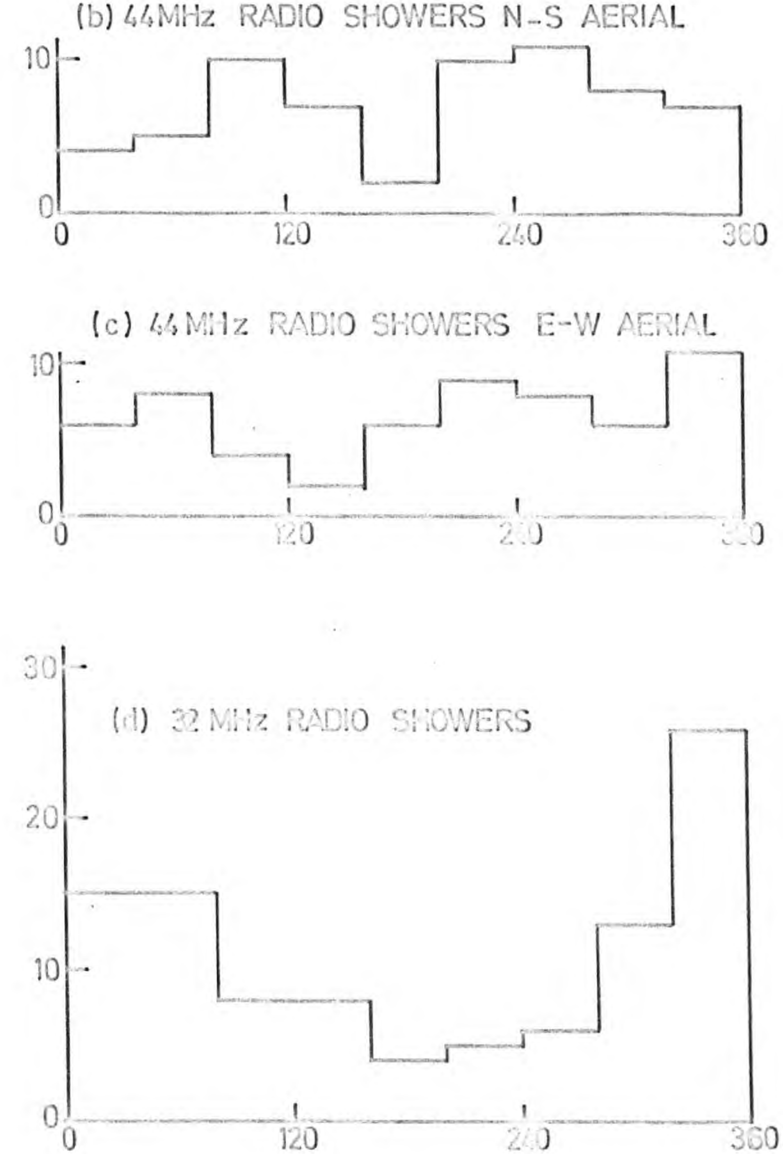


FIG. 5.8 DISTRIBUTIONS WITH AZIMUTH ANGLE

directions. On the East-West aerial, the North to South ratio is 33 : 27, but even allowing for the slight anisotropy for all showers, there is still a 25% chance that this effect is due to a random fluctuation. For this aerial there is no difference in the number of showers observed from the North and South quadrants, as opposed to the East and West quadrants. On the North-South orientated aerial, however, there is a definite majority of showers observed from the East and West, rather than from the North and South. The ratio is 39 : 25, and the chance of this being a random fluctuation is only 7%.

These 44 MHz. results are rather difficult to interpret. In view of the observed anisotropy on the North-South aerial, we can effectively rule out vertical polarisation, which predicts a preponderance the other way. Either geomagnetically induced, or unpolarised radiation, would cause the effect observed. Unpolarised radiation should give a similar asymmetry on the East-West aerial, for which, however, the numbers are almost equal. The only asymmetry on the East-West aerial is the slight preponderance of showers from the North rather than the South. From this we can conclude that the radiation at 44 MHz. is to some extent caused by charge separation in the geomagnetic field, but that this mechanism is not nearly so dominant as at 32 MHz..

It is possible to check these conclusions regarding the radiation mechanism, by plotting the distribution of the angle between the shower axis and the geomagnetic field. If charge separation is the dominant mechanism, then we should expect the

	α	ζ	
HCl	38	34	4° larger
32	46.5	36	10.5° larger
44	42	38	4° larger

radio showers to make relatively high angles with the field direction.

Over all showers, the average angle made with the field direction is 38°. The average for the 32 MHz. radio showers is 46.5°, while at 44 MHz. the average for both channels together is 42°. However, one must be cautious in drawing conclusions from these figures, since we have already found in section 5.4 that radio showers tend to come from high zenith angles, which itself implies high angles with the earth's field. The mean zenith angle for all showers is 34°, and for the 32 MHz. and 44 MHz. radio showers, the averages are 36° and 38° respectively. From this we can conclude that the mean angle with the earth's field is significantly higher for 32 MHz. radio showers than the average over all showers, and this strongly supports the geomagnetic charge separation theory at this frequency. But at 44 MHz. the higher mean angle with the field is not significant at all.

5.7 Dependence on the Bearing of the Core Position from the Aerial.

So far we have not considered the excess charge mechanism suggested by Askaryan, which gives rise to radial polarisation. Apart from comparing the observed pulses on the North-South and East-West aerials, with the ratio expected under this model, the most direct method of analysis seems to be to look at the distribution of positions where the shower axis meets the ground. If the radiation is radially polarised then for the East-West aerial there should be a clustering of showers to the East and West, while for the North-South aerial the clustering should be to the North and South. In fact it is simpler to plot the bearing (East of Magnetic North) of the core position from the aerial.

On the Haverah Park array, the bias introduced by the triggering requirement causes the majority of showers observed to fall in the three "clover leaves". The distribution in the bearing therefore shows strong peaks in the directions towards these preferred areas. Because of this it will be difficult to draw any conclusions from the bearing distribution for a single dipole. However, if the ratios of the number of showers from the North and South quadrants, to the number from the East and West quadrants, are compared for the North-South and East-West aerials, then we should expect a difference if radial polarisation is present. The numbers actually observed for the two 44 MHz. channels are:

Aerial orientation	North	East	South	West
North-South	13	17	25	10
East-West	16	12	20	12

Now if radial polarisation is present, then we should expect the (North+South) : (East+West) ratio to be higher for the North-South aerial than for the East-West aerial. In fact the ratios are respectively 38 : 27 = 1.4 : 1, and 36 : 24 = 1.5 : 1. With the numbers involved these two ratios are virtually equal, so it seems that this test eliminates the possibility of the 44 MHz. radiation being radially polarised.

5.8 Dependence on the Pulse Height Predicted by the Various Models.

There remains one more method by which the data can be analysed in an attempt to establish the radiation mechanism. This is to compute, for each shower, from the arrival direction and core position relative to the aerial, the expected component of the polarisation vector in the aerial direction for each of the four radiation mechanisms we have considered. To this component must be applied the phase correction terms calculated in section 4.4. If the range of distances from aerial to core is now restricted, in this case to 300 m., on multiplying further by the primary energy, one obtains an estimate, in arbitrary units, of the pulse height expected for each shower, for each of the four models.

Histograms plotted for the four models should indicate the model responsible for the radiation, for there should be a strong peaking of the radio showers towards the higher predicted pulse heights. However, each model would be expected to show some preference for higher predicted pulse heights, since, as has already been shown, there is a preference for higher primary energies. It should be pointed out that for the three polarisation predictions geomagnetic, radial, and vertical, it is reasonable to assume that the radiation would be coherent, and should therefore depend linearly on the number of particles in the shower. However, if the radiation is unpolarised, then it must also be incoherent, and would be expected to depend on the square root of the number of particles, and therefore on $(Ep)^{\frac{1}{2}}$. It is not clear how this will affect the results.

Rather than present all the histograms, a simple numerical method has been used to examine the data. For each model, the numbers of radio showers with predicted pulse heights greater than, and less than, the median value have been found.

For the 32 MHz. radio emission, which other methods of analysis have shown to be geomagnetically induced, the results for the 83 radio showers falling within 300m. of the aerial, are as follows:

Polarisation model	$>$ Median	$<$ Median
Geomagnetic	71	12
Radial	54	29
Vertical	46	37
Unpolarised	56	27

As with the other methods of analysis, this method clearly indicates that geomagnetic deflection is the dominant mechanism at 32 MHz.. However, it is also interesting to consider the numbers for the other three models. The data seem slightly to favour radially polarised, or unpolarised, rather than vertically polarised radiation. One explanation for this is that the radio showers arrive mainly from the Northern quadrant, while for the vertical polarisation model, showers from the North would give a larger pulse in the North-South, rather than the East-West direction. Using the same argument, however, one might have expected an apparent preference for the unpolarised radiation model, since this model predicts a larger pulse on the East-West aerial for showers from the North or South quadrants. This could be interpreted as suggesting that the observed ratio for the radial polarisation model is somewhat higher than would be expected for a random set of showers with these energies, and therefore there may be very slight evidence for some degree of radial polarisation. However, these last few arguments are extremely qualitative, and all that can really be deduced from the data is that at 32 MHz., geomagnetic charge separation is definitely the dominant mechanism.

The situation is much less clear at 44 MHz.. Consider first the data for the East-West aerial, on which 50 radio events were recorded out of 424 showers falling not more than 300m. from the aerial.

Polarisation Model	> Median	< Median
Geomagnetic	40	10
Radial	33	17
Vertical	30	20
Unpolarised	37	13

On the North-South aerial, 57 radio events were recorded out of the 424 showers.

Polarisation Model	> Median	< Median
Geomagnetic	48	9
Radial	39	18
Vertical	36	21
Unpolarised	46	11

For both the aerials, the geomagnetic model emerges as the most likely, but in each case there seems to be also a good case for the radiation being unpolarised. As was pointed out previously, these two models are to some extent related in their polarisation predictions. In order to attempt to resolve this difficulty, the actual pulse amplitudes, which have not so far been considered, will be analysed in the next section.

5.8 The Integral Pulse Height Spectrum at 44 MHz.

A comparison of the pulse amplitudes on the two 44 MHz. channels with the ratio expected under each polarisation model for each shower, does not show a preference for any particular model, which is not surprising since neither do other methods of analysis. However, from the integral pulse height spectrum a rather tentative prediction about the nature of the radiation mechanism can be made.

The integral primary energy spectrum of showers recorded by the Haverah Park array has an average exponent of -2 above about 3.10^{17}eV and -1 below this energy. If the radio emission from showers is fully coherent, then we would expect the integral pulse height spectrum to have the same slope as the primary energy spectrum, since the pulse energy should be proportional to the square of the total number of particles. If the radiation is incoherent, then the slope should be twice as steep.

The integral pulse height spectrum for all the 44 MHz. radio pulses is shown in fig. 5.9. The slope above 35uV is -2.6, which would seem to imply mainly, but not fully, coherent radiation. However, since no definite functional relationship has been established between pulse amplitude and the main shower parameters, Ep, R, θ and Ø, it is doubtful whether this slope is at all meaningful. For what it is worth, the value can be compared with the -3 obtained by Jones at 60 MHz., which could indicate that the radiation is more coherent at the lower frequency. This would fit in with the expected onset of decoherence at higher frequencies due to the shower front thickness. Taken in conjunction with the results of section 5.7, this result can be interpreted as suggesting that the radiation at 44 MHz. is more likely to be coherent geomagnetically-induced radiation then incoherent unpolarised radiation.

5.9 The Percentage of Showers Giving Radio Pulses.

A comparison of the fractions of showers giving radio pulses at the two frequencies should give some indication of the relative merits of the various theories. Only the two East-West channels have been used in making this comparison, and to take account of the difference in the aerial dimensions, the pulses above 35uV at 32 MHz. have been compared with the pulses

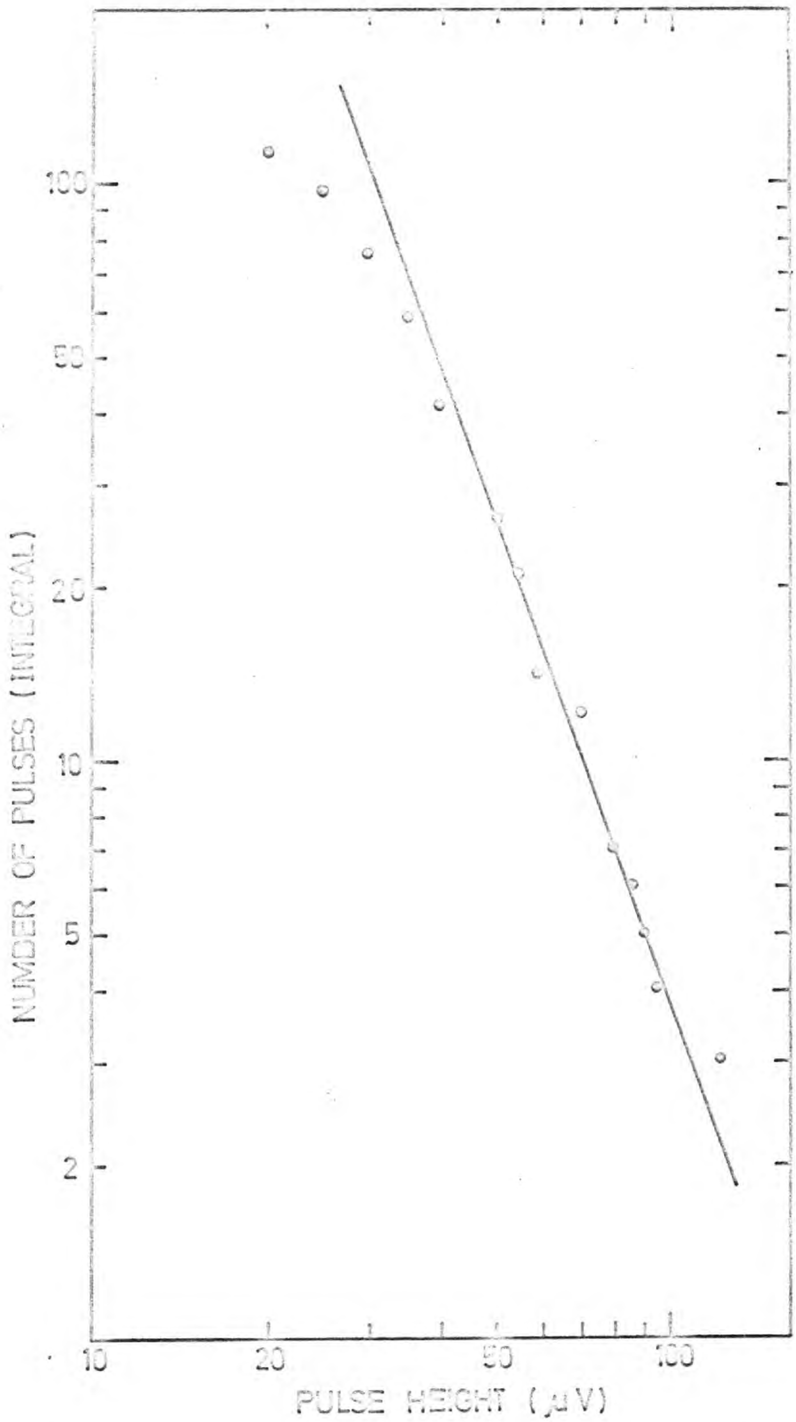


FIG. 5.9 44 MHz INTEGRAL PULSE HEIGHT SPECTRUM.

bandwidth ....

$10 \times \frac{4}{3} = 13.3$

above 25µV at 44 MHz..

With these restrictions, we find that 10% of all showers gave a pulse at 32 MHz., and 7.2% at 44 MHz.. It is of interest to know how the percentages vary with distance from the core and with primary energy. Fig.5.10 shows the variation with distance from the core. At 32 MHz. the percentage varies little between 0 and 300m., whereas at 44 MHz. there is a very steep falling off from close to the core. It is rather surprising that a higher percentage is recorded at 44 MHz. than at 32 MHz. for the interval 0-100m.. The general picture, however, is that the higher frequency radiation is restricted to distances close to the core. The overall percentages can be compared with the figure of less than 5% recorded by Jones at 60 MHz., and the indications are that less is observed at higher frequencies due to decoherence.

In fig.5.11 is shown the variation of the percentage of radio showers with primary energy. As expected, there is a considerable increase towards higher energies, but no significant difference appears between the two frequencies.

5.10 Corellation with the Gross Features of the Showers.

When the experiments at 32 MHz. and 44 MHz. were started, it was hoped that a functional relationship might be established between the radio pulse amplitude A and the parameters of the shower. This might take the form:

$$A = Ep^{a} . R^{b} . f(\theta,\phi) . g(\lambda)$$

Both $f(\theta,\phi)$ and $g(\lambda)$, which indicate the way in which

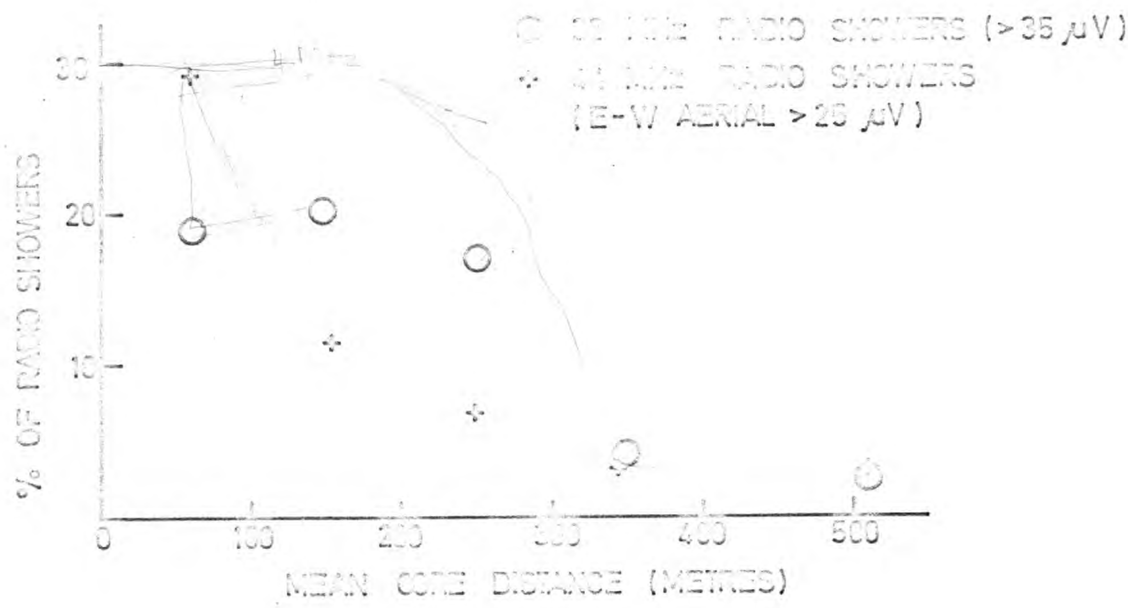


FIG. 5.10 VARIATION OF % OF RADIO SHOWERS WITH CORE DISTANCE

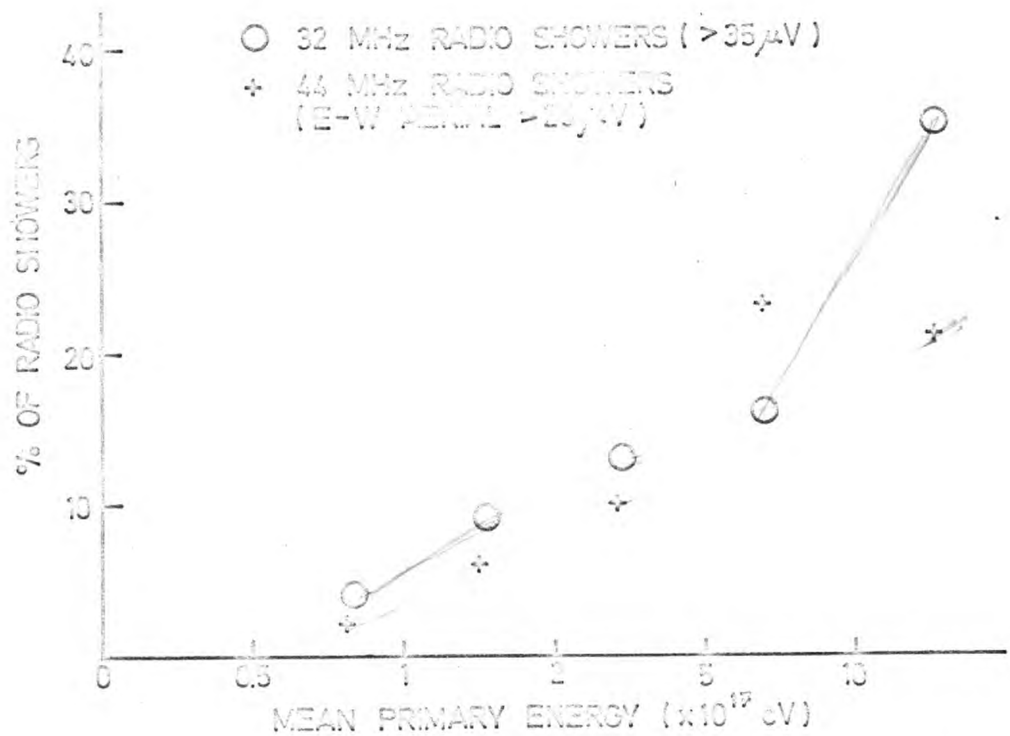


FIG. 5.11 VARIATION OF % OF RADIO SHOWERS WITH PRIMARY ENERGY

the radio emission varies with the shower arrival directions, and with the recording wavelength, have to some extent been determined in the preceding results. Thus $f(\theta,\phi)$ is a function which is largest for showers making large angles with the geomagnetic field, while $g(\lambda)$ increases towards longer wavelengths.

In order to investigate the dependence on Ep, the 32 MHz. data was split up into three distance intervals, and the variation of the percentage of radio showers with Ep is plotted in fig.5.12. Bearing in mind that some of the points on the graph represent only very few showers, the percentage of radio showers can be said to increase roughly linearly with Ep. Assuming that the percentage observed is related to the amplitude expected, we can tentatively suggest that for a given core distance interval, the radio pulse amplitude increases linearly with Ep.

Fig.5.13 shows the percentage variation with distance for three Ep intervals. In this case no obvious power law dependence is evident. As was stated earlier, the percentage of radio showers is almost constant out to 300m., beyond which it falls off steeply. However, it should be noted that from showers larger than 5.10^{17}eV, more than 10% give radio pulses even beyond 500m. from the core.

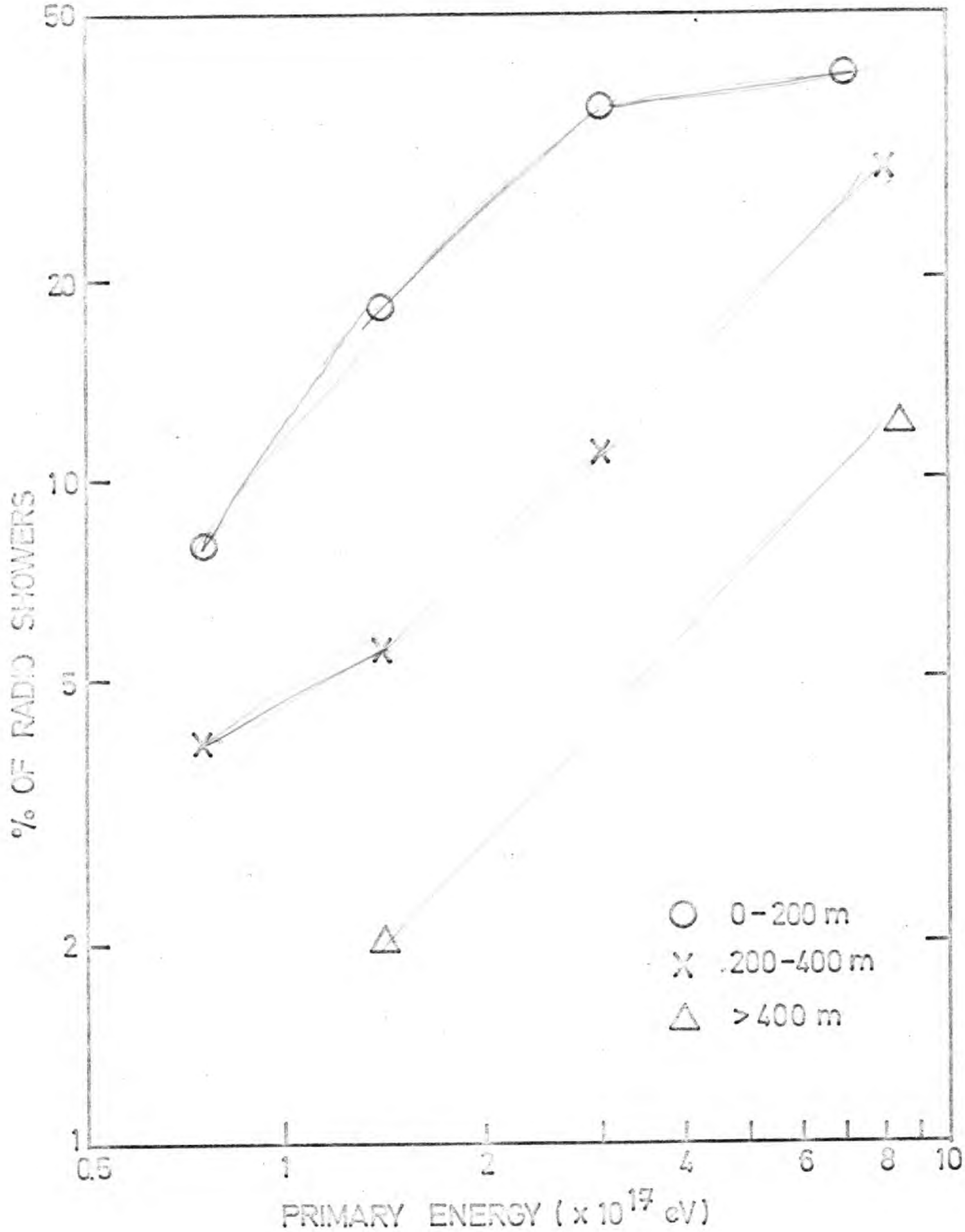


FIG. 5.12 VARIATION OF % OF 32 MHz RADIO SHOWERS WITH Ep FOR DIFFERENT DISTANT INTERVALS.

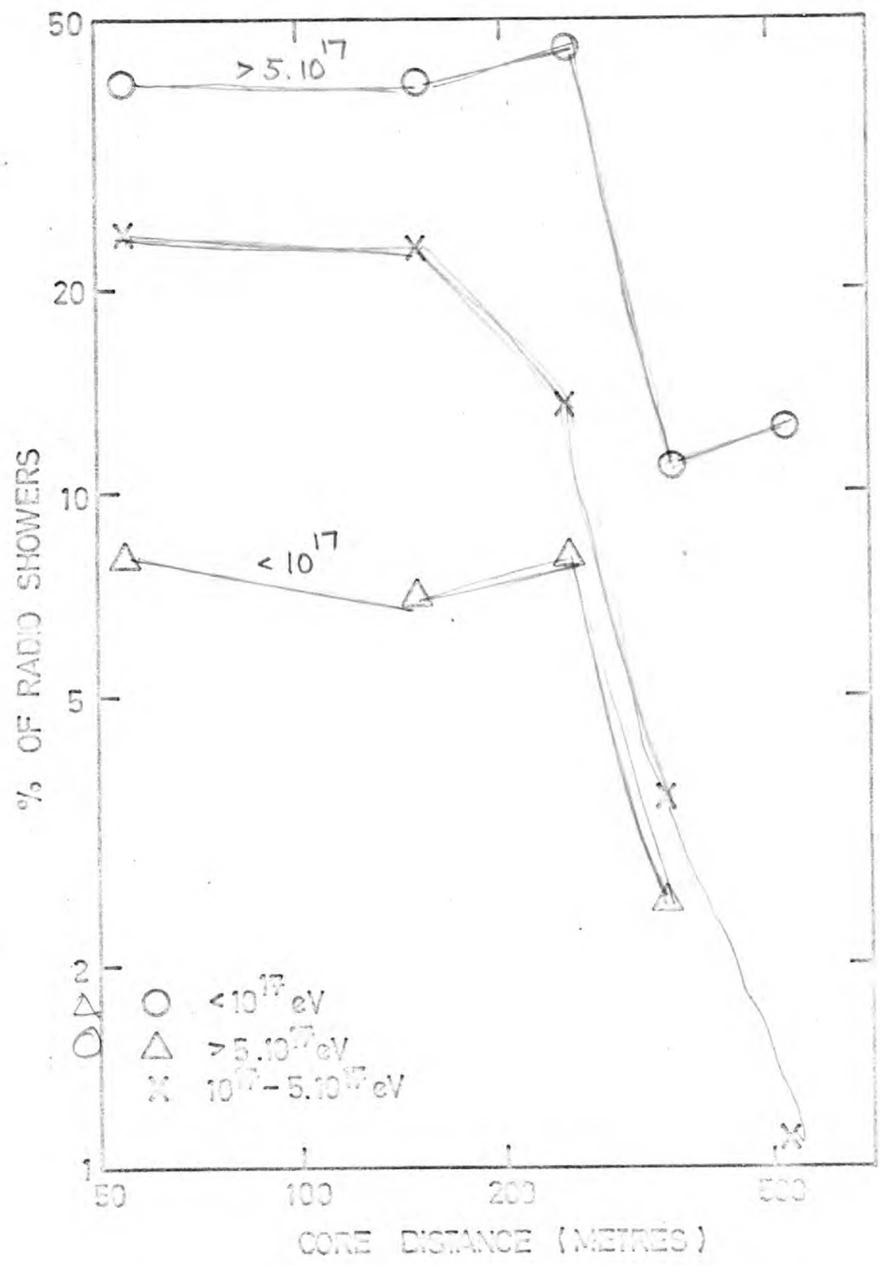


FIG. 5.13 VARIATION OF % OF 32 MHz RADIO SHOWERS WITH DISTANCE FOR DIFFERENT Ep INTERVALS.

CHAPTER SIX

DISCUSSION AND FUTURE WORK

6.1 Discussion of Results.

The results presented in the previous chapter are now discussed, and a comparison is made with the results of other experiments.

The most important result which has been decided is the nature of the polarisation of the radiation at 32 MHz.. There is no doubt that the mechanism which is dominant at this frequency is the separation of opposite charges in the earth's magnetic field. On the other hand, the 44 MHz. results indicate that no particular mechanism dominates at the higher frequency. These polarisation results fit in with the overall picture from other experiments. At frequencies around 30 MHz. and below, reliable evidence for the geomagnetic charge separation mechanism has now been obtained in three separate experiments, at Moscow, Calgary and Haverah Park. At frequencies above 40 MHz., on the other hand, several experiments have failed to reveal the radiation mechanism.

The explanation for this apparently sudden transition between the radiation at 32 MHz. and at 44 MHz. is probably that at the higher frequency, decoherence is already setting in. At wavelengths which are much greater than the assumed shower front thickness, then correlation is to be expected between the radio pulse and the gross features of the shower. At shorter wavelengths, the fine structure of the shower will become important, and so poorer correlation with Ep, R, θ, and Ø is to be expected.

The percentage of showers with associated radio pulses was found to be higher at 32 MHz. than at 44 MHz.. This fits in with the ideas of Colgate and Allan, who predict a low optimum frequency. It seems that a Cerenkov-like dependence on frequency is ruled out, unless the frequency at which decoherence begins to set in has been over-estimated.

Mention should be made here of the Dublin experiment, in which radio emission from showers was observed at 520 MHz.. Following the theory of Allan, one expects to observe the high frequency components of the radiation from showers falling very close to the aerial, or from showers at large zenith angles. However, at such a very high frequency, the radiation is expected to be totally incoherent, and the intensity expected is negligible. If we continue the argument stated above, then this radiation must reflect the extremely fine structure of the shower. Thus it is probable that no correlation with the gross features of the shower are to be expected. However, it is important that the Dublin result should be confirmed with a particle-detecting array.

Even though no actual pulse amplitudes were available, the 32 MHz. results have to some extent indicated how the pulse amplitude expected should vary with the gross features of the shower. It would be useful if we could find a category of showers with which a radio pulse above a certain threshold was always observed. We can refer back to fig.5.6, which is restricted to showers of primary energy greater than 2.10^{17}eV, falling closer than 200m. to the aerial, and with zenith angle less than 50°. It is evident that all the 13 showers arriving within 60° East or West of magnetic North, and therefore making appreciable angles with the magnetic field direction, produce an observable radio pulse at 32 MHz.. The 100% success achieved for this category of showers shows that at 32 MHz., the radio emission is largely dependent on the large-scale features of the shower, and not just on favourable fluctuations in its longitudinal development.

From the 32 MHz. data, we have also deduced that the radio pulse amplitude is expected to vary roughly linearly with Ep. This agrees with the 30 MHz. results reported from Moscow, where good correlation was established between the radio power and $(N\mu)^2$. However, our results on the lateral distribution of the radio emission do not agree well with those from Moscow. The Russian workers found that the radio power fell off roughly as R^{-2}: this is equivalent to the radio amplitude falling off as R^{-1}. Our 32 MHz. results, on the other hand, suggest that the radio emission is fairly constant out to 300m., beyond which it falls off steeply.

6.2 Future Work.

We must first discuss, in the light of the experimental results so far obtained, the feasibility of detecting large showers using radio methods alone. At frequencies of around

30 MHz. and below, the radiation has been found to be restricted to those showers whose axes make appreciable angles with the geomagnetic field direction. This means that a radio detection method will always detect more showers arriving from the North than from the South. Thus the solid angle from which showers can be detected will be restricted, and measurements of isotropy will be very difficult. In these respects, it seems that radio methods will always be inferior to the conventional particle-detecting methods.

On the other hand, we have found that for a shower which arrives favourably inclined with respect to the magnetic field direction, we can confidently predict that a radio pulse will be observed provided that the shower is larger than 2.10^{17}eV and falls within 200m. of the aerial. We have also found that the percentage of radio showers increases linearly with Ep, and from this it can be predicted that the pulse amplitude will also increase linearly with Ep. However, the variation with distance from the axis is not well understood. Since for a given zenith angle, larger showers reach their maximum development lower in the atmosphere, it would not be expected that the lateral spread of the radiation should increase a great deal with Ep. This is not very encouraging, since we would like to be able to observe the radio emission from showers at distances of the order of kilometres if the method is to be feasible. If the radio detectors can be widely spaced, this also has the advantage of eliminating local interference, as was explained in chapter 3.

The only other possibility is to look at showers arriving at very high zenith angles, as has been suggested by Colgate. However, a major difficulty now arises. The secondary shower particles due to primaries which arrive almost tangential to the earth's surface are mostly absorbed before they reach sea level. For these showers it will be almost impossible to obtain any correlation between particle and radio data. To make any use of the radio data, it will be necessary to trust theoretical expectations.

Although the prospects for the radio detection of very large showers may not be too bright, there is good reason to believe that a radio detection system used in conjunction with a particle-detecting array could give information on the primary composition. If a reasonable correlation can be obtained between the pulse amplitude and the shower parameters, then closer examination of the pulse structure and amplitude may reveal information about the longitudinal development, in particular the height of the first interaction, which depends upon the charge of the primary.

With these ideas in mind, experimental work at Haverah Park is continuing. A second 32 MHz. channel has been set up, the aerial being orientated North-South, and the gains of both channels have been adjusted so that it is hoped that the pulse amplitudes will be measurable. Thus more accurate information on the functional relationship between the radio amplitude and the shower parameters should be available, and also the polarisation of the radiation can be studied in individual showers. The 44 MHz. aerials have now been moved to the aerial site C (see fig.4.1) and the two channels will continue to be operated in the hope that the radiation mechanism can be discovered.

The results presented in this thesis have been mainly confined to showers of primary energies less than 10^{18}eV. The Haverah Park 2Km. array is now in operation (Earnshaw et al., 1967), and this opens up the exciting possibility of correlating radio data with particle data from showers of primary energies greater than 10^{19}eV. Of particular interest will be the lateral spread of the radiation from these very large showers.

Although both Colgate and Allan predict that the optimum frequency of the radio emission will be less than 20 MHz., no measurements have yet been made at such low frequencies, mainly due to the high background of man-made interference. Allan (Private Communication) has suggested that a favourable signal to noise ratio may be obtained using a broadband aerial with a flat frequency response up to about 15 MHz.. An experimental arrangement based on these ideas is soon to be tested at Haverah Park. The results should prove to be of considerable interest, since it is not clear that conventional receivers provide the best means of amplifying sharp pulses. If recording does prove feasible at around 10 MHz., the radio emission would be expected to show very good correlation with the large-scale shower parameters.

At the other end of the frequency scale, an aerial and receiving system at 408 MHz. are being set up, in the hope of confirming the surprising Dublin result, in which ultra-high radio frequency radiation, thought to be associated with showers, was observed. Although correlation with all the shower parameters is not expected, it is possible that the high-frequency radiation may be associated only with a certain type of shower, and so the system will be triggered as usual by the main particle-detecting array.

APPENDIX

Formulae used in the Analysis of Results

We first of all set up a right-angle co-ordinate system (x,y,z) in which the three directions are:

x - magnetic East, y - magnetic North, z - vertically upwards.

The zenith angle θ, of the arrival direction of a shower is measured from the vertical, while the azimuth angle ϕ is measured East of Magnetic North. The bearing, East of magnetic North, of the point of impact on the ground of the shower axis, relative to the receiving aerial, is called ψ. The Earth's magnetic field lies in the yz (North-South) plane, and makes an angle D, the Dip Angle, with the horizontal. At Haverah Park D is about 68.7°.

If L is the distance along the ground between the aerial and the point of impact of the shower axis, then the perpendicular distance, in the plane of the shower front, is given by $R = L(1 - \sin^2\theta\cos^2(\phi - \psi))^{\frac{1}{2}}$

The components in the three directions of the radiation expected from the four models are now given. These formulae assume that the arrival direction of the radiation at the receiving aerial is similar to that of the shower axis. This approximation is very good for showers falling close to the aerial, and even at a distance of 600m., assuming that the radiation originates at a typical height of 6 Km., the error is only about 6°.

Radial Polarisation (Askaryan enhanced Cerenkov mechanism)

x $\sin\psi - \sin^2\theta \sin\phi \cos(\phi - \psi)$

y $\cos\psi - \sin^2\theta \cos\phi \cos(\phi - \psi)$

z $-\sin\theta \cos\theta \cos(\phi - \psi)$

To give the direction cosines, these should all be divided by

$$(1 - \sin^2\theta \cos^2(\phi - \psi))^{\frac{1}{2}}$$

Geomagnetic Deflection (Kahn and Lerche, Allan, Colgate)

x $\sin\theta \cos\phi \sin D + \cos\theta \cos D$

y $-\sin\theta \sin\phi \sin D$

z $-\sin\theta \sin\phi \cos D$

'Vertical' Polarisation (Charman electric field mechanisms)

x $\cos\theta \sin\phi$

y $\cos\theta \cos\phi$

z $\sin\theta$

Unpolarised Radiation

x $(\cos^2\theta \sin^2\phi + \cos^2\phi)^{\frac{1}{2}}$

y $(\cos^2\theta \cos^2\phi + \sin^2\phi)^{\frac{1}{2}}$

z $\sin\theta$

To give the direction cosines these should be divided by 1.414.

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ADDENDUM

IMPLICATIONS OF THE EXPERIMENTAL RESULTS

In the previous chapters, the results of our observations of the radio emission from extensive air showers have been presented. The aim of this additional chapter is to relate these results to our present knowledge of shower structure. We will then be in a position to assess the possibility of using the radio technique to obtain new information on shower characteristics or the primary particles. First of all we will briefly summarize the experimental evidence.

We found previously that our results were not inconsistent with the radio pulse amplitude varying linearly with the primary energy E_p. Since then the author has been working at the Moscow State University E.A.S. Station, and the latest results from there agree with a linear dependence on E_p (Vernov et al., 1969).

With regard to the lateral distribution of the radio emission, we found that the percentage of radio showers did not vary appreciably with distance from the core out to about 300m., beyond which there was a rapid fall. The more recent results from Moscow, where the lateral distribution function can be measured in individual showers, suggest a dependence of pulse amplitude roughly $\propto R^{-1}$ in the region out to 300m. Beyond this a rapid steepening of the lateral distribution function is observed.

Our results suggest that the radio pulse amplitude falls off with increasing frequency between 30 MHz and 44 MHz. This effect has since been confirmed over a range of frequencies from 44 MHz to 408 MHz at Jodrell Bank. (Spencer, 1969). Over this frequency range, the field strength per unit bandwidth E_ν is roughly proportional to $1/\nu$.

Our results on the polarization of the radio emission strongly favoured the geomagnetic mechanism at 32 MHz, but only weakly at 44 MHz. The more recent Haverah Park measurements indicate that the conclusions drawn on the 44 MHz data may have been erroneous due to contamination by noise pulses, and that the evidence for the geomagnetic mechanism at this frequency is also strong. (Allan et al., 1969). However, the North-South asymmetry expected due to this mechanism has not been observed at Jodrell Bank at this frequency (Smith et al., 1968) and so it is interesting to speculate on possible causes of an apparent change in the radiation mechanism.

The most important factor determining the relation between the radio pulse amplitude and the shower characteristics is the degree to which the shower particles radiate coherently. This can depend upon the longitudinal devel opment of the shower, the lateral spread of the shower particles, and the wavelength considered, and we will show how these can affect the lateral distribution of the radio emission, the dependence on E_p , and the polarization observed.

We will firstly consider the longitudinal development of the shower. For a shower in the energy range 10^{17}ev - 10^{18}ev the height at which the number of shower particles becomes significant is $\sim$ 10 Km. (The value we use is not critical). We will call this height H_2 and for an observer at a distance R from the shower axis, observing at wavelength λ , we will calculate down to what height H_1 the radiation from the shower particles close to the axis will be coherent. If we ignore the refractive index of the air, it can be shown that the path difference for radiation from the two heights is approximately $R^2 (H_2 - H_1) / 2H_1H_2$. (see fig. 1) The problem is analogous to that of Fresnel diffraction, and for coherence this path difference should be $\lesssim \lambda/2$. If we consider two positions for the observer, at distances of 200m. and 400m., and the two observing frequencies 30MHz and 44MHz, we obtain the following minimum values for H_1:-

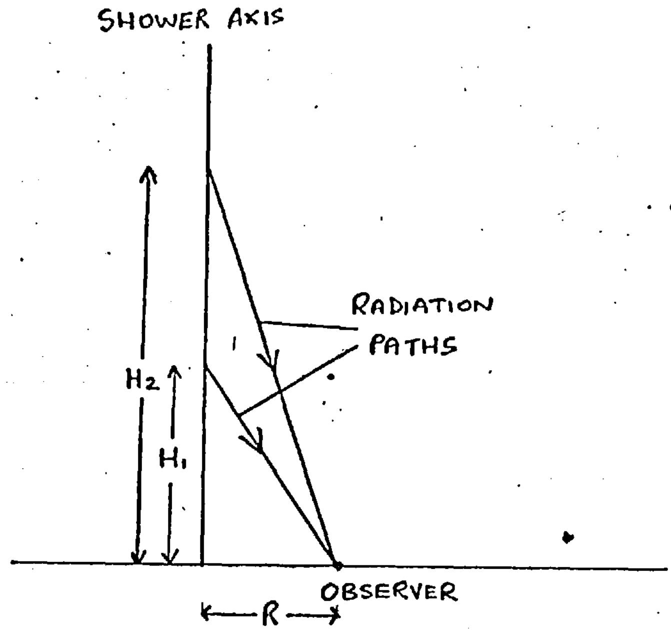

FIG. 1. TO ILLUSTRATE THE EFFECT OF LONGITUDINAL DEVELOPMENT.

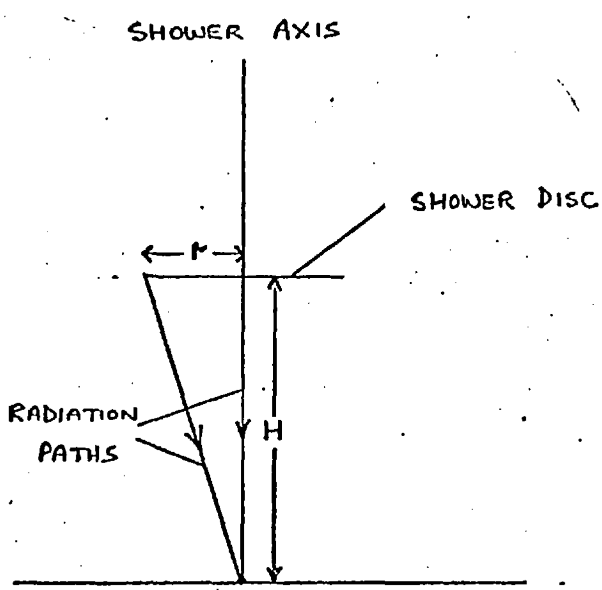

FIG. 2. TO ILLUSTRATE THE EFFECT OF LATERAL SPREAD.

	30 MHz		44 MHz	
R(m.)	200	400	200	400
H_1(Km.)	3	6.5	4	7.5

In the following table we give the approximate heights above sea level of maximum development for vertical showers of primary energy between 10^{16}ev. and 10^{19}ev.

E_p(ev)	10^{16}	10^{17}	10^{18}	10^{19}
H(Km.)	5	3.5	2	1

There are two conclusion that we can draw from a comparison of the two tables. Firstly, for showers with $E_p \sim 10^{17}$ev, and for R = 200m., almost all the shower particles on the axis up to shower maximum will radiate coherently at both frequencies. For R = 400m., on the other hand, the length of the shower which can contribute is reduced to less than one half, and so we would expect an appreciable fall in the radio pulse amplitude between these distances. Also if we increase the primary energy, so that the shower maximum occurs lower in the atmosphere, decoherence begins earlier at higher frequencies. Thus from this simple model, we would expect the frequency spectrum between 30 MHz and 44 MHz for an observer at 200m. to be fairly flat for a 10^{17} ev shower but to fall with increasing frequency for a 10^{18} shower. For a shower of even higher primary energy, we would expect a steeper fall-off.

We have so far only taken into account the longitudinal development of the shower. We must also consider the lateral spread of the shower particles which also causes diffraction effects. Referring to fig. 2, if we assume as a first approximation that the shower front is plane, then for an observer situated on or close to the axis we must evaluate the path difference between radiation from particles on the axis and at a distance r . This is given very nearly by $r^2/2H$, and if we let this have a maximum value of $\lambda/2$ we obtain the relation $r = (\lambda H)^{\frac{1}{2}}$.

Using this formula, we can calculate the radius within which particles must lie in order to radiate coherently from a height H. We can convert this into a minimum value for the energy of the particles (since low energy electrons are scattered more) remembering that the characteristic shower dimensions, such as disc thickness, front curvature and lateral spread, are related to the radiation length which is a constant in airwhen measured in gm.cm^{-2}, but when measured in metres, varies with the atmospheric depth. Thus for a height of 8 Kms., generally taken as the scale height of the atmosphere, all such dimensions will have approximately e times their values at sea level. In order to estimate the average lateral displacement of electrons of energy E in a shower, we refer to Galbraith (1958). The r.m.s. Coulomb scattering angle is given roughly by $\phi = {}^{20}/E$ radians per radiation length where E is in MeV. The radiation length in air is 37.7 gm.cm^{-2} which varies with atmospheric height from 380m. at 2Km. to 1050 m. at 10 Km. The typical lateral spread S of particles of energy E is given by the radiation length times the typical scattering angle. Thus the typical lateral displacement of particles at 2Km. is $\sim 8 \times 10^3/E$ metres (with E in MeV) which varies to $2.2 \times 10^4/E$ metres at 10Km.

We can now consider the case of an observer situated on the axis. The following tables give for various heights the radius at which the radiation begins to lose coherence, as well as the typical electron energy at this distance.

λ = 10m.

H (km.)	2	4	6	8	10
r (m.)	140	200	245	280	310
E (Mev)	57	52	55	61	71

$\lambda = 6.8m.$

H (Km.)	2	4	6	8	10
r (m.)	120	165	200	235	260
E (Mev)	67	64	67	72	85

Thus although at higher altitudes the radius over which shower particles can radiate coherently naturally increases, this is compensated by the change in atmospheric pressure, so that the typical electron energy at this distance and the fraction of contributing particles remain approximately constant. The above tables also indicate that fewer particles will contribute coherently at the higher frequency, so that we would expect to see a falling-off of the frequency spectrum.

The case with the observer situated at an appreciable distance from the core is more complex, since the particles on the radius of a disc are not all at the same distance from the observer, and the problem should be treated 3-dimensionally. Obviously the fraction of the total number of particles which can contribute coherently will decrease as R increases, since the density of particles is greatest on the axis. In addition, the average energy of the contributing particles will become lower. On the other hand, there is no reason why the conclusion drawn for the case of the observer on the axis, namely that the fraction of particles contributing coherently remains roughly constant with height, should be substantially different.

We should mention here two factors which have been ignored in our analysis. The first is the effect of the refractive index of the air which causes radiation to travel slower than relativistic particles. As a result, radiation from high in the atmosphere is delayed relative to that from lower in the atmosphere, but the additional path difference is only $\sim$ 1m. which will not seriously affect our conclusions.

The curvature of the shower front should also be taken into account in an exact analysis. The effect will be to further reduce the radius within which particles can radiate coherently.

We can now discuss the expected dependence of the radio emission on the primary energy E_p. If showers of different primary energies had similar longitudinal developments, then for a fixed distance R we would expect a linear dependence on E_p since the fraction of particles able to contribute coherently would be roughly constant. But we know that as E_p increases the position of maximum development occurs lower in the atmosphere. We have also shown in this case that the length of the shower which can radiate coherently will decrease, and so a dependence on E_p^{α}, where α is less than unity, should be expected. Against this we should point out that the triggering requirement of an array such as Haverah Park selects showers such that the mean zenith angle increases as E increases, so that the maximum development occurs progressively higher relative to a vertical shower. From this it is evident that there are many factors to take into account, and it is very difficult to predict how the radio pulse amplitude should vary with E_p. All we can say is that we should not necessarily expect a linear dependence on E_p.

Our analysis has shown that the diffraction effects due to both longitudinal development and to lateral spread become more serious as the distance R increases. In particular, we noticed a significant decrease in the length of shower which can contribute coherently as R increases from 200m. to 400m. This is in good agreement with the experimental results which show a slow fall-off with R out to $\sim$ 300m., followed by a rapid steepening of the lateral distribution function.

Our analysis has shown that the 'Fresnel volume', the volume within which shower particles must be in order to radiate coherently becomes smaller as the wavelength decreases. If we assume the frequency spectrum of the radiation actually emitted to be roughly constant, then we would expect to observe a falling-off of the radio emission with increasing frequency. Would we expect to observe a change in the radiation mechanism as the frequency increases? As the frequency increases, only the increasingly high energy particles can contribute coherently to the radiation, whereas it is the low energy particles which contribute most to the transverse current of the geomagnetic theory. Thus it is possible that some mechanism which depends upon the radiation of high energy particles could become comparable with the geomagnetic mechanism. But this could hardly be the Cerenkov mechanism, since although an excess of negative electrons no doubt exists at high energies (due to positron annihilation), the excess will be much larger at low energies (due to Compton electrons and δ-rays).

The general agreement of experiment and theory with regard to the lateral distribution of the radio emission appears to rule out any possibility of the radio technique being used for the economical detection of ultra high energy showers. Unless measurements can be made at low frequencies, of the order of a few MHz, diffraction effects effectively cut off the radiation beyond a few hundreds of metres from the axis.

The other basic problem of high energy cosmic ray research is the determination of the mass composition of the primaries. Conventional particle-detecting arrays sample the shower at one stage of its development, but the study of the radio emission can give information on the longitudinal development of the shower. It is perhaps premature to speculate on ways in which this might be approached since until some definite relationship can be established with the known parameters of the shower, namely arrival direction, primary energy, and distance from the axis, we cannot expect to be able to obtain any information about an unknown parameter.

ADDITIONAL REFERENCES

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