HIGH ALTITUDE BALLOON EXPERIMENTS AND MEASUREMENT OF THE HEAVY PRIMARY RADIATION FLUX AT THE GEOMAGNETIC EQUATOR

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Received April 12, 1952

1. INTRODUCTION

THE flux and charge spectrum of heavy primary cosmic radiation has been studied by several workers by exposing nuclear emulsions at high altitudes, and geomagnetic latitudes from 30° N. to 55° N. (Bradt, *et al.*, 1950 *a*; Dainton, *et al.*, 1950; Freier, *et al.*, 1951). To obtain the integral energy spectrum of the primaries, it is necessary to extend these observations to other latitudes. The present paper reports experiments made for this purpose near the geomagnetic equator. Flights were made from Tambaram, near Madras, and from Bangalore, during October and November, 1950. Bcth places have geomagnetic latitude 3° N. A summary of the flight data is given in Table I.

TABLE I

Summary of Flight Data

Flight number	Launched from	Date of launching	Maximum height reached in ft.	Plates flown	Remarks
1	Tambaram	15-10—1950	40,000	NT4–250μ	Main line gave way about 50 min. after launching
2	,,	20-10—1950	76,600	G5–500 μ	Plates developed at Bristol
3	,,	22-10—1950	79,400	NT4–250 μ	Plates developed at Bombay
4	,,	29-10—1950	81,300	NT4–250 μ	,, ,,
5	,,	31-10—1950	50,000	G5–500 μ	Plates flown again in flight 9
6	,,	5-11—1950	52,700	NT4–250 μ	Plates flown again in flight 7
7	,,	8-11—1950	79,600	NT4–250 μ	Plates developed at Rochester
8	,,	18-11—1950	81,100	G5–500 μ	Plates lost at sea
9	,,	23-11—1950	..	G5–500 μ	,, ,,
10	,,	26-11—1950	94,500	G5–500 μ	Highest flight in series. Plates lost at sea
11	Bangalore	7-12—1950	84,700	Brass Stack	Plates developed at Rochester
12	,,	8-12—1950	91,800	Brass Stack	Balloon break-up. Plates used again in flight 13
13	,,	9-12—1950	62,700	Brass Stack	Plates not recovered

One object of these experiments was to study the E.-W. asymmetry of the heavy primary radiation, which has not yet been measured. For this purpose a servomechanism was designed to maintain the plates during flight in a fixed orientation. Kodak NT4–250 μ and Ilford G5–500 μ were the types used. In a typical flight a stack of 80 plates was used, each 3″ by 8″, placed vertically with the plane of the plates perpendicular to the magnetic meridian. To study the spectrum of the high-energy primaries the "brass stack" was employed. This consists of 20 horizontally stacked plates, individually sandwiched between brass plates of 3 mm. thickness. The plates are positioned with great accuracy. The heavy primaries interact principally with the brass, forming narrow showers of break-up products which can be followed through successive plates. Either the opening angle of such showers or the relative scattering of evaporation alpha particles and heavier fragments can be used to determine the energy of the primary (Kaplon, *et al.*, 1952).

Plates exposed at high altitudes record large π-meson showers of high energy similar to the "R" shower (Bradt, *et al.*, 1950 *b*). The study of the development of soft cores in such showers enables one to place an upper limit on the lifetime of the neutral π-meson (Kaplon, *et al.*, 1952).

The objects of these experiments have not been fully realised, but values of the flux have been obtained for the C-N-O group of primaries and for the group with $Z > 10$. The detailed altitude curves have also yielded new information on the behaviour of high-altitude balloons.

2. THE ORIENTATION UNIT

Fig. 1 shows the orientation unit with the plate box in position. The dome on the right goes over the unit, and is bolted to the circular base. A rubber gasket makes the assembly airtight, so that normal pressure is maintained inside during the flight. The dome is of aluminium and is painted black.

The photograph shows the batteries (A), the electronic circuit (B), the plate box (C), the compass box (D), and the monitor (E). Fig. 2 shows the circuit diagram. The ends of a compass needle are provided with wires dipping into semicircular troughs of water which form part of an impedance bridge, to which the output of a 1,000-cycle oscillator is applied. A deviation of the needle results in a signal whose phase depends on the direction of the deviation. The signal actuates a servomotor which rotates the plate assembly in such a direction as to annul the deviation. The initial balance is brought about by adjusting the two potentiometers. Thereafter the burst. The new value of L is L_3, for which the system is above the equilibrium level. It therefore falls to S, and if another balloon bursts, to T. As S and T are below the bursting level the system may persist for long periods at these levels.

The points Q, R, S, T in Fig. 4 have been computed for a flight of 10 balloons weighing $1 \cdot 4$ kg. each, inflated to a diameter of $1 \cdot 9$ m. or to a lift $F = 2 \cdot 5$ kg. For this inflation $m = 0 \cdot 3$ kg. A payload of 16 kg., together with 10 balloons and the hydrogen, gives a total load of 33 kg. carried by 3 kg. of hydrogen. When a balloon bursts we assume that half the rubber ($= 0 \cdot 7$ kg.) is blown off. The total decrease of W is thus 1 kg. The bursting level is assumed to be at 23 mb. With these data we construct Table II.

TABLE II

Number of Balloons ..	10	9	8	7	6
Total load : W ..	33	32	31	30	29
Mass of Hydrogen : m ..	3·0	2·7	2·4	2·1	1·8
Load/ kg. of Hydrogen : L_0 ..	11·0	11·8	12·9	14·3	16·1
Equilibrium pressure in millibars ..	..	..	25·0	38·0	Ground

The system has therefore two floating levels, and if the bursting level were higher there might be 3 or 4. In practice balloons vary in weight, some are weaker than others, and it is not possible to fill them all precisely to the same lift. The amount of rubber lost on bursting is also very variable, and there are cases where balloons develop pinholes and shrink slowly, so that no rubber is lost at all. For these reasons floating levels cannot be predicted accurately in advance, but the present results show that the flights behave substantially in the manner to be expected from this theory.

The rise in p_1 for high inflations does not occur with neoprene balloons when blown up to bursting point at the ground though the rubber balloons show it clearly. The difference is almost certainly a temperature effect. The manufacturers, in a private communication, have stated that neoprene 'freezes' or becomes less estensible at stratosphere temperatures. This would correspond to a large value of k in the above theory.

6. DETERMINATION OF PRIMARY FLUX

The experiments provided 4 sets of plates for analysis, obtained in flights 3, 4, 7 and 12. The plates of the brass stack in flight 12 showed stripping of the emulsion on development, and have not yielded satisfactory

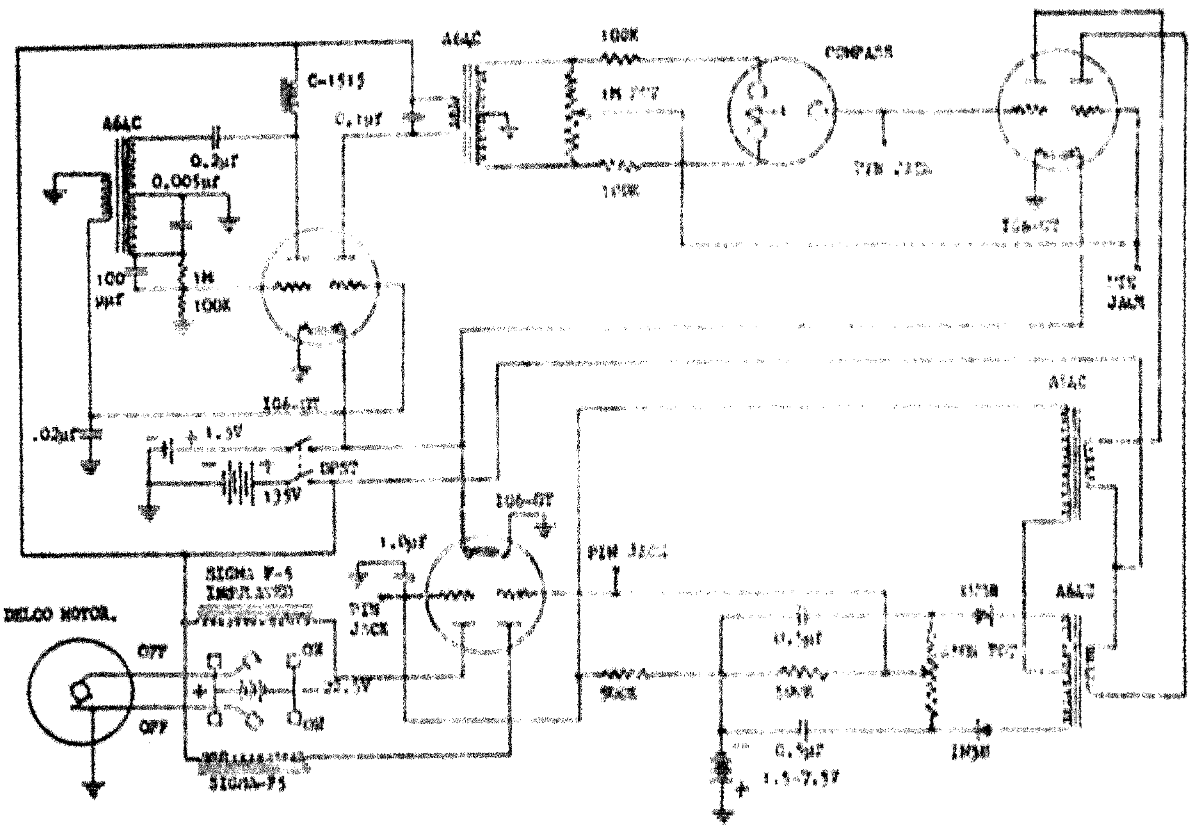

FIG. 2

orientation of the plate assembly is maintained, provided the rate of rotation of the gondola is not more than about three revolutions per minute. The apparatus showed no tendency to 'hunt' or to maintain the gondola in oscillation, and with careful preliminary adjustment it behaved well in practice.

The monitor consists of a magnetic needle horizontally pivoted and centrally mounted in a flat circular box. The needle carries a polonium source at one end, and a circular piece of Kodak NTB 3 35μ film is mounted inside the lid of the box to record alpha particles from the source. On descent the rapid downward acceleration causes the lid to fly open. It is then held by a catch, so that no further irradiation of the film occurs to confuse the record. The distribution of alpha particle tracks on the film indicates the degree to which orientation has been maintained during the flight. In flights where the apparatus was recovered intact the monitor record showed that orientation had been maintained within about ± 15°. A magnetic orientation unit of similar design has recently been described in detail (Golian and Reilly, 1951).

3. BALLOON TECHNIQUE

Dewey and Almy balloons were used for these flights, the types being K 2,000, J 2,000, J 800 and J 1,400. K balloons are of latex (natural rubber), and J balloons of neoprene (plastic). The number indicates the nominal weight of the balloon, but there are large individual variations. K balloons require no pretreatment, but J balloons, in accordance with manufacturer's instructions, are heated for a few minutes in nearly boiling water shortly before filling. Many balloons are uneven, and develop bulges or blisters on filling, but there is no evidence that these defects appreciably weaken the balloons.

Balloons are filled from hydrogen cylinders through a flexible hose, until they just pick up a pre-determined load. Considerable errors are possible in judging the precise moment when the load is balanced, particularly when there is any wind. Cooling takes place as the hydrogen expands through the nozzle, and as the balloon warms up there is a noticeable increase of lift. It is therefore difficult to achieve accurately the desired lift, the uncertainty being of the order of 10% either way.

Each flight is planned for a definite rate of rise, given by the empirical formula

$$R = 1\cdot 34\,\frac{\sqrt{F} - g}{\sqrt[3]{F + B}},$$

where R is the rate in 1,000 ft./min., F is the weight the balloon will just pick up at the ground, g the external load per balloon during flight, and B the balloon weight, all in kg. The formula holds reasonably well for balloons attached separately to a long line; but it is not applicable to balloons in large clusters, where the rate of rise is noticeably less than given by the formula. High rates of rise (800 to 1,200 ft. per min.) appear to be associated with a high probability of balloon failure, especially between 35,000 and 50,000 ft., where turbulent motion is often very evident.

The necessary hydrogen was produced as required in standard generators by means of ferrosilicon and caustic soda. By connecting cylinders to the generators it was possible to use double the normal charge. The first generator was used to fill one empty cylinder to a pressure of 900 lb./sq.in., and another to 300 lb./sq.in. The next charging filled the first cylinder to the full pressure of 1,400 lb., and the second to 800 lb. The third charge filled the second cylinder to the full pressure and an empty cylinder to 300 lb. By repeating this process, five workers could fill 20 cylinders in about 16 hours, using 15 generators. Previously the generators have been used to fill balloons directly, but the present method is more advantageous and involves fewer generators. It does not appear to have been used before in India.

Balloons on 35-foot strings were attached individually or in small clusters to a long nylon line at 35-foot intervals. Clusters of 3 to 7 balloons were used in different flights. In flight 12, 12 balloons on 80-foot strings and 11 on 60-foot strings were flown as a single two-layer cluster. Most of these survived to a height of 92,000 ft., when atleast a dozen burst simultaneously. In this case the central balloons would, when fully expanded, be pressed tightly together, and the failure of a single balloon would endanger all the others.

The equipment was attached to the lower end of the line in the order (1) clock release, set to detach the load at a predetermined time, (2) parachute, (3) the gondola carrying the orientation unit, (4) barograph, (5) ballast. The clock release was used only in the earlier flights. The purpose of the ballast is to reduce the initial rate of rise, and to compensate for loss of lift as balloons burst. In the earlier flights 8 kg. of sand, running at the rate of 1·2 kg. per hour, was used as ballast. In later flights hot water was used successfully.

The launching of a 400-foot line, carrying upto 32 balloons, and with equipment weighing upto 40 kg., presented some problems. The method adopted was to hold both ends of the line, with the top end to windward of the load, and allow the central balloons to lift the line into a vertical arc. The top end was then released. When the line was approximately vertical the load was released. In this way it was possible to avoid the danger of the load being dragged along the ground by an inclined balloon line.

4. ALTITUDE MEASUREMENTS

In flight 11 a recording aneroid barometer was used. This gave an excellent record, reproducing the details of the trigonometrically determined path with great fidelity, but the absolute calibration was uncertain. On other flights a specially designed mercury barograph was used, in which the movement of the mercury meniscus is photographed on a revolving drum. Illumination was provided either by a 2-volt lamp working on batteries, or by daylight. Unfortunately the barograph was tampered with by the finders on several occasions, and developed defects on others, with the result that only one satisfactory record was obtained, for flight 4, which again agrees very well with the trigonometrical trajectory.

The altitude curves for these flights are therefore based entirely on the trigonometrical data obtained from theodolite stations. For the Tambaram flights five permanent stations were used: Tambaram, Meenambakkam (6 miles N.E.), Vellore (67 miles W.), Kolar (125 miles W.), and Bangalore (177 miles W.). The locations were known with precision, and the three distant stations were in continuous touch with Tambaram by two-way short-wave radio. Synchronised measurements of altitude and azimuth were made at five-minute intervals during the flights. For the Bangalore flights, the theodolites at Bangalore and Kolar were used. On the last flight the balloons were followed across country by a mobile party taking theodolite readings from various locations, making azimuth corrections by reference to map positions and sun observations. The resultant altitude curves have been computed by an analysis of all the observations available. These curves are shown in Fig. 3.

5. FLOATING LEVELS OF BALLOON SYSTEMS

The detailed altitude-time curves obtained for these flights have revealed an important feature of balloon behaviour which has not been previously reported. As the flight rises balloons progressively burst until approximate equilibrium is reached. The system then shows a series of stable floating levels, which may be maintained for considerable periods. In Fig. 3, flight 13 shows a single level maintained with very small variations for 9 hours. Flights 3 and 4 show cases where the system of balloons falls suddenly from one level to another, three such levels being clearly shown in flight 4. When ballast is steadily running a 'level' becomes a steady increase of height with time, but the discrete set of 'levels' is still apparent, as in flights 8 and 10. The sudden fall from one level to another is almost certainly caused by the bursting of a balloon, but owing to the great distances at which the balloons were observed this could not always be checked observationally.

In previous studies it has always been assumed that the pressures inside and outside a balloon are equal, and that "the effects of pressure created by the elastic contraction of the rubber balloon fabric....may be neglected" (Clarke and Korff, 1941). On this assumption the lift due to the hydrogen is independent of the pressure. If the total lift is greater than the load the balloon rises indefinitely, otherwise it descends to the ground. A group would behave in the same way as a single balloon, and could only float if the lift happened exactly to equal the load. Even so there could be no floating level, for there would be equilibrium at all heights.

The existence of stable floating levels contradicts the above assumption. We have to take into account a contribution p_1 to the internal pressure given by

$$p_1 = 2T/r, \qquad (1)$$

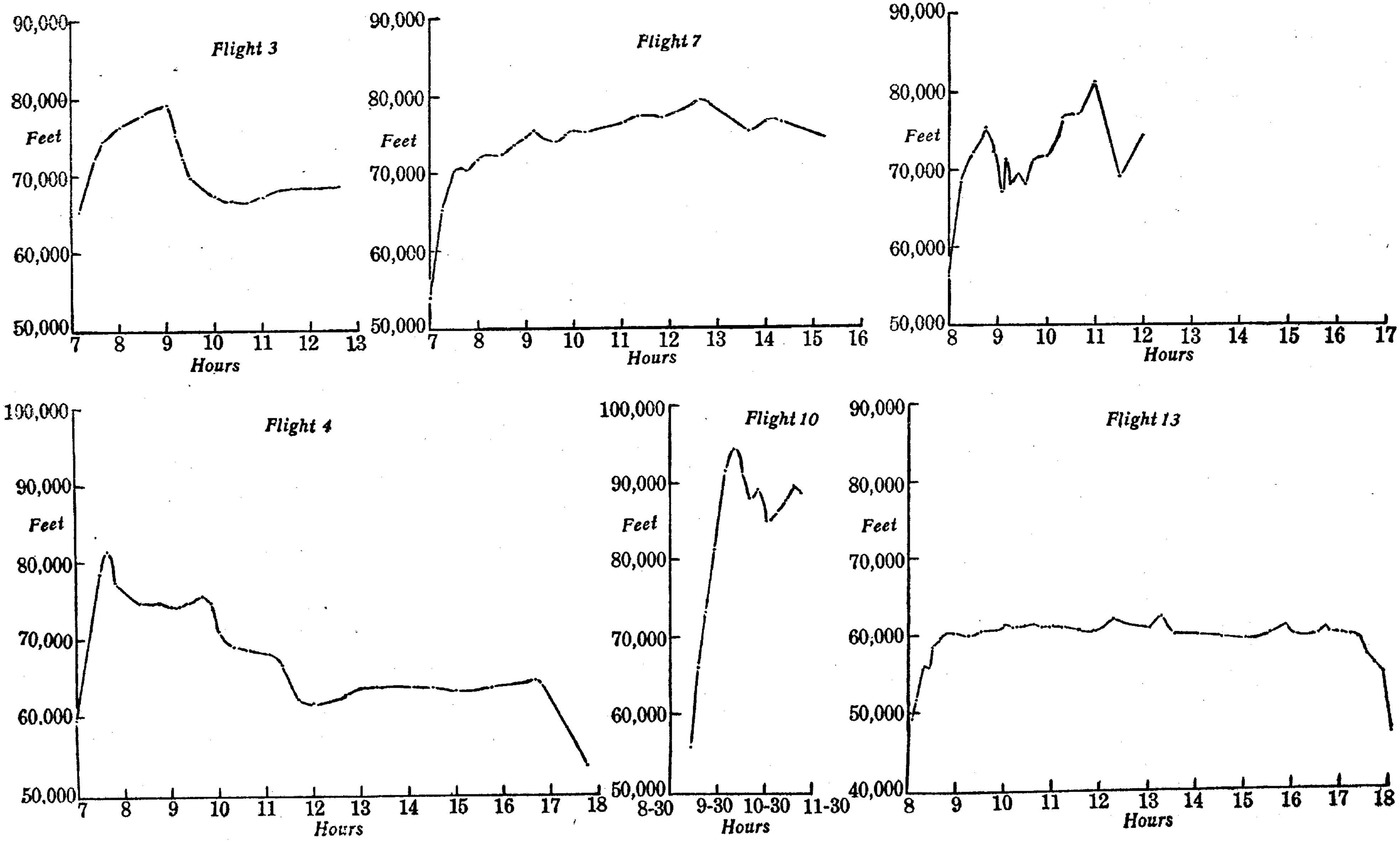
Flight 3
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FIG. 3

where T is the tension in the rubber and r the radius of the balloon. At the ground p_1 is of the order of a millibar and is negligible, but it becomes increasingly important, both absolutely and relatively, as the balloon expands. Rubber balloons blown up on the ground show a minimum value of p_1 at moderate inflation, followed by an increase which is roughly proportional to the volume. This suggests that at high altitudes the elastic contribution to the internal pressure might reasonably be represented by the equation

$$p_1 = p_0 + k/p, \tag{2}$$

where p is the external pressure and p_0, k are constants for a given type of balloon.

We adopt the following notation:

m = mass of hydrogen in a balloon,
V = volume of balloon,
T = the absolute temperature of the surrounding air,
t = excess internal temperature of the balloon,
M_H, M_A = molecular weights of hydrogen and air,
W = total load (= hydrogen + rubber + payload),
L = W/m = load per gram of hydrogen,
R = gas constant per mole.

The volume is given by $V = (m/M_H) R (T + t)/(p + p_1)$

The density of the air is $M_A p/RT$

The upthrust is thus $m (M_A/M_H) (1 + t/T)/(1 + p_1/p)$

At a floating level this must be equated to W. Hence

$$(M_A/M_H)(1 + t/T)/L = 1 + p_1/p$$

The value of t is unknown but must be appreciable, since the balloon is exposed to the sun's radiation, and a system of balloons always loses lift very quickly at sunset. A fair estimate appears to be $t/T = 0{\cdot}11$. With $M_A/M_H = 14{\cdot}4$ the equation becomes

$$16/L = 1 + p_1/p. \tag{3}$$

If we assume the validity of equation (2) the equilibrium equation becomes

$$16/L = 1 + p_0/p + k/p^2 \tag{4}$$

This equation is plotted in Fig. 4 for the values p_0=2 mb. and k = 100. These values have been chosen to give a reasonable fit with the observations,

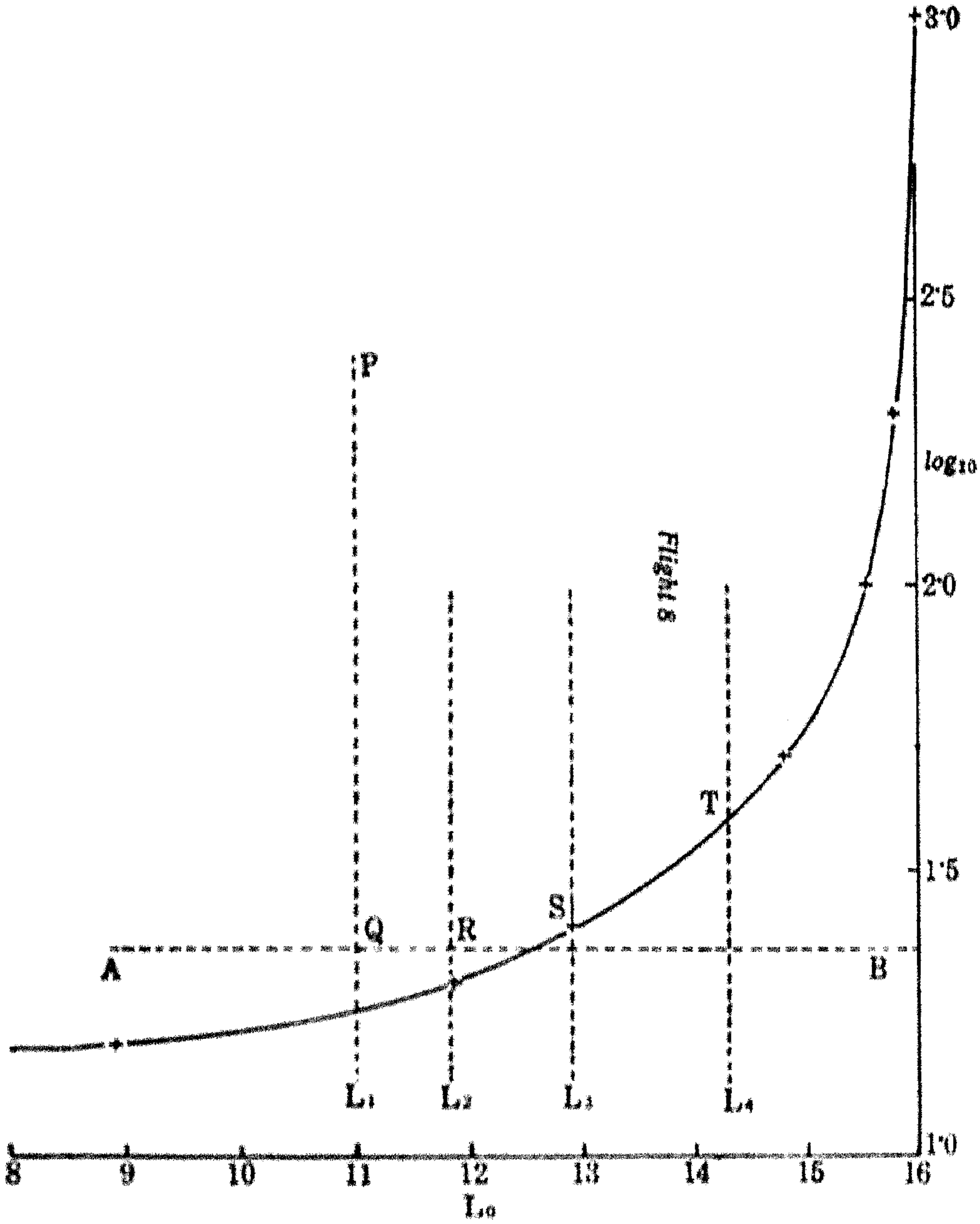

Fig. 4

Initially a system of balloons has a definite load per gram of hydrogen, say L_1, which remains constant as long as the balloons remain intact. The rise of the balloons is therefore represented in Fig. 4 by the line PQ. AB represents the bursting level, at which a balloon reaches its maximum distension. At Q one balloon bursts. *m* grams of hydrogen are lost, and W decreases by the weight of the hydrogen and the rubber which falls off. L changes discontinuously to L_2, and the representative point on the diagram is now R. As R is still below the equilibrium level another balloon will measurements. The mean altitude in flight 3 was rather low, and though the plates are good, the primary tracks are too few to give a reliable determination. The results reported are therefore based on flight 4, and flight 7. Flight 4 was analysed at Bombay and flight 7 at Rochester.

Of the 80 plates from flight 4, the two end plates and two from the middle were scanned systematically for heavy tracks. When found, these were followed from plate to plate through the stack to distinguish primaries from slow secondaries. Primaries have an energy above the cut-off, which is approximately 6·5 Bev/nucleon at the geomagnetic equator, and at these energies the primaries pass completely through the stack unless they suffer nuclear collisions. The mean free path in the material of the stack is known to be 34·5 g./cm.^{2} for incident particles with $6 \leqslant Z \leqslant 10$, and 25·5 g./cm.^{2} for $Z > 10$. A break-up occasionally occurs in the emulsion, and the break-up products can often be recognised as alpha particles (4 times minimum ionisation) and singly charged particles (minimum ionisation). In such cases, a lower limit to the charge of the primary may be assigned from the break-up products.

δ-Ray measurements were made on all tracks for which Z could be assigned in this way with some assurance, and also on alpha particle tracks. The number of δ-rays in a standard length of track ($100\,\mu$) is given by the formula (Bradt and Peters, 1950 *c*).

$$N_\delta = AZ^2 + B.$$

From the results obtained from the known tracks, the constants A and B were evaluated, and the relation was then used to determine the charge on all the primary tracks found. As all the primaries have relativistic speeds the δ-ray count over a reasonable length of track, usually $1{,}000\,\mu$ or more, gives the value of Z. The uncertainty is of the order of one unit in Z. For analysis the tracks are divided into two groups (1) those for which $6 \leqslant Z \leqslant 10$ (generally called the C-N-O group), (2) those for which $Z > 10$. For each track the orientation and dip (with due correction for emulsion shrinkage) were recorded, these angles being then converted to true zenith angle and azimuth. The direction of travel is determined from the fact that a primary particle must be moving downwards.

Let z be the vertical axis normal to the plate. The zenith angle of the track is θ, and its azimuth, measured from the x, z plane, is ϕ. The dip β is the complement of the angle between the track direction and x. These angles are related by the equation

$$\sin \beta = \sin \theta \cos \phi.$$

Owing to difficulties of recognition, only tracks of a certain minimum projected length are included in the analysis. This is equivalent to the condition $\beta < \beta_0$. This implies that $\phi > \phi_0$,

where

$$\cos \phi_0 = \sin \beta_0 / \sin \theta.$$

When θ is less than β_0, all values of ϕ between 0 and $\pi/2$ are included, but when θ exceeds β_0 the permissible azimuth ϕ has the lower limit ϕ_0.

Consider an isotropic incident flux of N_0 particles per sq. cm. per sec. per sterad. The plate presents a projected area (A sin β), where A is the area of the plate, and the element of solid angle is $\sin \theta \, d\theta \, d\phi$. The rate of incidence on the plate at the angles θ, ϕ is therefore

$$n(\theta, \phi) = N_0 A \sin^2 \theta \cos \phi \, d\theta \, d\phi$$

Integrating over ϕ with the given limits, the rate of incidence for a given zenith angle becomes

$$n(\theta) = 2 N_0 A f(\theta) \, d\theta,$$

where

$$f(\theta) = \sin^2 \theta \text{ for } \theta \leqslant \beta_0$$

$$f(\theta) = \sin^2 \theta \left(1 - \sqrt{1 - \frac{\sin^2 \beta_0}{\sin^2 \theta}}\right) \text{ for } \theta > \beta_0.$$

To allow for the absorption in the atmosphere, $n(\theta)$ must be multiplied by a factor $e^{-h/\lambda \cos \theta}$, where λ is the mean free path in air, and h the vertical height of the atmosphere above the point of observation. h is known as a function of the time from the altitude curve, and the total number of tracks recorded at the zenith angle θ is thus given by

$$N_\theta = 2 N_0 A f(\theta) \, d\theta \int_0^T e^{-h/\lambda \cos \theta} \, dt.$$

Denoting the integral by $\phi(\theta)$, the total number of tracks recorded between any given limits of zenith angle is

$$N(\theta_1, \theta_2) = 2 N_0 A \int_{\theta_1}^{\theta_2} f(\theta) \phi(\theta) \, d\theta.$$

Some of the observed tracks represent particles which have had an appreciable path in the stack before reaching the selected plate. If the path in the stack is L, and the mean free path λ', each track must be assigned a statistical weight $e^{L/\lambda'}$. The appropriate value of N (θ_1, θ_2) to employ is the sum of the statistical weights of all the observed tracks.

The analysis has been made for several plates of the stack, and for different values of β_0. High values of β_0 give smaller flux values, showing that tracks (especially of the C-N-O group) are liable to be missed or excluded by the observer if the minimum projected length is too small. The value of β_0 finally adopted is 34°, corresponding to a minimum projected length of $300\,\mu$ in a $200\,\mu$ emulsion. With this criterion a single end plate has yielded 24 tracks, with a total statistical weight of 33.

Taking the mean free path in air of the C-N-O group as 27 g./cm.^{2} (Bradt and Peters, 1950 *c*), $\phi(\theta)$ is determined by treating the altitude curve as a series of sections of constant height. The product $f(\theta)\,\phi(\theta)$ is then tabulated at 10° intervals, and the integral is evaluated by quadrature. The procedure for the group $Z > 10$ is similar, except that the value 21 g./cm.^{2} is used for the mean free path in air, and the value 25·5 g./cm.^{2} for the mean free path in the material of the stack.

The tracks recorded in flight 4 show an apparent excess of particles coming from the south. This is almost certainly due to an unforseen tilt of the stack, which would cause an excess of particles to be recorded on the face tilted upwards. A tilt of some 10° would account for the observed asymmetry. Calculation shows that the total number of particles recorded in the tilted plate will not differ, within the limits of accuracy of this experiment, from the number recorded in a vertical plate.

The final values adopted, after considering these results and comparable results of flight 7, are as follows:

For $6 \leqslant Z \leqslant 10$, $N_0 = 1{\cdot}45 \pm 0{\cdot}30$ particles/m.^{2} sec. sterad

For $Z > 10$, $N_0 = 0{\cdot}33 \pm 0{\cdot}08$ particles/m.^{2} sec. sterad.

7. CHARGE AND ANGULAR DISTRIBUTION

The charge specturm of the primaries has been determined by others at higher latitudes (Bradt and Peters, 1950 *a*; 1950 *c*). The present results agree with this in general, but some uncertainty in the δ-ray calibration and the relatively small number of particles observed make the specturm uncertain in detail. The relative intensity of the two groups of particles agrees well with previous observations.

For a major part of the duration of the flight, the plates remained under about 55 g./cm.^{2} of matter. The primaries have large collision cross-sections, and hence those at large zenith angles were completely cut off. This resulted in a relatively small observable E.W. asymmetry of the incoming heavy primary radiation. Thus, this asymmetry, in the present experiment, is within the statistical uncertainty of the results.

8. SUMMARY

The paper describes high-altitude balloon experiments with nuclear plates, made near the geomagnetic equator. A magnetic orientating unit was used. The behaviour of balloons is discussed, and it is shown that systems of balloons may have a series of stable floating levels at determinate altitudes. Analysis of the tracks observed in the plates has given the following values for the primary cosmic ray flux at the geomagnetic equator:

For $6 \leqslant Z \leqslant 10$, $N_0 = 1 \cdot 45 \pm 0 \cdot 30$ particles/m.^{2} sec. sterad.

For $Z > 10$, $N_0 = 0 \cdot 33 \pm 0 \cdot 08$ particles/m.^{2} sec. sterad.

Any observable E.W. asymmetry at the heights reached by the plates is within the statistical uncertainty of the results. The charge spectrum is in general similar to what has been previously observed.

9. ACKNOWLEDGEMENTS

These experiments were initiated and directed by Dr. B. Peters. Others who took part in the experiments were Messrs. R. R. Daniel, D. Lal, R. C. Murthy, G. S. Shrikantia, G. V. Vasudevachar, D. Venkat Rao, K. G. Vohra, and Yash Pal. We are grateful to Dr. M. F. Kaplon who provided us with results of the analysis of plates from flight 7. We are indebted to The Madras Christian College, The Vellore Medical College and The Central College, Bangalore, for facilities generously given, and to the Meteorological Department, All India Radio, and the Defence Department, Government of India, for their valuable help. The experiments were financed partly by the University of Rochester and partly by the Indian Atomic Energy Commission.

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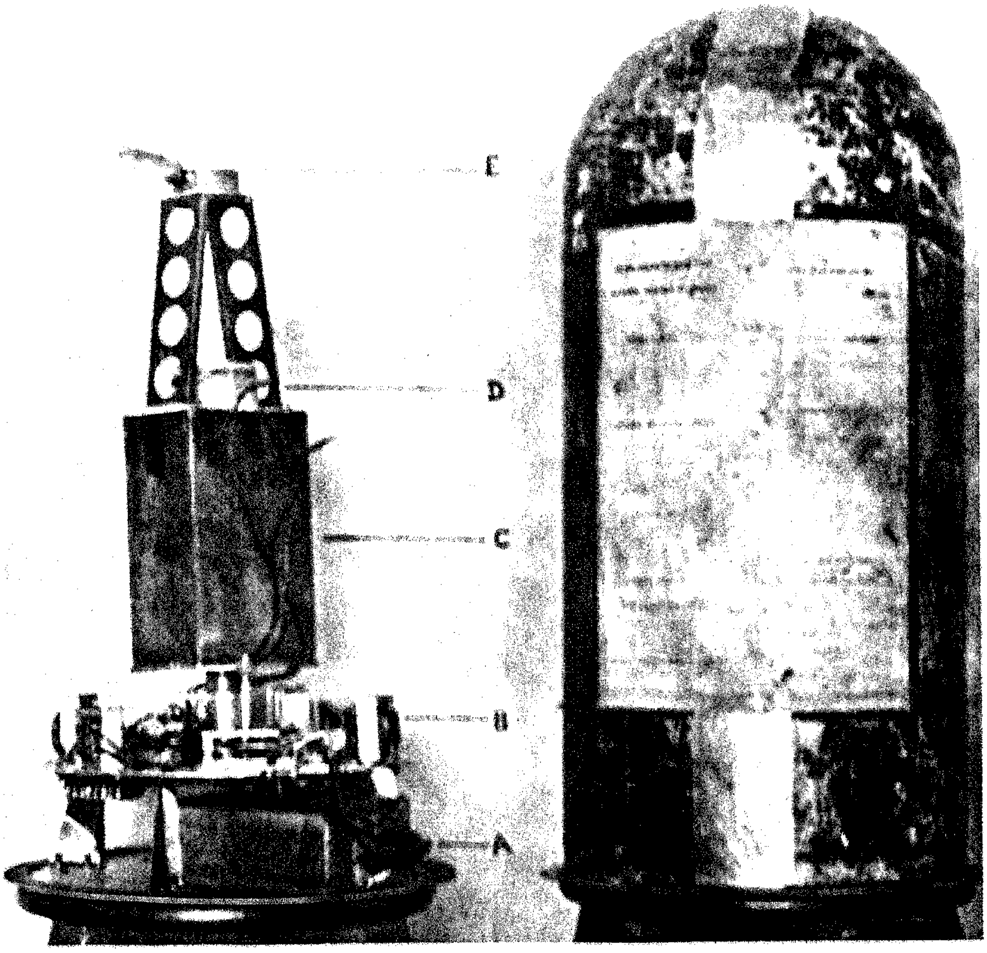

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