The Discovery of Radio Pulses from Extensive Air Showers

Trevor Weekes

Harvard-Smithsonian Center for Astrophysics

Summary

- The Pre-history
- The Idea
- The Experiment
- The Results
- The Follow Up

National University of Ireland
Faculty of Science
University College, Dublin

RADIO AND OPTICAL METHODS
OF
DETECTING COSMIC RAYS

Thesis for the degree of
DOCTOR OF PHILOSOPHY

Presented by
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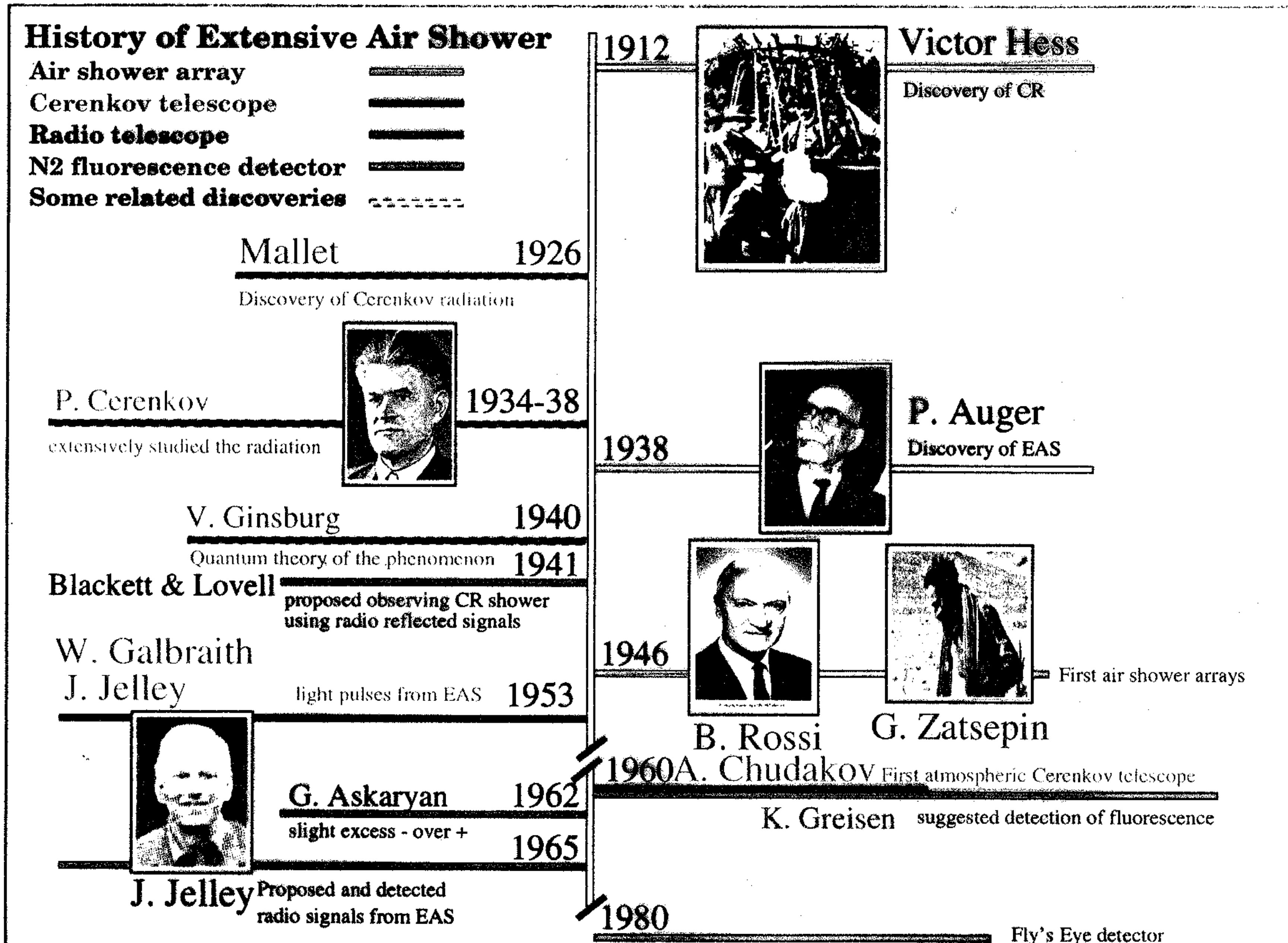
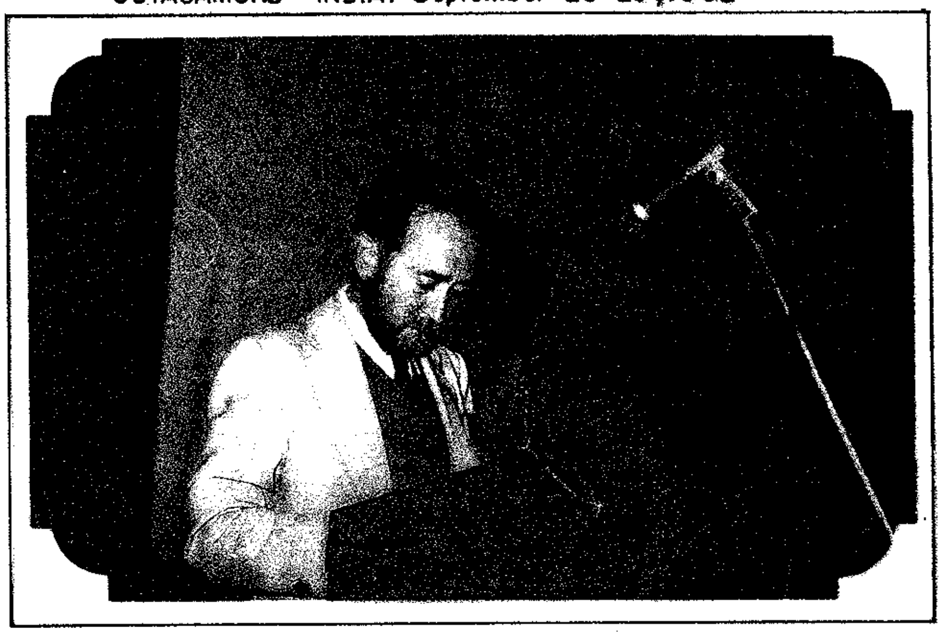
Research Supervisor
N.A. PORTER, PH.D.
Professor of Electron Physics

March, 1966.


History of Extensive Air Shower
Air shower array
Cerenkov telescope
Radio telescope
N2 fluorescence detector
Some related discoveries
1912 Victor Hess
Discovery of CR
Mallet 1926
Discovery of Cerenkov radiation
P. Cerenkov 1934-38
extensively studied the radiation
1938 P. Auger
Discovery of EAS
V. Ginsburg 1940
Quantum theory of the phenomenon
1941 Blackett & Lovell
proposed observing CR shower using radio reflected signals
1946 B. Rossi G. Zatsepin
First air shower arrays
W. Galbraith J. Jelley
light pulses from EAS 1953
1960 A. Chudakov First atmospheric Cerenkov telescope
G. Askaryan 1962
slight excess - over +
K. Greisen suggested detection of fluorescence
1965 J. Jelley Proposed and detected radio signals from EAS
1980 Fly's Eye detector

H. BADRAN

THE INTERNATIONAL WORKSHOP ON VERY HIGH ENERGY GAMMA RAY ASTRONOM
OOTACAMUND – INDIA. September 20-25, 1982



...onsored by Smithsonian Institution, USA and Tata Institute of Fundamental Research, INDIA

How it came about:

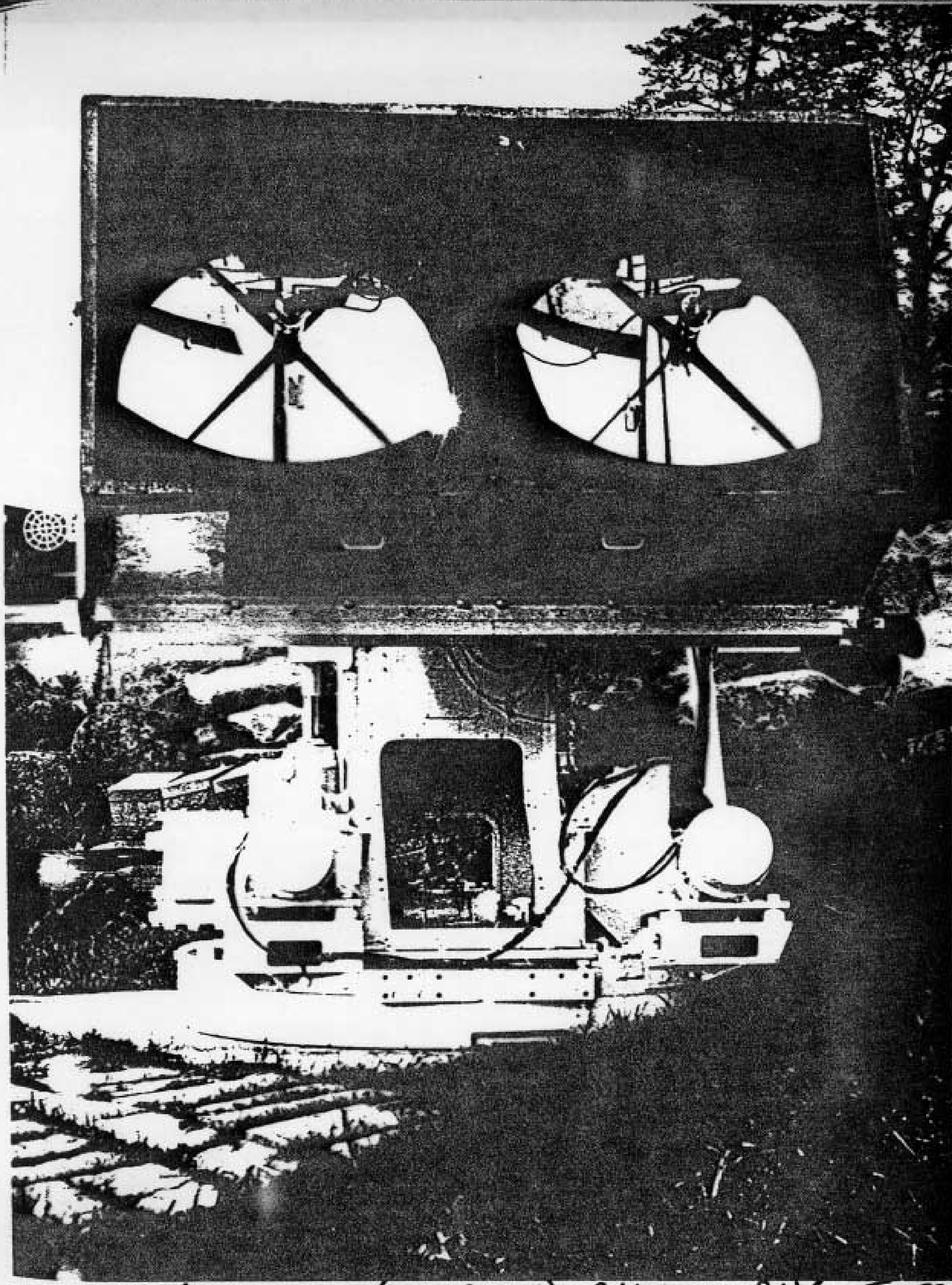
Prehistory:

- Possible Radar detection: Blackett and Lovell (1941)
- Cherenkov Radiation from EAS: Jelley (1958)
- Jodrell Bank Experiment (1947)

The Scene in 1962:

- Collaboration between J.V. Jelley (Atomic Energy Research Establishment, Harwell, U.K.) and
  N.A. Porter (Physics Department, University College, Dublin, Ireland)

- Using the atmospheric Cherenkov Technique
  to do Very High Energy Gamma Ray Astronomy:
  Glencullen, Ireland 1962-66



GLENCULLEN (DUBLIN) GAMMA RAY TELESCOPE
11.3. P.M. System. c. 1964

The Experiment at Jodrell Bank

Sequence of Events:

- Paper in Russian by Alikhanyan on Detection of Neutrinos on Moon; noted by N.A.Porter and brought to J.V.Jelley's attention (1963)
- Paper by Askaryan on detection of radio emission from EAS referenced
- Correspondance between Jelley and Porter re feasibility of experiment to detect radio emission from EAS
- Decision to seek aid of radio astronomers; Jelley and Weekes visit Cambridge and discuss experiment with Ryle and Graham-Smith
- Graham-Smith moves to Jodrell Bank as Assistant Director; Jodrell bank to provide the radio telescope, Harwell-UCD to provide the EAS trigger and manpower
- Some history of cosmic ray studies at Jodrell Bank
- Fear that J.B. would get the credit for successful experiment
- Small EAS array designed at UCD; built and tested at Harwell (Spring, 1964)

Radio Technique:
24 Hours
Sensitive
Inexpensive
Expertise

EXCESS NEGATIVE CHARGE OF AN ELECTRON-PHOTON SHOWER AND ITS COHERENT RADIO EMISSION

G. A. ASKAR'YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 24, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) 41, 616-618 (August, 1961)

We investigate the excess of electrons in an electron-photon shower. This excess is caused by annihilation of the positrons in flight and by the Compton and δ-electrons in the cascade. It is shown that at the maximum of the shower the excess may comprise ten percent of the total number of shower particles. The Cerenkov radiation from this excess charge in a dense medium is estimated. It is indicated that this radio emission from showers produced by high-energy accelerator particles or cosmic rays in blocks of dense matter can be recorded and used. The possibility of recording radio waves from penetrating particle showers in the moon's ground, by apparatus dropped on the lunar surface, and in underground layers on the Earth in which radio waves can propagate, is also noted.

1. EXCESS NEGATIVE CHARGE OF ELECTRON-PHOTON SHOWER

THREE processes contribute to the formation of an excess of electrons in a cascade, namely annihilation of the positrons in flight and dragging of the Compton and δ-electrons into the shower cascade. Let us estimate this excess charge.

We write the equation for the average number of electrons n_- and of positrons n_+ with energies of interest to us in the form

$$\dot{n}_- = \Phi(t) - n_-/\tau_- + \dot{n}_{\delta,\,C}, \quad \dot{n}_+ = \Phi(t) - n_+/\tau_+,$$

where $\Phi(t, n_\pm, n_\gamma)$ is a function of the electron and positron pair production by γ rays and shower particles, $\dot{n}_{\delta,\,C}$ is the number of Compton and δ-electrons with energies of interest to us produced per unit time by the quanta and shower particles, $\tau_\pm$ is the lifetime of the charged particles prior to energy loss to production of the γ quanta. We put $1/\tau_+ = 1/\tau_- + 1/\tau_a$, where τ_a is the lifetime of the positron prior to annihilation.

Subtracting the equation for n_+ from the equation for n_- we obtain for the excess particles $\nu = n_- - n_+$ the equation

$$\dot{\nu} + \nu/\tau_- = n_+/\tau_a + \dot{n}_{\delta,\,C} \approx n_+/\tau_a.$$

The value of ν can be estimated by putting $n_+/\tau_a \approx Ae^{t/T_+}$, where T_+ is the characteristic build-up time of the number of annihilating positrons. For this case we obtain

$$\nu \approx Ce^{-t/\tau_-} + \frac{Ae^{t/T_+}}{1/T_+ + 1/\tau_-} \approx \frac{n_+}{\tau_a(1/T_+ + 1/\tau_-)} \qquad t \gg \tau_-.$$

It is easy to see that $T_+ \sim \tau_-$, and therefore $\nu \sim n_+\tau/\tau_a$. Inasmuch as $\tau \approx l_{rad}/c$ and $\tau_a \approx 1/N_e\sigma_a c$, where the annihilation cross section is

$$\sigma_a \approx \pi r_0^2 (mc^2/E_+) \ln (2E_+/mc^2),$$

and the radiational length

$$l_{rad} = 137/4ZN_e r_0^2 \ln (183/Z^{1/3}),$$

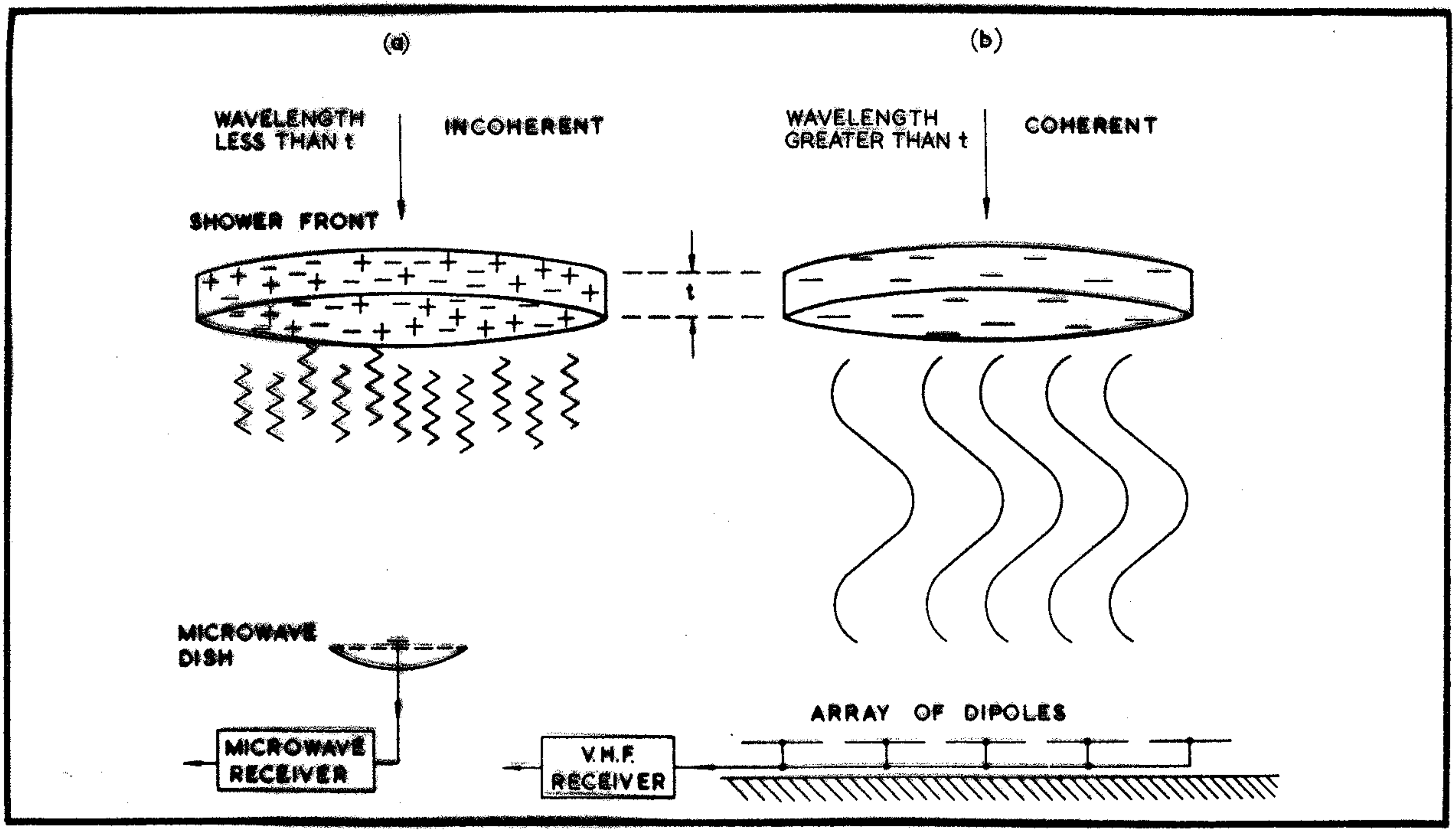
we obtain

$$\frac{\tau}{\tau_a} \approx \frac{137}{4Z}\left(\frac{mc^2}{E_+}\right)\frac{\ln (2E/mc)}{\ln (183/Z^{1/3})} \approx \frac{B}{ZE_+}.$$

This ratio is independent of the density of the medium, and depends only on its atomic number Z and on the particle energy. For example, when $Z \approx 10$, with a mean particle energy at the maximum of shower development $E \approx 10^8$ ev, we obtain $\tau/\tau_a \sim 0.1$, i.e., the number of moving electrons in the shower can exceed the number of positrons by some ten percent.

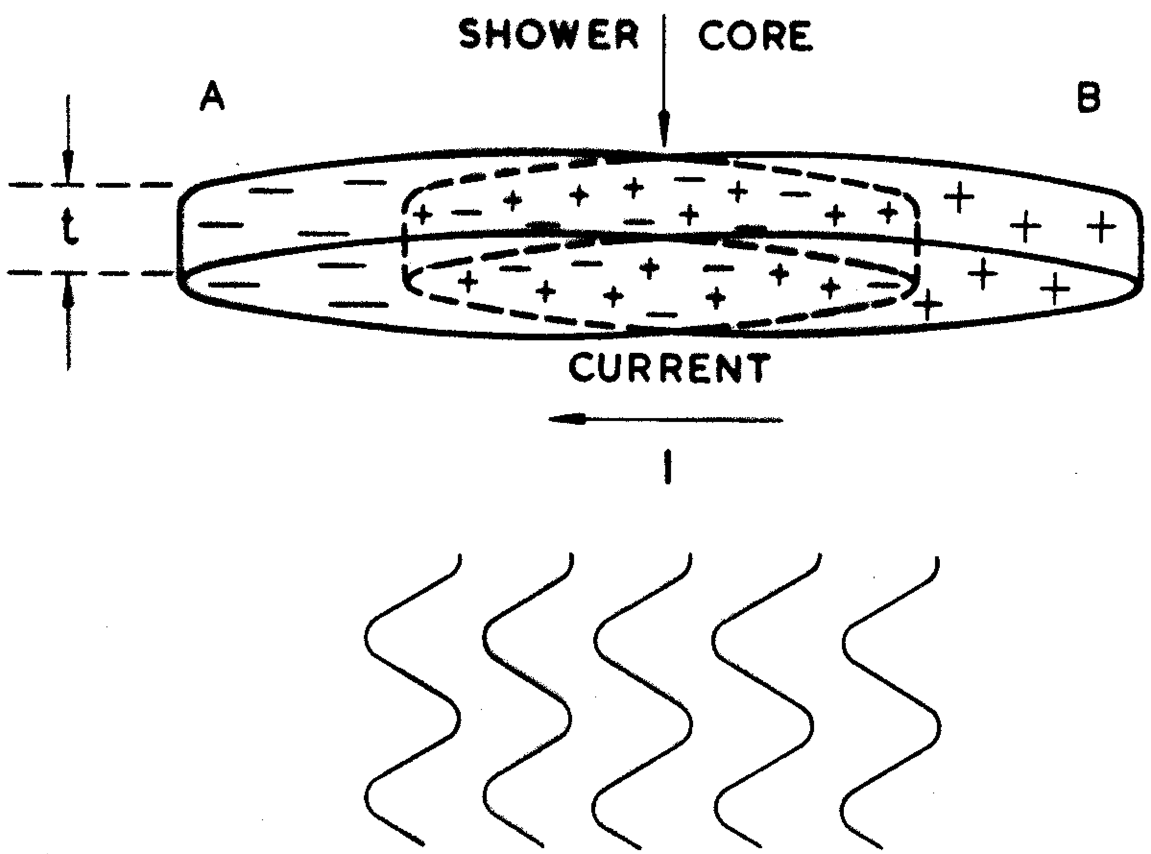
2. COHERENT RADIO EMISSION FROM THE SHOWER

The presence of a moving uncompensated charge in a shower may increase by many orders of magnitude a flash of Cerenkov, bremsstrahlung, or transition radiation in the radio range. Various possibilities of recording cosmic showers by radio emission bursts have been discussed numerous times (see, for example,[1]). Coherent amplification of the radio emission from the excess charge increases the chances of registering



Jelley (1958)   Porter + Jelley (1964)

GEOMAGNETIC EFFECT



COHERENT IF WAVELENGTH IS LONGER THAN t

Kahn + Lerche (1966)

(1) DIPOLE

(2) CURRENT ELEMENT

The Experiment: I

$S \propto \nu . d\nu$

$\propto N$ incoherent

or

$\propto (\varepsilon N)^2$ coherent $\varepsilon \sim 10\%$ Askaryan

$\sim 4\%$

Design

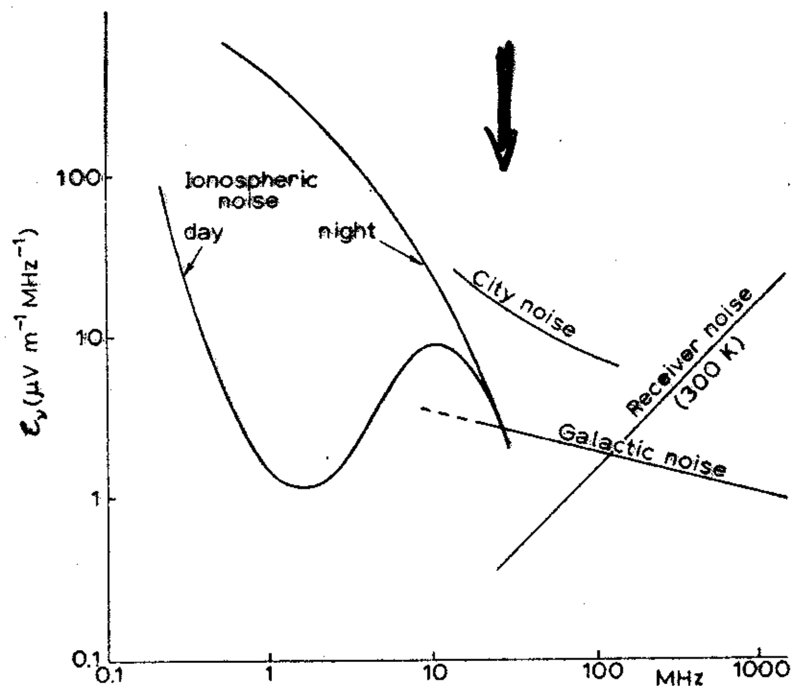
- Choice of Frequency, Bandwidth
- BBC at 44Mhz 00.00 → 09.00 P.M.
- Dipole Array Yes
- Analog Recording
- Background
- Delays
- EAS Trigger

10^{16} eV 4% excess

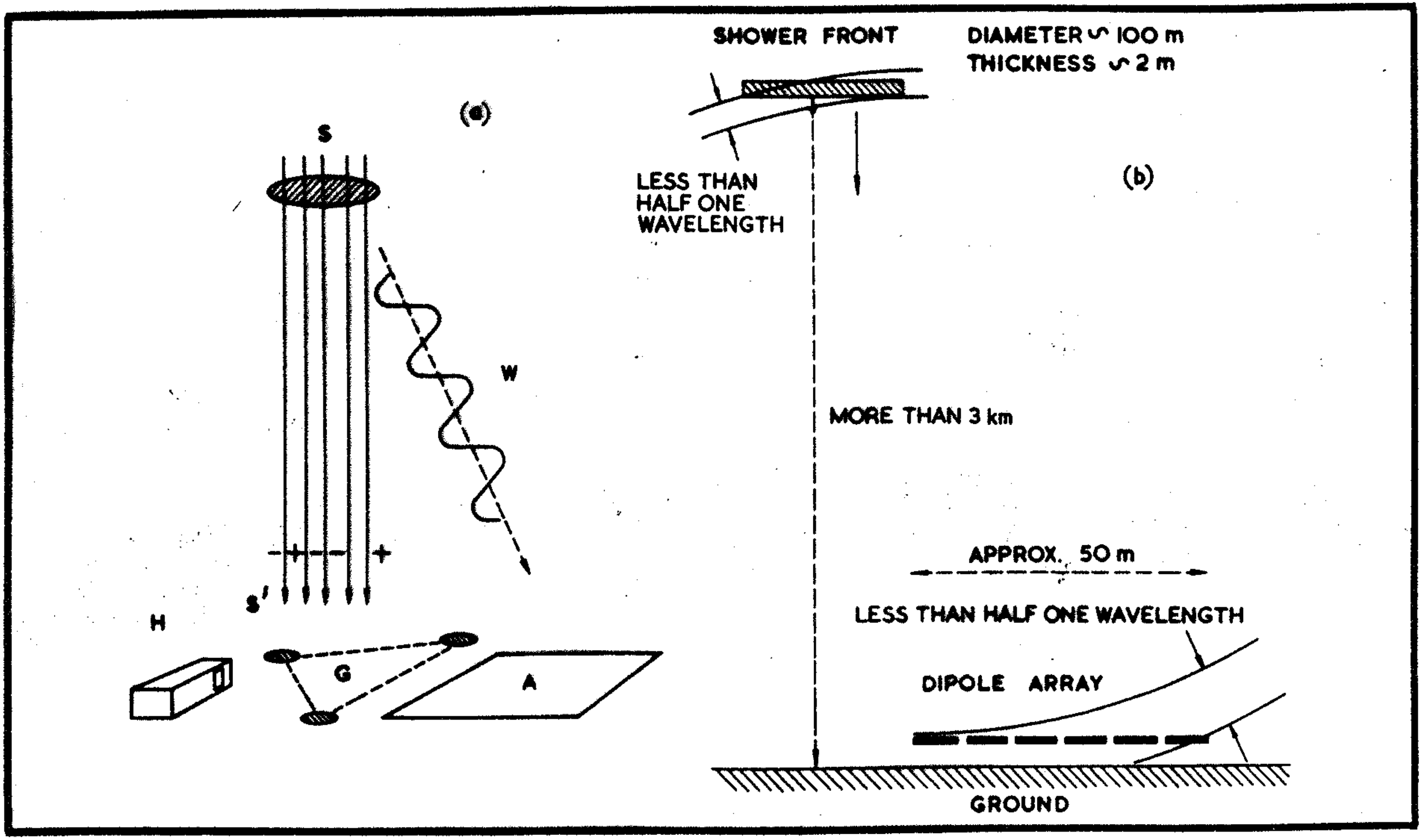
$\nu \sim 44$ MHz, $d\nu \sim 4$ MHz

$S \sim 1.1 \times 10^{-12}$ watts

$N \sim 2.8 \times 10^{-13}$ watts

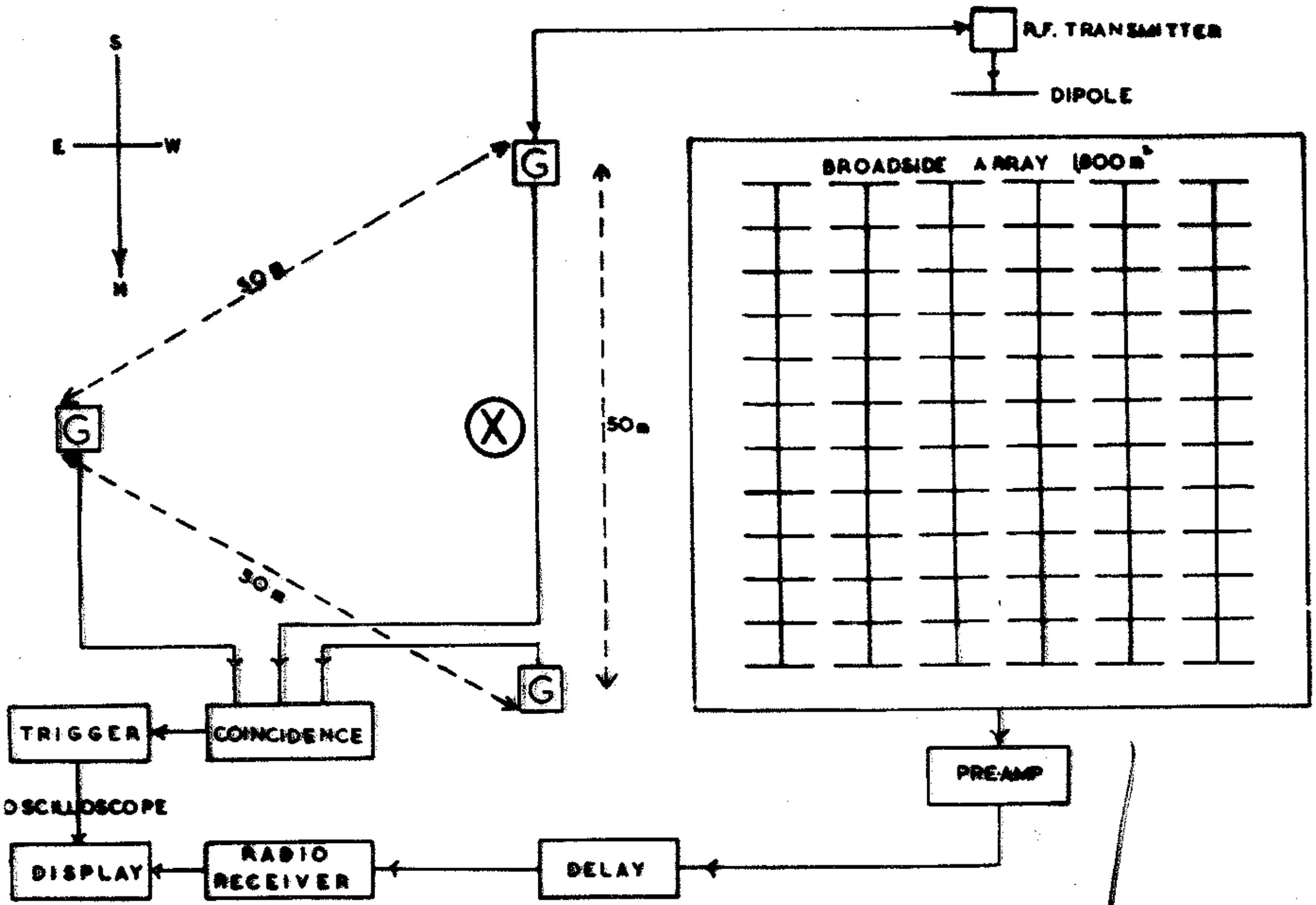


. Minimum detectable field strengths for a half-wave dipole antenna at differ receiver frequencies, in a bandwidth of 1 MHz.


(a)
S
W
S'
H
G
A
SHOWER FRONT
DIAMETER ∼ 100 m
THICKNESS ∼ 2 m
LESS THAN HALF ONE WAVELENGTH
(b)
MORE THAN 3 km
APPROX. 50 m
LESS THAN HALF ONE WAVELENGTH
DIPOLE ARRAY
GROUND

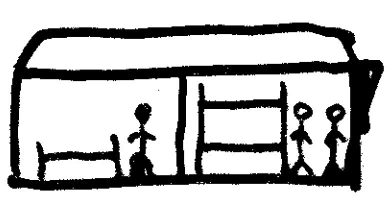
The Experiment: II

Layout of Jodrell Bank Experiment



4 sections,
3λ by 3λ
area ~ 1,700 m²
T ~ 450°K

Setting Up at Jodrell Bank, July, 1964



The Experiment: III

EAS Array

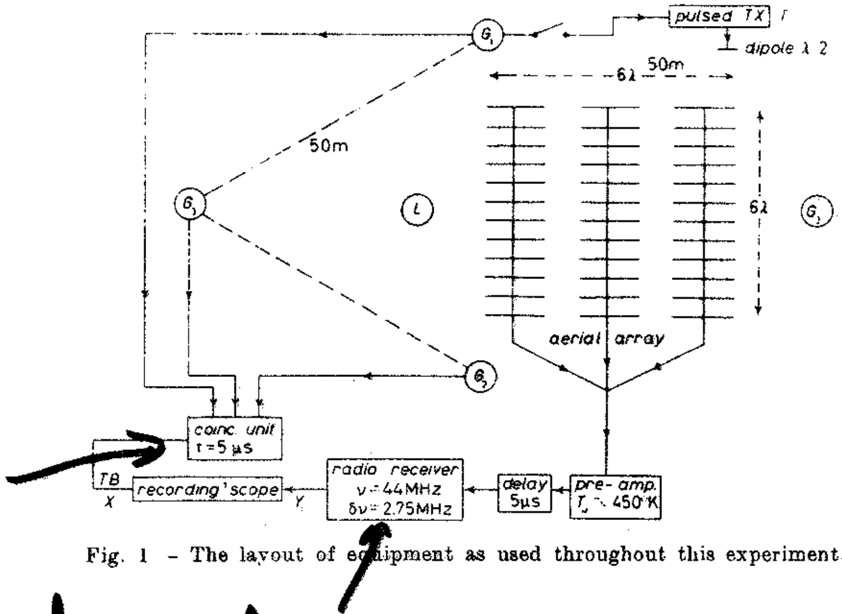


Fig. 1 – The layout of equipment as used throughout this experiment.

Battery - powered

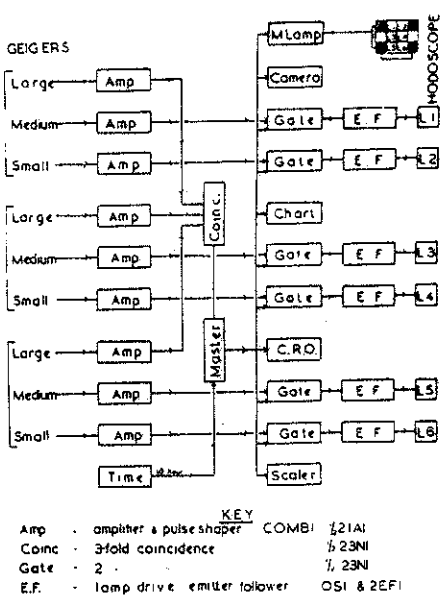


FIG. IV.5. GEIGER ARRAY ELECTRONICS

Geiger Tray.

Delays

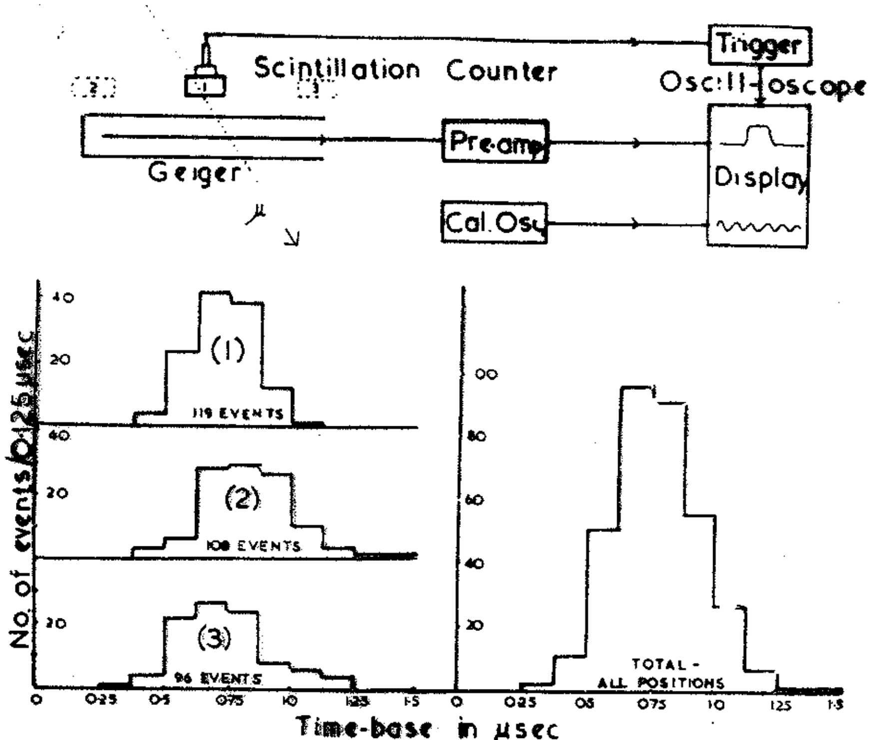


FIG. IV.7 GEIGER COUNTER DELAY

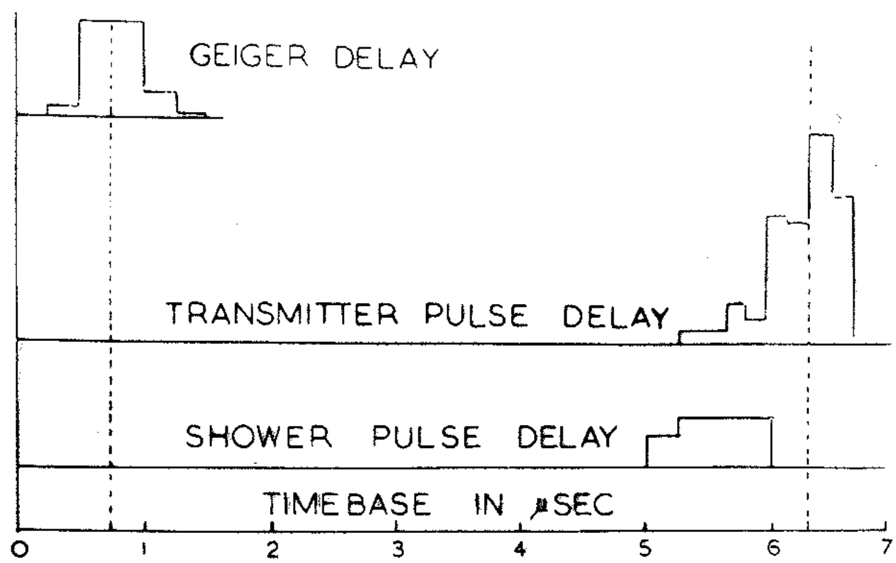
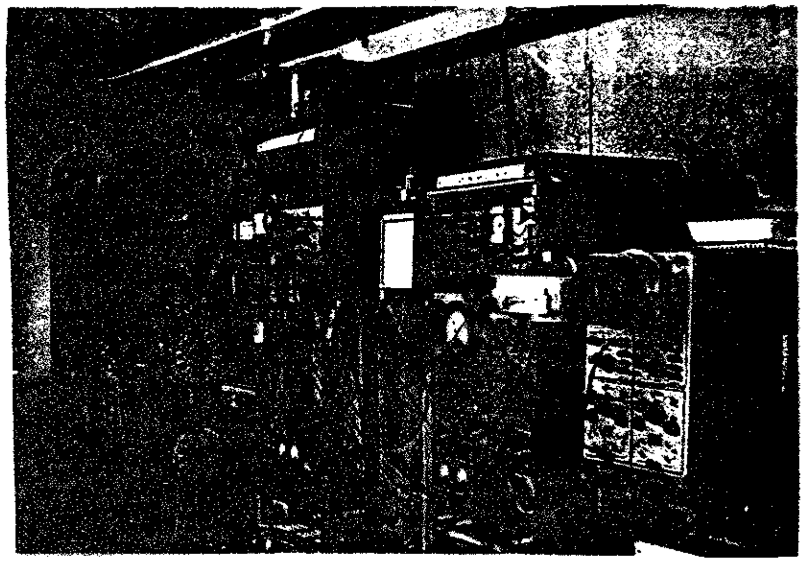


FIG. IV 8 RADIO PULSE POSITION HISTOGRAM

⟷ WINDOW

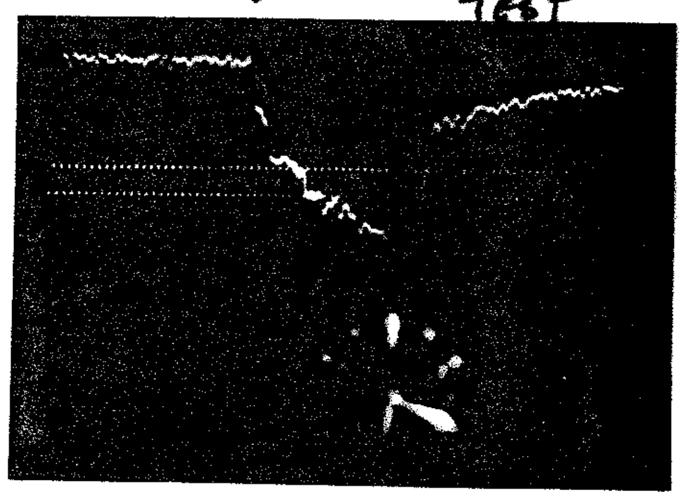
The Experiment: V

Recording System



TYPICAL

TEST

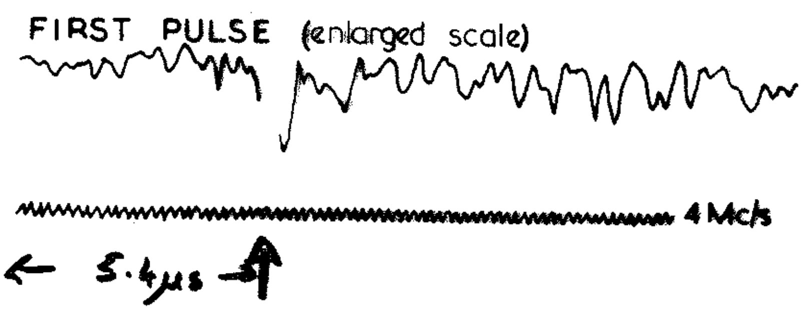


Results: I

Jodrell Bank, August, 1964

- One quarter array completed
- Nightly operation
- The Mad Hatter's Tea Party
- Daily Record
- First run August 19, 1964
- Joys of scope photography
- Be more careful!
- Success?
- Celebration

The First Event



Verification?

- Eight more nights of operation
- Decision time
- Full array, November-[redacted], 1964 — March 1965
- ~~Six~~ 11 large events, 4500 triggers ~ 10^{16} eV
- 5×10^{16}eV
- 1eV per event

Random in sidereal & solar time.

(Reprinted from *Nature*, Vol. 205, No. 4969, pp. 327–328, January 23, 1965)

RADIO PULSES FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

By DR. J. V. JELLEY and J. H. FRUIN
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PROF. N. A. PORTER and T. C. WEEKES
University College, Dublin
AND
PROF. F. G. SMITH and R. A. PORTER
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank

VARIOUS proposals have been considered for the detection of large cosmic-ray air showers by radio techniques. Neither the original proposal of pulse radar[1] nor the passive detection of Čerenkov radiation at microwave frequencies[2] now appears to be feasible. A re-assessment of the possibilities of Čerenkov radiation at longer wave-lengths has, however, been stimulated by the recent suggestion[3] that a considerable enhancement of the intensity may be expected in the radiation from an electron–photon cascade. This is due to a fractional negative charge excess ε arising from the annihilation of positrons in flight. For a shower with a total of N particles, the radiation intensity at low frequencies is proportional to $(\varepsilon N)^2 \nu\delta\nu$ within a bandwidth $\delta\nu$ at a frequency ν, and the enhancement factor is $\varepsilon^2 N$ over that from N particles radiating incoherently. In a typical shower of primary energy $E_0 \sim 10^{16}$ eV, for which $N \sim 10^6$ and the electron and positron energies are of order 10^8 eV, we expect $\varepsilon \sim 0{\cdot}1$, and $\varepsilon^2 N \sim 10^4$.

If we consider a shower front as a disk of thickness t and area S incident vertically close to an aerial array of area A, two conditions must be satisfied to achieve the maximum mutual coherence: (i) the wave-length λ must exceed t, and (ii) the radiation from all parts of the shower front must arrive in the same relative phase at all elements of A. In such a shower $t \sim 2$ m (ref. 4) and the effective radius of the shower is ~ 50 m (ref. 5), so that these conditions are reasonably satisfied for $\lambda \gtrsim 4$ m and for altitudes $\gtrsim 3$ km.

The present experiment was conducted on the basis of favourable estimates of the expected yield from this enhanced Čerenkov radiation. Cosmic-ray showers in the energy region 10^{15}–10^{16} eV were detected at a rate of $\sim 3{\cdot}2$ h^{-1} with a simple array of three Geiger–Müller counter trays G (Fig. 1) operated in coincidence (resolving time 5 μsec). These detectors also included smaller counters which operated a hodoscope; the display on this

Follow-up Experiments:

① Replace EAS Array by Cherenkov light telescope ~ 8×10^{13} eV
10^4 events — no ~~trigger~~ radio pulses

② Radio Telescope (15 m) @ 150 MHz, ~~[illegible]~~ $d\nu = 1$ MHz

No radio pulses at 150 MHz
Some " " at 44 MHz
Consistent with incoherence

Possible Alternative Mechanisms:

(a) Cosmic rays hitting receivers/amplifiers

(b) Reflection of TV signal

(c) Bremsstrahlung

(d) Transition Radiation

(e) Induction at Aerial

(f) Molecular emission

J. V. JELLEY, *et al.*
21 Dicembre 1966
Il Nuovo Cimento
Serie X. Vol. 46, pag. 649 667

Radio Pulses from Extensive Air Showers.

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Nuclear Physics Division
Atomic Energy Research Establishment - Harwell

F. GRAHAM SMITH and R. A. PORTER

Nuffield Radio Astronomy Laboratories
The University of Manchester - Jodrell Bank

N. A. PORTER, T. C. WEEKES and B. McBREEN

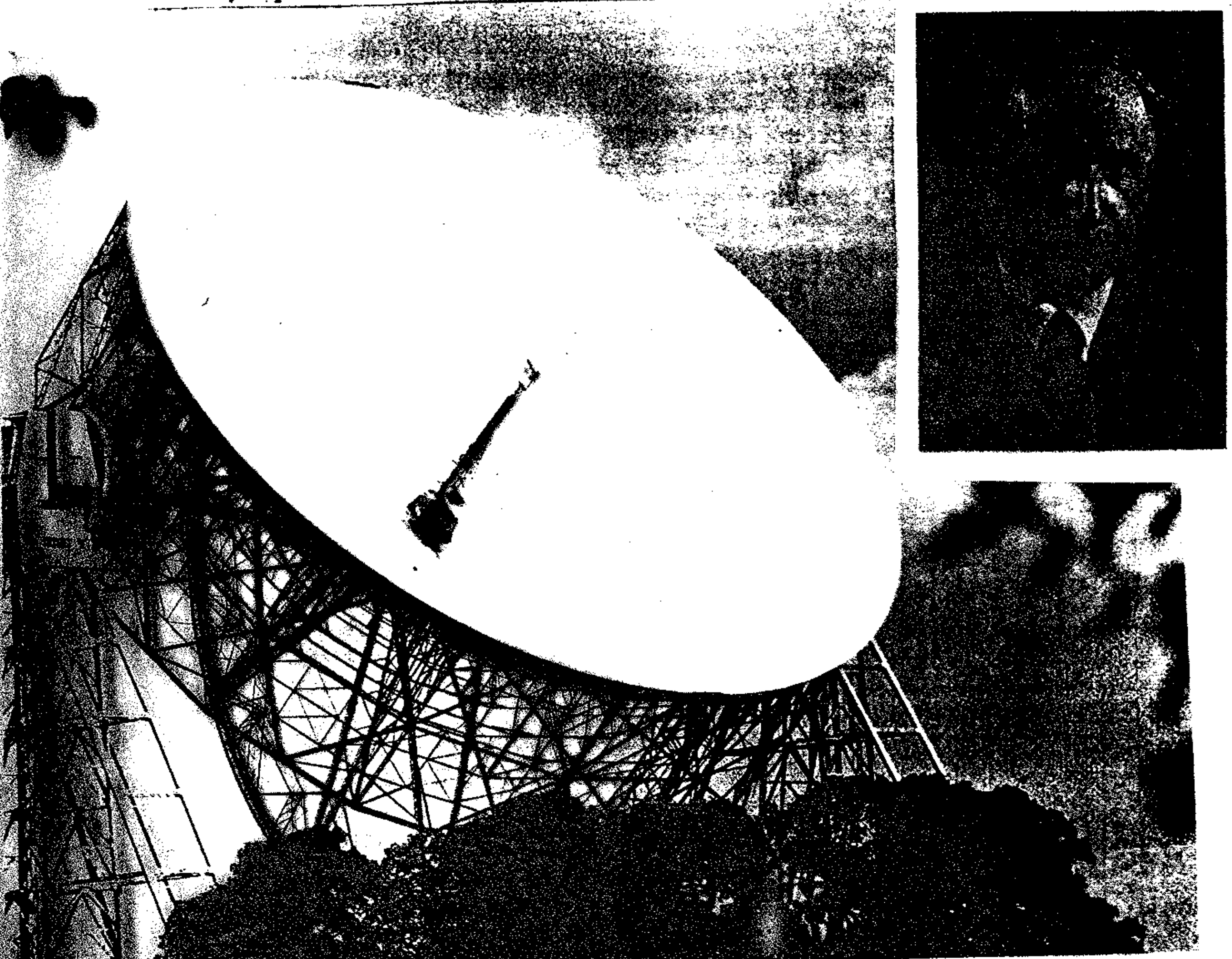
The Physics Department, University College - Dublin

(ricevuto il 17 Giugno 1966)

Summary. — Radio pulses of short duration ($< 0.15\ \mu s$) have been observed at a frequency of 44 MHz ($\lambda = 6.8$ m), in coincidence with extensive cosmic-ray air showers having $\sim 5 \cdot 10^6$ particles. The energies of these pulses ranged from $\sim 10^{-12}$ erg (receiver noise level) to $\sim 10^{-9}$ erg. The preliminary results reported briefly elsewhere [19,27] were consistent with the hypothesis that the observed pulses arose as a result of enhanced Čerenkov radiation at low frequencies [10]. However, following the treatment of Kahn and Lerche [16], it is evident that the observed energy of the radiation is also consistent with charge separation effects in the earth's magnetic field. Experiments at a higher frequency (150 MHz, $\lambda = 2$m), and a tentative analysis of the pulse-height spectrum, suggest that the radiation observed is enhanced by effects of mutual coherence among the particles in the shower. The paper concludes with a discussion of other alternative radiation mechanisms.

210 ft telescope

This large transit telescope, as it became known, was a great success. Early in the autumn of 1947 we tried some experiments with it to detect the cosmic ray showers but by that time the new instrument was proving to be so valuable in other fields of work that we eventually gave up the cosmic ray experiment.[1]



[1] By a strange twist of fate a successful experiment to detect the emission of pulses of radio energy from cosmic ray showers was carried out at Jodrell Bank in 1964 by Prof. Graham Smith and his colleagues. As far as I am aware the radio echo experiment which I originally proposed has never been revived.

[2] Miss Ella Ryder, subsequently Mrs. Ella Bradley, who still works part of the day at Jodrell.

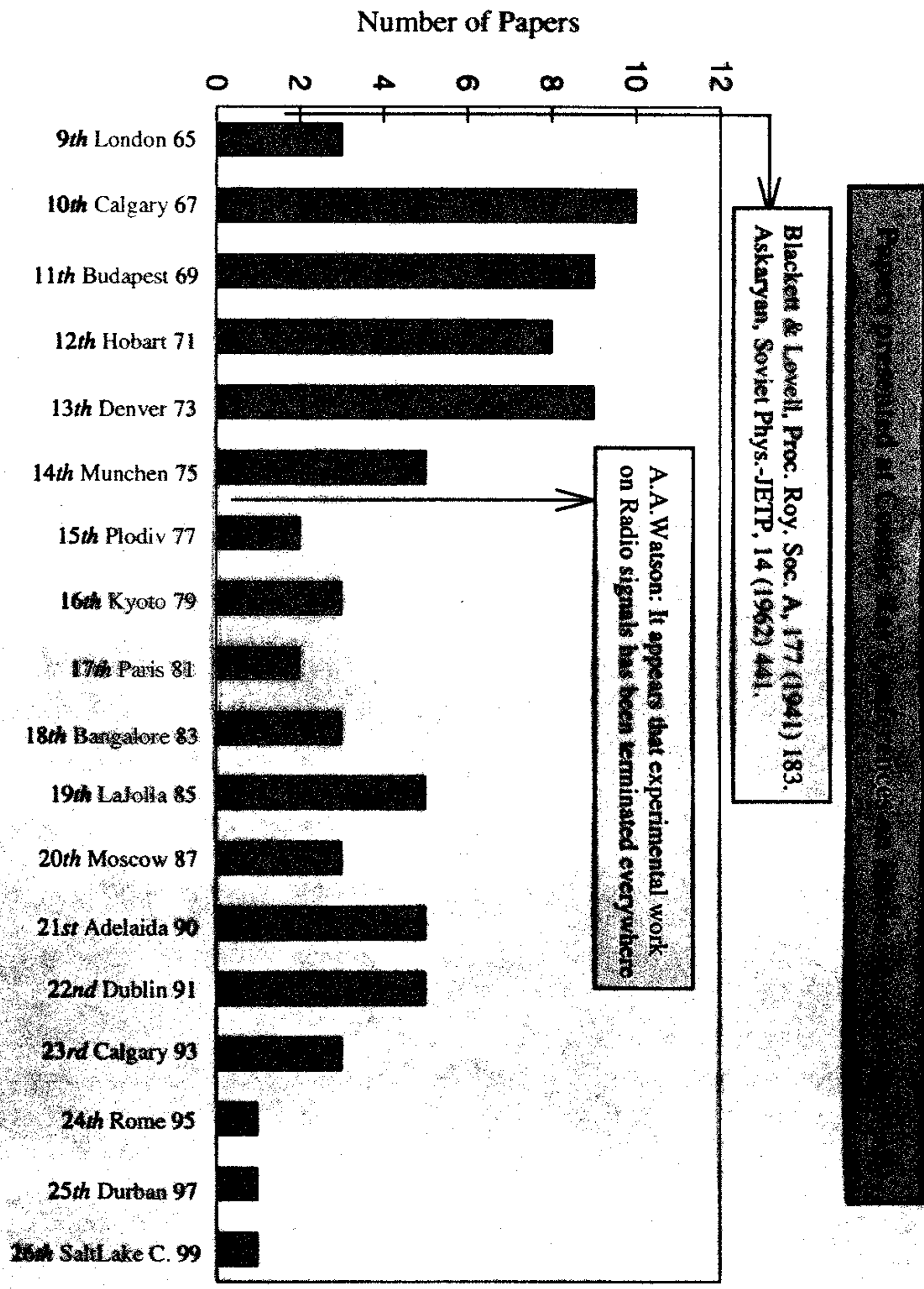
"The Story of Jodrell Bank"
Sir Bernard Lovell

Proc. Int. Conf. Cosmic Rays 1965

A radio system for the detection of air showers*

N. A. PORTER, C. D. LONG, B. McBREEN, D. J. B. MURNAGHAN† and T. C. WEEKES
University College, Dublin, Eire

Abstract. A radio receiving system with broad band helical aerial is in operation, in conjunction with a Cerenkov particle detector which selects showers. The frequency is 70 Mc/s and the bandwidth about 20 Mc/s. The angular beamwidth of the aerial is 50°, centred at the zenith. In 650 hours of operation, five large bandwidth-limited pulses have been observed in association with showers. No such pulses have been seen in comparison traces or at times before or after the expected time of arrival. In an analysis of one third of the data, 16 smaller pulses have been observed at the expected time of arrival, with none in a comparison interval slightly later. The rates of pulses observed are lower than expected theoretically, which may indicate some degree of decoherence. Operation of the radio system without a particle detector indicates that while interference pulses do occur, they are easily distinguishable from shower pulses. The use of a wide-band radio detecting system without particle detectors may therefore be feasible.



Number of Papers
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2
4
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12
9th London 65
10th Calgary 67
11th Budapest 69
12th Hobart 71
13th Denver 73
14th Munchen 75
15th Plodiv 77
16th Kyoto 79
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18th Bangalore 83
19th LaJolla 85
20th Moscow 87
21st Adelaida 90
22nd Dublin 91
23rd Calgary 93
24th Rome 95
25th Durban 97
26th SaltLake C. 99
Blackett & Lovell, Proc. Roy. Soc. A, 177 (1941) 183.
Askaryan, Soviet Phys.-JETP, 14 (1962) 441.
A.A.Watson: It appears that experimental work
on Radio signals has been terminated everywhere

I.C.R.C. (London) 1965. K. GREISEN (Rapporteur)

In conclusion then the assessment of the technique by Greisen (98) at the London Conference might be considered. "The technique is barely in its infancy, and too little is known about it to justify elaborate predictions. However, we feel confident that this achievement is a significant breakthrough, and that further study will reveal ways of obtaining types of information about the showers that were not available by other means. The signal will not, of course, be sensitive to fine details like the structure of the shower core; nor does the method seem adaptable to surveying at the same time all directions in which showers may arrive. However, it appears that the method may offer new orders of angular resolution; and it may complement particle detectors by being sensitive to the condition of the showers far above ground level. Also it will be able to detect showers in steeply inclined directions, in which the particles are absorbed before reaching the ground. Time will probably reveal many other possibilities that are not apparent at this early stage."