THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 53, No. 11 | JUNE 1, 1938 | SECOND SERIES

New Light on the Nature and Origin of the Incoming Cosmic Rays

I. S. BOWEN, R. A. MILLIKAN AND H. VICTOR NEHER
California Institute of Technology, Pasadena, California
(Received April 18, 1938)

Cosmic-ray electrons enter the atmosphere only in a definitely limited and relatively narrow energy range. The maximum of this energy distribution curve lies at about 6 billion e-volts. At 1 billion e-volts the curve has fallen to about a third of its maximum value, and on the other side of the maximum at some 17 billion e-volts the incoming energy also has about a third of its maximum value. The observed banded structure may possibly be partly due to the blocking effect of the sun's magnetic field on electrons trying to pass through it to the earth. The total cosmic-ray energy brought in by electrons of energy above 17 billion e-volts plus all that brought in by photons of all energies is about the same as the energy brought in by electrons alone of energies between 6 and 17 billion e-volts, and this energy is fully twice that brought in by all entering electrons of energies less than 6 billion e-volts. The smallness of the fraction of the total incoming energy that can be assigned to photons shows that the cosmic rays cannot ever have come through an appreciable amount of matter in comparison with an atmosphere before entering the solar system. The energies of the incoming rays correspond roughly to the annihilation energies of the atoms of the most abundant elements.

1. THE EXPERIMENTAL DEPTH IONIZATION CURVES UP TO THE TOP OF THE ATMOSPHERE IN FOUR LATITUDES

THE new light which we have recently obtained on the properties of the *incoming* cosmic rays has resulted from our measurements on the ionizing power of the incoming rays in electroscopes carried practically to the top of the atmosphere in four different latitudes between 3°N magnetic and 60°N magnetic.

Two of the depth ionization curves thus obtained, those at Madras, India (3°N mag.) and at San Antonio, Texas (38° 30′N mag.), have already been published[1] and certain conclusions drawn from them, the most important of which is that the incoming rays consist practically entirely of highly absorbable rays, i.e., of electrons or a combination of electrons and photons, for, so far as absorbability is concerned, these two are not easily distinguishable. Such depth ionization curves at two more latitudes are added herewith. These represent the results of eleven new flights made by us up to a minimum pressure of 9.9 mm of mercury, or 98.8 percent of the way to the top of the atmosphere, with Neher recording electroscopes in August and September, 1937, three at Saskatoon, Canada (60°N mag.), and eight at Omaha, U. S. A. (51°N mag.). Table I shows the minimum pressures reached and other characteristics of the nine flights which yielded us useful data.

These four depth-ionization curves, reduced from argon at a pressure of 2 atmospheres to air at 20°C 76 cm Hg, are given in one graph in Fig. 1.

A comparison shows that the Omaha curve (*B*) does not agree very well with the curve

[1] See Bowen, Millikan and Neher, Phys. Rev. **52**, 83 (1937) and Phys. Rev. **53**, 217 (1938). Also, Millikan, Neher and Haynes, Phys. Rev. **50**, 996 (1936).

obtained by us in the Fordney-Settle manned-balloon flight in 1933[2] in nearly the same magnetic latitude. This is presumably due to the fact that much lead and other heavy matter was in the Fordney-Settle gondola, and that secondaries generated in this heavy matter passed through the electroscope resting near them, thus unduly raising the values so obtained, especially near the top where the rays come in from all directions. In any case, however, the four curves shown in Fig. 1 are strictly comparable, since the flights are all made with essentially identical thin-walled electroscopes (0.5 mm of steel). The whole instrument, with accessories, weighs but 1400 grams. In a number of cases the flights in different latitudes were made with one and the same instrument, for in last summer's work our recovery of instruments was so good (94 percent) that we sent the *same* instrument up repeatedly in different latitudes.

The two new curves A and B reveal at once the quite unexpected but very significant fact that the total ionization (area underneath the curve) produced in the electroscope by all the rays that at Saskatoon have been able to get through the earth's magnetic field and into the atmosphere is only a trifle larger than that produced by all the rays that get in at Omaha (curve B). In other words, *there is a very surprisingly small amount of additional energy brought in by any additional field-sensitive rays (electrons)* that first should be able to enter the atmosphere when the magnetic latitude becomes greater than 51°N.

How little uncertainty there is in the readings represented by these curves can be judged, first, from Fig. 2, which is the record of a typical flight, and, second, from Tables II and III, which

TABLE I. *Balloon flights, summer 1937.*

Location	Date	Time of Release (local time)	Instrument No.	No. of Balloons	Minimum Pressure
Saskatoon	Aug. 14	15h 16m	1	5	14.3 mm Hg
Saskatoon	Aug. 16	16h 12m	4	5	26.2
Saskatoon	Aug. 17	10h 20m	9	5	47.2
Omaha	Aug. 21	10h 20m	2	5	40.0
Omaha	Aug. 25	13h 30m	2	7	46.3
Omaha	Aug. 31	13h 20m	9	7	55.9
Omaha	Sept. 1	11h 0m	4	7	23.4
Omaha	Sept. 1	13h 25m	6	7	26.0
Omaha	Sept. 5	14h 22m	6	10	9.9

[2] See Bowen, Millikan and Neher, Phys. Rev. **52**, 82, curve A (1937); also **46**, 650 (1934).

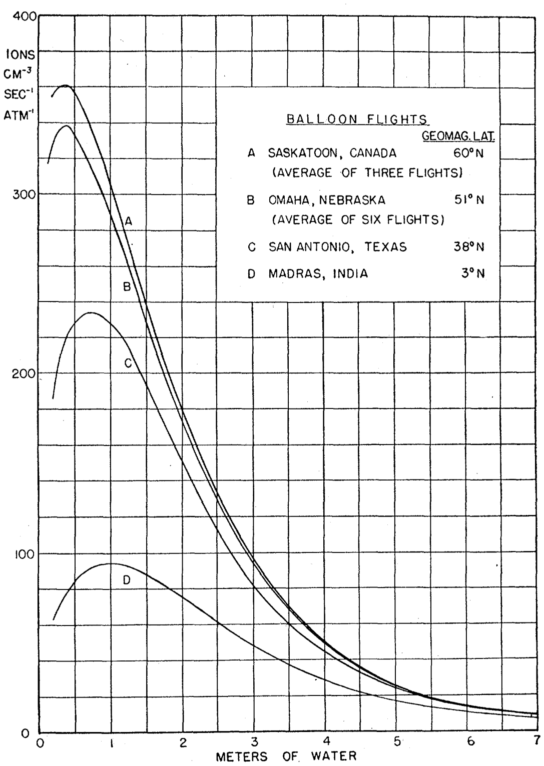

FIG. 1. Results of balloon flights at four different latitudes.

show in the figures in each horizontal row the sort of agreement found at each altitude between the results of the different flights made from the same starting point. The *percentage* of divergence between the readings taken on different flights is of course higher at the low altitudes, but the divergences *in ions* are comparable, as they should be, with those found at the higher altitudes.

The area under curve D, Fig. 1, of course represents the background of ionization due to non-field-sensitive incoming radiation, which is uniform the world over and upon which is superposed, to form curve C, all the additional field-sensitive rays (electrons) which can get through the blocking effect of the earth's field at San Antonio and produce ionization within the electroscope. The additional field-sensitive rays that at Omaha can get through the blocking effect of the earth's magnetic field are responsible for curve B. In a similar way, A is formed at Saskatoon. The three curves A, B, C of Fig. 3 then represent, respectively, the differences

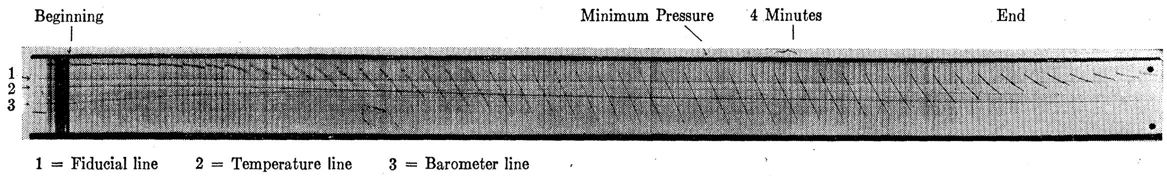

FIG. 2. A typical record taken at Omaha, Nebraska in summer, 1937. The slope of the discharge line is a direct measure of the ionization.

between the curves *C* and *D*, *B* and *C*, and *A* and *B* of Fig. 1. The area under curve *A* of Fig. 3 corresponds to the total, or integrated, ionization produced in the electroscope by all the incoming electrons passing through it of energies between 6.7 billion e-volts and 17 billion e-volts. The last two numbers represent, according to Lemaitre and Vallarta's calculations, the energy required by an electron to break through the blocking effect of the earth's magnetic field at San Antonio and at Madras, respectively, and to enter the atmosphere vertically. The mean energy, then, of the incoming electrons producing this ionization is about 10 billion e-volts.

Similarly, the area under curve *B*, Fig. 3, is the ionization due to the incoming band of electrons of energy between 2.9 billion e-volts (Omaha) and 6.7 billion e-volts, or a mean of 4.8 billion e-volts. Likewise, the area under curve *C*, Fig. 3, is the ionization due to the incoming band of electrons of energy between 1.4 billion e-volts (Saskatoon) and 2.9 billion, or a mean of 2.1 billion e-volts.

In Fig. 4 the rectangular area (1) erected on the *V* (or e-volt$\times 10^9$) axis is made proportional to the total or integrated ionization produced in the electroscope by all the electrons that enter between the latitude of Saskatoon (60°N mag.) and Omaha (51°N mag.). This is the area underneath curve *C*, Fig. 3. Similarly, the rectangular area 2 is made proportional to the total ionization produced in the electroscope by all the electrons which get through the earth's field between Omaha and San Antonio. This is the area underneath curve *B* of Fig. 3. Again, the rectangular area 3 is the area underneath curve *A*, Fig. 3, while the rectangular area 4 is the area underneath curve *D* of Fig. 1, i.e., it represents the total ionization produced in the electroscope

TABLE II. *Comparison of flights at Saskatoon, Canada.*

Meters of Water	Film No.			Average
	1*k*20	4*k*20	9*k*20	
0.2	355			355
0.3	363	356		359
0.4	362	360		361
0.5	357	358		357.5
0.6	350	349	341	347
0.8	333	330	323	329
1.0	311	307	305	308
1.2	279	279	282	280
1.4	250	252	254	252
1.6	224	225	227	225
1.8	199	203	203	202
2.0	177	181	181	180
2.25		155	156	156
2.50			134	134
2.75			115	115
3.0			97	97
3.5			68	68
4.0	56		47	51
4.5	40		32	36
5.0	28		22	25
5.5	20		16	18
6.0	14		11	13
7.0	10			10

TABLE III. *Comparison of flights at Omaha, Nebraska.*

Meters of Water	Film No.						Average
	2*k*20	2*k*21	4*k*21	6*k*21	6*k*22	9*k*21	
0.2					328		328
0.25					333.5		333.5
0.3					337		337
0.4			323	335	340		333
0.5	330	338	322	338	337		333
0.6	321	330	317	335	330		326
0.8	304	309	304	322	314	304	310
1.0	285	286	287	301	294	290*	290
1.2	264	261	267	276	267		267
1.4	242	236	242	249	241		242
1.6	219	213	215	223	217		217
1.8	196	194	191	199	193		195
2.0	175	175	168	177	171		173
2.25	150	152	143	152	146		150
2.5	128	131	122	131	123		128
2.75	109	113		113	104		110
3.0	92	96		98	89		94
3.5	68	72		70	66		69
4.0	50			49	48		49
4.5	37			33	35		35
5.0	28			25	26		26
5.5	21			19			20
6.0	16						16
7.0	11						11

* Mean of 16 four-minute discharges.

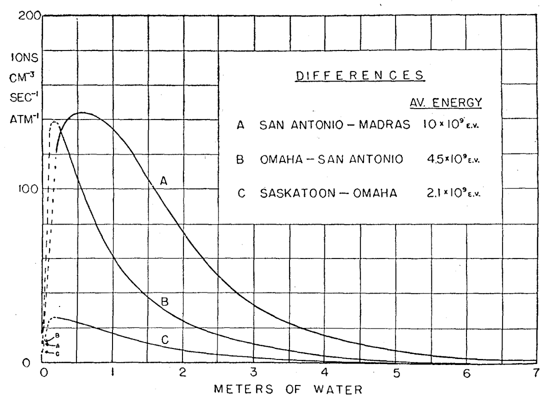

FIG. 3. The areas under these curves are the same as the areas between the corresponding curves of Fig. 1, and represent the energy brought in by electrons of known mean energy. The points A, B, C on the y axis are the computed values of ionization due to these electrons just outside the atmosphere.

by all the rays of whatever nature, photons or electrons, which enter the atmosphere in the equatorial belt, i.e., at Madras.

The areas 1, 2, and 3 of Fig. 4 of course represent ionizations due to *incoming electrons* of energies between the limits shown on the V axis in the figure, but area 4, on the other hand, represents the total measured ionizing effect of all the rays that enter the equatorial belt, no matter what their nature may be. Insofar as these rays are photons we have no knowledge as to what energies are associated with them. We merely include them with the *electron rays* of energy above 17 billion e-volts (the part of area 4 underneath the dotted line) because they are found with them in the equatorial belt.

Having thus built up from the directly observed ionizations the rectangular areas 1, 2, and 3, we proceed without in any way changing these areas to readjust their shapes at the tops in the manner that is dictated by the single condition that there must be some *continuous* distribution of energies of the incoming electrons as their energies vary from 1 billion to 17 billion e-volts. This imposed condition leads to the final shapes of the areas 1, 2, and 3 as shown in Fig. 4, and it is notable how little flexibility in the shape of this curve up to the energy value 17 billion e-volts is left when the one condition of "no sudden breaks in the curve" is imposed. This curve then undoubtedly represents quite closely the actual distribution of incoming *electron* energies up to 17 billion e-volts. The extrapolation of this electron-energy curve beyond 17 billion e-volts (see dotted lines passing through area 4) has a reasonable chance of corresponding to reality, but obviously no certainty. As we have extrapolated it in Fig. 4 it takes care of about half of the integrated ionization which the electroscope actually experiences in the equatorial belt. The remainder of the observed ionization at Madras we have here represented by the remainder of the rectangle 4, which has been quite arbitrarily made to extend about as far to the right as the electron-energy curve extends before getting close to the V axis. This is more or less natural because of the rough interconvertability of electrons and photons through nuclear impacts. Nevertheless, it is to be emphasized that rectangle 4 is inserted merely to have on the chart the representation *of the total ionization due to all the cosmic rays, no matter what their nature may be, that enter the equatorial belt*, and not to assert that the photon part of area 4 lies between the energy limits between which it is found in the figure. Where these hypothetical photons lie in the energy spectrum is of no particular importance for the present considerations.

2. The Distribution of Energies Among the Incoming Electrons

There are certain definite conclusions that can be drawn from Fig. 4, as follows:

1. The first is that the cosmic rays as they enter the atmosphere unquestionably have a definite banded structure. This has been pointed out repeatedly before, but never until now as the result of direct, indubitable energy measurements.

2. The second conclusion is that the maximum of the cosmic-ray energy brought into the atmosphere by electrons in the northern hemisphere, where our measurements are made, lies at about 6 billion electron volts, and that the energy distribution curve of the incoming electrons falls off rapidly on both sides of this point, dropping on the low energy side, at one billion volts for example, to less than a third of the maximum value and on the high energy side at say 20 billion e-volts, also to about a third of its maximum value.

3. The total cosmic-ray energy brought in by electrons of energy above 17 billion e-volts plus

all that brought in by photons of all energies is about the same as the energy brought in by electrons alone of energies between 6 and 17 billion e-volts, and this energy is fully twice that brought in by all entering electrons of energies less than 6 billion e-volts.

4. The smallness of the amount of energy brought in by photons, namely, only a fraction (probably not more than a half) of that represented by the area of 4, means definitely that *the entering electrons have not at all got into equilibrium with their secondaries before entering the atmosphere,* for in equilibrium Carlson and Oppenheimer have shown that "at any energy and thickness $t>1$ ($t=0.4$ m of water) there are always more γ-rays than electrons,"[3] while in Fig. 4 the area assigned to photons is scarcely more than a sixth that assigned to electrons. This last conclusion does not rest solely upon the accuracy of the Carlson-Oppenheimer computations for, as shown by the turn-over points of the curves in Fig. 3, entering electrons even of a mean energy of 10 billion volts do actually get into equilibrium with their secondaries before they have penetrated even a twentieth of the way through the atmosphere, so that after it has become established that the entering particle-rays are electrons[4] the smallness in the number of accompanying photons shows from nothing more than a qualitative point of view that these rays cannot ever have come through an appreciable amount of matter in comparison with an atmosphere before entering the solar system.

3. The Place of Origin of the Cosmic Rays

The conclusion drawn in 4 above means that the cosmic rays cannot have originated within the stars or in any portions of the universe in which matter is present in appreciable abundance. This conclusion also appears to be indicated by the mere fact that the curve of Fig. 4 goes through a definite maximum at about 6 billion e-volts, unless the improbable assumption be made that the observed maximum is wholly due to the action on the incoming rays of the sun's magnetic field. For when an electron of given energy, say 10 billion e-volts, passes through matter, since the main mechanism of its absorption is first the formation of an impulse-radiation-photon, then of an electron-pair, then of two impulse-radiation-photons, then of four

[3] Carlson and Oppenheimer, Phys. Rev. **51**, 225 (1937).

[4] This was proved in Phys. Rev. **53**, 217 (1938).

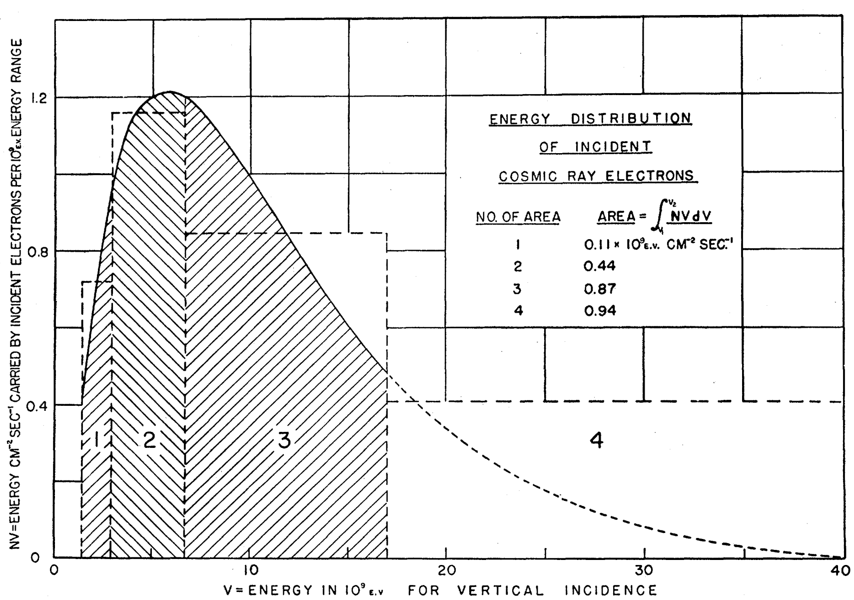

FIG. 4. The areas under A, B, and C of Fig. 3 are plotted between the corresponding values of individual electron energy, V, for vertical incidence. The ordinate thus gives the energy carried to the earth by electrons having energies lying between V and $V+dV$.

electron-pairs, etc., it follows that the energy corresponding to each value of V (Fig. 4) should remain a constant for all values of V lower than the original value of the incident electron-energy. This permits of no such maximum as appears in Fig. 4, so that if this maximum is inherent in the character of the rays as they enter the solar system, then no such process of degredation of energy through the bremsstrahlung-pair-formation process can have taken place. Further, if the original electrons had energies of many different values, some low, some intermediate, and some high, then the energy distribution curve resulting from the passage of these electrons through a small amount of matter would be one *rising continuously with decreasing values of* V. The evidence drawn from the existence of this maximum appears, then, to be in agreement with that drawn from the smallness of the photon component (see 5, §2) that the incoming cosmic-ray electrons have not passed through an appreciable amount of matter on their way from their point of origin to the earth.

4. The Effect of the Sun's Magnetic Field

We have given attention to the question as to whether the influence of the sun's magnetic field could have been responsible for the appearance of the strong maximum at about 6 billion e-volts, as shown in Fig. 4, and have thought this unlikely from the consideration of the fact that if the blocking effect of the sun's field is not sufficient completely to prevent 1.4 billion volt electrons from getting through to the earth at Saskatoon (and we certainly find some of them getting through between 1.4 and 2.9 billion e-volts as Fig. 4 shows), then 5 and 6 billion-volt electrons would probably get through to the earth, i.e., they could not be blocked off in appreciable amount by any sun's magnetic field which would let through even a small number of say 2 billion e-volts. But 5 and 6 billion volt electrons are both beyond the point of inflection which begins near the top of Fig. 4, and which indicates a maximum, or *a banded structure of the incoming rays before they reach the sun's magnetic field at all*. This conclusion is at least not contradicted by the more rigorous computations of Dr. Epstein (as shown in the following article), who made careful quantitative study of the effect of the sun's field on electrons coming into our solar system. On the other hand, the sun's magnetic field may well cut off largely from the earth electrons of original energies of say 2 billion e-volts, and it would probably block off entirely electrons starting toward the earth through that field if they have energies of 1 billion electron-volts, or less.

5. Speculations as to the Mode of Origin of the Cosmic Rays

A number of possible modes of origin of the cosmic rays have been suggested, and it will be appropriate to consider each of them in relation to the new data contained in Fig. 4.

1. It has been suggested that the energies of the cosmic rays are imparted by the fall of electrons through some sort of celestial electrostatic fields which thus impart the observed enormous energies of many billions of electron volts. This conception, difficult enough any way to reconcile with the uniformity of distribution of the incoming rays over the celestial dome, is also not easily reconciled with the fact that the energies of the incoming rays are limited to so narrow a range of energies as from one to some twenty billion e-volts. This form of origin would be expected to give a *continuously rising* curve with diminishing V in Fig. 4, since the electrons to be accelerated would normally be expected to be so distributed in the field as to take on all sorts of energies rather than energies in the near neighborhood of 6 to 12 billion e-volts. At any rate it is very difficult to get a banded structure with a maximum at about 6 billion volts out of such a conception.

2. Mr. Hannes Alfvén has been trying to find the origin of the cosmic rays in the accelerating effect on electric charges of a pair of rotating double stars, each possessing a magnetic field.[5] Such a conception has as yet had no quantitative success, and it is difficult to reconcile with our conclusion that the incoming charged-particle rays contain no protons or other nuclei, but only electrons.[6] Also, it is difficult to reconcile with Fig. 4 because, since the charges to be accelerated would have to be distributed between the two

[5] Alfvén, Zeits. f. Physik **107**, 579 (1937).
[6] Bowen, Millikan and Neher, Phys. Rev. **53**, 219 (1938).

stars and would thus be given widely different energies even when emerging from the same double star, not to mention the great diversities in double stars, so that a narrow band of energies such as we find, and above all an inflection point near 6×10^9 e-volts would not be expected.

3. It was suggested years ago that the cosmic rays might be due to the partial or complete transformation, in accordance with the Einstein equation $mc^2=E$, of the mass of the atom into cosmic radiation. If this transformation is assumed to be complete and the rays generated by this supposed transformation have suffered no degradation by passage through any matter at all—an extreme assumption—it is easy to compute the energies of the incoming rays from the fact that the mass of the atom of hydrogen is equivalent very closely to a billion electron volts. The energies released, then, by this sort of annihilation of the atoms of the most abundant elements (save hydrogen and possibly helium), namely, carbon, nitrogen, oxygen, aluminum, silicon, and iron, would be, respectively, 12, 14, 16, 27, 28 and 56 billion electron volts. To correspond to the somewhat extreme assumption of no degradation of energy whatever in traveling from the place of origin to the earth such complete annihilation of mass would have to occur, not in the stars, where both temperature and density are relatively high, but rather in the portions of space where matter is not abundant. In any case, the momentum principle would require that half of the energy shoot away from the point of annihilation in one direction, and half in the opposite direction. The energy of the cosmic rays shooting out in this way through the annihilation of the foregoing abundant common elements would then be a band of rays of energies lying between 6 and 28 billion e-volts,—in other words, *in just the energy range in which the band of energies of the incoming rays are most abundantly found*. The whole curve of Fig. 4 would then be a reflection primarily of the abundance of the different elements save for hydrogen and helium. But cosmic rays corresponding to the half-mass of the hydrogen atom, namely, half a billion e-volts, would in any case, according to Epstein's computations, be entirely cut out by the magnetic field of the sun, as would also all electron rays of lower energy. Also the cosmic rays due to the annihilation of helium—two billion e-volts—would be largely cut out in the same way. At any rate, the distribution of energies of the cosmic rays shown by Fig. 4 would apparently not be irreconcilable with such an origin. If there is in fact the possibility of the complete transformation of the *mass* of a nucleus into cosmic radiation, i.e., into oppositely ejected electrons (or less frequently into two oppositely ejected photons), since only positive charges exist inside the nucleus, the hitherto strange fact that the incoming electrons are certainly predominantly positives, quite possibly exclusively so, would perhaps be less surprising than it is at present.

The question left not yet fully decided as to whether or not the maximum found in Fig. 4 is due to an inherent property of the cosmic rays, should be definitely answerable through similar flights made in two or three intermediate latitudes. These experiments we hope soon to perform. At any rate, these experiments show that it ought to be possible to determine the strength of the sun's magnetic field by the type of cosmic-ray studies herewith reported.

We wish to express our very hearty appreciation of the assistance furnished by the U. S. Weather Bureau in supplying us with hydrogen at Omaha; by Professors E. L. Harrington, C. A. MacKay, and B. W. Currie, who assisted us in our flights at Saskatoon; and above all, to the Carnegie Corporation of New York for the funds with which these researches have been made possible under the general direction of the Carnegie Institution of Washington.

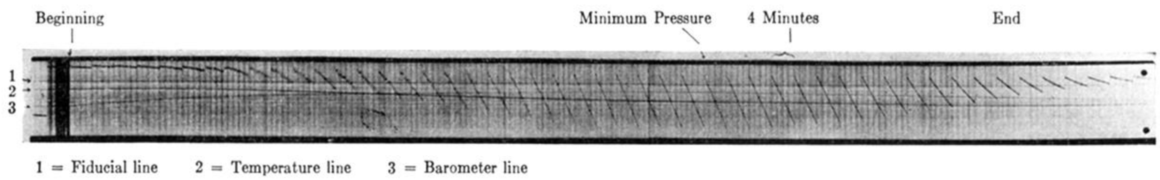

FIG. 2. A typical record taken at Omaha, Nebraska in summer, 1937. The slope of the discharge line is a direct measure of the ionization.