New High-Altitude Study of Cosmic-Ray Bands and a New Determination of Their Total Energy Content

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(1) The Millikan-Cameron cosmic-ray curve extending for 80 equivalent meters of water below the top of the atmosphere up to 7.5 m has here been extended by accurate measurements in the critical region from 7.5 m up to 3.34 m (29,200 ft.) of water beneath the top in latitude 34, and up to 4.5 m (22,000 ft.) in the equatorial belt. *The comparison of the two curves permits of the separation of the magnetically deflectable particles from the primary non-deflectable cosmic rays.* (2) The rays thus separated reveal with much definiteness a banded structure of not less than three rather widely separated components, and by virtue of the high altitudes reached fix with considerable certainty the absorption coefficient of the least penetrating band. This single band is responsible for 90 percent of the cosmic-ray ionization of the atmosphere. The absorption coefficients of the more penetrating bands of indefinite number (not less than two) cannot be sharply determined, but their general character is indicated herein, as well as the limitations of this method of their determination. (3) These measurements combined with Bowen and Millikan's stratosphere observations, which agree well with the present measurements in the region in which they overlap, make possible the plotting of *a complete cosmic-ray intensity curve extending from the lowest depths to the top of the atmosphere.* (4) The graphical integration of this curve shows that the total energy reaching the earth in the form of cosmic rays is about one-half that coming to the earth in the form of heat and light from the stars. This makes the cosmic-ray energy in the universe from 30 to 300 times that of all other radiant energies combined.

THE EXTENSION OF ACCURATE COSMIC-RAY MEASUREMENTS UP TO 29,000 FT. ALTITUDES

MILLIKAN and Cameron's[1] accurate measurements extended from 80 meters of water below the top of the atmosphere up to the top of Pike's Peak, which corresponds inside their lead shielding to 7.5 meters of water below the top. However, for the most significant study of the softest and most powerfully ionizing component contained in the cosmic rays, measurements at altitudes above those obtainable on any mountain peaks are essential. We have therefore been particularly interested for several years past in developing methods of pushing accuracy of readings to the highest points at which airplanes can remain aloft at constant altitude long enough to obtain dependable and duplicable intensity measurements.

Our best flights have recently (April and June, 1933) been made at March Field near Riverside, California through the generous assistance of the Army Air Corps, the pilot flying at a constant altitude at different levels up to 29,200 feet long enough at each level to enable the electroscope to be discharged over its complete range three separate times. Fig. 1 shows the record of the flight when time is plotted as abscissa and rate of discharge as ordinate, the crosses at each level showing the sort of duplicability of the different readings at a given level. This graph also brings to light clearly the enormous rate of rise in ionization as the higher altitudes are reached; the total ionization being more than doubled in going from 22,000 feet (4.49 meters of water) to 29,000 feet (3.34 meters of water), although this corresponds to a change in the barometer of but 3.5 inches of mercury or about a tenth of an atmosphere.

Fig. 2 shows the same data with ionization plotted against depth in meters of water beneath the top of the atmosphere. The way the points fall on a smooth curve shows clearly the consistency yielded by these recording electroscopes as here used. The natural interpretation of these curves is that a soft component of the incoming rays, one which is so soft as to be scarcely perceptible at sea level, is responsible for most of the ionization at altitudes at which the pressure is less than say 6 meters of water (altitude 14,000 feet).

But in order more carefully to interpret such readings as are here found new considerations

[1] Millikan and Cameron, Phys. Rev. **37**, 235 (1931).

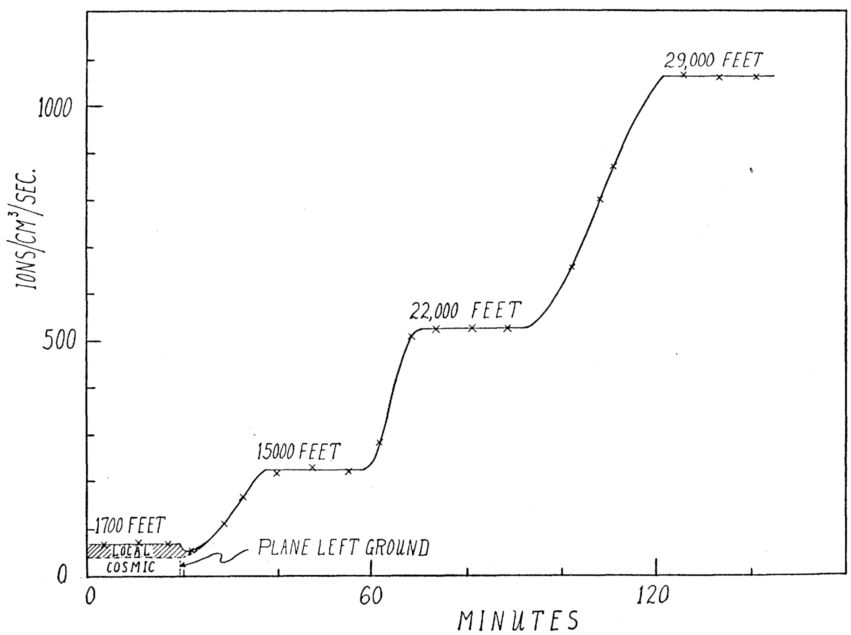

FIG. 1. Record of the rates of ionization in the airplane flight at March Field.

arising from recent studies of the geographical distribution of the rays are significant. The simplest interpretation of the slight equatorial dip in the sea level intensity first announced by Clay,[2] found also by the group of observers working with A. H. Compton[3] and quite recently appearing to the extent of about 7 percent in our own trips[4] back and forth between Mollendo, Peru and New York and Los Angeles is, as already outlined by one of us,[4] that while about 93 percent of the rays reaching sea level are of a sort to be wholly uninfluenced by the earth's magnetic field, the remaining 7 percent of the ionization observed at sea level within our 10 cm lead shield is due to rays magnetically deflectable by that field. If this hypothesis is correct, the ionization that we have found above March Field (lat. 34°N) would be a mixture of that due to magnetically undeflectable rays, and that due to a deflectable component, i.e., it would be a mixture of the ionization produced in the atmosphere by the photons (or neutrons) absorbed therein and that produced by rays which enter the earth's magnetic field (which is supposed to extend for thousands of miles above the earth) as

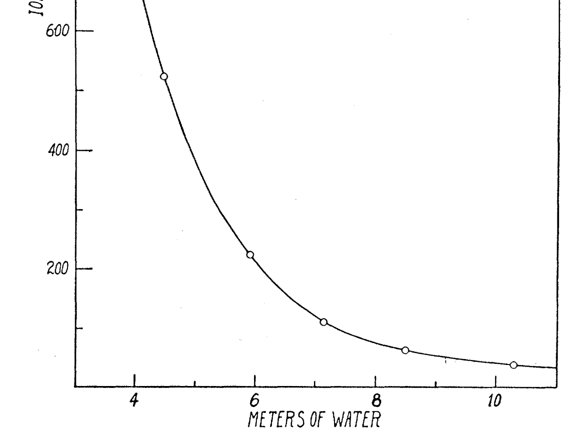

FIG. 2. Cosmic-ray intensities plotted as a function of depth in meters of water below the top of the atmosphere. Observations taken in airplane flight at March Field.

[2] J. Clay, Proc. Roy. Acad. (Amsterdam) **30**, 1115 (1927); **31**, 1091 (1928); **33**, 711 (1930); Naturwiss. **20**, 687 (1932).

[3] A. H. Compton, Phys. Rev. **43**, 387 (1933).

[4] R. A. Millikan, Phys. Rev. **43**, 666 (1933).

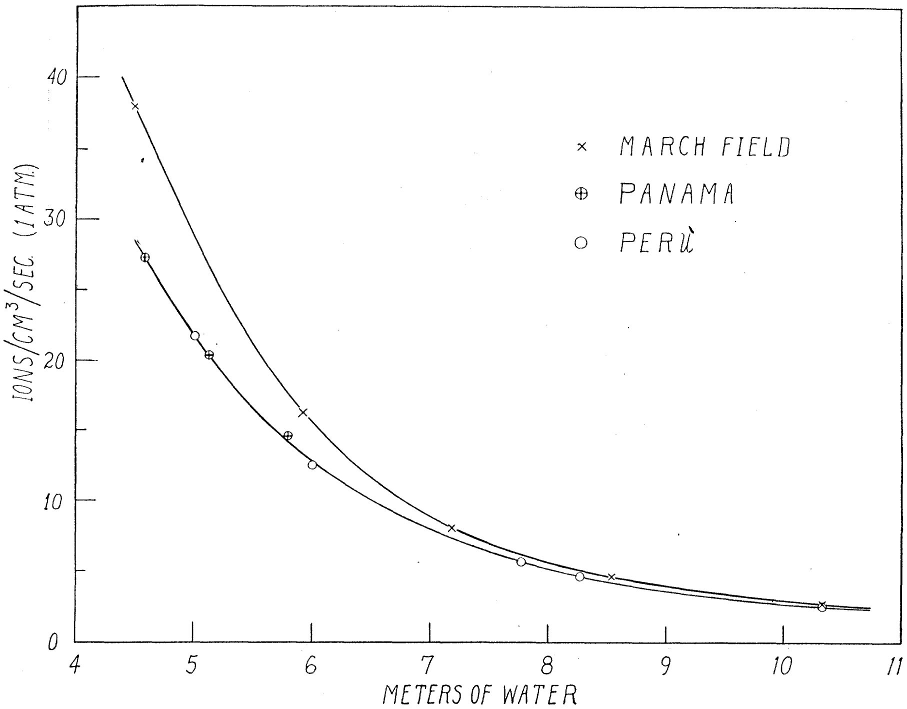

FIG. 3. Comparison of cosmic-ray measurements taken on airplane flights at March Field, Panama and Peru.

charged particles, whether primary or secondary is not here important. *But since in the equatorial belt no deflectable rays of such energies as those actually found by Anderson,*[5] *Kunze*[6] *and ourselves*[4] *to exist in the cosmic rays can possibly penetrate the earth's magnetic field so as to get into that portion of the atmosphere under observation,* it is quite clear that in order to observe in a region in which all the rays are of the kind which are wholly uninfluenced by a magnetic field it is merely necessary to make, somewhere in the equatorial belt, flights similar to the March Field flights.

II. The Separation of Magnetically Deflectable Particles from the Incoming Cosmic Rays

Accordingly in January, 1933, we arranged through the generous assistance of the U. S. Army Air Corps to have one of our new vibration-free recording electroscopes taken in a high altitude flight between Christobal, Panama and Balboa (lat. 8° 43′ N). The plane actually flew for 45 minutes at each of the altitudes 16,000 feet (5.75 m of water), 19,000 (5.08 m) and 22,000 (4.50 m). A similar flight was also made by Neher in a commercial plane between Arequipa, Peru (Lat. 17 S) and Lima, Peru, (Lat. 12 S). The results of these three flights are all plotted in Fig. 3 and show with much conclusiveness that *there is no latitude effect whatever between Panama and Arequipa.* Since the electroscopes actually used were yielding at 22,000 feet 379 ions per cc per sec. this lack of a latitude effect over this stretch is here brought to light with a very considerable accuracy.

Since, then, this equatorial ionization is necessarily due to rays which are not only magnetically undeflectable themselves but have been entirely freed from all charged particle components of all sorts it is of much interest to determine what kind of cosmic-ray bands, *as defined by their absorption coefficients alone,* make up the incoming beam. Millikan and Cameron carried their analysis of this sort from a depth of 80 meters be-

[5] C. D. Anderson, Phys. Rev. **41**, 405 (1932).

[6] Paul Kunze, Zeits. f. Physik **79**, 203 (1932); **80**, 559 (1933).

low the top of the atmosphere up to 7.5 meters, but according to the foregoing observations and points of view their analysis was somewhat vitiated by the presence at sea level (10.33 m of water) of the 7 percent of ionization due to incoming particles. Also the difference between curves 2 and 3 shows that at 22,000 feet (4.5 m) the effect of this particle component has risen to some 39 percent. The rapid decrease of this hypothetical effect of particles in going from 4.5 m to 10.33 m shows, then, that not far below sea level this particle component must in any case drop out entirely. This means that the analysis of the underwater curve, so far as concerns the portion that is lower down than say 15 m below the top of the atmosphere, will be the same as that already published by Millikan and Cameron, but from that point up to 4.5 m, the highest altitude reached in the equatorial flights, it will be peculiarly interesting to know what sort of absorption coefficients are able to reproduce the readings. The results are shown in Tables I, II, and III.

III. The Banded Structure of the Cosmic Rays

In computing the Tables I to III we have used the following procedure. The Millikan-Cameron data make it possible to avoid entirely all errors due to transition effects such as make it necessary for Professor Regener[7] to treat his air and water curves separately. For these Millikan-Cameron under-water data were taken in lakes at altitudes so high that there is a considerable stretch of under-water data which overlaps the airplane data, so that we combine these two sets of observations into one continuous curve, all taken in latitude about 34 N, and extending from the highest point reached in the airplane flight, *viz.*, 3.34 m below the top of the atmosphere, down to 80 m below the top, which is the lowest point reached in the under-water work.

To obtain the corresponding curve in the equatorial belt, in the absence of actual underwater readings near the equator we have simply extended the airplane equatorial curve until it touches the foregoing complete curve obtained in latitude 34, this point of tangency being actually found, to well within the limits of observational uncertainty, at about 15 m below the top. At a later time we hope to obtain direct measurements in the equatorial belt upon this little stretch of the curve connecting air readings and underwater readings, but the foregoing procedure cannot involve errors of appreciable magnitude for the present purposes.

In order, however, to extend the curve still farther down we have fitted Regener's observations at 80 meters to the Millikan-Cameron curve at that point and thus added to the foregoing equatorial observations between 4.5 m and 80 m a tail obtained from Regener's readings from 80 m to 240 m and have obtained thus a complete curve corresponding to observations on the equatorial belt between 4.5 m and 240 m. In order to get the best possible fit we have made slight adjustments in the instrumental zeros reported both by Millikan and Cameron and by Regener, but such adjustments are within the observational uncertainties which appear in the recorded data of both sets of observers. Incidentally, when these very minute rates of ionization are being measured these zero uncertainties introduce a large percentage of error into the resulting limiting absorption coefficient, so that the differences reported in this coefficient by the different observers have no real significance. It is in the foregoing way, then, that the numbers found in the observed column of Table I have been obtained, these numbers representing the number of ions formed per cc per sec. in an electroscope in which the pressure is 1 atmosphere of air. According to our own analysis, as well as that of Professor Epstein, who has had the opportunity to study our data, *it is in no way possible to build up this curve without the assumption of at least three cosmic-ray bands of widely different penetrating power*. This simply fortifies the conclusion reached by Millikan and Cameron from their former less extended data.

Table I shows how this observed curve is built up from the three absorption coefficients $\mu=0.5$ per m of water, $\mu=0.07$, and $\mu=0.015$. The last two of these are very close to those used by Millikan and Cameron in their first attempt to synthesize their under-water curve,[8] their chosen

[7] E. Regener, Phys. Zeits. **34**, 306 (1933).

[8] Millikan and Cameron, Phys. Rev. **32**, 548, 9 (1928).

TABLE I. *Comparison of observed cosmic-ray intensities with those calculated under the assumption that the cosmic rays are made up of three bands with absorption coefficients* $\mu=0.5$, *0.07 and 0.015 per m of water.*

h (meters of water)	0.8 $G(0.015)$	6.7 $G(0.07)$	795 $G(0.50)$	Total	Observed	Obs.-Cal.
4.5	0.63	3.06	21.73	25.42	24.62	−0.80
5.0	.62	2.86	15.76	19.24	19.25	+ .01
6.0	.59	2.52	8.46	11.57	11.53	− .04
8.0	.55	1.98	2.54	5.07	4.65	− .42
10	.51	1.57	0.79	2.87	2.52	− .35
15	.436	0.928	.047	1.411	1.414	+ .003
20	.375	.561	.003	0.939	0.939	.000
25	.326	.350		.676	.664	− .012
30	.285	.223		.508	.505	− .003
40	.221	.091		.312	.308	− .004
50	.174	.039		.213	.220	+ .007
60	.138	.017		.155	.166	+ .011
70	.111	.007		.118	.123	+ .005
80	.089	.003		.092	.088	− .004
90	.0721	.0015		.0736	.0680	− .0056
120	.0390	.0001		.0391	.0389	− .0002
160	.0180			.0180	.0188	+ .0008
180	.0124			.0124	.0128	+ .0004
200	.0085			.0085	.0080	− .0005
240	.0041			.0041	.0041	.0000

values being then $\mu=0.08$, $\mu=0.04$, and $\mu=0.02$, though for the foregoing reasons they were then careful to state that "there is no very great importance to be attached to this synthetic curve." Their observations had not then gone to high enough altitudes to get the softest coefficient with any certainty, the value they then used being $\mu=0.3$. In their 1931 paper[9] they had gone high enough to find that this value of the softest coefficient was definitely too small, and they then used for it $\mu=0.8$, while for the harder components they used $\mu=0.20$, $\mu=0.10$, and $\mu=0.03$. It is of course the softest coefficient which the present experiments are calculated to fix with greater certainty. The same uncertainty as to the other components exists as heretofore.

In this present synthesis we have simply added, with the aid of the Gold tables, three ionizations each obtained from

$$I=I_0\int_0^{\pi/2} e^{-\mu h/\cos\theta}\sin\theta d\theta=I_0\int_1^{\infty}\frac{e^{-\mu hx}}{x^2}dx=I_0G_\mu,$$

the numerical factor at the top of each column being the I_0 (number of ions per cc per sec. at the top of the atmosphere in an electroscope filled with air at 1 atmosphere) of this formula, and the letter G_μ standing for the above-mentioned Gold function. We would emphasize, however, as one of us has repeatedly done before, that though there is no unique solution to such an absorption curve, *all possible solutions give absorption bands or regions bearing a close general resemblance to the foregoing solution.*

To illustrate the extreme types of possible divergence of solutions, we present in Tables II and III two other modes of building up the observed curve, both of which fit the observational data quite as well as does the mode shown in Table I. Table II corresponds to four bands of absorption coefficients, $\mu=0.55$, $\mu=0.12$, $\mu=0.03$, and $\mu=0.0075$, but the following four will fit the observations just as will $\mu=0.55$, $\mu=0.12$, $\mu=0.06$, $\mu=0.015$; but in that case the corre-

TABLE II. *Comparison of observed intensities of cosmic rays with those calculated under the assumption that cosmic rays are composed of four bands of absorption coefficients* $\mu=0.55$, *0.12, 0.03, and 0.0075 per m of water.*

h(meters of water)	0.2 $G(0.0075)$	1.9 $G(0.03)$	11.5 $G(0.12)$	1000 $G(0.55)$	Total	Observed	Obs.-Cal
4.5	0.17	1.26	3.51	20.48	25.42	24.62	−0.80
5.0	.17	1.22	3.18	14.49	19.06	19.25	+ .19
6.0	.17	1.14	2.62	7.40	11.33	11.53	+ .20
8.0	.16	1.00	1.81	2.01	4.98	4.65	− .33
10	.15	0.89	1.28	0.56	2.88	2.52	− .36
15	.140	.677	0.561	.026	1.404	1.420	+ .016
20	.128	.525	.259	.001	0.913	0.945	+ .032
25	.118	.413	.122		.653	.670	+ .017
30	.109	.328	.059		.496	.511	+ .015
40	.094	.211	.014		.319	.314	− .005
50	.082	.139	.004		.225	.226	+ .001
60	.071	.093	.001		.165	.172	+ .007
70	.063	.063			.126	.129	+ .003
80	.055	.043			.098	.094	− .004
90	.0490	.0295			.0785	.0738	− .0047
120	.0345	.0098			.0443	.0447	+ .0004
160	.0222	.0024			.0246	.0246	.0000
180	.0180	.0012			.0192	.0186	− .0006
200	.0146	.0006			.0152	.0138	− .0114
240	.0098	.0001			.0099	.0099	.0000

TABLE III. *Comparison of observed intensities of cosmic rays with those calculated under the assumption that the cosmic rays consist of a band with absorption coefficient* $\mu=0.55$ *together with a continuous spectrum. The intensity in the continuous spectrum is distributed with respect to absorption coefficient according to the following expression.* $I=K\int_{0.00667}^{\infty}(\mu-0.00667)^{1/6}G_\mu d\mu$.

h(meters of water)	I	940 $G(0.55)$	Total	Observed	Obs.-Cal.
4.5	6.30	19.30	25.60	24.62	−0.98
5.0	5.54	13.61	19.15	19.25	+ .10
6.0	4.41	6.96	11.37	11.53	+ .14
8.0	3.07	1.89	4.96	4.65	− .31
10	2.32	0.53	2.85	2.52	− .33
15	1.352	.024	1.376	1.416	+ .040
20	0.914	.001	0.915	0.941	+ .026
25	.666		.666	.666	.000
30	.510		.510	.507	− .003
40	.326		.326	.310	− .016
50	.225		.225	.222	− .003
60	.164		.164	.168	+ .004
70	.124		.124	.125	+ .001
80	.096		.096	.090	− .006
90	.0756		.0756	.0698	− .0058
120	.0403		.0403	.0407	+ .0004
160	.0198		.0198	.0206	+ .0008
180	.0143		.0143	.0146	+ .0003
200	.0105		.0105	.0098	− .0007
240	.0059		.0059	.0059	.0000

[9] Millikan and Cameron, Phys. Rev. **37**, 246 (1931).

sponding I_0s must assume the sequence of values 775., 5., 4.4, 0.8. In general in any four band analysis the two most penetrating of the components have little significance beyond indicating that there is an exceedingly small number of very penetrating rays mixed with the cosmic-ray beam and that the coefficient of this penetrating tail must then have a value not far from $\mu = 0.02$. In Table III the three most penetrating bands of Table II have been combined into the continuous distribution function indicated at the head of the first column. In each of these tables the instrumental zeros of both Millikan and Cameron's and Regener's experiments have been slightly adjusted, but always within the estimated limits of observational uncertainty, so as to obtain the best fit between the "total" and the observed columns.

This whole analysis has been inserted merely to show how large, or better how small, a divergence of types of solution is possible, and the most striking result is that previously emphasized repeatedly by one of us, even with less extensive data, namely, that *more than 90 percent of the ionization of the atmosphere is due to the softest cosmic-ray band, which stands out by itself quite alone and reasonably monochromatic.*

The maximum variation in the absorption coefficient of this band, as here directly observed, is between say $\mu = 0.5$ and $\mu = 0.6$. *That one single coefficient will take care of the whole ionization between so wide limits within which that ionization is so intense and varies over so wide a range, is one of the most striking and significant features of the cosmic rays brought to light by these studies.*

It is of some interest that $\mu = 0.79$ is the coefficient computed from the Klein-Nishina formula for 27 million volt rays, the energy released in the building of helium out of hydrogen. This formula, however, can in our judgment no longer be regarded as having any validity in the cosmic-ray field. If this band arises from atomic building processes at all its energy relations obtained in other ways point to the synthesis, either of helium or of oxygen out of hydrogen as its cause, but confining ourselves here to its absorption-properties alone one of the striking facts of this present experimental situation is that *this softest and most powerful cosmic-ray component appears to possess a coefficient which is from three to five times that of its nearest neighbor* to which any appreciable intensity can be assigned.

In a somewhat similar attempt at an analysis of the depth-ionization curve Regener[7] has used a function, developed by Kulenkampff,[10] which attempts to correct for the ionization produced by secondary photons. In the derivation of this function, however, Kulenkampff made the as-

[10] V. H. Kulenkampff, Phys. Zeits. 30, 561 (1929).

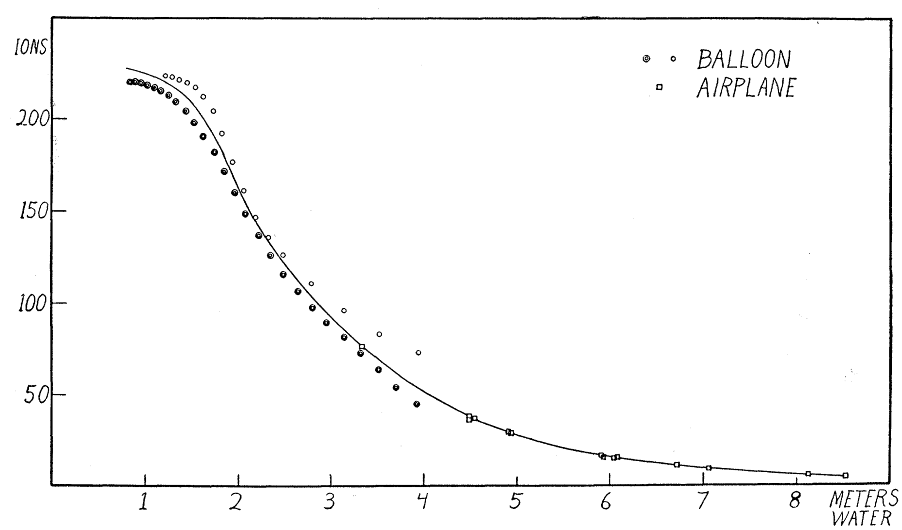

FIG. 4. Complete curve showing variation of cosmic-ray intensities with altitude as given by combining airplane observations and those made with free balloons.

sumption that in Compton scattering 70 percent of the energy of the primary quantum is retained by the scattered secondary photon, 49 percent by the tertiary, etc. A simple calculation on the basis of the Klein-Nishina formula, however, shows that for cosmic rays the secondary photon on the average receives only 20 percent, the tertiary 4 percent, etc. Furthermore, recent cloud chamber experiments by Dr. C. D. Anderson indicate that a large part of cosmic-ray absorption is photoelectric absorption in which no secondary photons are formed. This means, then, that the secondary photons contribute at most only a very few percent of the total ionization. Also, as most of the secondary photons are very much softer than the primaries, equilibrium between them has been practically attained at all observed points. Consequently we have continued to use the simple Gold function in building up the above depth ionization curves.

IV. Comparison of Cosmic-Ray Energy and Star-Light Energy

Having thus obtained with much greater accuracy than heretofore the complete cosmic-ray curve up to an altitude of 29,000 ft., we are now in position to extend it to within 0.6 meter of the top with the aid of the observations made last summer[11] at Dallas, Texas. The result is shown in Fig. 4, and the way the accurate airplane observations fit the balloon-points where the two curves overlap lends additional support to the general correctness of these balloon observations. The integral over this curve *from the top of the atmosphere*, to which it can be easily extrapolated, gives the result that a total of 6.25×10^7 ions are formed per sec. per sq. cm of the earth's surface. If we assume that each ion requires 32 electron-volts of energy for its formation this corresponds to a total energy of 3.2×10^{-3} erg per sq. cm per sec. falling on the earth in the form of cosmic rays. This may be compared with 6.91×10^{-3} erg sq. cm per sec. received from star light[12] at our position in the Galaxy, or to from 2×10^{-5} erg to 2×10^{-4} erg for a position in intergalactic space. In other words, according to these most recent and most dependable of our integrated cosmic-ray measurements *the energy falling on the earth in this form is about half of the total radiant energy received from the stars*, *while the cosmic-ray energy of the universe is from 30 to 300 times greater than all other radiant energies combined.*

[11] Bowen and Millikan, Phys. Rev. **43**, 695 (1933).

[12] See accompanying paper by Dr. Korff of this laboratory, p. 300.