The Influence of the Earth's Magnetic Field on Cosmic-Ray Intensities up to the Top of the Atmosphere

I. S. BOWEN, R. A. MILLIKAN, AND H. V. NEHER
California Institute of Technology, Pasadena, California
(Received May 8, 1937)

Accurate observations on cosmic-ray intensities as measured by Neher electroscopes were made in the equatorial belt (Madras, India, mag. lat. 3 N) up to more than 98 percent of the way to the top of the atmosphere with the following results: 1. Cosmic rays whatever their nature are so rapidly absorbed in the outer layers of the atmosphere that even in the equatorial belt they get into equilibrium with their secondaries and produce their maximum ionization before they have penetrated through the first tenth of the atmosphere. 2. From that point on they fall off exceedingly rapidly in intensity following an exponential equation, their law of absorption being like that of x-rays and not that of particles that exhibit range phenomena such as low energy β-rays, proton rays or α rays. 3. The differences between the present curve, the San Antonio curve (mag. lat. 38.5 N) and the curve obtained on the Settle-Fordney flight (mag. lat. 53 N) fix for the first time the complete curves of ionization produced in the atmosphere by incoming charged particles having energies in the $2.5-6.7\times10^3$ Mev and $6.7-17\times10^3$ Mev ranges. These curves are reasonably well in accord with the Bethe Heitler theory as extended by Carlson and Oppenheimer. 4. The exceedingly rapid absorption of this latitude sensitive radiation with a coefficient nearly constant and independent of energy qualitatively justifies the shower theory of the foregoing authors. 5. The latitude sensitive part of the cosmic-ray ionization found in the lower portion of the atmosphere is practically all due to the secondary effects of varied nature resulting from the absorption of the incoming electrons in the upper tenth of the atmosphere. 6. The apparent absorption coefficient of the whole progeny of secondary influences resulting, down to sea level from the absorption of incoming electrons in the very top layers of the atmosphere is approximately the same as that found by Johnson and by Neher for the east-west effect thus proving that the particles causing the latitude and the east-west effects are of the same type. Both absorption coefficients are such as to suggest that these particles are electrons (predominantly positive) and not protons.

1. THE NEW EXPERIMENTAL LATITUDE FINDINGS

IMMEDIATELY after the San Antonio flights[1] we set about obtaining similar data at, or very near, the magnetic equator. Through the exceedingly generous and efficient cooperation of the Indian Meteorological Department represented by Director-General Dr. C. W. B. Normand, Assistant Director Dr. S. K. Banerji, Meteorologist Dr. K. Das and Assistant-in-Charge of the Madras Observatory, Mr. Narayanamurthi, H. Victor Neher, who sailed with our equipment for India on the S. S. President Van Buren on August 12, 1936, succeeded in the month of October 1936 in obtaining in Madras (mag. lat. 3° N) successful flights to nearly the same altitudes (98 percent of the way to the top) reached in San Antonio, 1936. Sample record of two of these flights is shown in Fig. 1. As heretofore explained[1] the barometer and thermometer

[1] R. A. Millikan, H. V. Neher and S. K. Haynes, Phys. Rev. **50**, 992 (1936).

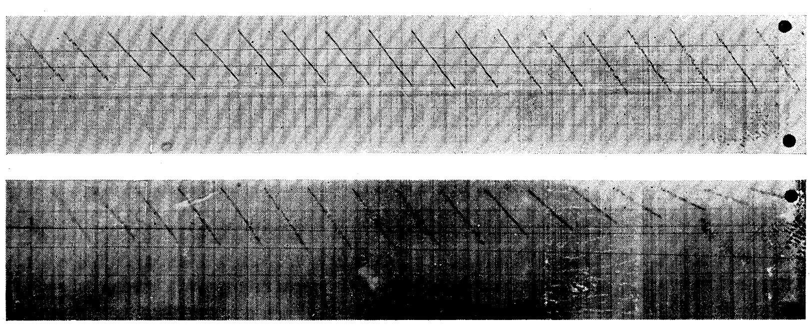

FIG. 1. Sample portions of two electroscope records taken at Madras, India (mag. lat. 3° N) in October 1936.

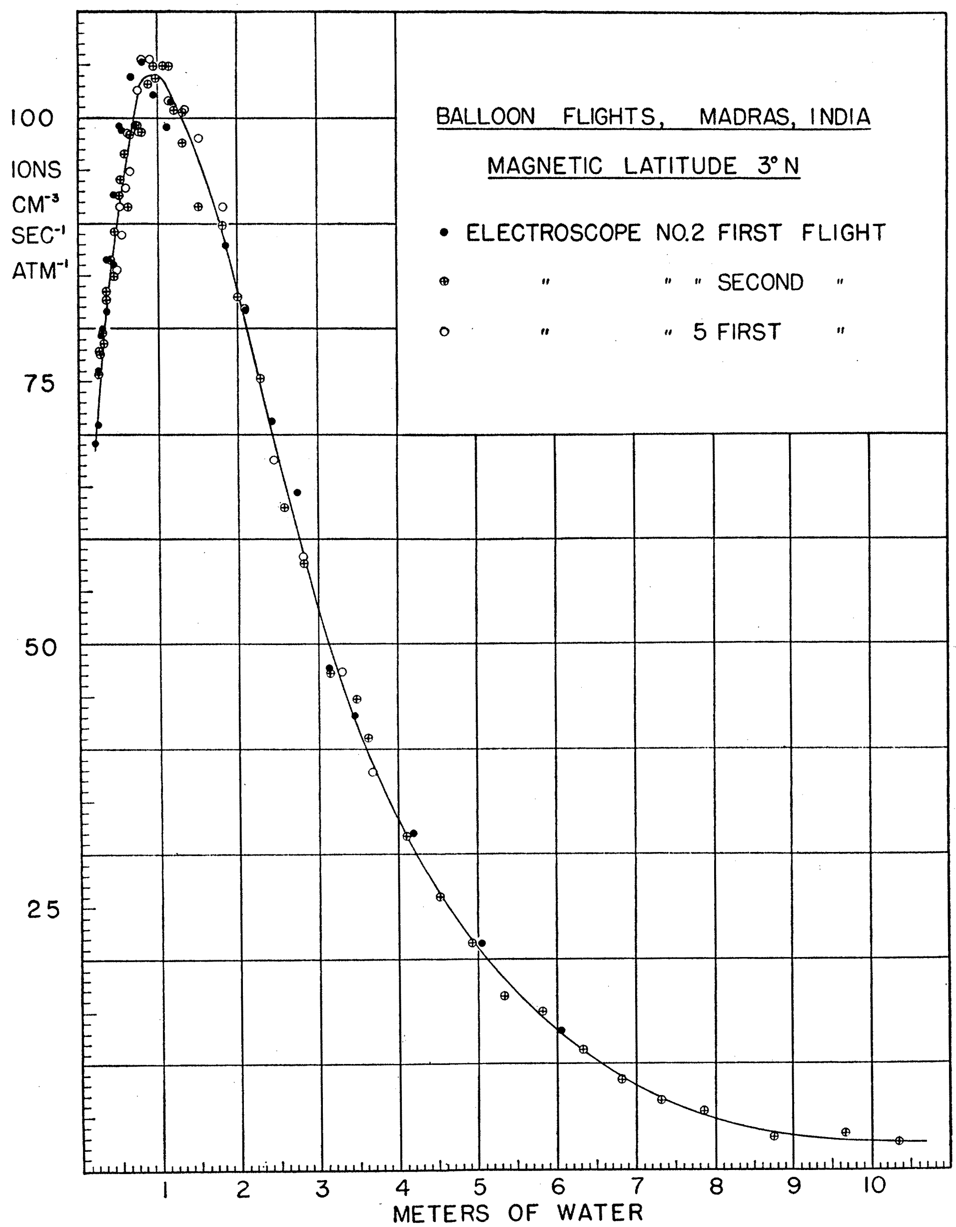

FIG. 2. Ionization as a function of depth, in meters of water equivalent, below the top of the atmosphere at Madras, India (mag. lat. 3° N).

lines and the changing slopes of the fine electroscope-discharge lines enable us to obtain a most satisfactory curve showing the relation of cosmic-ray ionization and altitude at the magnetic equator. Such a curve is shown in Fig. 2.

In order to show the effect of latitude on such curves we give in Fig. 3 the results of all of our high altitude observations. The upper curve combines our data obtained (a) in the Settle-Fordney flight[2] of November 1933, (b) in the Kepner-Stevens-Anderson flight of July 1934 (these latter data not before published) and (c) in the airplane flights[2] made at Spokane in September 1932. All of these flights were made in a magnetic latitude

[2] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **46**, 641 (1934).

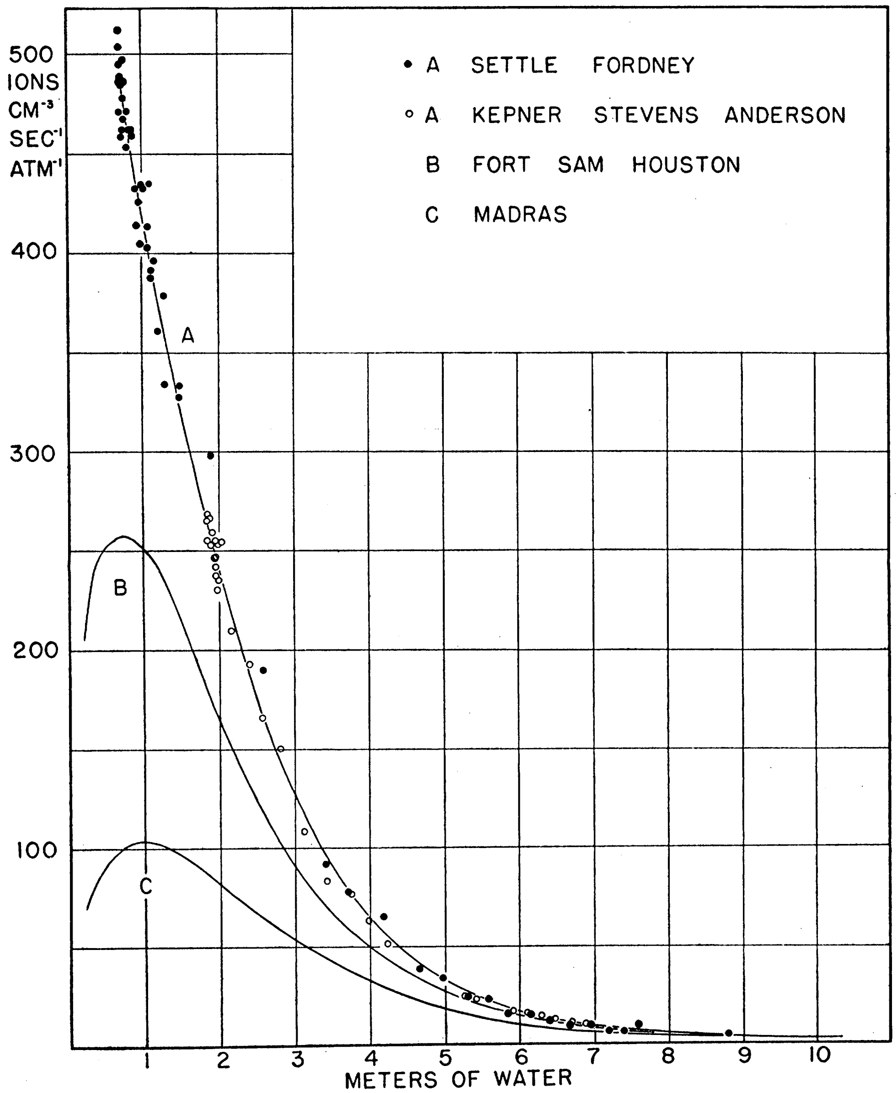

FIG. 3. Comparison of the ionization at Madras, India (mag. lat. 3° N), Fort Sam Houston, San Antonio, Texas (mag. lat. 38.5° N) and on the Settle-Fordney flight (mag. lat. 53° N).

of approximately 53° and between them carry the curve to a pressure of approximately 5 cm of mercury. The second curve gives the results of the Fort Sam Houston balloon flights[1] (San Antonio, Texas, mag. lat. 38.5°) combined with the airplane flights at March Field[2] (corrected for the slight difference in magnetic latitude). The lower curve indicates the ionization at mag. lat. 3° N as given by the balloon flights at Madras and the airplane flights at Manila,[3] made in November 1935. In order to make the data, obtained with the thin walled electroscopes used in the sounding balloon flights at Madras and Fort Sam Houston agree with the results obtained with the thick walled electroscopes used in the airplanes and manned balloons at the same latitude it was found necessary to increase by 10 percent all readings of the thin walled instruments.

The difference between the San Antonio and the Madras flights makes possible for the first time a particularly reliable and unambiguous determination of the absorption of the atmos-

[3] I. S. Bowen, R. A. Millikan, S. A. Korff and H. V. Neher, Phys. Rev. **50**, 579 (1936).

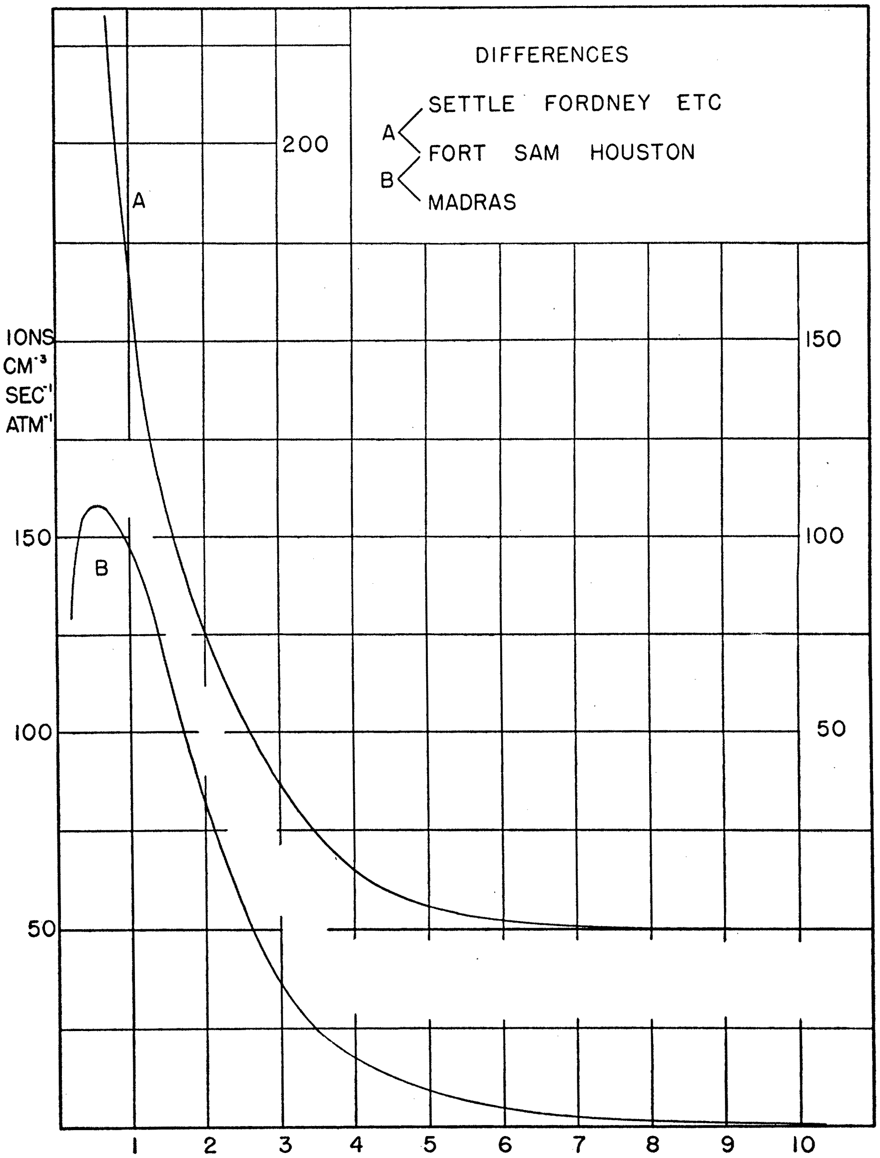

FIG. 4. Differences in ionization between Fort Sam Houston and Madras and between the Settle-Fordney flight and Fort Sam Houston.

phere for electrons having a mean incident energy of about 10,000 million electron volts, this being the weighted mean between the energy of 6700 Mev necessary for electrons (+ or −) to just get through the earth's magnetic field at the zenith in magnetic latitude 38.5° and that of 17,000 Mev necessary to get through at the equator in the longitude of Madras.

Similarly the difference between the curves corresponding to the flights in magnetic latitude 53° and those in magnetic latitude 38.5° gives a fairly reliable determination of such a mean absorption of the atmosphere for electrons having a weighted mean energy of about 4 billion ev. These two difference curves are shown in Fig. 4.

2. Qualitative Results from Curves

A first and most significant result obtained from a comparison of these curves is embodied in the statement that cosmic rays of all energies, even as high as 10,000 Mev coming into the earth from all directions on the average can penetrate not more than one-tenth of the way through the earth's atmosphere before coming into equilibrium with their secondaries. Everyone of the five curves shown save those taken at magnetic latitude 53°, which did not go high enough to reach the turn-over point, shows that the incoming cosmic rays whatever their nature act just like x-rays or gamma-rays in that as greater and greater thicknesses of the absorbing material, in this case air, are introduced between the source and the measuring electroscope the ionization in that electroscope increases to a maximum which is reached when the incoming rays are first in equilibrium with their secondaries and thenceforward falls off at a rate which is rapid if the absorption of the incoming rays is large, slower if that rate of absorption is smaller. This is in general a characteristic of rays, like x-rays, that lose a large fraction of their energy in one act and are therefore absorbed exponentially. It is not a characteristic of rays, like α- and β-rays, which have a range and ionize more or less uniformly along their paths.

Further, since the difference curves can only be due to the effect of the earth's magnetic field on incoming electrons these curves show that the nuclear absorption of electrons is unlike the extranuclear absorption in that it is an exponential absorption as required by the Bethe-Heitler theory and that the absorption coefficient is *very large* and does not vary rapidly with energy, also as required by that theory. Indeed the penetrating power of all the cosmic rays is so small that one meter of water is enough to get the whole group of incoming rays, whatever their nature, to the depth at which they are producing their maximum of ionization and close to the depth at which they are in equilibrium with their secondaries. This is seen from a comparison of the curves in Figs. 2, 3, 4, all of which reveal that the maximum of ionization is reached before the rays have penetrated through the upper tenth of the atmosphere.

In the case of the incoming 10,000 Mev electrons the lower curve of Fig. 4 shows that while these electron rays are intense enough to produce 160 ions per cc per sec. at a distance of but one-fifteenth of the way (0.7 meter of water) through the atmosphere, at a distance halfway through (5 meters of water) their influence has fallen off so rapidly that their total ionizing effect has dropped to 10 ions and at sea level (10 meters of water) it has fallen to three-tenths of an ion per cc per sec.

A further qualitative result of the study of all these curves is to emphasize the conclusion which one of us stressed in 1932[4] and suggested as a possibility in connection with the report on the 1926 expedition[5] from Los Angeles to South America made expressly to test the effects of the earth's magnetic field on the incoming cosmic rays, namely, that practically all of the observed cosmic-ray ionization at or anywhere near the earth's surface is due to the secondary effects of incoming rays which are absorbed in the very top of the atmosphere and through that absorption create secondary radiations of some sort that reach down to sea level and beyond.

TABLE I. *Comparison of differences with Gold formula.*

Meters of Water	Fort Sam Houston-Madras: Obs.	Fort Sam Houston-Madras: 580 G(0.54)	Settle, Fordney-Fort Sam Houston: Obs.	Settle, Fordney-Fort Sam Houston: 1800 G(0.80)
0.2	135.5			
0.4	156.3			
0.7	156.8	235.5	233	532
1.0	147.9	177.1	167	362
1.5	115.8	114.7	108	200
2	83.6	76.7	74.3	115
2.5	56.1	52.3	—	—
3	36.2	36.1	—	—
3.5	24.4	25.2	24	24.5
4	17.2	17.8	15.0	15.0
4.5	13.0	12.6	9.3	9.3
5	9.6	9.0	5.4	5.8
5.5	6.8	6.4	3.6	3.6
6	—	—	2.2	2.27
7	2.14	2.41	1.0	0.90
8.5	0.79	0.93	—	—
10.33	0.30	0.30	0.046	0.046

[4] R. A. Millikan, Phys. Rev. **43**, 661 (1933).

[5] R. A. Millikan and G. H. Cameron, Nature **121**, 21 (1928). In this first report made at the meeting of the B.A.A.S. at Leeds in Sept. '27 on the purpose and results of this voyage from Los Angeles (mag. lat. 41° N) to Peru (mag. lat. 1° S) to look for the effect of the earth's magnetic field on incoming electrons, the authors state that "if the northern hemisphere and southern hemisphere curves (of ionization with altitudes) coincide it would go a long way toward eliminating the possibility the rays are generated by the incidence of high speed beta-rays on the outer layers of our atmosphere . . . for such beta-rays would be expected to be influenced by the earth's magnetic field so as to generate stronger radiation over the poles than over the equator."

3. Quantitative Treatment of Field Sensitive Rays

As in our report to the London Conference[6] we find it essential to divide all incoming rays into field-sensitive and non-field-sensitive rays. We leave the nature of the non-field-sensitive rays for the present undetermined and attempt to see what can be done in the way of an understanding of the field sensitive rays, i.e., the rays which are the cause of the ionization represented by the difference curves of Fig. 4. These rays can only be due to incoming charged particles.

One way of analyzing the results of the direct measurement of the absorption of 4 and 10 billion volt electrons, without calling in any theory at all, is by building up the observed ionization curves from Gold integrals following the method already used by us in the study of the total cosmic-ray ionization curve.[7] This analysis is made in Table I for both of the difference curves. It is at once seen that unlike the total cosmic-ray ionization curve discussed in the previous article the whole difference curve (from 1.5 meters of water from the top of the atmosphere down to sea level (10 m)) representing the ionization produced in our electroscopes by 10 billion volt incoming electrons, with the progeny of secondaries of all kinds, may be approximately represented by one single absorption coefficient, namely 0.54 per meter of water, over a range in the ionization of a factor of 400. Similarly the ionization produced by 4.0 billion volt incoming electrons is fairly closely reproduced by an apparent absorption coefficient of 0.80 per meter of water. Of course the numerical values of the coefficients thus obtained have no simple relationship to the absorption coefficients of the primary particles involved since the observed ionization curve, which these values describe is produced by a complex mixture of primaries, secondaries, tertiaries, etc. The coefficients are here given merely as a convenient method of describing quantitatively the observed variation of ionization with depth which can then be compared with similar results obtained with counters (see Section 4) or with measurements on the total ionization (see above).

[6] I. S. Bowen, R. A. Millikan and H. V. Neher, *Papers of the International Conference of Physics* (London, 1934), p. 206.

[7] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **44**, 246 (1933).

These observed absorption coefficients are of the order of magnitude given by theory for the apparent absorption of electrons after coming into equilibrium with their secondaries as determined primarily by the formation of "impulse radiation" or bremsstrahlung (see below). This absorption is on the other hand much greater than that of heavy charged particles such as protons since neither according to theory nor to experiment can *heavy* charged particles lose energy in appreciable amount by exciting x-radiation of the bremsstrahlung type. We know this experimentally because neither protons nor alpha-rays have ever been observed to give rise to appreciable amounts of such radiation and we know it theoretically because this radiation is due to rapid deceleration of the charged particle as it approaches or passes by a nucleus, but the mass of a heavy particle precludes the possibility of such rapid deceleration while the electron (+ or −) must, because of its lightness and its charge, experience such decelerations exceedingly easily and suddenly. This therefore rules out incoming protons as a significant source of the latitude sensitive part of cosmic radiation. Furthermore the constancy of the absorption coefficient of the latitude sensitive rays is perhaps another indication that the ionization produced by them may be explained without the introduction of incoming particles as penetrating as protons. Of course this last argument would no longer be valid if heavy particles should be found to have another mechanism of absorption such as nuclear transmutations with a coefficient comparable to the observed values discussed above.

The present experiments seem therefore to give the first direct measurements on the nuclear absorption by air of up to 10 billion volt electrons over a wide range of depths in the atmosphere. They show conclusively that incoming electrons of such stupendous energy are absorbed exceedingly rapidly in the first tenth of the earth's atmosphere. *They transmit, not themselves, but only their secondary influence to the lower regions of the atmosphere.* According to the Oppenheimer-Bethe-Heitler theory these secondary influences are limited to the following. The impulse rays, or scattered x-rays, into which the energy of the 10 billion volt incoming electrons (+ and −) are at first partially transformed, produce in turn by

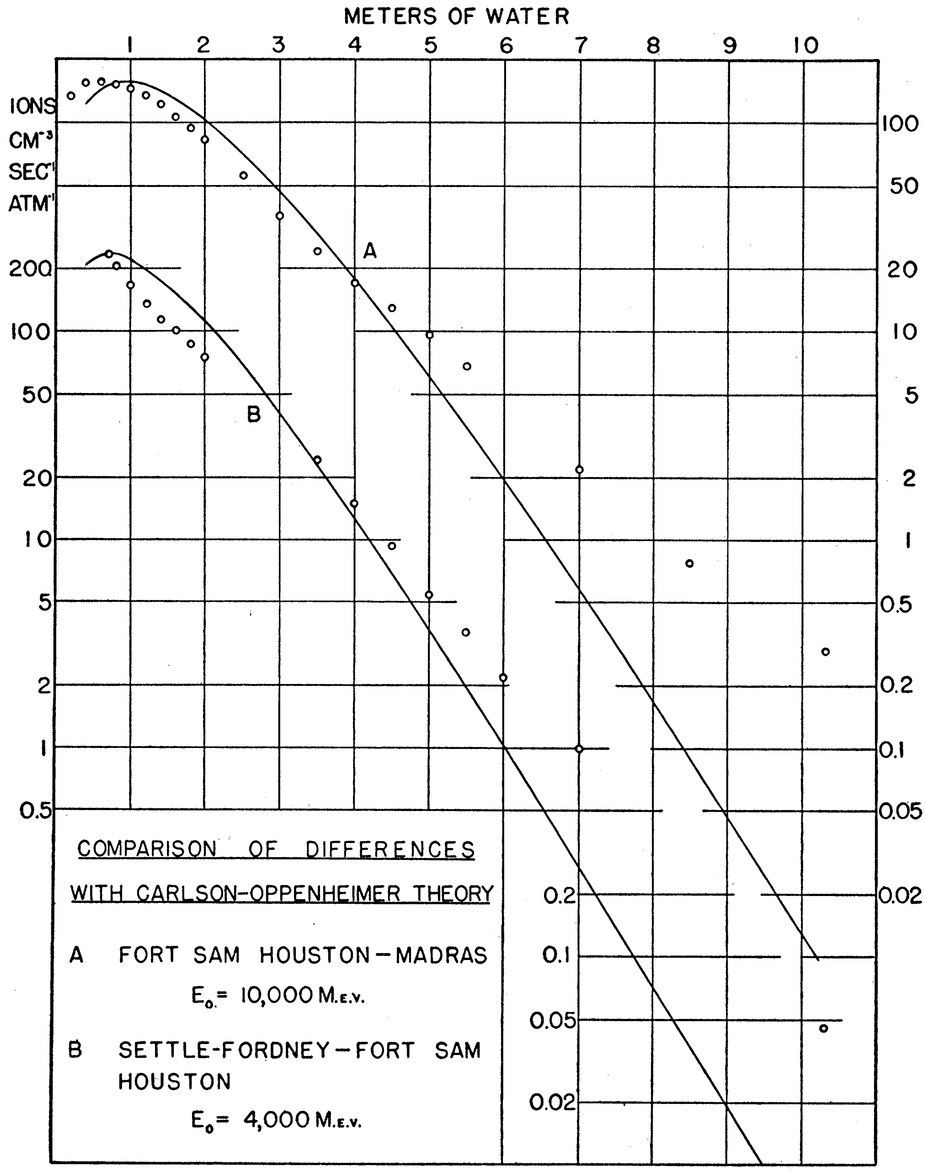

FIG. 5. Comparison of the difference curves with the Carlson-Oppenheimer theory.

their absorption by the nuclei of the molecules of the air, electron pairs, the energy of which is in turn quickly again transformed into lower energy impulse radiation and so on until the whole energy of the incoming electron has been frittered away by the summed ionizing power of the very large progeny of beta-rays of all energies which are ultimately formed. Carlson and Oppenheimer[8] have recently carefully followed through this whole process, and without introducing further mechanisms of absorption have so extended the Bethe-Heitler theory as to make it possible to compare the full curve of variation of 10 billion volt cosmic-ray ionization as a function of altitude with our observed variation. Similar calculations have also been made by Bhabha and Heitler[9] with results in substantial agreement with those of Carlson and Oppenheimer. To make

[8] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937).

[9] H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **159**, 432 (1937).

possible this comparison Carlson and Oppenheimer's equations which were worked out for radiation coming in vertically, were transformed so as to make them applicable to rays coming in from all directions such as those to which our electroscopes actually respond. This is a purely geometrical transformation which is essentially the inverse of the Gross analysis.

The comparison of this transformed Carlson-Oppenheimer formula with the observed difference curves, plotted on a log scale, is shown in Fig. 5. In both cases the general form of the calculated and observed curves are in agreement thus indicating that the mechanisms discussed above play a major role in the production of ions by these high energy particles. In detail however it is evident that certain systematic differences occur between observation and theory, namely, (a) the maxima are observed at about $\frac{2}{3}$ of the predicted distance from the top of the atmosphere and (b) the apparent absorption coefficient near sea level is from $\frac{1}{2}$ to $\frac{2}{3}$ of the value predicted by theory. Both Carlson and Oppenheimer and Bhabha and Heitler emphasized the second discrepancy but did not find the first type of difference in comparing their curves with the observations of Pfotzer[10] who used vertical coincidence counters at mag. lat. 50° N. However, in making the comparison both groups of authors used the theoretical curve for an energy of the incident electrons of 2.5×10^3 Mev, this being the minimum energy that can enter at this latitude. Our own Fig. 2, however, indicates unambiguously that at this latitude over half of the ionization is due to incoming particles of energy greater than 6.7×10^3 Mev. If one compares Pfotzer's observed curve with the theoretical curve for the correct mean energy, say 6 to 8×10^3 Mev, the observed maximum occurs at a depth about $\frac{2}{3}$ as great as that given by the theoretical curve in agreement with our own findings. As pointed out to us privately by Dr. Oppenheimer the theoretical calculations are more uncertain in the initial part of the curves than at greater depths and consequently the first type of discrepancy (position of maximum) is probably less serious than the second (absorption coefficient near sea level). Since in our curves the ionization is produced by particles in a definite range of energy the discrepancy in the apparent absorption coefficient at sea level cannot be explained by the presence of a few primary particles of very high energy.

It is interesting to observe too as our data (see Table I) have already shown that at a depth of 3 or 4 meters of water equivalent where the theory fits best, the apparent coefficient of absorption is essentially the same as at 6 or 7 meters where the present theory explains less than half of the observed ionization. This is in line with the fact which we have earlier reported that there seems to be a constancy at these elevations in the fraction of the radiation removed by 6.5 cm of lead.[11] Similarly some observers report constancy in the ratio of number of showers to total ionization over this range.[12] The last two observations were made on total radiation which, however, is made up largely of the radiation of the type under consideration at depths of 6 or 7 meters of water or less. In these cases the constancy breaks down at depths greater than 6 or 7 meters where the penetrating non-field-sensitive component of the cosmic rays becomes an important factor of the total ionization. This similarity in the behavior of the radiation at 3 or 4 meters and 6 or 7 meters seems to indicate that the discrepancy near sea level cannot be explained by the addition of a small penetrating component whose influence extends to sea level but that a rather more fundamental modification or extension of the interpretation must be made.

4. The East-West Effect and the Longitude Effect

Both of these effects are best observable at the magnetic equator and both must be considered as a part of the field sensitive subdivision of cosmic-ray phenomena. They are here treated together because the understanding of the former should carry with it that of the latter also.

Johnson[13] has measured with very great care the east-west effect in Peru, in Mexico and in the United States both at sea level and at altitudes up to 4300 meters. By comparing the excess of west over east counts as the amount of at-

[10] G. Pfotzer, Zeits. f. Physik **102**, 41 (1936).

[11] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **46**, 646 (1934).

[12] R. H. Woodward, Phys. Rev. **49**, 711 (1936) and H. J. Braddock and C. W. Gilbert, Proc. Roy. Soc. **156**, 570 (1936).

[13] T. H. Johnson, Phys. Rev. **48**, 287 (1935).

mosphere through which the particles have passed is varied by changing the zenith angle and also by changing the elevation of the observing station, he has computed the absorption of the atmosphere for the particles producing the east-west effect. He found this coefficient to vary between 0.33 and 0.53 per meter of water. These observations are also in substantial agreement with a fairly extended series of measurements on the east-west effect made by Neher in India in October 1936. The point upon which we would here lay emphasis is the approximate agreement between this coefficient of absorption of the particles which give rise to the east-west effect and the apparent coefficient of absorption of the 10^4 Mev electrons which give rise to the lower curve of Fig. 4, namely 0.54 per meter of water. This general agreement seems to require that the east-west effect like the latitude effect be due to incoming particles of the electronic type, in this case positrons rather than protons. The net result then of this whole study of the east-west effect in its relation to the latitude effect is to indicate that the particles responsible for this east-west effect are positive electrons. Further as observed above it does not even require accurate analysis to show that they cannot be protons for if protons or any other similarly penetrating particles were found in appreciable numbers in the incoming swarm of charged particles, these penetrating particles would be found in abundance at zenith angles between, say, 75° and 90°, where in fact the number of incoming cosmic rays at sea level is very small.

We reach the conclusion then that for the understanding of latitude effects, east-west effects and longitude effects, or in a word for the interpretation of all field sensitive phenomena we require only incoming electrons (+ or −) and if protons or other penetrating particles are present at all they have a negligible influence upon measuring instruments of either the electroscope or the counter types.

In conclusion the authors wish to express their indebtedness to Dr. S. K. Haynes for preparing the condensers used in these electroscopes and otherwise assisting in the preparation for the flights. We also wish to make grateful acknowledgement to the Carnegie Corporation of New York and the Carnegie Institution of Washington for providing the funds which made this investigation possible.

JULY 15, 1937 PHYSICAL REVIEW VOLUME 52

The Near Infrared Absorption Band of Liquid Water at 1.79μ

J. R. COLLINS
Cornell University, Ithaca, New York
(Received May 20, 1937)

The near infrared absorption band of liquid water at 1.79μ has been studied at various temperatures. No apparent changes in the band were detected in the temperature range from 4°C to 137°C.

INTRODUCTION

RECENTLY, Kellner[1] has raised a doubt concerning the existence of the weak absorption band of liquid water at 1.79μ which was discovered and reported by Ellis.[2] The presence of this band is of considerable interest in connection with the classification of the near infrared absorption bands of liquid water. If this band really exists, it is the second band to be found in the absorption spectrum of liquid water which has not been found in the spectrum of the vapor phase. The other such band is the well-known one at 4.7μ.

To classify all the bands except the three fundamental vibrational bands of the water molecule it is customary to regard them as harmonic or combination bands of the fundamental bands. Since these fundamental bands are located at 2.8μ, 2.9μ, and 6.1μ, respectively, it is evident

[1] Kellner, Proc. Roy. Soc. **159**, 410 (1937).
[2] Ellis, Phys. Rev. **38**, 693 (1931).

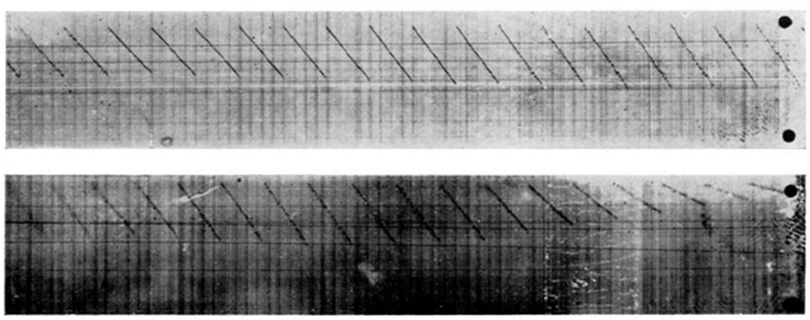

FIG. 1. Sample portions of two electroscope records taken at Madras, India (mag. lat. 3° N) in October 1936.