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A Hypothesis as to the Origin of Cosmic Rays and Its Experimental Testing in India and Elsewhere

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The hypothesis here adopted as to the mode of origin of the cosmic rays makes possible the prediction of five definite cosmic-ray bands, each of which should reach the earth in a particular latitude, and of four plateaus of unchanging cosmic-ray intensity, these plateaus being delimited by the latitudes of entrance of the successive bands. These bands will be designated as (1) a silicon band of energy 13.2 Bev, (2) an oxygen-nitrogen band of mean energy 7.1 Bev, (3) a carbon band of energy 5.6 Bev, and (4) a helium band of energy 1.9 Bev. The experimental evidence that has been so far obtained in India and elsewhere for the existence of these five bands and four plateaus may be thus summarized: The evidence seems to be excellent for the existence of the silicon band and the joint nitrogen-oxygen band, and some indications have appeared for the existence of the carbon band and the helium band. Also all of these bands are found, roughly at least, in the predicted latitudes and of right order of intensities. The evidence also appears to be good for the existence of at least three of the four above-mentioned plateaus of constant cosmic-ray intensity.

I. THE PREDICTION OF FIVE COSMIC-RAY BANDS AND FOUR PLATEAUS OF CONSTANT COSMIC-RAY INTENSITY

IT was suggested more than ten years ago, in view of the two most surprising properties of the cosmic rays, namely, (1) their enormous energies, and (2) their uniform distribution over the celestial dome, that it was difficult to conceive of any mode of origin that was at all capable of yielding such energies and such directions save the one that had been so successfully invoked since about 1905 in accounting for the otherwise inexplicably large evolution of energy by the sun and stars. Thus, for at least thirty-five years astronomers have recognized the fact that there is no way of accounting for the known evolution of heat by the sun save through the assumption that it is actually somehow radiating away its mass. Einstein in the development in 1905 of his equation $mc^2=E$ gave quantitative expression to this hypothesis. The successes of this equation have not only now made it a universally accepted basis for astronomical calculations but the equation has not yet failed in any of the nuclear transformation phenomena, like those involved in radioactive change, in which it has been found possible to subject it to careful test. *The transformation of rest mass into other forms of energy is now the corner stone of practically all work in the field of nuclear physics.*

In 1928 Millikan and Cameron[1] used the Einstein equation, as applied to the partial annihilation of mass in the atom-building process, for the interpretation of cosmic-ray energies. This was before those energies had

[1] R. A. Millikan and G. H. Cameron, Proc. Nat. Acad. Sci. **14**, 637 (1928); Phys. Rev. **32**, 533 (1928).

become definitely known through direct measurement, and when their indirectly estimated values seemed to make the loss of mass through the building up of the heavier elements out of the lighter elements yield adequate energies from the known values of so-called "packing fractions." Beginning in 1931 this possibility was eliminated for two reasons: First, the largest energy obtainable from packing fractions in the case of any element of appreciable abundance namely, iron, was 0.48 g per g-atom, or about half a billion electron volts, but in the fall of 1931 Anderson and Millikan first measured *directly*[2] the energies of cosmic rays and found them running up above 6 Bev, much higher than could be accounted for by any possible packing fractions. This alone was definite and final. Second, precisely these same atom-building processes involving the same "packing fractions" seem now to be successfully accounting for the sun's heat.[3] If this be so one must now assume that those very processes, of *partial* annihilation through atom building, which were assumed going on *outside* the stars to account for cosmic rays, are instead going on *inside* the sun to account for its evolution of heat. But since the cosmic rays do not come from the sun or the stars one is now debarred also from using these same processes to account for them. In other words, there is abundant reason for retaining the principle, beautifully illustrated by Bowen's interpretation of the nebulium lines, that the conditions existing in interstellar space make possible at least some sorts of atomic energy transformations that are forbidden within the stars. There is, of course, no doubt about it at all in the case of the origin of the nebulium lines.

Both of the foregoing difficulties—namely, that occasioned by the enormous energies and that by the uniformity of distribution of the apparent sources—disappear if one simply reverses the former suggestions and assumes that the sun's heat is due to atom building going on in its interior while cosmic rays are due to the complete annihilation process going on in interstellar space, or better to the *complete*, instead of the partial, transformation of the rest mass of the atoms into cosmic-ray energy. The question which one then faces is, how well does this last suggestion work quantitatively?

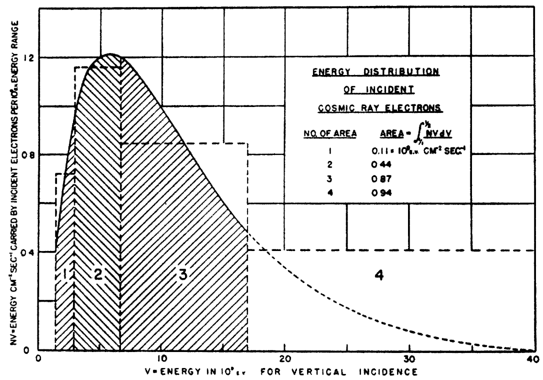

FIG. 1. The rectangular area 4 is made proportional to the total cosmic-ray energy that enters the earth at the equator. It is, in fact, the area underneath a complete cosmic-ray curve taken up to the top of the atmosphere at Madras. It is the sum of the energies of all non-field sensitive cosmic rays, no matter whether this non-field sensitiveness arises from the fact that incoming charged particles have too high an energy to be blocked off by the earth's magnetic field or whether some of the incoming rays consist of photons or neutrons which cannot, because of their nature (no matter what the energies), be affected by a magnetic field. Rectangle 4 then represents the total cosmic-ray background that is uniform all over the earth's surface. The sum of the rectangular areas 1, 2, 3 represents the total energy of the field-sensitive cosmic rays. This sum is more than 60 percent of the total incoming cosmic-ray energy. This means that the cosmic rays cannot have come through an appreciable amount of matter in getting from their place of origin to the earth.

There are two definite quantitative facts that have been established, namely, (1) Fig. 1, reproduced from Phys. Rev. **53**, 859 (1938), shows a maximum of incoming "charged-particle"[4] energy somewhere between 5 Bev and

[2] R. A. Millikan and C. D. Anderson, Phys. Rev. **40**, 325 (1932); also **41**, 405 (1932) and **45**, 352 (1934); also *Electrons (+ and −), Protons, Photons, Neutrons, and Cosmic Rays* (University of Chicago Press, 1935).

[3] H. A. Bethe, Phys. Rev. **55**, 103, 434 (1939); Phys. Soc. Reports pp. 1–15 (1939).

[4] It would make no difference so far as all the results considered in this paper are concerned whether the "charged particles" are electrons, mesotrons, or protons, for at the very large energies here involved, the effect of a magnetic field is essentially the same upon them all. What is known with certainty about incoming particles is that, as shown by Bowen, Millikan and Neher [Phys. Rev. **52**, 83 (1937), and **53**, 218 (1938)], even when they have energies as high as 10 billion electron volts they *are very rapidly absorbed as soon as they get into the atmosphere*, not 1/500 of their energy being able to get down to sea level. This is as it should be for *electrons* but not normally for heavier particles, for the former, because of their extreme lightness, must be quickly "bremsed" in collisions with nuclei and thus have their energy almost completely transformed into photons which, in turn, in succeeding collisions transform their energy into electron pairs, etc., and thus proceed to fritter it away in showers. Particles like protons (2000 times heavier) on the other

10 Bev; and (2) certainly not less than, and probably much more than, 60 percent of the total incoming cosmic-ray energy is carried by these charged particles, for this is the ratio of the sum of the areas of the blocks 1, 2, 3 to that of 1, 2, 3, 4. (See table in Fig. 1.)

But now, to carry through the desired computation one must know what are the most common elements in interstellar space where the cosmic rays seem to originate. Here again another of Bowen's remarkable discoveries is ready to be called upon, for Bowen and Wise,[5] by spectroscopic observations on the ring nebulae, have recently made determinations of the relative abundance of the atoms in the spaces between the stars. Since the ring nebula studied is a light year, 6,000 billion miles or more, from the exciting star, one can scarcely fail to take their estimates of relative abundance as applying to interstellar space. Here are their results. They find that hydrogen atoms and helium atoms stand first and second in abundance, hydrogen being about ten times as abundant as helium. They find, further, four other atoms all having about the same abundance, which, however, in each case is only about one-tenth the abundance of helium. No other atoms have more than a tenth of the abundance of any of these four, and most of the rest have less than a hundredth. These four most abundant atoms are *carbon*, *nitrogen*, *oxygen*, and *silicon*.[5] The predominant abundance of these four atoms is also in line with their known structures and stabilities.

Now, the rest mass energy of the hydrogen atom comes out by Einstein's equation just a little less than one Bev (accurately, 938 million). If, then, this rest mass is capable of being transformed completely into cosmic rays, since the momentum principle must in any case be satisfied, the only way these two conditions can be met is through the appearance of a pair of electrons or photons (in the case of hydrogen, though not in the case of the heavy atoms, deficiency in mass would bar out protons or neutrons) starting out from the point of annihilation of the rest mass of H_1 in opposite directions each of energy of about 500,000 ev. Epstein[6] has shown that an electron endowed with this energy could not get through the sun's magnetic field and reach the earth so there is no use expecting to find it here. Even if the sun's magnetic field were not strong enough to prevent its reaching the earth it could get through the earth's magnetic field only quite close to the

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hand cannot be thus suddenly bremsed, the absorption coefficient of air for such particles being inversely proportional to the square of the mass of the particles. For this reason protons, for example, should be millions of times more penetrating than electrons. It is then impossible to reconcile the observed high absorbability of the incoming particles with masses many times greater than the mass of the electron, *unless one assumes the existence of some new kind of absorption utterly different from the bremsung-pair-formation process.*

That there must indeed be other types of absorption than that due to the shower process has been clearly pointed out (see R. A. Millikan, *Cosmic Rays* (Macmillan Company, 1939), p. 100), but we have in the past thought it much simpler to get the existing very high absorbability by adding one or more of the effects of these new processes to the large normal absorbability of electrons, rather than to violate so completely the normal and theoretically necessary high penetrability of heavier particles. This argument, however, will have to be abandoned in case it can be shown that the energy of hypothetical incoming protons is practically completely transformed into mesotrons in the upper layers of the atmosphere by one of these other types of absorption; but that, we think, involves more knowledge than is as yet available as to the relative frequencies of collisions giving rise to mesotrons and to showers.

It may be pointed out that our own curve shown in Fig. 10 (reference 7), has not the right shape at high altitudes to be due alone to the absorption of electrons by shower-production, for this would require it to be concave upward near the top of the atmosphere instead of nearly straight. In any case, however, the well established facts of mesotron formation near the top of the atmosphere must cause a marked departure from such a theoretical curve.

[5] Bowen and Wise have recently made by spectroscopic means a determination of the abundance of the elements in the nebulae and published the same in the Bull. Lick Observatory **19**, 1 (1939). Their results are shown in the accompanying table in which the figures given in the abundance columns are the exponents required to indicate the number of atoms in a given volume of space. Thus the number 11 following hydrogen means 10^{11} hydrogen atoms, while the number 9 opposite carbon means 10^9 carbon atoms, etc. The uncertainty sign ⩽ associated

Element	Abundance	Element	Abundance	Element	Abundance
H	11−	Ne	8	K	6+
He	10	Na	⩽7+	Ca	7−
Li	<8−	Mg	7+	Sc	<6+
Be	<8−	Al	<8−	Ti	<7−
B	<9	Si	⩽9	V	<8
C	9	P	<8	Cr	<7
N	9−	S	8	Mn	<7
O	9	Cl	7+	Fe	7+
Fl	6	A	7		

with Si in the table is due, Bowen says, to a slight uncertainty as to whether one of the critical lines used is surely a silicon line or not, but in any case, since aluminum has an atomic weight of 27 its cosmic-ray influence would be inseparable by our tests from that of silicon (at. wt. 28), and similarly any possible effects due to phosphorus or sulphur would be so close to those of silicon as to be separately distinguishable with great difficulty. This composite influence may then for simplicity be called the hypothetical silicon band.

[6] P. S. Epstein, Phys. Rev. **53**, 862 (1938). See also L. Janossy, Zeits. f. Physik **104**, 430 (1937).

pole and, in view of its low energy, would be absorbed in the upper regions of the atmosphere where it would be undetectable by our electroscopes or counters. Again, if the rest mass of a hydrogen *molecule*, instead of a hydrogen atom, underwent such a complete transformation, it would produce two oppositely directed one-Bev electrons. This radiation also could not be detected here for the reason just given even if one makes the *very unlikely* assumption that hydrogen molecules have sufficient abundance to produce such rays in detectable amounts; but the case of a molecule is here considered since, if the possibility of the complete transformation in interstellar space of rest mass into cosmic-ray energy exists at all, there is probably no more reason for excluding molecules, or even larger aggregates, from the operation of the principle than there is for excluding such aggregates from the operation of the equipartition principle applied so successfully by their inclusion to the interpretation of the Brownian movements.

By the foregoing procedure one finds that helium atoms of atomic weight 4 would produce 2 (more accurately 1.9) billion volt cosmic rays. According to Epstein, if one takes the value of the general magnetic field of the sun at not over 16 gauss—an assumption in line with most recent work—then 2 Bev charged-particle-rays would not be barred by the sun's field from reaching the earth, and further they would be able to get through the earth's magnetic field vertically at all latitudes north of about Bismarck (Mag. lat 56.7° N). Also, if there were any incoming rays of energy between 1.9 Bev and 1.4 Bev, which is the energy required to penetrate vertically through the earth's magnetic field at Saskatoon, (Mag. lat 60° N) such rays would not be barred by the aforementioned sun's field from reaching the earth, and the total cosmic-ray energy reaching the earth at the latitude of Saskatoon and higher should be larger than that entering at the latitude of Bismarck. But if the rays found at Bismarck are in fact the hypothetical helium band then there should be no increase in cosmic-ray intensity in going north from Bismarck, and in fact there appears to be none, though still further checks on this point are being sought.

Altogether similarly, carbon rays of energy 6 (accurately 5.6) Bev would begin to get through the earth's field at about latitude 42° N, a little north of San Antonio, for at San Antonio the voltage required to get electrons down to earth vertically is 6.7 Bev. This is also very close to the latitude at which nitrogen rays of energy 7 (better 6.6) Bev would first be found as the observer moves northward from the equator. A few degrees farther south, say at about 33° or 34°, the southern edge of the oxygen cosmic-ray plateau corresponding to an energy of 8 (better 7.5) Bev would be found. Another southern edge of a wide cosmic-ray plateau corresponding to the entrance of silicon rays would be expected to appear, as one moves northward from the equator, at a magnetic latitude at which the energy required to break through the earth's magnetic field vertically is 14 (13.2) Bev and from that point down to the magnetic equator, where in India the energy required to get through vertically is 17 Bev, there should be no further change in the intensity of the incoming vertical cosmic rays. The observed edges of this succession of overlapping cosmic-ray plateaus corresponding to the energies 2, 6, 7, 8, and 14 Bev would not be expected to be sharp so long as one uses for the detecting instruments electroscopes, which respond to rays from all directions (see Fig. 2), for the computed energies correspond only to vertically incoming rays.

II. THE EXPERIMENTAL TESTING IN INDIA OF THE ABOVE PREDICTIONS

In order to test the foregoing predictions with any sort of accuracy it was obviously necessary to measure directly *vertical* incoming cosmic-ray energies as a function of latitude. It was also obvious that, if equipment for so doing were available, India was the best, indeed the only suitable, place in the world for the most significant of the tests. For while in India it takes 17 billion-volt, vertical, charged-particle rays to break through the blocking effect of the earth's magnetic field at the equator, it takes but about 13 billion to do so on the other side of the earth, i.e., in Peru, so that only in India was there any possibility of finding the latitude north of which the hypothetical silicon rays, of energy 13.2 Bev,

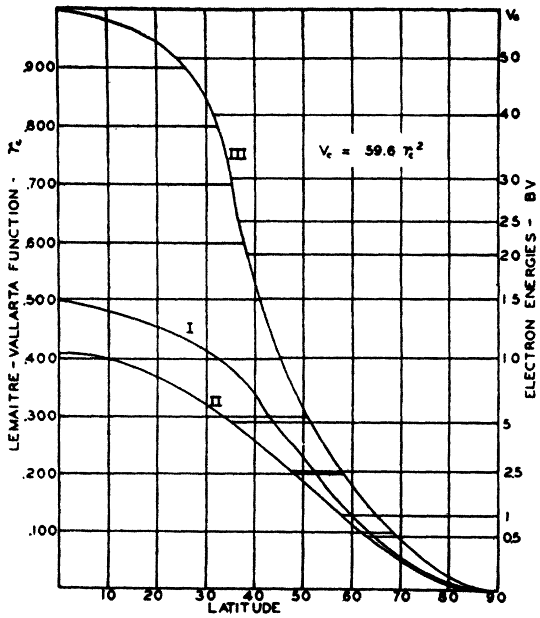

FIG. 2. The Lemaitre-Vallarta function r_c for three directions plotted against latitude. Curve I is for the vertical direction, curve II is for the western horizon, and curve III is for the eastern horizon. Electron energies are given along the right margin. (Lemaitre and Vallarta.)

would be found and south of which they would be absent. Since, according to Bowen, there were no atoms of atomic weight between oxygen and silicon sufficiently abundant to send into the earth any appreciable cosmic-ray energy, and similarly none of atomic weight higher than silicon and of comparable abundance, one might expect to find in India a perfectly flat cosmic-ray plateau for vertical rays extending from Madura on the magnetic equator clear up to about latitude 20° where silicon rays should be able to break through vertically, and then on going still farther north one should find a sudden rise to a new plateau-level at the latitude at which this break through for silicon rays occurs.

From the Lemaitre-Vallarta curves it was estimated that the vertical energy necessary to get through at Agra (Mag. lat 17.3° N) was 15.4 Bev, and that at Peshawar, only 7.7° farther north, at 12.4 Bev. On account of some uncertainty as to the accuracy of these computations Agra was chosen as the most northerly point at which it was safe to make the test and still be fairly sure that the point of observation would be south of the latitude of entrance of the silicon band of energy 13.2 Bev and still on the hypothetical equatorial plateau. Peshawar, the most northerly city in India, was chosen as the best available place for getting north of the latitude of entrance of the hypothetical silicon band and upon the plateau between the latitudes of entrance of the silicon and the oxygen bands. For reasons of convenience Bangalore was chosen instead of Madura for making the observations on the equator, since the approximate law of change of incoming energy with latitude φ, namely, $\cos^4 \varphi$ differed for $\varphi = 3°$ quite immeasurably from the value for $\varphi = 0$. These considerations then determined the choice of locations in India for making the tests on the incoming energies of the vertical rays.

When the measuring instruments sent to the top of the atmosphere are electroscopes or single counters which respond to rays reaching them from all directions instead of merely from the vertical, the analysis becomes much more complicated, especially in equatorial latitudes, for the Lemaitre-Vallarta curves (see Fig. 2) show that the hypothetical silicon rays of energy 13.2 Bev would be shooting through the top of the atmosphere to some extent even at the equator, and that the atmospheric ionization due to these rays would therefore increase continuously up to the latitude at which the vertical rays get down to earth, and even beyond that to some extent, clear up to a latitude of about 40° N.

As shown in the accompanying paper by Neher and Pickering[7] (see especially Figs. 1, 4, and 6), both of the foregoing predictions as to the behavior of electroscopes, single and double counters, were precisely what was found in the India experiments between the magnetic equator and magnetic latitude 25° N, so that, so far as India is concerned, the hypothetical silicon band may properly be said to predict the thus far observed latitude effects satisfactorily.

III. THE INTERPRETATION OF EARLIER SEA-LEVEL EXPERIMENTS IN THE LIGHT OF THE PRESENT HYPOTHESIS

In 1933 it was first observed[8] that there was a marked increase in the sea-level intensity of

[7] H. V. Neher and W. H. Pickering, Phys. Rev. **61**, 407 (1942).

[8] R. A. Millikan and H. V. Neher, Phys. Rev. **47**, 205 (1935).

cosmic rays in sending a recording electroscope around the world in the equatorial belt from India to Peru. Since according to the hypothesis here being tested the only one of the five hypothetical bands of cosmic rays that has the energy to get into the equatorial belt at all is the silicon band, the foregoing observation can only mean that these silicon rays that have not sufficient energy to get to earth at the equator in India, *are able to do so in Peru.* Furthermore, the energy of these rays is 13.2 Bev, while the energy needed to get in vertically in Peru has been taken for years as only 13 Bev, according to Epstein somewhat less. Hence there is nothing in the observed longitude effect that is out of line with the hypothesis under test; the decrease in the blocking effect of the earth's magnetic field in going from India to Peru is sufficient to permit the hypothetical silicon rays to get in in full strength vertically in Peru.

But again, on account of the strong absorption of the atmosphere, sea-level observations made with electroscopes certainly correspond very roughly to vertically incoming cosmic rays and should therefore exhibit, though somewhat less sharply, the series of bands and plateaus char-

TABLE I. Electroscope discharge rates at eight-hour intervals between latitude 28° N. magnetic and 0° N. magnetic. The readings of electroscope No. 3 are more significant than those of No. 1 since in these electroscopes the sea level ionization due to the cosmic rays themselves is only about 1.6 ions, the rest being background which is seen to be much larger in No. 1 than in No. 3.

SS. Mongolia enroute Los Angeles to Balboa No. 1	No. 3	SS. Ebro enroute Balboa to Mollendo No. 1	No. 3
8.70	3.86	8.64	3.82
8.84	4.02	8.51	3.85
8.97	3.88	8.39	4.19
8.73	3.79	8.92	3.77
8.63	3.78	8.37	3.80
9.02	3.76	8.43	4.15
8.57	3.68	8.66	3.99
8.57	3.96	8.38	3.93
8.60	3.85	8.66	3.91
8.70	3.96	8.53	3.95
8.53	4.18	8.54	3.97
8.93	4.33	8.84	3.99
9.09	3.84	9.18	3.89
8.54	4.18	8.37	3.86
9.14	4.02	8.35	3.90
8.69	4.18	8.61	3.97
9.03	3.94		3.81
8.64	4.23		3.92
8.80			3.85
Mean 8.77	3.97	8.586	3.92

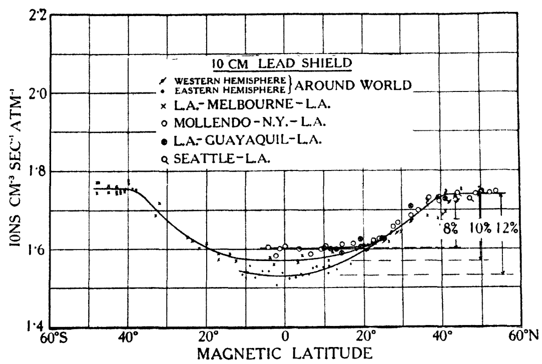

FIG. 3. The longitude effect taken with a shielded electroscope. The 12 percent equatorial dip is found in the neighborhood of India (eastern hemisphere). The 10 percent equatorial dip is found in going from Los Angeles to Melbourne. The 8 percent or 7 percent equatorial dip is found in going from Los Angeles to Guayaquil.

acteristic of vertical rays rather than the very gradual changes with latitude in the equatorial belt that are characteristic of electroscopes when sent up to the top of the atmosphere where rays can pass through them from all directions.

Since, then, the hypothetical silicon rays are already reaching the earth in Peru one may expect, in going north from Mollendo, to find at least indications of the long plateau that should exist for vertical rays between the latitude at which the silicon rays of energy 13.2 Bev can get through the earth's magnetic field and the latitude at which the next possible band of rays of lower energy, namely, oxygen rays of only 7.5 Bev, begin to get through.

In fact, Millikan and Cameron appear to have brought to light this plateau with the use of their sea-level electroscope measurements in the very first trip to South America that was undertaken in August 1926 to test for a latitude effect in cosmic rays; for they found no change at all in sea-level cosmic-ray intensity in going from about magnetic latitude 28° N, where they first got their observations under way in the wireless room of the SS. Mongolia, and the end of their journey at Mollendo just below the magnetic equator. Table I, not heretofore published, and not included at all in the data graphed in Fig. 3, gives the actual day by day series of continuous readings taken in 1926 at eight-hour intervals between about latitude 28° and latitude 0°.

But the existence of this predicted sea-level plateau is more significantly indicated by the much more careful readings shown in Fig. 3, which is reproduced here from a preceding publication[9] prepared when the authors were guided by no theory at all, but were merely trying to get as accurate observations as they could on the variation of sea-level intensities as their electroscopes were taken from Los Angeles to Mollendo, the Allan Hancock yacht, Vallero III, stopping, according to instructions, for days at a time enroute so as to get accurate observations at a given latitude.

From the results of at least the five different sea-level expeditions between Los Angeles and Mollendo recorded in Table I and the upper curve of Fig. 3 the conclusion seems justified that from the magnetic equator clear up to 20° N, or possibly even 25° N, there is a plateau of unchanging cosmic-ray intensity as measured by an electroscope at sea level. This contrasts strikingly, as the lower curve of Fig. 3 shows, with the rise between 0° and 25° found on the India side of the earth where the hypothetical silicon band should come in between these latitudes.

There is indeed in the upper curve of Fig. 3, as it is drawn, the beginning of a rise between 20° and 25° but it is, in any case, very slight and from the point of view of this hypothesis would not be there were it not for the imperfectness with which electroscopes at sea level isolate vertical rays. Indeed, for strictly vertical rays the plateau should extend up to about latitude 33° or 34° N. It is hoped in the near future to be able to present experimental tests in Mexico of this prediction.

The sea-level observations made in 1932 both by Bowen, Millikan, and Neher and by A. H. Compton brought to light with great definiteness the "cosmic-ray shelf" shown so strikingly in Fig. 3 and *which is in exactly the latitude in which it should be to indicate the entrance into the atmosphere of the hypothetical oxygen and nitrogen bands of energies 7.5 Bev and 6.6 Bev.* From the Lemaitre-Vallarta curves reproduced in Fig. 2 it is estimated that these two bands should have been able to get to the earth vertically at magnetic latitudes between 33–36 and 37–39, respectively.

However, it is to be especially noted that the flatness of the cosmic-ray sea-level plateau, which is actually found above magnetic latitude 41°, cannot be taken as indicating the absence of incoming cosmic rays of energies immediately lower than 6 Bev, since there is every evidence that 6 Bev is about the lower limit of the energy of incoming rays which have the capacity to throw appreciable influences of any kind down to sea level through the absorbing effect of the atmosphere. Other evidence from higher up in the atmosphere must then be sought for the existence of bands of carbon and of helium rays, as well as for the theoretical cosmic-ray plateau between these hypothetical carbon rays of energy 5.5 Bev and helium rays of energy 1.9 Bev.

IV. THE BEARING OF THE 1932 AIRPLANE FLIGHTS UPON THE HYPOTHESIS

Much stronger evidence for the existence of the long plateau of constant cosmic-ray intensities between the latitudes of entrance of the

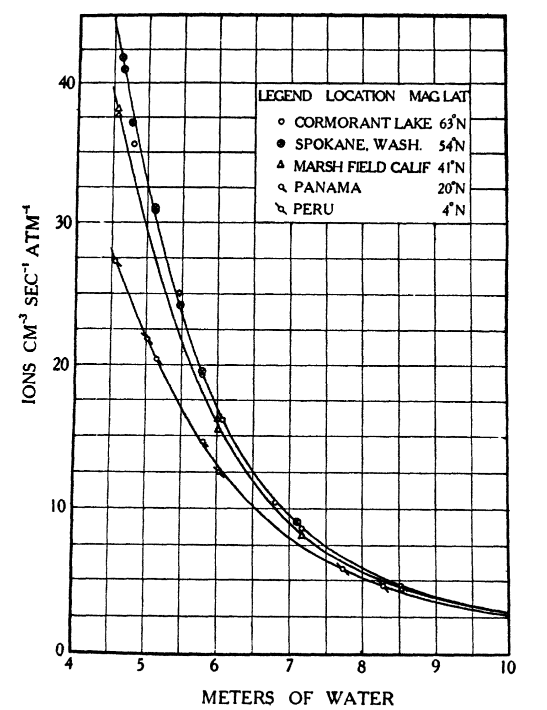

FIG. 4. The striking element in these curves is that the intensities at 4° N and at 20° N are identical all the way up, as are also those at 54° N and 63° N.

[9] R. A. Millikan and H. V. Neher, Phys. Rev. **47**, 207 (1935).

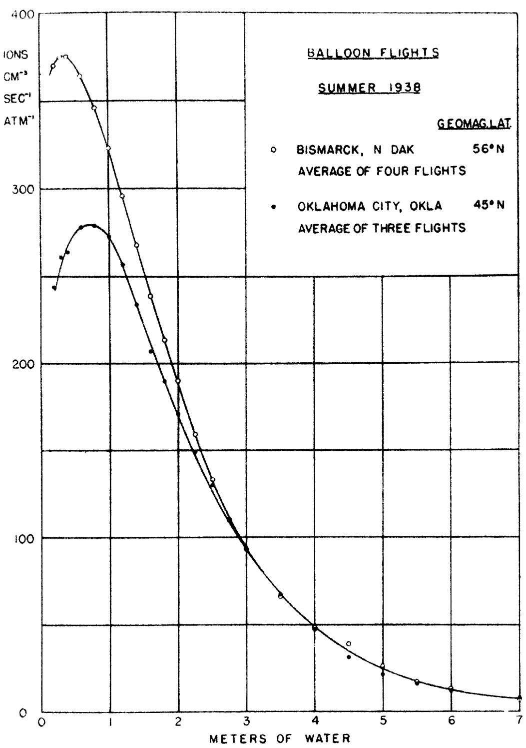

FIG. 5. The most significant element in these curves is that they seem to coincide below about 2.5 m of water, but it is to be remembered that these are electroscope readings, not double counter readings. This introduces an element of some uncertainty.

hypothetical silicon and oxygen bands is found in the records of airplane flights made in both Peru and Panama in the fall of 1932 and reproduced[10] in Fig. 4. The lower of the three curves shows that even up to the altitude of 22,000 feet one could find no difference between cosmic-ray intensities in the latitude 0° and 20° for one and the same curve is nicely fitted by the points taken at both latitudes. This is not only in marked contrast with what is found in India with electroscopes at these altitudes in going only from 0° up to 17.3° instead of from 0° to 20° (see Fig. 1 reference 7, the Agra curve being consistently above the Bangalore curve), but it could not exist if there were any rays of any appreciably larger energy than the oxygen rays coming in between the hypothetical silicon and oxygen bands. For the Lemaitre-Vallarta curves (Fig. 2) show that oxygen rays of energy 7.5 Bev could not get in at all at 20°, while any rays of energy much closer to that of the 13.2 Bev band should have been able to do so, hence arguing merely by analogy with the behavior of the silicon band in India there should certainly have been a difference between the readings in Panama and Peru, especially at 22,000-foot altitudes. *These Panama-Peru observations are, in fact, in all respects consistent with the hypothesis as to the existence of the long plateau between the latitudes of entrance of the hypothetical silicon and oxygen bands.*

Again, the readings reproduced in Fig. 4 furnish some uncertain evidence for the existence of the hypothetical carbon band. This is found in the difference between the upper curve and the intermediate one. The difference between the lower curve and the intermediate one is due to the fact that the latter is taken at a latitude (Mag. lat 41° N) a little farther north than those latitudes at which the hypothetical oxygen and nitrogen bands have been able to get through the earth's magnetic field. The fact that the differences between these curves extend down to sea level (Fig. 4) shows that these two bands have enough energy to extend their ionizing influences in small measure down that far. The fact that careful sea-level observations made by two different observers with two different instruments in the same month, September, 1932, in which the curves of Fig. 4 were taken, revealed no sea-level changes at all between Los Angeles and Vancouver, shows that no incoming rays of lower energy than those represented by the intermediate curve of Fig. 4 are able to extend any measurable influences to sea level. But the upper curve, also taken in September, 1932 at Spokane, reveals unambiguously other entering rays of sufficient energy to throw their influences between eight-tenths and nine-tenths of the way down to sea level. This is just what the hypothetical carbon rays of energy 5.5 Bev should be able to do. This is some little evidence for the existence of the carbon band which is supplemented by further data given below. It is significant, too, that all these data were taken and the curves of Fig. 4 drawn years before any such interpretations as those here given were thought of.

[10] Bowen, Millikan, and Neher, Phys. Rev. **46**, 642 (1934).

V. EVIDENCE FOR THE EXISTENCE OF HELIUM RAYS

The hypothetical helium rays could not be brought to light by any such observations as those recorded in Fig. 4, for such rays of energy but 1.9 Bev could not possibly be expected to throw their influences more than from a third to a fourth of the way through the atmosphere if nitrogen rays of energy 6.6 Bev can just extend a measurable influence to sea level. There is, then, nothing significant in the fact that the points taken at Cormorant Lake (Mag. lat 63) and Spokane (see Fig. 4) all lie on one and the same curve for the airplane flights involved extended only to 22,000 feet or to a pressure of 4.5 meters of water, so that no rays whatever that could get in north of Spokane could possibly extend their influences down far enough to be here observed. Higher altitudes must be reached before any effects of helium rays are to be expected.

The best evidence for the existence of a band of helium rays is found in observations taken by Millikan and Neher in Saskatoon in the summer of 1937, and in other observations taken at Bismarck, North Dakota, and Oklahoma City in the summer of 1938. The results of the 1938 flights are presented in Fig. 5. As indicated, the points through which these curves are drawn are the mean values at each altitude obtained from the four flights at Bismarck and the three flights at Oklahoma City taken within two weeks of one another. Their consistency indicates a good degree of reliability in the curves. The curves show that somewhere between Oklahoma City, Mag. lat 45°, where we estimate that it takes 4.3 Bev to get through the earth's magnetic field vertically, and Bismarck, where it takes about 1.9 Bev to get through vertically (see the Lemaitre-Vallarta curves in Fig. 2) a new group of rays does get in which is capable, however, of

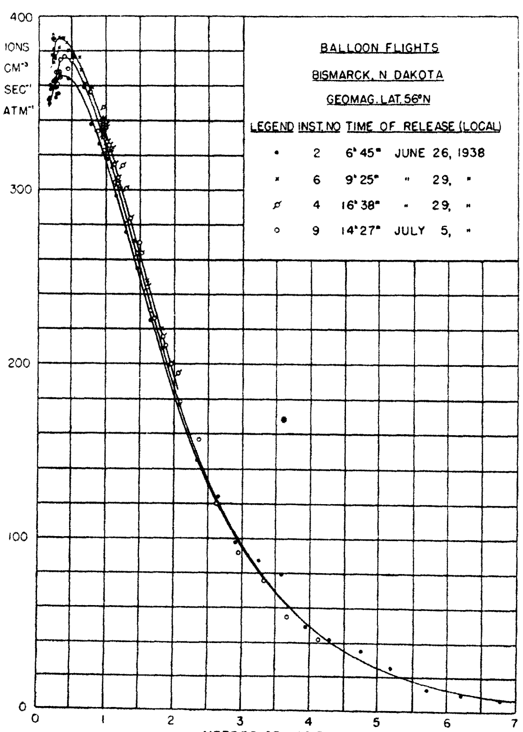

FIG. 6. These curves, all taken in the same week, reveal fluctuations in the hypothetical helium rays coming in at Bismarck. In later experiments we have found that these fluctuations, *in the case of these particular rays,* may introduce differences in readings taken *in different years* amounting to as much as 30 percent.

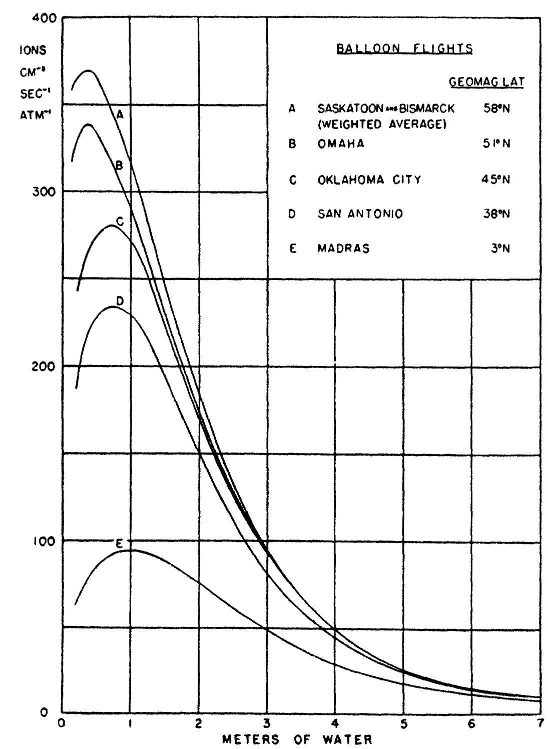

FIG. 7. The differences in the areas underneath the successive curves *A, B, C, D, E* represent the energies coming in between the corresponding latitude limits. These energies are the blocks 1, 2, 3, 4, of Fig. 8. Blocks 5 and 6 (Fig. 8) are obtained similarly from the Peshawar, Agra, and Bangalore curve in the accompanying paper by Neher and Pickering.

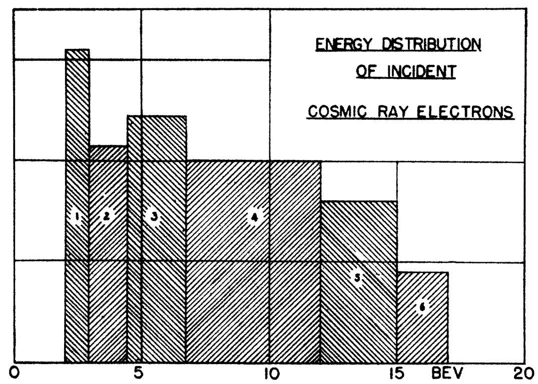

FIG. 8. The above energy blocks correspond to electroscope readings not double counter readings.

penetrating not more than a fourth of the way through the atmosphere for the two curves coalesce at a depth of but between 2 and 3 meters of water below the top. For the reason just advanced the hypothetical helium rays of energy 1.9 Bev would fit this specification admirably, and no rays of very much larger energy would fit it.

Nor is that all the evidence. For in comparing the 1938 readings at Bismarck with those obtained at Saskatoon (Mag. lat 60° N) in 1937 we wrote as follows: "It is found that in the upper fifth of the atmosphere, i.e., about 2 m of water, the readings at Bismarck are consistently about 4 percent or 5 percent *higher* than those at Saskatoon. *For the lower four-fifths of the atmosphere the readings at Bismarck are identical with those at Saskatoon.*" To understand how the readings near the top of the atmosphere at Bismarck can be *higher* than those at Saskatoon we must of course postulate some sort of a cause which produces differences at different times in the cosmic-ray intensity over the whole polar cap made by those electronic energies which according to the Lemaitre-Vallarta curves should get through the earth's magnetic field at about the latitude of Bismarck, but in any case, since it is the Bismarck readings that are the higher, the conclusion seems fairly well justified that there are no electrons entering the atmosphere of energies lower than those that normally can just get through vertically at the latitude of Bismarck. In other words, the theory of a helium cosmic-ray band enables the prediction of the observed plateau of constant cosmic-ray intensities north of Bismarck. The best of present evidence is that the sun's magnetic field cannot be greater than 16 gauss and this would mean that it could not be the cause of the absence of less energetic rays than those of helium north of Bismarck.

But also since the Bismarck-Saskatoon curves are identical in the lower four-fifths of the atmosphere their difference must be due to fluctuations in incoming 1.9-Bev rays, such as seem to be shown in Fig. 6, and since the Bismarck-Oklahoma City curves also are identical in the lower three-fourths of the atmosphere, it appears that the difference between the Oklahoma City and Bismarck curves of Fig. 5 must also be due primarily to the hypothetical helium rays, the argument being merely that these observed rays do not penetrate far enough into the atmosphere to be due to rays of higher energy than helium rays. This argument is strengthened by a glance at the curves in Fig. 7, which show that the rays which cause the difference between the curves taken at San Antonio and Oklahoma City and which must be largely the carbon rays of energy 5.5 Bev, do penetrate far down toward sea level, as they should. It should be said, however, that this evidence is somewhat less certain than that furnished by the data of Fig. 4 which were all taken in one summer (1932), while, though the Oklahoma City-Omaha-Bismarck data were also all taken in a single summer (that of 1938), those at San Antonio were taken in the summer of 1936.

VI. RELATIVE ENERGIES IN DIFFERENT BANDS

In a word, then, the hypothesis here made has had some measure of success in predicting four cosmic-ray bands, namely, a silicon band at about 13.2 Bev, a nitrogen-oxygen band at 6.6 Bev and 7.5 Bev, a carbon band at about 5.6 Bev, a helium band at about 1.9 Bev, and four cosmic-ray plateaus, one between 17 Bev and 13.2 Bev, one between 13.2 and 7.5 billion, one between 5.6 Bev and 1.9 Bev, and one extending in all probability from about magnetic latitude 58° to the pole.

Has it had any success in predicting the amounts of energy in these bands? Bowen gives carbon, nitrogen, oxygen, and silicon about the same abundance. The silicon has twice the energy per ray of the mean of carbon, nitrogen, and oxygen, so that it might be expected to carry about 40 percent of the energy of the four bands. That is not very much more than what it does carry if one attributes to it all the increase in electroscope readings between Bangalore and Peshawar (blocks 5 and 6 Fig. 8). Again, if the band between San Antonio and Oklahoma City (block 3) is taken as the contribution of carbon rays it comes out reasonably close to half of what is left of the energy carried by carbon, nitrogen, oxygen, and silicon after the carbon and silicon have been deducted. Also, if the helium band is responsible for all the new rays added above carbon its energy is a little more than the mean of the carbon, nitrogen, and oxygen bands. It ought to carry roughly twice as much energy as any of them, since each ray has about one-fourth as much energy as the mean of these three, but Bowen gives it ten times their abundance. He probably would not regard his estimates as sufficiently quantitative to make the discrepancy serious.

In conclusion, it may properly be asserted that there is already a reasonable amount of evidence for the actual existence of the five predicted bands and the four predicted plateaus, and the relative energies brought in by the five bands are in every case at least of the predicted order of magnitude.

This comparison of prediction and experiment has been made possible largely through the generous support of the investigation by the Carnegie Corporation of New York and the Carnegie Institution of Washington. The success of the work in India was made possible by the extraordinarily generous and complete cooperation of the British Indian Meteorological Service.

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Results of a High Altitude Cosmic-Ray Survey Near the Magnetic Equator

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Electroscope and Geiger counter observations have been taken with free balloons at geomagnetic latitudes of 3°, 17°, and 25°N. The most important results are as follows: (1) The Geiger counter technique with a single counter will give results very close to those obtained with the electroscope and of comparable accuracy. (2) Vertical coincidence measurements give rise to markedly different values for the relative amounts of incident energy at various latitudes, as compared with the electroscope or single counter data. (3) Within the experimental error, no difference was obtained between the vertical coincidence curves at 3° and 17°, and thus no new energy lies in the primary energy spectrum between the limits of 17 and 15 Bev. (4) This is direct evidence for a banded structure in the primary cosmic-ray spectrum. (5) Flights made with triple and quadruple coincidences, and also with counters arranged to record showers, showed that showers do not significantly affect the vertical coincidence measurements.

INTRODUCTION

In order to measure the primary energy distribution of the cosmic radiation, observations of the incident energy at the top of the atmosphere in different parts of the earth are necessary. These data, in conjunction with the analysis of the effect of the magnetic field of the earth upon incoming charged particles, can yield the required information. During the last few years Millikan and Neher have taken such data with self-recording electroscopes in several different magnetic latitudes. Although this technique is entirely satisfactory in most respects, there are two limitations inherent in the method. These are: (1) the electroscopes can be released only in such places and at such times that the chance of