Fluctuations of Cosmic-Ray Ionization

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The cosmic-ray ionization in air contained at a pressure of 157.5 atmospheres in the 13.8 liter steel chamber surrounded by the 5.5–6 ft. water shield as previously described, was measured at four-hour intervals during a period of fifteen consecutive days, April 6–20, 1932. Controlled laboratory conditions and compensation features of the measuring equipment contributed to the constancy of measured ionization values. By means of recording instruments, simultaneous records of the atmospheric potential gradient, the atmospheric temperature, the barometric pressure, and the relative humidity were also secured. It was determined that a decrease of 2.1 percent in the cosmic-ray ionization corresponded to an increase of 1 cm in the barometric column. No correlation was established between the ionization and the atmospheric potential gradient, the atmospheric temperature, or the absolute humidity. There appeared to be no regular diurnal variation of the ionization either before or after the application of corrections for variations in barometric pressure. When deviations from the average of the ionization values corresponding to a particular time of day were regarded as statistical fluctuations, the average probable error so calculated was 0.21 percent. The greatest difference between the grand average and the average ionization for a particular time of day was only about one-third of one percent, less than twice the probable error. It seems very likely that the fluctuations observed were of a statistical nature.

If the intensity of the primary penetrating radiation varies in a regular manner with definite periodicities, the detection of these should provide valuable indications as to the origin of the radiation. If fluctuations of the radiation intensity could be correlated with variations in specific atmospheric conditions, further inferences regarding the origin and possible nature of the radiation might be expected to result. This situation has long been realized and numerous studies[1] of the fluctuations of the residual ionization in closed vessels were made even during the early stages of the investigation of the radiation. The conclusions of investigators were varied, there being no general agreement as to whether or not regular fluctuations not attributable to laboratory conditions actually existed, or as to their single or double diurnal periodicity if they did exist.

With progress in the study of the penetrating radiation it has been possible to improve the conditions of measurement of the ionization produced, to eliminate certain disturbing influences, and to estimate better to what extent actual fluctuations in the intensity of the penetrating radiation may have been detected. In spite of refinements of measurement, however, the most recent researches have led to conclusions nearly as much at variance among themselves as was the case in the early period of investigation, although fluctuations on a smaller scale are now being investigated. Hoffmann[2] has recently summarized very briefly the contents of 57 papers on the subject, published during the last decade by 19 investigators. These investigators differ widely in their conclusions regarding the existence, nature, and causes of the fluctuations, and the inferences to be deduced from them.

The following examples illustrate the lack of agreement still existing. Steinke[3] initially found the ionization intensity essentially constant, but later[4] detected a periodicity according to sidereal time even at sea level. Hess and Pforte[5] have noted a regular maximum at about noon and have concluded that an appreciable portion of the primary radiation originates in the sun. Millikan[6] observed a maximum in the early afternoon and attributed it to decreased shielding

[1] See references 11 to 18, incl., Phys. Rev. **27**, 552 (1926).

[2] G. Hoffmann, Phys. Zeits. **33**, 633 (1932).

[3] E. Steinke, Zeits. f. Physik **42**, 570 (1927).

[4] E. Steinke, Phys. Zeits. **30**, 767 (1929); Zeits. f. Physik **64**, 48 (1930).

[5] V. F. Hess, Nature **127**, 10 (1931); V. F. Hess and W. S. Pforte, Zeits. f. Physik **71**, 171 (1931).

[6] R. A. Millikan, Phys. Rev. **36**, 1595 (1930).

of the atmosphere not represented by alteration of the barometric pressure. Since then he has pointed out that the earlier measurements, particularly those at high altitudes, were affected by fluctuations of temperature of the ionization equipment, and concludes from more recent measurements[7] that there are no regular fluctuations exceeding $\frac{1}{3}$ percent. Although he appears rather in doubt as to the reality of these, he considers that if they do exist, his explanation is correct. Bennett, Stearns and Compton,[8] although at first considering no regular fluctuations existed, concluded after applying corrections for changes in barometric pressure and variations of battery e.m.f. with temperature, that at an altitude of 3900 m (and at a station distant less than 36 miles from the University of Colorado campus) there was a regular diurnal variation with an amplitude of the order of one percent, and with a maximum at about noon. They attributed the variations to an excess of penetrating radiation originating in space in the neighborhood of the sun. Gunn[9] has offered an explanation of these fluctuations in terms of diurnal fluctuations of the terrestrial magnetic field, assuming the radiation to be corpuscular in nature, in accordance with Compton's[10] conclusions as to variations with latitude. Messerschmidt[11] has concluded that the intensity of the primary penetrating radiation is constant, but has observed regular diurnal fluctuations of the ionization measured with only laterally shielded apparatus, and together with Hoffmann[12] has correlated them with the temperature of the atmosphere. He concludes that the observed variations are due to fluctuations in the intensity of subsidiary radiations generated in the neighborhood of the ionization chamber. Mott-Smith and Howell[13] have investigated the ionization due to penetrating radiation at altitudes up to 27,000 ft. They found "no significant decrease in intensity . . . during the night-time observations even at the highest altitudes."

In view of the continued lack of agreement regarding fluctuations of the penetrating radiation intensity as inferred from ionization measurements, it was decided to make a series of observations of the cosmic-ray ionization at regular intervals with very carefully controlled laboratory conditions. Because of their possible relation to the ionization values, simultaneous values of the barometric pressure, the outdoor atmospheric temperature, the humidity of the atmosphere, and the atmospheric vertical potential gradient were also recorded.

Procedure

Details regarding the equipment used in measuring the cosmic-ray ionization have been described by the senior author.[14] This same equipment, with the identical air used in a recent determination[15] of the ionization—temperature effect at high pressures, was employed during the present investigation. With its very thorough guard system and its compensation features eliminating effects of variations of electrometer sensitivity and of the P.D. impressed across the ionization chamber, this equipment, closely resembling that designed by Professor Swann,[16] was remarkably well adapted to an investigation extending over a considerable time interval.

Not only were fluctuations of ionization values due to several possible sources eliminated by the method of measurement, but controlled laboratory conditions eliminated other possible local causes of variations. With the indoor location and the $5\frac{1}{2}$–6 ft. water shield[14] about the ionization chamber, the gradual variation of the temperature of the chamber amounted to less than 1°C during the entire 15-day period of the measurements. The temperature effect having been investigated under these specific conditions, the temperature correction, although practically negligible, could be made. The gas content of the ionization chamber was found to remain con-

[7] R. A. Millikan, Phys. Rev. **39**, 391 (1932).

[8] R. D. Bennett, J. C. Stearns and A. H. Compton, Phys. Rev. **41**, 119 (1932).

[9] R. Gunn, Phys. Rev. **41**, 683 (1932).

[10] A. H. Compton, Phys. Rev. **41**, 111 (1932); Phys. Rev. **41**, 681 (1932).

[11] W. Messerschmidt, Zeits. f. Physik **78**, 668 (1932).

[12] G. Hoffmann, Zeits. f. Physik **69**, 703 (1931).

[13] Lewis M. Mott-Smith and Lynn G. Howell, paper presented at Atlantic City meeting, December, 1932. See Phys. Rev. **43**, 381 (1933).

[14] J. W. Broxon, Phys. Rev. **37**, 1320 (1931).

[15] J. W. Broxon, Phys. Rev. **42**, 321 (1932).

[16] W. F. G. Swann, J. Franklin Inst. **209**, 151 (1930).

stant not only during the period of this investigation, but for considerable intervals before and after. Even had some leakage occurred, previous work has shown that the effect would have been negligible at the pressure (157.5 atmospheres) employed. Former work had shown that at the pressures employed any possible contribution to the ionization by radioactivity of the chamber or its contents was negligible. Consequently, no fluctuations could arise on this account. Moreover, the heavy shield very effectively cut off possible gamma-radiations from external sources, thus eliminating the possibility of fluctuations due to variations in the emanation content of the atmosphere.

Six series of observations were made at regular intervals each day for fifteen consecutive days, April 6–20, 1932. One such series was begun at about 1:00 A.M. After the P.D. of about 875 volts had been impressed across the ionization chamber for at least 15 minutes, an ionization current observation was made in the usual manner, the interval during which charges were collected being about eight and one-half minutes in duration. Usually three, but occasionally two or four such observations were made in fairly rapid succession. Normally the series of observations was completed before 2:00 A.M. Such a series of observations has been considered to represent the ionization at 1:30 A.M. In this manner the value of the ionization current was determined at 1:30 A.M., 5:30 A.M., 9:30 A.M., 1:30 P.M., 5:30 P.M., and 9:30 P.M. each day. On only two occasions did considerable departures from this procedure inadvertently occur: the 1:30 P.M. readings on April 6 were actually made between 1:18 and 3:08 P.M., and the 1:30 P.M. readings on April 18, between 2:01 and 2:25 P.M.

All ionization measurements were made by the authors. As far as feasible, the observations made during a particular day, as well as those made at a particular time of day during the 15-day period, were distributed equally among the three observers.

The atmospheric potential gradient was obtained from equipment installed in a building on the University campus. This equipment yielded continuous photographic records, and a reduction factor was determined which gave absolute values of the potential[17] at a point one meter above the surface of the earth. The equipment was not in operation during about four of the fifteen days.

The relative humidity and the temperature of the atmosphere were obtained from recording instruments of the Department of Geology, located in an outdoor "shelter house." From these the absolute humidity was calculated. With the exception of a few readings, the atmospheric pressure was obtained from a Short and Mason (London) micro-barograph operated by the Mechanical Engineering Department. The barometric pressure values from 5:30 P.M., April 16 to 5:30 A.M., April 18, inclusive, were obtained from a less sensitive Geology Department barograph.

Observations

Certain significant relations among the data have been represented graphically. From the observed ionization values, "corrected" ionization values were obtained by reduction to the average ionization chamber temperature of 17.42°C by application of the minute temperature corrections in accordance with previous determinations, and by reduction to the average barometric pressure of 24.73 inches in accordance with the observed dependence upon barometric pressure to be discussed later. The observed ionization values are shown plotted against the barometric pressure in Fig. 1. In this diagram 1:30 A.M. readings are designated by 1A; 5:30 A.M. readings, by 5A; 1:30 P.M. readings, by 1P, etc., all of which refer to Mountain Standard Time. Both observed and corrected ionization values are plotted against the outdoor temperature in Fig. 2; corrected ionization values, against absolute humidity (as determined from the atmospheric temperature and the relative humidity) in Fig. 3; and corrected ionization values, against the atmospheric potential gradient in Fig. 4. It was considered that this treatment would make a possible relation between the ionization and any of the measured atmo-

[17] A study of the local atmospheric potential gradient determined more or less continuously over a period of more than a year has been made. It is hoped to have the results of this investigation ready for publication in the near future.

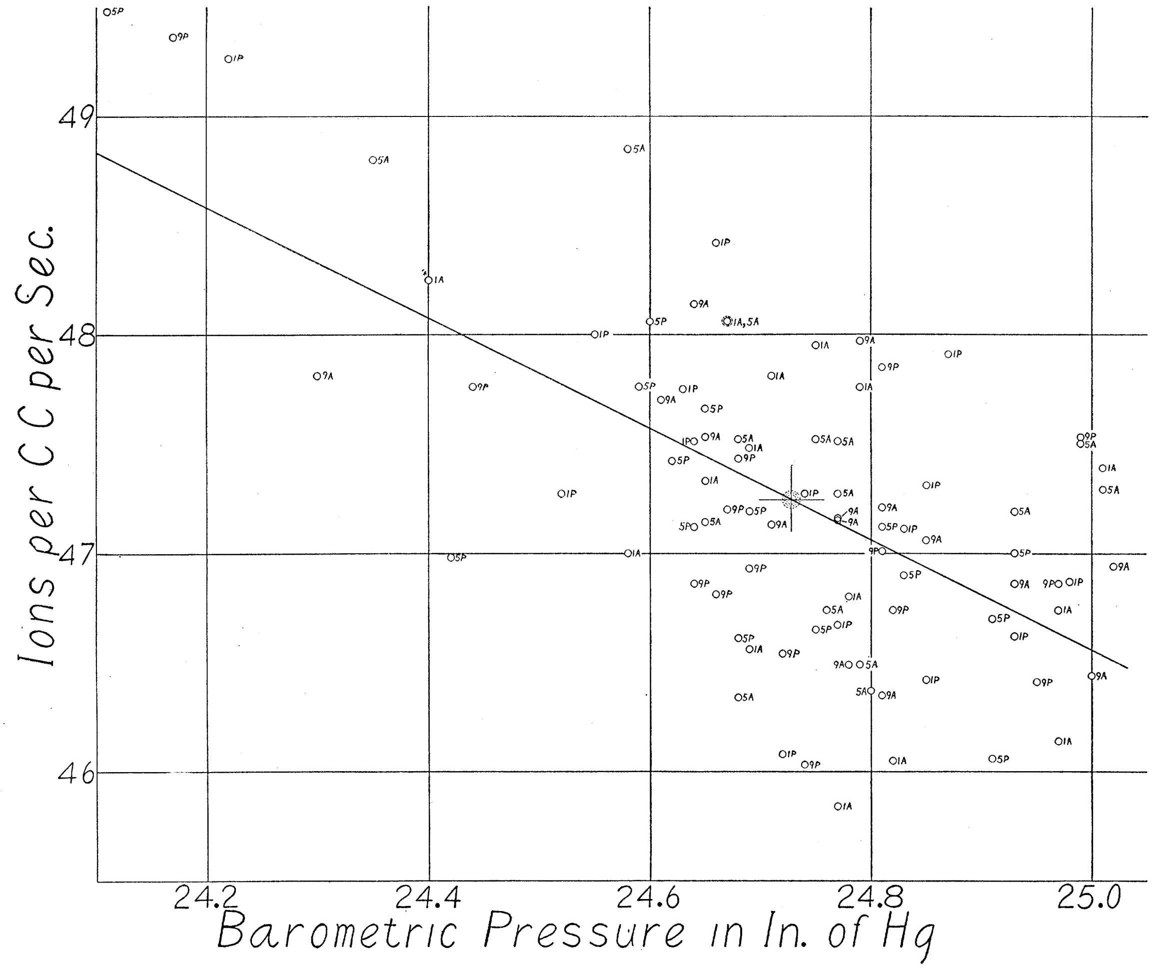

FIG. 1. Observed ionization plotted against barometric pressure.

spheric characteristics more readily apparent than would the construction of neighboring curves showing the variation of each of these with time in the usual manner. For a similar reason the ionization-time curves for the fifteen days are shown superimposed in Fig. 7, in preference to a continuous small-scale time curve extending over the entire period.

Discussion

An inspection of Fig. 1 discloses a definite dependence of the cosmic-ray ionization upon barometric pressure, an increase in atmospheric pressure resulting in general in decreased rate of production of ions. This is in general agreement with the results of various investigations made during the last several years, both in relation to the direct barometric effect at a given location, and to the variations of ionization with altitude. The rather wide distribution of points probably may be attributed to the short duration of the individual ionization current measurements, and to the small range of atmospheric pressures involved.

Assuming a linear relation between the ionization and the barometric pressure, the slope of the line was determined by the method of least squares to be $dI/dp = -2.526$ ions per cc per sec. per inch of mercury, using the 90 values plotted. With only the 1:30 A.M. values, then only the 5:30 A.M. values, etc., the slopes obtained were −2.295, −2.403, −1.985, −2.970, −3.043, −2.461, in the order given. Since each of these slopes corresponding to a particular time of day depended upon only 15 values, and because of the small range of the variations involved, the agreement among them is considered rather good. It is concluded, therefore, that the ionization-barometric pressure relation is direct rather than due to variations of each with the time of day. The average of the six 15-point slopes, equal to the 90-point slope and designating a decrease of 5.3 percent in ionization per inch (2.1 percent per cm) increase in the barometric column, is considered adequately to represent the ionization-barometric pressure relation under the actual conditions of measurement.

To have determined from the observations of other experimenters the barometric effect to be expected in the present instance would have been difficult because of the shielding arrangement, particularly the irregular shielding offered by the building in which the equipment was located. A rough comparison with the observations of others may be effected by reversing the procedure, however. The observed variation of 2.1 percent in ionization per cm change in the barometric column is apparently nearly coincident with that defined by the slope at sea level of the ionization-altitude curve obtained by Millikan and Cameron[18] with a 3 mm-wall steel ionization chamber surrounded by a 7.64 cm lead shield. Not only the barometric effect but also the absolute value of the ionization determined by them at sea level (27.90 ions/cc-sec. at 20 ft.) is nearly equal to the 26.7 ions/cc-sec. previously measured[14] in the present heavily shielded ionization chamber at its altitude of 5400 ft. and at the pressure of 30 atmospheres used by Millikan and Cameron. The variation with barometric pressure is also slightly greater than the 1.92 percent change in ionization per cm change in the barometric column observed by Messerschmidt[11] at Halle (altitude, 110 meters) with an ionization chamber surrounded on all sides by a 10 cm lead shield, the top of the shield having been removed.

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

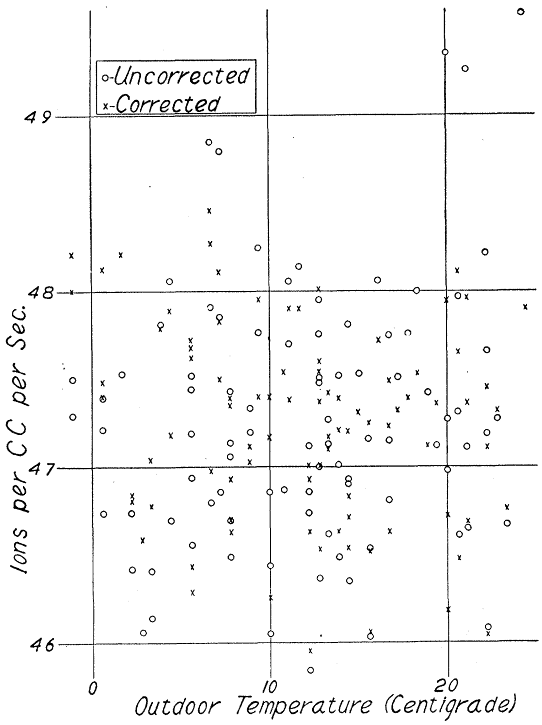

FIG. 2. Observed and corrected ionization values plotted against outdoor temperature.

Figs. 2, 3 and 4 do not show any decided relation between the cosmic-ray ionization and the atmospheric temperature, the absolute humidity, or the atmospheric potential gradient. In Fig. 2 are included two sets of points, one designating observed ionization values, and the other indicating the corresponding values after reduction to the average barometric pressure and ionization chamber temperature. All values shown in Figs. 3 and 4 have been so reduced.

On the basis of the observations of Hoffmann[12] and Messerschmidt[11] there might have been anticipated some relation between the ionization and the atmospheric temperature even though the ionization due only to the softer portion of the incident cosmic radiation varied with the temperature, since as shown above, in the present work the total shielding against radiation from outside the atmosphere was probably comparable to that offered in the case of Messerschmidt's measurements at Halle with the top of the lead shield removed. If their explanation is correct, however, and the dependence upon

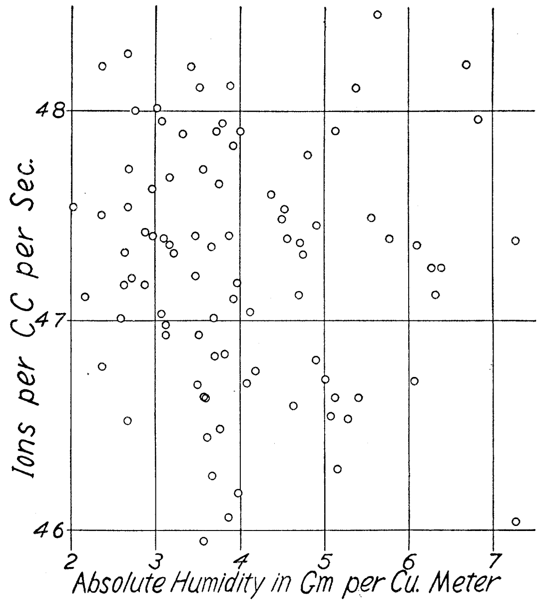

FIG. 3. Corrected ionization values plotted against absolute humidity.

atmospheric temperature occurs only through the agency of subsidiary radiations generated locally in materials of varying temperature, then in the present equipment with its very heavy constant-temperature shield, it is not surprising that no relation between the ionization and the outdoor temperature was observed.

In view of the dependence of the ionization upon the barometric pressure, it would seem there might also be a dependence upon the water content of the atmosphere. The absolute humidity is likely to be a rather local affair, however, and is probably not representative of the water vapor content of the atmosphere at considerably different altitudes. Consequently, a random distribution such as that shown in Fig. 3 was not wholly unexpected.

The likelihood of a dependence of the cosmic-ray ionization upon the atmospheric potential gradient would depend upon the nature of the radiation and perhaps upon the extent to which the gradient at the earth's surface is representative of electrical conditions at higher altitudes. According to Fig. 4 no specific relation of this type appears to have been disclosed by the present investigation. However, it is noticeable that the largest potential gradient values occur in connection with ionization values in the neighborhood of the mean. It is regrettable that more data of this variety were not secured.

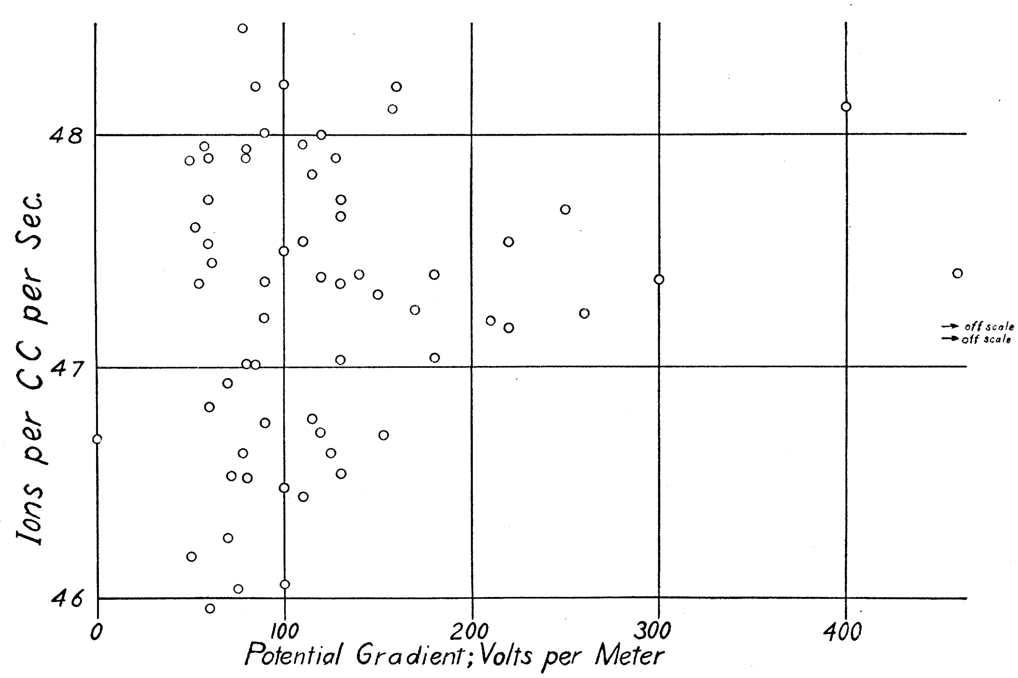

FIG. 4. Corrected ionization values plotted against atmospheric potential gradient.

It should be emphasized that only first order relations would be made apparent by the Figs. 1–4. Could the others have been maintained constant, the dependence of the ionization upon a particular one of the four additional variables investigated might have been made apparent. To enable one to test this possibility adequately a much larger number of observations should have been available, from which special classes could have been selected. However, a certain attempt in this direction was made. In Fig. 3 it will be noted that a large fraction of the observations correspond to absolute humidities in the limited range between 3 and 4 g per cu m. When the observations corresponding to these were selected, there was still no apparent relation between the ionization and either the atmospheric temperature or the potential gradient, with the humidity so restricted.

Fig. 5 illustrates the dependence of the ionization upon the time of day. The average of the ionization values at a particular time of day during the entire 15-day period is here shown as a function of the time. The averages of both observed and corrected values are designated by the two sets of circles. In an attempt to determine the significance of the curves obtained in this manner, the probable error of the corrected ionization values at a particular time of day was determined on the basis of the differences between these values and their average. In this manner the probable errors were found to be 0.12, 0.11, 0.08, 0.10, 0.08, 0.11 ions/cc-sec. for the 1:30 A.M., the 5:30 A.M., etc., readings in the order given. The average of these, 0.10, amounts to 0.21 percent of the grand average ionization (corrected) of 47.25 ions per cc per sec. Vertical lines have been drawn through the points designating average corrected ionization values, extending above and below the points a distance equal to the average probable error. It is apparent that three of these values differ from the grand average by less than the probable error, two by just a trifle more, and even the 5:30 A.M. average which departs most from the grand average differs from it by less than twice the probable error. The curve obtained without the application of the barometric pressure and ionization chamber temperature corrections is seen to lie rather nearer the average than the corrected ionization curve.

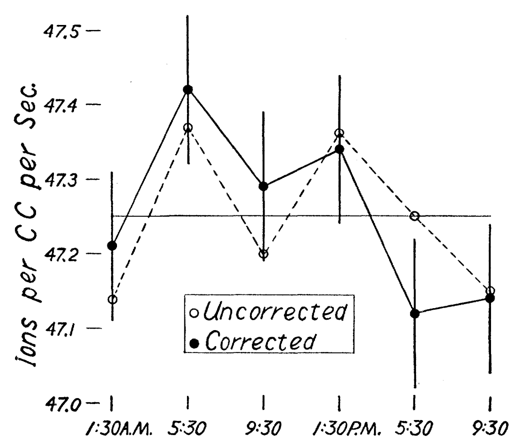

FIG. 5. Dependence of ionization upon the time of day.

It should be mentioned that in obtaining these curves the ionization at a particular time on a particular day was considered to be represented by the arithmetical mean of the individual eight-minute observations obtained during the corresponding interval as described above, irrespective of whether 2, 3, or 4 such individual observations were made. It was found that weighting these initial averages in proportion to the number of eight-minute observations from which they were obtained produced no appreciable alterations in the final corrected ionization-time curve of Fig. 5. Because of this fact, and because no other method of obtaining values representative of such small numbers of individual readings appeared justifiable, the unweighted averages have been employed throughout. Upon application of the Chauvenet criterion to the individual eight-minute observations, it was found that only one of these should be considered improbable. The average of the group of four in which it occurred satisfied the criterion. Consequently, none were rejected.

To test further the likelihood that fluctuations of the averages shown by Fig. 5 occurred by chance, the averages for the three successive five-day intervals were determined, and are shown in Fig. 6. It is seen that there are no general similarities among the three curves. Similarly, the averages of the ionization values determined at particular times of day by a particular observer were also calculated, and the

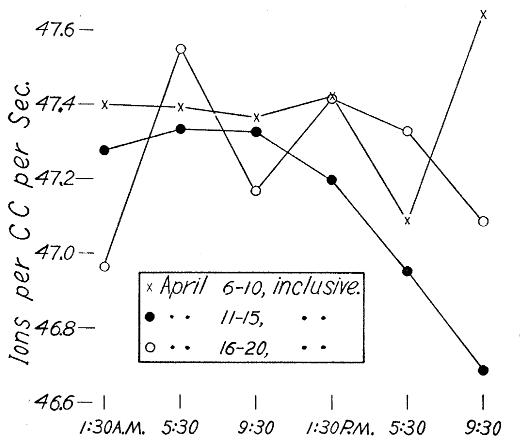

FIG. 6. Average ionizations for three successive five day intervals.

three ionization-time curves (not shown) corresponding to the three observers were found to have no apparent common characteristics. Incidentally, the respective probable error of each observer, calculated on the basis of deviations from the average of his own ionization values, was smaller than those recorded above.

The ionization-time curves for the individual days, shown superimposed in Fig. 7, constitute a rather complicated diagram, but they show that no particular type of diurnal variation is reproduced with any considerable regularity on several days.

In view of the above considerations and the further fact that the maximum of the average ionization values of Fig. 5 occurs at 5:30 A.M. whereas other experimenters who have detected a diurnal variation agree rather well on a maximum at about noon or in the early afternoon, it is concluded that the fluctuations observed were probably statistical in nature and that no regular diurnal variation of the cosmic-ray ionization capable of being detected with the equipment used can be considered to have existed under the conditions of measurement. Not only was no regular diurnal variation observed, but there appeared to be no appreciable dependence of the ionization upon the atmospheric potential gradient, the outdoor temperature, or the absolute humidity, while the dependence upon barometric pressure was in good accord with that observed by others.

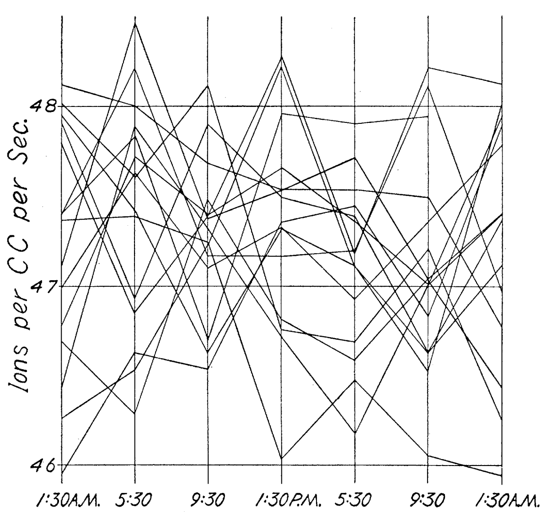

FIG. 7. Ionization-time curves for individual days.

Relative to the "sudden increases" or "bursts" of ionization occasionally observed and previously[15] mentioned, it is perhaps worth remarking that seven instances of these appear to have occurred during the 41.1 hours occupied by the 291 readings distributed over the 15-day interval. (Of these, five were detected by one observer, and only one by each of the others.) On the other hand, during a nearly continuous series of measurements which occupied 20.4 hours of the interval from 10:00 A.M. April 29 to 10:00 A.M. April 30, only one such occurrence was observed. (About nine minutes of each hour were taken for resetting apparatus.) The average rate of occurrence of one "burst" in six hours in the first interval and one in twenty hours in the second instance can have only slight significance in view of the short intervals involved. However, the observations do give some indication as to the order of magnitude of their frequency, in surprising agreement with the very much more reliable determinations of Steinke and Schindler[19] and of Messerschmidt[11] by continuous observations extending over vastly longer time intervals.

The writers gratefully acknowledge their indebtedness to Professor J. A. Hunter of the Mechanical Engineering Department and Professor H. A. Hoffmeister of the Geology Department for supplying the charts mentioned above.

[19] E. Steinke and H. Schindler, Zeits. f. Physik **75**, 115 (1932).