A Very High Altitude Survey of the Effect of Latitude upon Cosmic-Ray Intensities And an Attempt at a General Interpretation of Cosmic-Ray Phenomena

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(Received July 24, 1934)

The results of a very high altitude geographical survey extending in airplanes from Northern Canada to Peru, to altitudes of 22,000 feet, and, in three stratosphere flights made within the United States, to altitudes of 60,000 feet, are interpreted in the light of (1) the Epstein and the Lemaitre-Vallarta analysis of the effect of the earth's magnetic field, and (2) the Bowen-Millikan proof that the immediate agents responsible for the ionization of the atmosphere are electrons (+ and −), rather than protons or heavier nuclei. The main conclusions reached are: (1) that the resistance of the atmosphere to incoming electrons is 1 billion volts because of extranuclear encounters, 5 billion volts because of nuclear encounters; (2) that nuclear electron encounters produce only very soft secondaries, both photons and electrons; (3) that incoming photons produce most of the ionization found at sea-level or at sub-sea-level depths; (4) that nearly all of the non-field sensitive part of the ionization of the atmosphere above sea-level is due to photons of energy 200 ± 170 million electron volts; (5) that in the equatorial belt a small part of the ionization is due to incoming secondary electrons of energies as high as 10 billion volts; (6) that these are responsible for the east-west effect and the longitude effect found in the equatorial belt; (7) that the field sensitive part of the ionization increases rapidly with increasing latitude in going from Panama to Spokane because incoming secondaries of energies decreasing from 8 billion to 2 billion volts get through the blocking effect of the field in rapidly increasing numbers with increasing latitude and add greatly in northern latitudes to the underlying ionization of the upper-air produced by the incoming photons; (8) that the only source now in sight of the observed cosmic-ray energies is matter-annihilation; (9) that the softest components of the cosmic rays have the energies corresponding to the partial annihilation or atom building hypothesis, while the hardest components have energies corresponding to the complete atom-annihilation hypothesis; (10) that these processes may conceivably be taking place (1) because of the very low temperatures that facilitate the clustering of hydrogen in interstellar space, or (2) because of such extreme temperature conditions of the opposite sort as are found in novae, as suggested by Zwicky.

§I. INTRODUCTORY

THE following is a detailed report of the results of a very high altitude survey of the effect of latitude upon cosmic-ray intensities planned in the late fall of 1931, a preliminary report upon which was made at the Atlantic City meeting of the A. A. A. S. in December, 1932.[1, 2] As indicated in that report, as well as in a lecture[3] delivered in Paris in November, 1931, such latitude effects were to be anticipated at high altitudes, even if they did not appear at low. For cosmic-ray photons traversing space in all directions must in any case produce secondary electrons wherever they traverse matter, whether that be in interstellar space, in nebulae, or in the atmospheres of suns through which they must sometimes pass in their travel of billions of years through space. So that if cosmic-ray photons exist at all, space must be traversed in all directions to some extent, at least, both by these photons and by their secondary electrons. The only question for experiment to determine is as to the proportions between the two.

It was thought that a suitable high-altitude survey would throw light upon this question. For these electronic secondaries were expected, from the direct cosmic-ray-energy measurements already under way at the Norman Bridge Laboratory and from Epstein's calculations published as early as 1930, to possess insufficient energy to get to the earth's surface at the equator through the blocking effect of the earth's magnetic field, but amply sufficient to penetrate that field in the higher magnetic latitudes. To be specific, Epstein[4] had found that billion volt electrons could only get in north of magnetic latitude 59°. Since, however, such latitude effects had been shown to be non-existent at the earth's surface in the region between Pasadena (mag. lat. 41°) and Churchill, Manitoba[5] (mag. lat.

[1] Robert A. Millikan, Phys. Rev. **43**, 665 (1933).
[2] Bowen, Millikan and Neher, Phys. Rev. **44**, 246 (1933).
[3] Robert A. Millikan, *Annales de Institut H. Poincare*, 1933, p. 452.
[4] Paul S. Epstein, Proc. Nat. Acad. Sci. **16**, 658 (1930).
[5] R. A. Millikan, Phys. Rev. **36**, 1597 (1930). These results were checked in 1932 by Millikan and Neher

70°), it was thought highly important from the standpoint of our planning in 1931 to look for them at high altitudes in northern Canada where electrons of too little energy to penetrate to sea-level might get through the earth's magnetic field and make their presence felt in the upper regions of the atmosphere.

Indeed, Epstein's analysis had shown that electrons of a given energy *should be distributed uniformly over a polar cap* which should of course extend farther and farther south the higher the incoming energy. In this analysis, however, atmospheric absorption had been ignored. But the greater part (about three-fourths) of the electrons the energies of which were being directly measured in the Norman Bridge Laboratory actually had energies under a billion volts, and since no appreciable number of billion-volt electrons could possibly penetrate the atmosphere (see below), even if they could get through the earth's magnetic field, it is obviously only at high altitudes that the effects of such entering electrons could be expected to be observed. Epstein's figures were available to us when we planned this high altitude survey in the late fall of 1931. We therefore arranged at that time, through the kind assistance of the Royal Canadian Air Force, to make our northernmost high altitude airplane flight at Cormorant Lake, Manitoba in magnetic latitude 63° N, where we hoped to get a crucial test of the existence inside this cap of incoming electrons of billion-volt energies or less. The other localities in which we planned and carried out flights in the succeeding summer (1932) were Spokane (54° N), where Captain Breene flew most skilfully for us, March Field, California (41° N), where Colonel Arnold and the other officers of the Field were extraordinarily generous in their assistance, Panama (20° N), where General Foulois gave directions again for Army assistance, and Peru (4° S), where the Pan American Airways pilots flew to high altitudes for us. The success of these airplane observations is largely due to the development of a vibration-free electroscope yielding as good photographic records on a moving and tipping platform, like an airplane, as in a laboratory.

(between Los Angeles and Victoria, B. C.) and by Bennett, Dunham, Bramhall and Allen, Phys. Rev. **42**, 446 (1932).

§II. The Results of the 1932 Airplane Latitude Survey

The whole of the results of the aforementioned survey are given in Fig. 1, in which the readings at different depths, in meters of water, beneath the top of the atmosphere, are given in ions per cc per sec. formed in air at atmospheric pressure. The geomagnetic latitude is determined from the assumption generally made now by geophysicists that the chief component of the earth's magnetic field is a dipole, the northern pole of which emerges at 69° 8′ W, 78° 30′ N.

The main points to be noted in connection with Fig. 1 are (1) that up to the altitude reached, namely, 4.5 m of water beneath the top, no detectable difference is found between the readings at Cormorant Lake (63° N) and those at Spokane (54° N); (2) that at 4.5 m (22,000 ft.) there is a 12 percent larger ionization at Cormorant Lake and Spokane than at March Field, and that this difference decreases smoothly to zero at sea-level; (3) that no measurable difference appears between the curves taken in Panama (20° N) and Peru (4° S); (4) that the Panama reading at 20° N is 29 percent lower

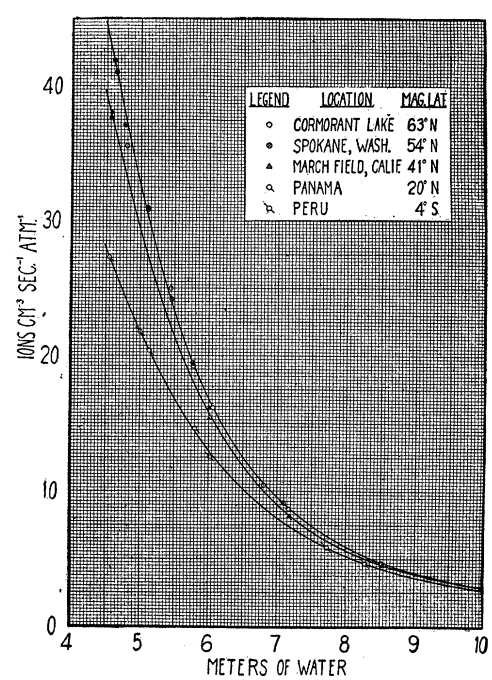

Fig. 1. Summary of results of the 1932 airplane latitude survey.

than the March Field reading and 38 percent lower than the Spokane and Cormorant Lake readings; (5) that the area between the uppermost and the lowermost curves represents that portion of the ionization which is due directly or indirectly to field-sensitive rays, while the area underneath the lower curve is that portion of the ionization which is due to non-field sensitive rays.

§III. Loss of Energy of Incoming Cosmic-Ray Electrons in Reaching Sea-Level about Six Billion Electron Volts

Anderson and Neddermeyer have counted with a great deal of care the average number of ions formed per centimeter by a high speed cosmic-ray electron at normal pressure. This can be done accurately if cloud-chamber tracks are chosen which correspond to the passage of an electron a little before the expansion so that the ions have had say a second to diffuse before the water condenses upon them, for the droplets are then well separated. Their result is 32 ions per cm. According to Kuhlenkampf's measurements, each electron removed from the molecules of air represents an expenditure of 32 electron volts of energy. These figures give 1020 electron volts of energy lost per cm of air-path. This, multiplied by the number of centimeters of air in an atmosphere, namely, $1033/.00117=8.83\times10^6$, gives 900,000,000 electron volts loss of energy in penetrating the atmosphere. Since the greater part of the electrons that reach the earth's surface have come in within 45° of the normal, we may take the average electron as entering at say 26°, the cosine of which is 0.9, so that a billion electron volts per atmosphere may be taken as the energy dissipated per electron in reaching the surface *on the incorrect assumption that no secondary rays are formed in so doing.*

There are, however, three different ways of determining the *total* resistance of the atmosphere, *including the formation of secondaries.*

(1) According to Epstein's computations, which are in excellent agreement with those made by Lemaitre and Vallarta,[6] 2.4 billion volt rays will just begin to get through the earth's magnetic field at magnetic latitude 49, and be completely through at latitude 57, so that there should be a latitude effect due to these rays, as well as to those of lesser energy, between Spokane (mag. lat. 54°, where 2.4 billion-volt rays should be varying most rapidly) and Cormorant Lake, provided incoming secondary electrons of these energies exist at all. Anderson's direct energy measurements have revealed the existence of such rays, and in addition the high altitude latitude effect found farther south (Fig. 1) shows that even higher energy electron-secondaries are formed. *The reason, then, that we did not find a latitude effect between Spokane and Cormorant Lake must be that rays of this energy cannot penetrate the atmosphere so as to show their effect at the highest altitude at which we made measurements, namely, 4.5 equivalent meters of water beneath the top of the atmosphere.* This means that the total resistance of the atmosphere (equivalent to 10 m of water) to incoming electrons (+ or −) must be more than $10/4.5\times2.4$, or 5.3 billion volts. A possible uncertainty in this mode of approach to the problem lies in the fact that we do not know whether locating the effective position of the north magnetic pole for the purposes here under consideration at 78 N, 69 W, is strictly legitimate, though it is the recognized practice of geophysicists, and, in addition, it introduces a larger measure of self-consistency into our own geographical readings than does any other point when used as a magnetic pole.

(2) The second mode of approach is to start with Anderson's and Neddermeyer's direct measurements of the loss in energy of electrons of energy between 40 million and 300 million volts in passing through lead. The mean value of this energy-loss (see accompanying paper by Anderson and Neddermeyer) is now 52 million volts per cm of lead. Since the mass absorption law holds fairly well in the highest energy range in which the loss of energy of electrons in traversing matter has been measured, lead having in fact some 9 times the absorptive power of water[7] per cm³, we assume that this relation holds for cosmic-ray electrons, and obtain for the resistance of the atmosphere (10 m water) $=52\times10^6\times1033/9=6$ billion volts. This might

[6] Lemaitre and Vallarta, Phys. Rev. **43**, 91 (1933).

[7] See *Radiations*, etc., Rutherford, *et al.*, p. 427, 1930; also Bethe, Zeits. f. Physik **76**, 293 (1932).

be in error by 20 percent, but probably not more than that.

(3) The third mode of approach is to utilize the fact that there is no sea-level latitude effect between Pasadena (41° N) and Churchill (70° N), while there is a marked latitude effect higher up in the atmosphere (Fig. 1). But according to Epstein it takes just 4 billion-volt electrons to begin to get through the earth's magnetic field at 40° N, and these will produce a latitude effect up to mag. lat. 52. A marked latitude effect is actually shown in the upper air (Fig. 1) in this region, but none at sea-level. Hence, if there are 4 billion-volt incoming secondaries, the resistance of the atmosphere must be at least 4 billion electron volts to prevent them from reaching sea-level. Indeed, a few 6, 7 and even 8 billion-volt electrons are needed to produce the latitude effect shown in Fig. 1 between Panama (20° N) and Pasadena (41° N). Again, according to Epstein and Lemaitre, the latitude effect of 5.5 billion-volt electrons should begin at lat. 34° and be finished at lat. 50°. Its practical absence at sea-level means that the resistance of the atmosphere is at least that much. The effect of the few 7 and 8 billion-volt electrons needed to carry the observed latitude effect both in high altitudes and at sea-level down to 20° would be finished at about 45° and should be very small down to 41°, so that the practical absence of a sea-level effect between 41° and the pole fixes the total resistance of the atmosphere at about 6 billion electron volts. In view of the three modes of approach, especially the last two, this value can scarcely be in error by as much as 20 percent.

The main result of this whole analysis of atmospheric resistance to incoming electrons is found in the conclusion that *about five-sixths, or 83 percent, of all the "field-sensitive" ionization found between the upper and lower curves of Fig. 1 is due to secondaries formed within the atmosphere.*

A second result of nearly equal importance is that since none of these secondaries, either photons or electrons, are sufficiently penetrating to get down to sea-level and reflect there the latitude effects actually existing at higher altitudes they are on the average low energy secondaries, the photons probably having an average energy, estimated from their inability to reach sea-level, of less than say 50 million volts, while the secondary electrons must for the same reason have an energy under say 500 million volts. This checks qualitatively with the results already published, for the energies of these very photons are exhibited in Figs. 7, 8 and 10,[8] and those shown all have energies under 30 million volts and many of them under a million. In fact, the energy of the photons produced by the disappearance of positive-electrons, such as are always formed in high energy nuclear encounters, is known from the experiments of Thibaud[9] and Lauritsen[10] to be about 0.5 million volt, and many such must be formed. On the other hand, the electron secondaries formed by electrons, examples of which are shown in Figs. 13 and 14,[8] are in these particular cases seen to possess energies only up to 50 million volts. Indeed, not only Anderson's and Neddermeyer's photographs, but all beta-ray photographs, show that the transfer of a very large part of the energy of an electron to another electron is a very rare event, while a high energy photon in general transfers a large fraction of its energy to the electron with which it collides.

§IV. Second Proof of the Atmospheric Origin of the Great Bulk of the Observed Ionizing Cosmic-Ray Particles

A preliminary report was made at Atlantic City in December, 1932 upon the results of a second method of testing whether or not a very large fraction of the ionization of the atmosphere is due to secondary electrons formed within our atmosphere. The method consists in taking an unshielded electroscope to a very high altitude and then observing the ionization found inside the same electroscope when it is taken to the same altitude inside a heavy shield of lead.

Fig. 2 shows the results of such tests made at March Field through the cooperation of the Army officers stationed there. If the lead screen, here 10 cm thick, acted simply as a resistance of the type considered in the first paragraph of §III, so that no secondary rays, photons, or

[8] Anderson, Millikan, Neddermeyer and Pickering, Phys. Rev. **45**, 352 (1934).
[9] Thibaud, Phys. Rev. **45**, 781 (1934).
[10] I. R. Crane and C. C. Lauritsen, Phys. Rev. **45**, 430 (1934).

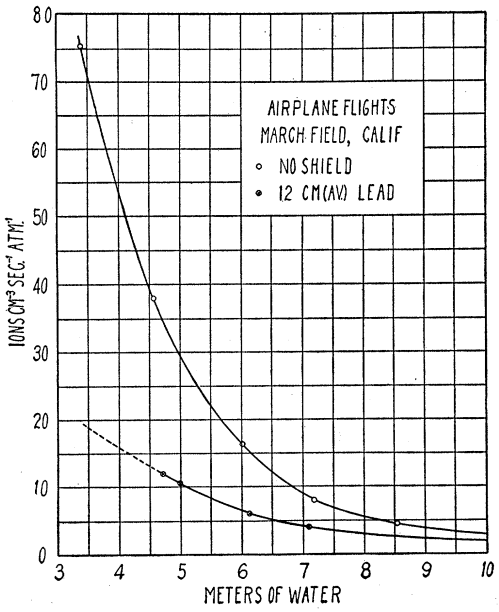

FIG. 2. Measurements in shielded and unshielded ionization chambers at various altitudes.

electrons were stimulated within it, then the ratio between the ionization found within it, first without screen, second with screen, would reveal what fraction of the electrons existing at the given altitude possess sufficient energy to penetrate the given thickness of lead. Since it is known that many new secondaries are actually stimulated within the lead, and since these all increase the actual ionization existing within the shielded electroscope, the foregoing ratio gives merely the lower limit to the number of electrons having energies under the value required to penetrate the lead. Since the shield was here 10 cm thick, the figure shows that at 29,000 feet at least 70 percent and more, probably 90 percent, of all the electron-rays existing at that altitude have energies under 520 million volts, this being, according to the Anderson measurements, the energy required to traverse 10 cm of lead. *Practically none of these electron-rays could have come in from outside, since it requires at this latitude at least 4 billion-volt electrons to get into the atmosphere through the blocking effect of the earth's magnetic field.*

§V. THE FORDNEY-SETTLE FLIGHT

The recent Fordney-Settle flight was even better adapted to bringing to light the cogency of the foregoing mode of approach to the problem of the origin of the ionization of the atmosphere. We had one of our self-recording instruments on that flight. Fig. 3 gives a section of the film. The electroscope was automatically charged up at five minute intervals and the slope of the line running diagonally across each interval gives the rate of discharge. The balloonists rose to the top very rapidly—in some 20 minutes, as the record shows—and remained there for three and a half hours, then descended rapidly. The result is that the mean readings at the top 62,000 feet are very reliable, but the intervening points are less so on account of the rapidity of the ascent. The results are plotted in Fig. 4, the lower curve giving the results obtained by Dr. A. H. Compton with his electroscope inside of 6.5 cm of lead. Fig. 5 gives the lower limit to the fraction of the electron-rays existing at each altitude, the energies of which must lie under 330 million volts. It is seen, then, that from a depth beneath the top of the atmosphere of

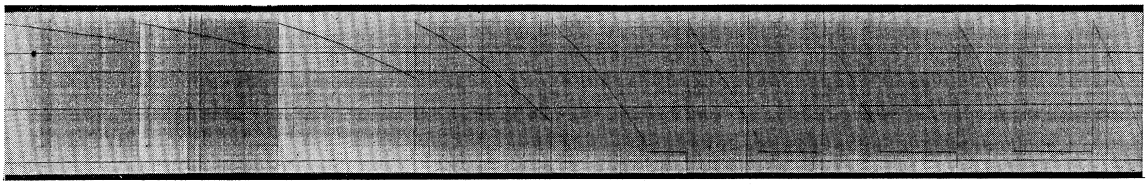

FIG. 3. Section of film from the Neher automatic recording electroscope taken during the ascent to the stratosphere of the balloon in the Fordney-Settle flight of November 20, 1933. Each of the nine panels across which the sloping dark line moves from left to right corresponds to a five-minute time interval. The slope is proportional to the rate of discharge of the electroscope, which in turn is proportional to the intensity of the cosmic rays. In the first panel the balloon was at an elevation of about 20,000 feet, and in the next twenty minutes (four panels) while the balloon was rising to a height of 45,000 feet the slope, or cosmic-ray intensity, rose tenfold. From there on to the highest altitude attained, 62,000 feet, the rate of rise of the balloon was much less rapid. It remained at or near the top for three and a half hours, so that this film yielded accurate measurements of cosmic-ray intensities at the higher and lower altitudes, but not at the intermediate ones.

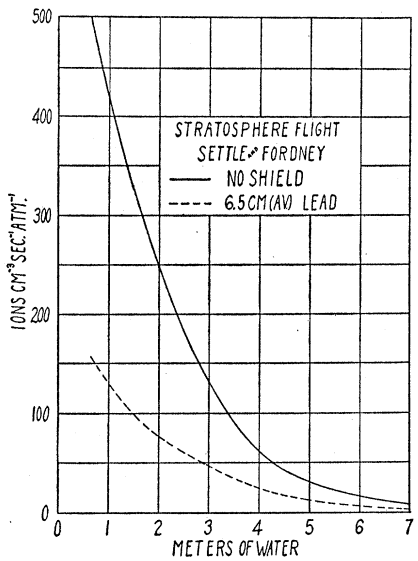

FIG. 4. Measurements made with an unshielded ionization chamber on the Fordney-Settle flight. The dotted curve gives the results obtained by A. H. Compton (Phys. Rev. **45,** 441 1934)) with his shielded electroscope.

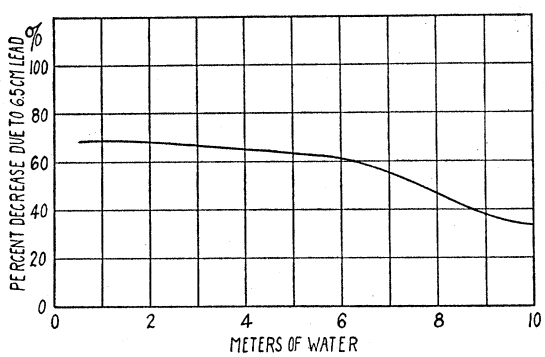

FIG. 5. Effect of a 6.5 cm lead shield on the ionization measurements.

about 6 meters of water, i.e., from Pike's Peak up to a point but 60 cm of water beneath the top, not less than 70 percent and probably more than 90 percent of the electron rays have too small energies to penetrate the 6 cm lead shield, i.e., they have energies under 330 million volts. Since these figures apply to the whole atmosphere, i.e., to both the field-sensitive and the non-field-sensitive parts of the ionization, *we may conclude with certainty that as I stated in the Atlantic City paper in 1932, "all but a very small part of the ionization of the air is due to secondaries produced within the atmosphere."*

§VI. Nature of the Non-Field Sensitive Incoming Rays

As a result of four different trips by our sensitive, self-registering, vibration-free electroscopes, between Los Angeles and Mollendo, or other points on the west coast of South America, all of which yield results in close agreement, the sea-level equatorial dip in cosmic-ray intensity in this part of the world is 7 ± 1 percent. In other words, 93 percent of the sea-level ionization here is due to non-field sensitive rays, and only 1/6 of the remaining 7 percent is due *directly* to incoming electrons, the other 5/6 being due to secondaries produced within the atmosphere by these incoming electrons, all of which in order to get down to sea-level and produce the observed sea-level latitude effect must, according to the preceding computations, have an energy of between 6 and 8 billion electron volts. *There need then be only enough incoming electrons of this energy to produce directly at sea-level about 1 percent of the observed ionization.*

The 93 percent of non-field-sensitive ionization must be due either to photons or else to incoming electrons of energies somewhat above 8 billion, or possibly 10 billion, electron volts so that they can get through the earth's magnetic field into the equatorial belt. We have evidence which will be presented in another paper that there are at least a small number of such incoming electrons that reach sea-level in the equatorial belt—enough to produce directly at sea-level another 1 or $1\frac{1}{2}$ percent of the observed sea-level ionization. *Indeed, it is just these rays, multiplied 6-fold in their effectiveness in exciting counters by their progeny of secondaries, which are responsible for the east-west effect observed in Peru by Johnson*[11] *and Korff.*[12] The incoming electrons here in question may all be assumed to be positives either arbitrarily or better, from our point of view, because the highest energy photons, which may be assumed to have produced them some time in their travel through space, tend to be absorbed primarily by the nuclei of atoms, and in all nuclei positive electrons, of course, predominate, while hydrogen nuclei contain no negatives at all, and hydrogen constitutes,

[11] Thos. H. Johnson, Phys. Rev. **45,** 569 (1934).
[12] S. A. Korff, Phys. Rev. **46,** 75 (1934).

according to Russell, 95 percent of the universe. On the other hand, the lower energy photons will of course tend to be absorbed in all substances more by extra-nuclear electrons, which are all negatives, for it is these extra-nuclear electrons that are responsible for all the ionization described by the Klein-Nishina formula. The earth's magnetic field then separates out the incoming electrons on the basis of energy, the lower energies, primarily negatives, coming in at the poles—the very highest energies, very few in number, and coming mostly perhaps from hydrogen, being alone able to break through at the equator.

The foregoing facts and considerations lead, then, to the presentation of the following reasons for the view that the great bulk of the *sea-level ionization*, more than 85 percent of it, and indeed of all the non-field sensitive effects, must be attributed to photons.

(1) It is precisely the above-mentioned smallness in the required number of incoming positives that is needed to remove the contradiction heretofore existing between the demands of the east-west effect for an excess of positives at sea-level, and Anderson's direct determination[13] of the general equality in the numbers of positives and negatives passing through his cloud chamber at all energies, even up to 3 billion volts. Practically all of these electrons (+ and −) observed by Anderson are secondaries formed within our atmosphere and in the materials surrounding the cloud chamber. These may all be expected to be about equally divided between positives and negatives, while the 1 to 2 percent of ionization that must be attributed to the direct effect of incoming 10 billion-volt positives in order to account for the 6 to 12 percent west excess observed in Johnson's and Korff's Peru work with counters, involves an excess of positives wholly negligible in Anderson's work. This is powerful support for the view that the great bulk of the sea-level ionization must be due to photons. If it were due wholly, or even in any considerable measure, to incoming positives of 10 billion-volt energies and more, why do these not appear in the cloud chamber measurements which are capable of measuring with considerable dependability electron energies up to 4 billion volts, which is what is left of the energy of the 10 billion-volt electron after it has penetrated to sea-level? These 4 billion-volt tracks should be present in large numbers and they should be predominantly positives, quite contrary to the observations of both Anderson and Kunze.

(2) On the other hand, photons of this order of energy are actually and unquestionably found in photographs such as Figs. 9 and 11.[8] Here there are seen to spring directly from the body of the lead showers that can be due only to photons, since no ionizing track enters the top of the lead. Further, the joint energy of these showers is here from one to three billion volts, i.e., much too large to permit them to be accounted for as secondaries produced within the atmosphere by incoming electrons (see §III). There seems to be no escape, then, from regarding these showers as resulting from incoming photons themselves.

(3) If the great bulk of the non-field sensitive part of the ionization of the atmosphere is not due to these incoming photons, but rather to incoming electrons, then these latter, in order to ionize as strongly near the equator as near the poles—this is the definition of non-field-sensitive rays—must possess incoming energies of 10 billion volts or more, and produce directly one-sixth of all the ionization found at sea-level. The other five-sixths of the ionization which these rays produce directly or indirectly at sea-level would be due to the *very low* energy secondaries that incoming electrons were found to create in the atmosphere (see §III). In other words, the distribution of electron energies in a cloud chamber should then be, many energies below 50 million volts, few if any between 50 million and 4 billion, and many above 4 billion. This is a distribution completely at variance with that directly observed by both Anderson and Kunze, who find the great majority of the observed particles having energies between 300 million and 2 billion volts. These are much too energetic to be the secondaries produced by electrons, not energetic enough to be the incoming electrons themselves. Further, though neither Anderson nor Kunze find any large number of electrons of 4 billion volts or more, the one or two percent of such rays necessary to account for the latitude

[13] Carl D. Anderson, Phys. Rev. **44**, 406 (1933).

effect, longitude effect, and east-west effect, are so few in number as to be easily reconcilable with their observations. *The great bulk of the sea-level ionization, then, appears to be due to the effects of incoming photons.* And the energies of these photons must be of the same order of magnitude as those of the observed electrons, three-fourths of which are under a billion volts and half of which under 700 million volts.

(4) The photons of from 1 billion to 3 billion volts of energy *actually observed* in our 20,000 gauss field at the Norman Bridge Laboratory have ample penetrating power (see below) to produce all the effects observed by Millikan and Cameron and by Regener down to depths of from 100 to 300 meters of water, i.e., 10 to 30 atmospheres, whereas since the resistance of the atmosphere to an electron is 6 billion volts, incoming electrons to get down to such depths would have to have from 60 to 180 billion volts of energy. Such energies are out of all relation to those that have been found either in Pasadena or in Rostock; so that the ionization found in lakes by Millikan and Cameron, and checked by others, can scarcely be due to anything but such photons as are actually observed in our cloud chamber. (See 2 above.)

Incidentally, the relative penetrating power of photons and electrons of the same energy is of the order of 100 to 1 up to the highest accurately measured energies, and there is evidence that it remains of this order also for cosmic rays of the highest observed energy. Thus, the total number of ion pairs formed per cm of air path by electrons of energy 1,450,000 volts is given as 46[14] and at 32 volts per pair this gives a maximum range to electrons of this energy of 1.1 cm of water. But photons from Ra C of this energy pass easily through as much as a meter of water before being reduced to say 1 percent of their original intensity. Similarly, in the cosmic-ray field if photons have 100 times the penetrating power of electrons, the foregoing 180 billion volts required to drive electrons through 30 atmospheres of water is replaced by 1.8 billion volts for photons. But photons of 2 billion volts energy are in the range actually and commonly observed in the cloud chamber work at the Bridge Laboratory, so that the foregoing relative penetrating powers of 100 to 1 are at least in keeping with the above-mentioned facts.

(5) As for the characteristics of the ionization of the atmosphere *above* sea-level, they are even more difficult to reconcile with the hypothesis that the non-field sensitive portion is due in any large measure to incoming electrons, for Fig. 1 shows that the ionization, even in the equatorial belt, rises exponentially, or better as a sum of exponential terms,[15] clear up to the highest point reached (4.5 m below the top). This behavior is characteristic of photon absorption, but not at all of electron absorption. Indeed, it was shown by Bowen, and independently by both Epstein and Langer, that any rays coming in uniformly from all directions as the cosmic rays do, and ionizing uniformly along their path, as electrons do, when we neglect their nuclear secondaries, will give rise to a linear variation of ionization with altitude measured from the end of their range, i.e., from the level of the mean depth to which they penetrate.

Now, since the energy of all incoming electrons that can get through the blocking effect of the earth's field into the equatorial belt is 10 billion volts or more, the end of the range is nearly two atmospheres below the top so that a linear rate of increase above this level represents say a 50 percent increase from sea-level up to 22,000 feet (4.5 meters) and a still smaller increase from 4.5 meters up to the top. *The observed increase is, on the other hand, some 1000 percent from sea-level up to 22,000 feet, and much more than that above that point.*

This enormous discrepancy can be somewhat reduced, but not at all eliminated, by taking account of the secondaries produced by the incoming electrons through the mechanism of nuclear encounters, for since we have shown that these are all low energy secondaries, else they would produce a sea-level latitude effect between Pasadena and Churchill, the energy of the incoming electron must be frittered away in quite a large number of relatively small steps, i.e., more or less uniformly, even by these nuclear encounters.

[14] *Radiations*, etc., Rutherford, *et al.*, p. 447, 1930; also Bethe, Zeits. f. Physik **76**, 293 (1932).

[15] Millikan, Bowen and Neher, Phys. Rev. **44**, 250 (1933).

Nuclear photon absorption, on the other hand, whether brought about by photoelectric or by Compton encounters, consists in general—and we can also deduce this from our photographs—in the transfer of a large part of the energy of the photon to the ejected electron or electrons,[16] thus yielding an exponential law of absorption.

The absorption, then, by the atmosphere of incoming electrons of 10 billion volts and more, even though it might follow a law intermediate between that of linear and exponential absorption, must distinctly lean toward the former, and cannot possibly yield an altitude-ionization curve even remotely resembling that found experimentally from sea-level up to 4.5 m in Fig. 1 and up to 0.6 m in Fig. 4. *This constitutes the most general and the most cogent argument against the attempt to explain the non-field-sensitive portion of the cosmic-ray ionization as due primarily to incoming high-energy electrons, low-energy electrons being barred out by the blocking effect of the earth's field.*

If, on the other hand, incoming photons are the main ionizing agents, then, whether the nuclear absorption is of the photoelectric type or the Compton type,—and it is presumably the former—the mean energy of these photons must be of the same order of magnitude as the mean energy of the electrons produced by them, namely, say 200 ± 170 million electron volts. These figures are again consistent with the view that cosmic-ray photons have a penetrating power of the order of 100 times that of electrons of the same energy, for we have earlier shown that the effect of the main component of the cosmic rays—that for which the absorption coefficient is of the order $\mu=0.5$—just about reaches down to sea-level, while it requires six billion-volt incoming electrons to have such a range.

(6) Again, evidence for the view that the ionization found in the atmosphere *above sea-level* cannot be produced wholly or even chiefly by 10 billion-volt incoming electrons is found in the consideration that the penetrating power of such rays, both as to their primary and their secondary constituents, must obviously increase, or at most remain constant with increasing altitude, since the energy of the ionizing agents at the top of the atmosphere is 10 billion volts and at the bottom but 4 billion. On the other hand, *the observed mean penetrating power actually decreases very markedly as shown in Fig. 5 between sea-level (10 m) and 6 m of water beneath the top.* It is difficult to see how this can be interpreted save in terms of photons of decreasing mean hardness with increasing altitude. Above 6 m, Fig. 5 shows that the penetrating power continues to decrease, but now much less rapidly, as though the ionization were now due mainly to a single photon band of coefficient of absorption somewhere near $\mu=0.5$. This part of the curve of Fig. 5 must, however, be attributed to a mixture of causes, as shown in §VII below.

§VII. Effects Due to the Field-Sensitive Portion of the Incoming Rays

All of the field sensitive part of the ionization produced by cosmic rays is, of course, due directly or indirectly to incoming electrons. When we compute from the difference between the ordinates of the upper and lower curves of Fig. 1, the mean *apparent* absorption coefficient of the rays producing this ionization, it comes out roughly $\mu=1.0$ per meter of water. But we are not disposed to attach any physical significance to this *apparent* coefficient, since it is due to the ionization produced at the end of the ranges of electrons of widely varying energies. However, the rapid rise with altitude of the ionization between the upper and lower curves of Fig. 1 may be understood from the following considerations. We have already shown in §IV and §V why we regard the chief component of the non-field-sensitive portion of the upper-air ionization as due to a beam of incoming photons of energy of the order 200 ± 170 million electron volts. Such a beam would get into equilibrium with its secondaries at a depth below the top corresponding to the range of say 300 million-volt electrons which, since it takes 6 billion-volt electrons to penetrate the atmosphere—10 meters of water—would be at a depth beneath the top of $300/6000\times10=0.5$ m. If the earth had no magnetic field and if the cosmic rays were all of this frequency there would be at all latitudes an exponential rise of the ionization with altitude at a rate somewhere near $\mu=0.5$ per meter of

[16] Anderson, Millikan, Neddermeyer and Pickering, Phys. Rev. **45**, 363 (7) (1933).

water clear to the top if the beam were in equilibrium with its secondaries upon entering. On the other hand, if it entered as a *pure* photon beam, unmixed with any of its secondaries, the ionization would start from zero at the outer edge of the atmosphere and rise to a maximum a 0.5 m below the top and then fall off exponentially (with $\mu=0.5$) for increasing depths beneath the top.

The foregoing simple picture does not correspond to reality for at least two important reasons. First, the incoming cosmic rays are distributed over a wide range of energies, the distribution curve at sea level, according to Anderson[17] having a very weak intensity at energies as high as 3 or 4 billion volts, increasing rapidly with decreasing energy and going through a maximum at say 600 million volts. This maximum, according to our own measurements herewith presented, moves rapidly toward lower energies with increasing altitude.

The second big factor of disturbance to the foregoing simple picture is the earth's magnetic field. If the photons of all the preceding energies were in equilibrium with their secondaries before entering the earth's magnetic field, this equilibrium would in any case be entirely destroyed by that field. At Panama, for example, all the electron secondaries below about 8 billion volts are blocked out by that field, while at Spokane all electron secondaries down to say 2 billion volts get through. This accounts for the rapid rise with altitude of the field sensitive ionization represented by the difference between the Panama and the Spokane curves (Fig. 1). For, as Anderson's energy-distribution curves show, the number of incoming secondary electrons increases rapidly as the energy decreases from 8 billion down to 2 billion volts. The result is not at all the linear rise with altitude discussed in §VI 5 due to incoming electrons of a given energy above 10 billion volts, but a very much more rapid rise due to the fact that 2 billion-volt electrons, for example, first let in copiously through the field at magnetic latitude 52°, can only penetrate one-third of the way through the atmosphere and hence must do all their ionizing above that level. The effect here under con-

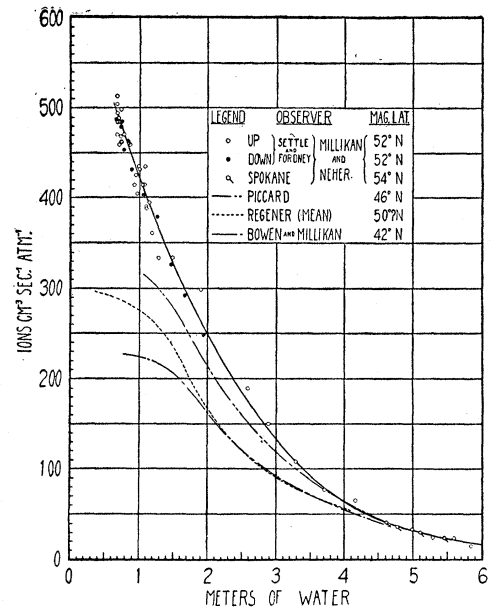

FIG. 6. Comparison of the results of recent high altitude measurements.

sideration is very beautifully shown in Fig. 6, in which we present a comparison of the results of all the recent stratosphere flights. In the most northerly of these, the Fordney-Settle one,—measurements by Millikan and Neher, the most accurate yet made—the ionization near the top is seen to be very much larger than in the two Bowen-Millikan flights or the Regener flight all made at about mag. lat. 42°, where no electrons of energies under about 4 billion volts can get through the earth's magnetic field. There is still some experimental uncertainty with respect to these three lower curves of Fig. 6, but not enough to change the main conclusion here drawn.

We interpret also the *shapes* of the upper part of the curves made by Bowen and Millikan and by Regener at latitude 42° as due to the effect of the incoming electrons of between 4 billion and 8 billion volts. For there are now no longer present the incoming 2 to 4 billion-volt secondaries to add to the ionization of the underlying photons in the upper part of the atmosphere, while the 4 to 8 billion ones are approaching the energies at which they penetrate the entire atmosphere and are therefore nearing the conditions that give rise to the linear ionization law discussed in §VI 5. In a word,

[17] Carl D. Anderson, Phys. Rev. **44**, 406 (1933).

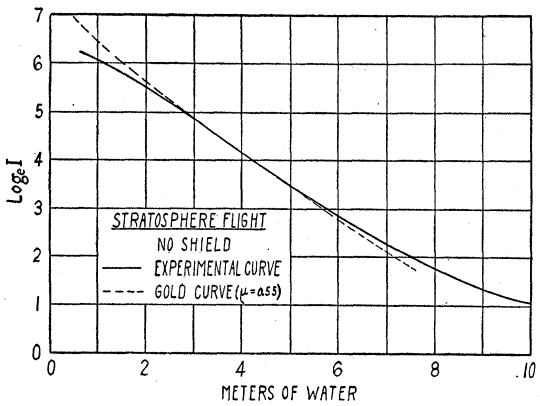

FIG. 7. Logarithmic plot of the ionization measurements made on the Fordney-Settle flight.

then, the altitude-ionization curve shown in Fig. 6 represents a combination of the effects of the incoming photons of energies of the order 200 ± 170 million volts, and such incoming secondary electrons as the earth's magnetic field will let through. These latter should be very strong ionizers in sufficiently northern latitudes and at great altitudes, but should do a relatively small part of the ionizing in the equatorial belt. There they must be responsible for the longitude effect and the east-west effect, both found in the equatorial belt. We are hoping to do some higher altitude flights near the equator to test further these conclusions.

Fig. 7 shows the results of the Fordney-Settle flight plotted on a log scale. This displays nicely (1) how from sea-level (10 m) up to the height of Pikes Peak (6 m) a sum of exponentials is needed to reproduce the observed ionization; (2) how a single absorption coefficient $\mu=0.55$ takes care of the ionization from 6 m to 2.5 m below the top, despite the complex character of the causes at work in this region, i.e., relatively low energy photons plus high energy (8 billion to 2 billion volts) incoming secondary electrons; (3) how at a depth of about 2.5 m below the top the constancy of the exponential rise at $\mu=0.55$ breaks down, presumably because of the effect of the incoming secondary electrons.

VIII. The Origin of the Cosmic Rays

The conclusions of the preceding sections rest upon the two fundamental postulates, namely, (1) the general validity of the analysis of Epstein and Lemaitre-Vallarta as to the effect of the earth's magnetic field on incoming electrons; and (2) the validity of the evidence that in general the immediate ionizing agents in the production of cosmic-ray ionization are free positive and negative electrons, other ionizing agents not being necessarily absent entirely but at any rate exerting a negligible influence. The general qualitative validity of the first postulate will scarcely be questioned, and its quantitative validity is not of vital importance. For example, if the energies necessary to get through the earth's magnetic field were but half those computed by Epstein, the whole scale of electron energies would be reduced one-half without fundamentally modifying the reasoning or the conclusions.

The second postulate that the immediate ionizing agents are electrons (+ and −) rests upon two sorts of evidence. First, we have studied most carefully thousands of cloud-chamber photographs without finding any evidence for the presence in appreciable amount of protons or other heavy particles of any sort. If the Newtonian laws of encounter hold, protons, neutrons, or other heavy particles cannot transfer energies of millions and billions of volts to electrons such as we find in all our photographs. Only electrons and photons can possibly produce the type of effects shown in Figs. 7, 8, 9, 10, 11, 12, 13, 14.[8] The combination of ionization, range and curvature shown in all these tracks fixes the ionizing agent in practically all cases as an electron (+ or −). Even more certain evidence on this point, however, is found in the fact that the multiplying factor due to raising the pressure in an electroscope is the same for gamma-rays and cosmic rays. We have tested this point directly or indirectly clear up practically to the top of the atmosphere. This means, as Bowen and Millikan first showed[18] that the fraction of ions formed that recombine is the same in both cases, and this can be true only if the immediate ionizing agent has in general the same ionizing power per cm of path in the two cases.

Given the correctness of these two postulates,

[18] R. A. Millikan and I. S. Bowen, Nature, Oct. 2, 1931; also R. A. Millikan, Phys. Rev. **39**, 397 (1932).

it follows, for the reasons given in §VI, that the whole non-field-sensitive portion of the ionization cannot possibly be due to incoming electrons of an energy of 10 billion volts and more, and yet these are the only electron energies which the earth's magnetic field permits to penetrate into the equatorial belt. The very fact, then, that we need incoming photons at all to interpret cosmic-ray effects eliminates entirely the possibility that the source of the cosmic rays is to be found in cosmic electrical fields which impart these 10 billion-volt energies to electrons that fall through them.

So far, then, as we can now see, the only remaining possible source of these observed energies lies in atomic transformations taking place in accordance with Einstein's equation $E=mc^2$. The building out of hydrogen of the common elements is of course only a special case of this transformation of mass into radiant energy, and since such building of the helium atom releases 30 million electron volts, of oxygen 116 million, of silicon 216 million, of iron 460 million, there is no other origin which we can now see of the great absorption band found by us in the equatorial belt at about $\mu=0.5$ and modified by its mixture in the temperate belt with incoming secondary electrons into something like $\mu=0.55$. This band alone seems to be responsible for about 90 percent of the cosmic-ray ionization in the equatorial belt. Its energy is at least of the right order to fit this hypothesis, and no other source of energies of these magnitudes is yet in sight. It will be recalled that the condensation or clustering of hydrogen atoms into hydrogen "dust" in the intense cold of interstellar space is a necessary antecedent to the building-up act. The conclusions of modern astronomers as to the existence of much interstellar dust is not out of line with this hypothesis.

But since the foregoing analysis requires a small number of cosmic-ray energies as high as 10 billion volts, there seems to be no origin in sight for these save the sudden *complete* annihilation of whole atoms of helium, 4 billion volts; carbon, 12 billion; oxygen, 16 billion, etc. We have already indicated in preceding papers how the extreme conditions of temperature and pressure existing in interstellar space might be favorable to the building-up process, but we must now add the further suggestion that any condition which once starts the matter-annihilating process might in some cases stop at the part-way stage, or, in extreme cases, carry it completely through. If this possibility exists it would account for the observed uniformity of distribution of all the cosmic-ray bands, high energy as well as low, over the celestial dome, the most extraordinary characteristic of these rays. If we discard such suggestions to locate the events giving rise to cosmic rays in interstellar space we then seem to be forced to postulate, as Baade and Zwicky[19] do, some other sort of extraordinary conditions not depending on low temperatures and pressures, such as those existing in novae, to call forth both these partial and complete annihilation processes; or, again, we could take the alternative already suggested by other scientists and associate these annihilation processes with conditions existing at some preceding time when the universe was in a different state from that now existing. *At any rate, in the present state of our knowledge both the partial annihilation of matter, like that exhibited in the building of the common elements out of hydrogen, and the complete annihilation of atoms, seem to be called for to account for the energies actually found in the cosmic rays.*

All of the foregoing work has been made possible through a grant from the Carnegie Corporation of New York, administered by the Carnegie Institution of Washington. We desire to express our deep appreciation for this assistance.

[19] W. Baade and F. Zwicky, Proc. Nat. Acad. Sci. **20**, 259 (1934).

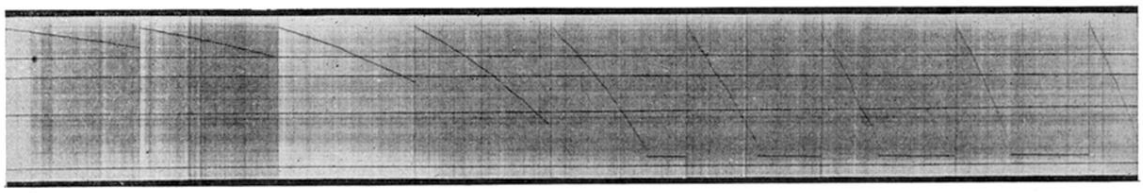

FIG. 3. Section of film from the Neher automatic recording electroscope taken during the ascent to the stratosphere of the balloon in the Fordney-Settle flight of November 20, 1933. Each of the nine panels across which the sloping dark line moves from left to right corresponds to a five-minute time interval. The slope is proportional to the rate of discharge of the electroscope, which in turn is proportional to the intensity of the cosmic rays. In the first panel the balloon was at an elevation of about 20,000 feet, and in the next twenty minutes (four panels) while the balloon was rising to a height of 45,000 feet the slope, or cosmic-ray intensity, rose tenfold. From there on to the highest altitude attained, 62,000 feet, the rate of rise of the balloon was much less rapid. It remained at or near the top for three and a half hours, so that this film yielded accurate measurements of cosmic-ray intensities at the higher and lower altitudes, but not at the intermediate ones.