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Cosmic-Ray Intensities in the Stratosphere

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Three flights which reached altitudes, according to official weather bureau records, corresponding to the barometric pressures 79 mm, 32 mm, and 16 mm of mercury respectively are reported. In two of these flights dependable electrometer readings down to pressures of 88 mm and 61 mm, respectively, are obtained. These flights enable a *weighted mean* ionization-altitude curve to be obtained down to a pressure of 61 mm or 92 percent of the way to the top of the atmosphere. The same shape of the ionization-altitude curve is obtained from both flights and also from the flights made by Regener and by Piccard. This shape is concave downward at the top, i.e., it shows a decreasing absorption coefficient as the top is approached. This indicates non-ionizing primary entering rays not yet wholly in equilibrium with their secondary particle rays. The absolute values of the ionization found in each of these two flights and on Regener's flight are in agreement within the limits of observational uncertainty.

I. THE PROBLEM

THE study of the ionization produced by the cosmic radiation in the upper layers of the atmosphere, i.e., in a region far above that accessible by airplanes or manned balloons, is of so much importance for the determination of the nature and origin of these rays that during the past summer we undertook again to attack this problem by the method which we first initiated in 1922;[1] namely, by sending up recording electrometers, barographs, and thermometers in sounding balloons and studying the records brought back to earth in parachutes, or otherwise.

II. THE INSTRUMENTS

The determinations of both pressures and temperatures were made by the Weather Bureau, which generously undertook this whole enterprise in cooperation with ourselves and placed their men, their facilities, and their experience at our disposal. The meteorographs used were the regular Fergusson Weather Bureau sounding balloon instruments made by Julian P. Friez and Sons, Baltimore, and the altitudes were worked out from these records by the Weather Bureau staff at Washington. The electrometers were of our own design, and were along the general lines of our 1922 instruments.[1] They were made by the machine shop force of the California Institute of Technology, the sensitive quartz systems, however, being built by Dr. H. V. Neher. These instruments, however, were larger than those used in 1922, being steel cylinders 10 cm in diameter and of walls 0.3 mm thick, provided with conical ends, the whole capacity being about 1165 cc. They could be filled with gas up to a pressure of four atmospheres through a needle valve in the bottom end. Actually the best flight herein described was made with a pressure of 4 atmospheres, while the second one corresponded to a pressure of 2.2 atmospheres. The quartz system was of the usual Wulf two-fiber type, differing from those which we have regularly used only in that the lower supporting fiber was not made as stiff as usual so that the restoring force resided chiefly in the stiffness of the recording fibers themselves. This modification was made to reduce the effect of temperature to a minimum and the success attained is shown by the fact that the electrical constants of the system were found to vary less than 2 percent when the temperature rose from −77°C to +23°C. The mechanism for charging the fibers was operated by an electromagnet which acted through the thin steel wall of the small hollow cylinder at the top upon an iron plunger inside so that the operation of charging could not in any way endanger the air-tightness of the vessel. Fig. 1 is a photograph of one of the

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[1] R. A. Millikan and I. S. Bowen, Phys. Rev. **27**, 353–361 (1926); *Millikan Carnegie Institute Year Book* **21**, 385 (1922).

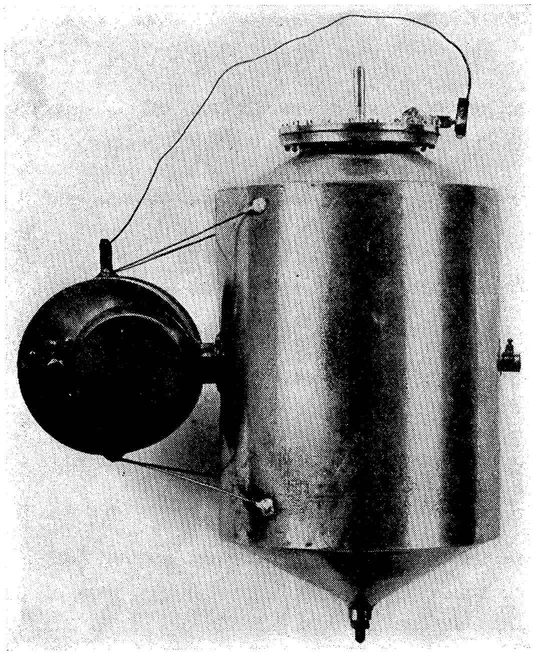

FIG. 1. Self-recording electrometer for observations in the stratosphere. Skylight falling through the 0.001 inch slit at the right casts shadows (diffraction images) of fibers on the photographic film placed just behind a horizontal slit in the recording attachment to the left.

four electrometers sent up this summer. The position of the fibers was recorded by throwing their shadow through a horizontal slit upon a moving photographic film. The film itself was wrapped around a drum of 5 cm diameter, which was attached directly to the mainspring of a 15 jewel watch which made one revolution in $6\frac{2}{3}$ hours. Suitable provision was made to stop the watch after one revolution. In order to insure the continuous running of the watch at the lowest temperatures encountered, namely, $-70°C$, kerosene lubrication was used and in addition a spring having about three times the normal tension was added to the normal spring. Also, the watch chamber was kept thoroughly dry with the aid of a side chamber containing P_2O_5.

The electrometer was hung in the middle of a wire protecting cage about a foot in diameter, so that the shock of hitting the ground with some speed as it was brought down in its parachute need produce no serious injury. The weight of the instrument alone was about 450 grams, and with the protecting basket it amounted to about 550 grams. The total weight carried by the balloon, consisting of electrometer, barograph, and parachute was about 1200 grams. To carry up this load we used sounding balloons $2\frac{1}{2}$ meters in diameter when deflated, made by the Continental Caoutchouc Company of Hanover, Germany. These balloons were inflated to give a free lift of about 1200 grams, and this gave a rate of ascent of approximately 250 meters per minute.

III. THE FLIGHTS

We made the flights in different latitudes because we expected to find latitude effects in the very high levels of the atmosphere. One flight was made at Ellendale, North Dakota, and three more were made at Dallas, Texas. The Ellendale instrument, however, has not been recovered, but the three Dallas flights have all brought a return of the instruments, two of which yielded satisfactory records.

In one of these flights an altitude was reached at which, according to the Weather Bureau's official measurement and report, the barometric pressure had fallen to 16 mm. This compares favorably with Regener's[2] flight of the summer of 1932, since he reports his highest reading as taken at a pressure of 22 mm. Despite our higher altitude, however, we have not used our electrometer readings corresponding to pressures below about 60 mm, for above that point the potential of the fibers had fallen below the value at which in our calibration runs we had found that it was safe to count on saturation. On our graph, therefore, the highest reading plotted is at 61 mm, which corresponds to an altitude of 18 km. Up to that point, however, altogether dependable readings could be obtained.

Fig. 2 shows, in the case of the highest ascent, the actual distance as measured in a microscope between the two traces on the film, made by the two fibers, as a function of the time elapsed since the beginning of the flight, a measurement of fiber-distance being made at time intervals 1.25 minutes apart. An inspection of the points so obtained shows how high was the accuracy in the electrometer readings despite the fact that the lack of contrast on the film makes it unsuitable for reproduction.

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[2] Regener, Naturwiss. **20**, 695 (1932).

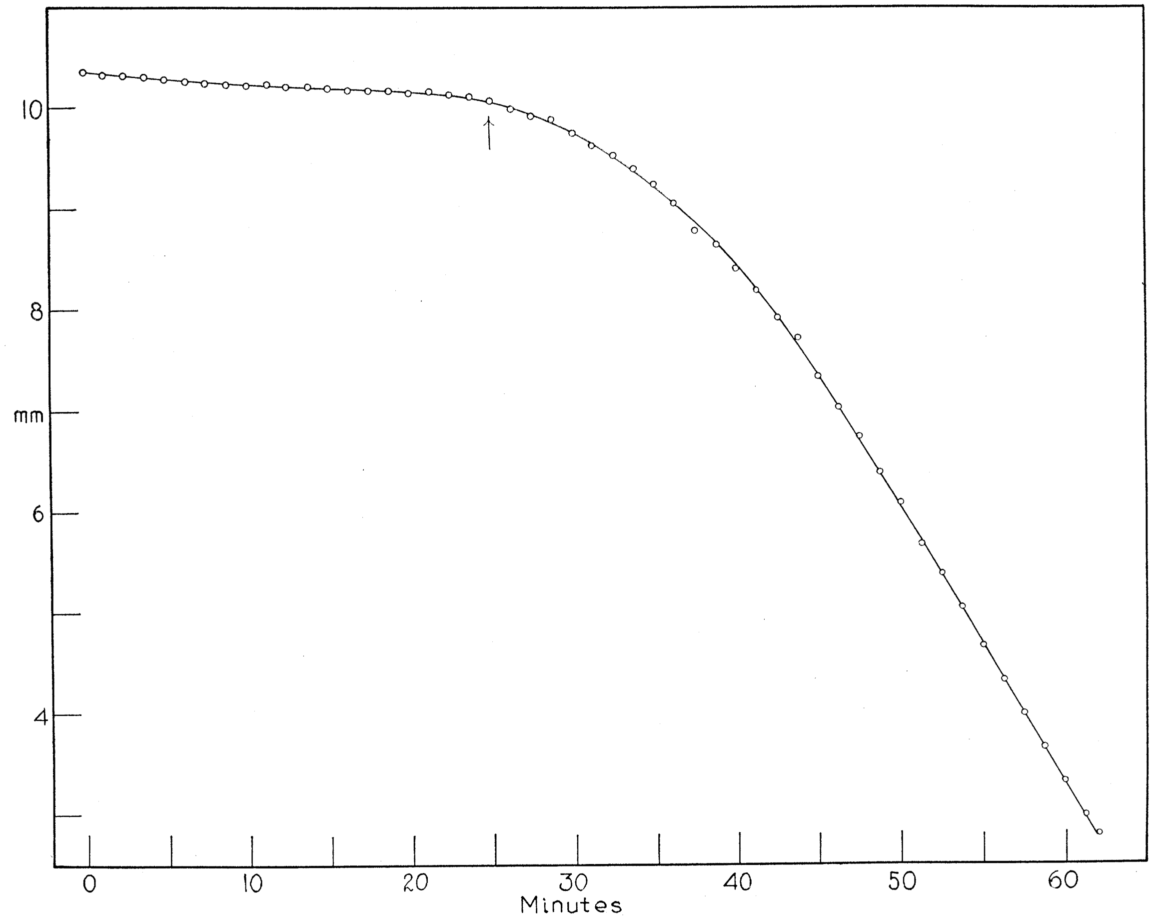

FIG. 2. Separation of traces of electrometer fibers as a function of the time after start of flight.

A second successful flight in which the last electrometer reading corresponded to a pressure of 79 mm (altitude 16.3 km) was also made and yielded a graph which up to that altitude was very nearly as good as that shown in Fig. 2. Our third instrument that came back also had an excellent barometric record which showed that it had reached a pressure of 32 mm (altitude 21.9 km) but the electrometer record was illegible. We succeeded, therefore, in our high altitude summer work of 1932 in obtaining two entirely independent records up to altitudes which correspond respectively to 88 and 93 hundredths of the way to the top of the atmosphere and which, therefore, permit for the first time of a comparison of readings of different instruments and hence of a fairly reliable estimate of the uncertainties actually inherent in this type of observing.

IV. THE TREATMENT OF DATA

In Fig. 2, as in all work of this sort, the actual readings represent necessarily observed deflections or voltages of the fiber system. To obtain the desired ionization as a function of barometric height it is customary to plot the voltage (or deflection) against time, as in Fig. 2, and then to fit the smoothest possible curve to the average positions of the observed points. The ionization at a given barometer reading is then obtained by taking the slope of this curve corresponding to the barometer reading in question. Following this procedure we have obtained from the smooth curve shown in Fig. 2

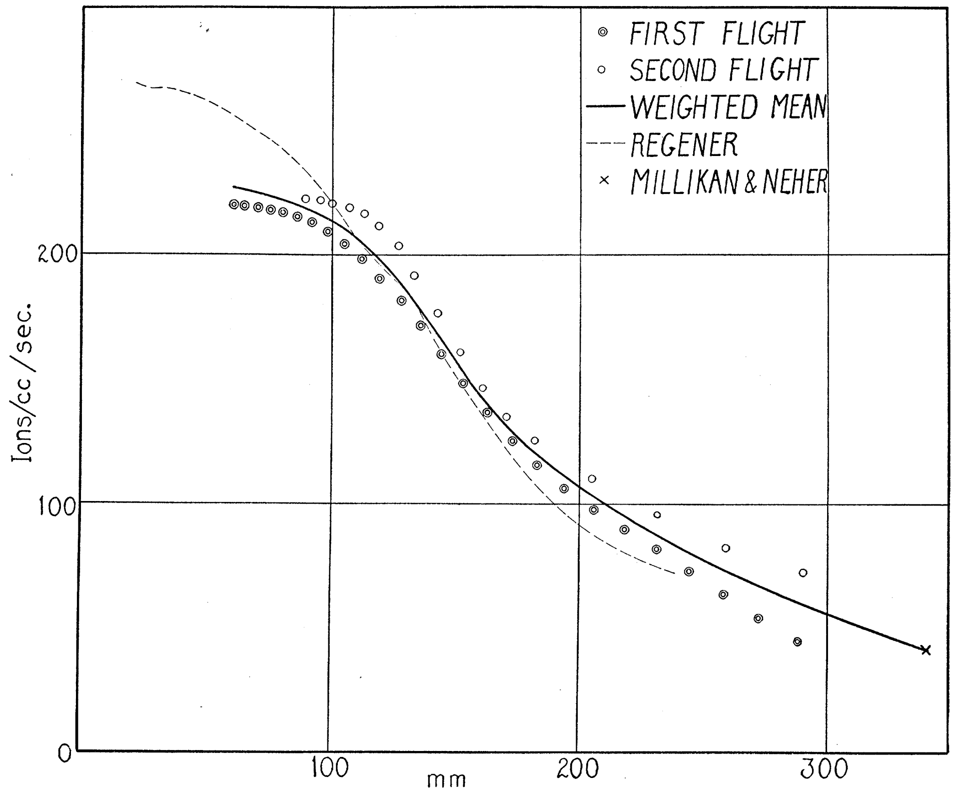

FIG. 3. Ionization per cc per sec. at one atmosphere as a function of barometric height. (Determined from smooth curve in Fig. 2.)

the series of points represented by the double circles in Fig. 3. The curve in Fig. 3 represented by the single circles is obtained precisely similarly from the photographic record of the other successful flight. The heavy curve is the best weighted mean of the two flights which we can make in the light of the whole of our knowledge as to the reliability and consistency of the two sets of readings. Over these curves of ours we have drawn a light dashed curve which represents the results obtained by Regener[2] in his single successful flight of the summer of 1932. The three flights agree well within the limits of uncertainty, which are, in fact, very much larger than the apparent spread of the points for a single flight would seem to indicate.

This matter is of so much importance that we have thought it worth while to devote a paragraph to it, for it is obvious that slopes obtained from such a smoothed out curve as we have considered above give an entirely erroneous idea of the consistency and dependability of the resulting ionizations since the very act of drawing a smooth curve assures the consistency of the differential curve obtained from it and washes out completely the irregularities in the readings. In order to make clear the actual uncertainties involved in the foregoing method of treatment, we have subjected both our own observations and Regener's to the following method of treatment, the results of which we will present in Fig. 4 for flight corresponding to Fig. 2. Instead of drawing a smoothed out curve through the points of Fig. 2, we have determined the ionization by taking the difference of the directly observed voltages of the fibers at intervals of 5 minutes and then dividing the observed voltage-change by the length of this interval. Since the readings plotted in Fig. 2 are taken at intervals of a minute and a quarter, the first point on curve 4 is then obtained from the first and fifth of observed points on curve 2, the second point on curve 3 from the second and sixth points on curve 2, etc. For the purpose of this plotting the first point on curve 2 which is so used is that marked with an arrow, since for points before this one the ionization is too small to be significantly measured with an instrument whose sensitivity was adjusted for the much larger rates existing at higher altitudes. The spread of the points shown in Fig. 4 will be seen to be quite wide enough to cover the discrepancies between the three curves in Fig. 2. Also, a similar treatment of the data given by Regener and also of the data corresponding to our own second flight, shows an even wider spread of points than that shown in Fig. 4, so that there can be no question about the essential agreement found in all the work done with the aid of balloons carrying up self-recording instruments in the summer of 1932.

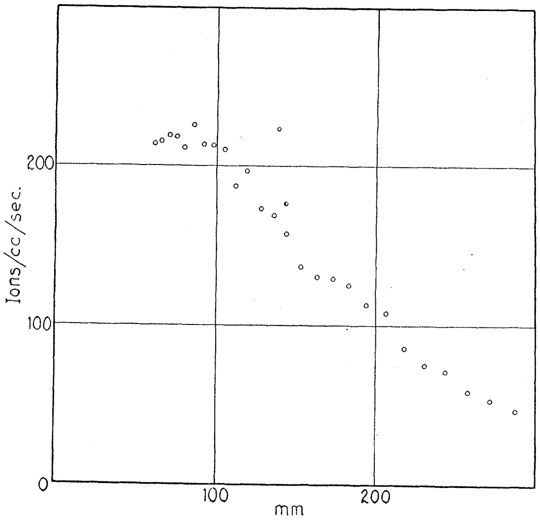

FIG. 4. Ionization per cc per sec. at one atmosphere as a function of barometric height. (Determined directly from points in Fig. 2.)

V. The Discussion of Results

These results are considerably higher at high altitudes than are those which we ourselves obtained in initiating this type of work in 1922.[1] Nevertheless, the only important conclusion which we drew from that first flight still holds (see below). The instruments which we then used were 1/25th as sensitive as those with which the present flights have been made, and we had not at that time succeeded in building instruments whose calibration curves showed an independence of temperature.

The present results are also not in good agreement as to absolute values with those obtained by Piccard[3] in his 1932 manned-balloon flight, for though the shape of his curve is quite like ours his ionization is in general about 40 percent higher than ours, a difference which presumably arises from a difference in the calibration of his capacities. Our own electroscopes were all carefully compared at two different intensities of ionization with the standard electroscope with which Millikan and Cameron[4] have done all their most accurate work. This procedure fixed accurately both the zeros and the capacities of the new electroscopes.

The most significant result which stands out in the curves obtained by all observers in the four high-altitude flights made in the summer of 1932 is that the ionization-altitude curve instead of rising exponentially clear to the top with the value of the apparent absorption coefficient at about 0.6 per meter of water—the value which all observers find between say 5 km and 9 km—shows a marked decrease in this apparent absorption coefficient between 9 km and the top. Indeed, in every one of the four flights, that by Regener, that by Piccard, and the two by ourselves, the ionization-altitude curve above about 12 km actually becomes concave downward instead of remaining strongly concave upward, as, in view of the Gold table, it should do if the coefficient of absorption remained constant. Indeed, the ionization at the highest point reached in these flights would have been twice that observed if the apparent coefficient remained at the value 0.6 per meter of water. Further, if the apparent coefficient is made up of a mixture of rays, as it undoubtedly is, it should have risen even faster. This behavior seems to us completely inconsistent with any theory which (1) makes the incoming rays consist primarily of charged particles of any speeds, or indeed (2) of photons entering the atmosphere in complete equilibrium with their

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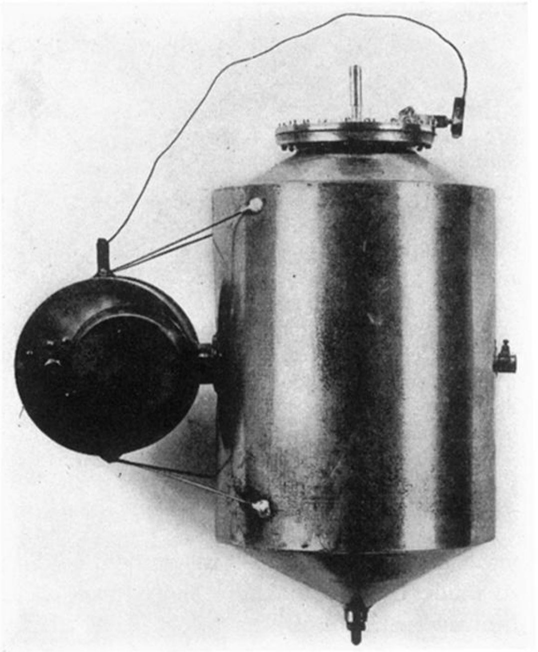
[3] A. Piccard and M. Cosyns, Comptes Rendus **195**, 604–606 (1932).

[4] R. A. Millikan and G. H. Cameron, Phys. Rev. **37**, 235–252 (1931).

secondaries. It also requires (3) that no rays of penetrating power the same as that of gamma-rays, or of rays intermediate in energy between gamma-rays and the least energetic cosmic rays, can enter the atmosphere in intensities comparable with those of the cosmic rays, for both our own flights and Regener's reach more than 92 percent of the way through the atmosphere and the remaining 8 percent (in Regener's case nearer 3 percent) which is the equivalent of 70 cm of water is insufficient to absorb even the gamma-rays of radium.

In spite of the agreement of all flights by all observers as to the trend of the curve toward a maximum as the top of the atmosphere is approached, caution must still be observed about asserting the correctness of this shape as a reference to Fig. 4 clearly shows. We ourselves regard the chief element of weakness in the accuracy of these curves to inhere not so much in the records of the electrometers as in those of the barographs, for at the very low pressures existing above say 17 km (7 cm of Hg) a small error in millimeters of mercury becomes a large percentage error, and the shape of the curve becomes here very sensitive to such errors. In spite of this caution the definite failure of all the curves to rise sharply as the top is approached to anything like the value required either by a constant absorption coefficient or one increasing in value near the top seems to us to justify the foregoing conclusions as the lack of equilibrium of the entering rays with their secondaries,—the most significant conclusion which we have at any time drawn from our very high altitude work.

The foregoing studies have been made possible, in the first instance, by the Carnegie Corporation of New York, to whom we make grateful acknowledgment for the necessary funds; in the second instance by the U. S. Weather Bureau whose Director, Charles F. Marvin, Assistant Director, Willis R. Gregg, Observer, T. A. Lawler, and other members of its Ellendale, N. D. staff, Meteorologist J. A. Riley and other members of its Dallas, Texas, staff, have rendered very important assistance both in making the flights and in supplying and reading the barographs; and in the third instance by Dr. H. Victor Neher, whose extraordinary skill in making the quartz systems of electroscopes is largely responsible for the excellent performance of these instruments, many of the details of whose mechanical features represent the work, as well as the design, of Mr. Julius Pearson of the Norman Bridge mechanical shop.



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