# Airplane Cosmic-Ray Intensity Measurements

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With the help of the United States Air Corps and particularly of Captain A. W. Stevens of Wright Field the following cosmic-ray measurements have been made: (1) day-time intensity curve from 1000 to 27,000 feet, (2) night-time intensity curve up to 27,000 feet, (3) absorption in a few cm of lead at various elevations, (4) intensity measurement at 27,000 feet during the solar eclipse of August 31, 1932. A change with altitude in the character of the "uebergangs" effect for cosmic-rays passing from air into lead is shown from the absorption-in-lead curves. Comparison with the earlier high altitude measurements, notably those of Kolhoerster, indicates that the present curve is steeper at 27,000 feet so that the marked decrease in the absorption coefficient above 20,000 feet is not observed. No significant decrease in intensity was observed during the night-time observation even at the highest altitudes. In accord with all previous eclipse measurements, no change in intensity was observed during the solar eclipse. The construction and technique of operation of the high-pressure Wulf-type electroscope used in these measurements are described.

## INTRODUCTION

ALTHOUGH accurate measurements of cosmic-ray intensities at altitudes up to 14,000 feet have been made on the ground and in lakes, practically no new observations in the higher region up to 30,000 feet have been made since the 1913–1914 balloon flights of Kolhoerster.[1] He found a very sharp maximum in the values of absorption coefficient as calculated from his intensity curve at a height of about 21,000 feet, which seemed difficult to account for. Under the circumstances, with the lack of new data immediately above 14,000 feet, it seemed desirable to make measurements of cosmic-ray intensities in this region. For obtaining such measurements, the airplane method[2] seemed the best suited. High altitudes can be attained easily and in a short time. Also the altitude of the airplane can be maintained constant while the measurement of the cosmic-ray intensity at any particular altitude is being made. This of course offers a considerable advantage over the free balloon method in which measurements are averaged over a range of altitudes. The weight of the apparatus is not limited to a small value in an airplane, and thus rugged and fairly sensitive instruments can be used for determining both the cosmic-ray intensity and the altitude. Since the work to be presented was begun, Piccard[3] has made intensity measurements up to an altitude of about 50,000 feet in a balloon. Also, Regener[4] has published results obtained with a recording electroscope carried by a pair of small balloons to an altitude corresponding to an atmospheric pressure of about twenty-two millimeters of mercury. His cosmic-ray intensity curve begins approximately where Kolhoerster's ends. Although his results are necessarily rough, they show the important result that the intensity of the cosmic rays increases to extremely high altitudes where the increase with altitude then becomes very small.

## EXPERIMENTAL PROCEDURE

A Wulf-type electroscope similar to those used by Millikan[5] has been found to be quite suited for making the measurements. This electroscope has a volume of 500 cc, made small in order that comparatively light lead shields could be provided. It contains argon at a pressure of 75 atmospheres inside a steel case of one-half inch thickness. The high pressure was used to increase

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[1] W. Kolhoerster, Phys. Zeits. **14**, 1153 (1913).

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

[3] E. Regener, Nature **130**, 364 (1932).

[4] K. Buettner, Zeits. f. Geophys. **2**, 254 (1926).

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

the sensitivity (the argon gas[6] was used for the same reason) and to decrease the "zero" of the electroscope, the zero being the rate of discharge due to the radioactivity of the electroscope itself. The zero was also reduced by eliminating some of the $\alpha$-ray activity of the inside walls with a covering of a film of electrolytic copper.

The zero was determined by measuring the rate of discharge of the electroscope, both unshielded and shielded with lead, in a salt mine 700 feet underground at Grand Saline, Texas. Here the electroscope was shielded from the cosmic rays by the thick layer of earth above. Also, the surrounding salt was found to be surprisingly free from radioactive materials so that it was possible to make a fairly reliable measurement of the zero. Incidentally, in these salt mine measurements it was found that the lead shields are not appreciably radioactive.

Inside the electroscope, the platinized quartz fibers, whose deflection is read, are insulated with quartz and mounted in an invar frame to avoid temperature effects. Tests in the laboratory showed the rate of discharge to be surprisingly free from temperature effect, probably due to accidentally compensating changes of the volt sensitivity with temperature and of the effective ionization. However, it was found that temperature gradients along the steel case set up convection currents of the argon which moved the fibers in an erratic fashion. To avoid sudden changes in temperature, the electroscope was placed inside an insulating wooden case. This wooden case was suspended in the airplane by means of laboratory rubber tubing in order to reduce sufficiently mechanical vibrations transmitted to the fibers.

From discharge curves, a range of about ten divisions on the scale of the reading microscope was found over which the change in deflection of the fibers is linear with time. In practice, thus, the discharge curve is obtained by making a number of observations of the deflection over this range simultaneously with the corresponding values of the time. Sample discharge curves are shown in Fig. 1. It can be seen that the discharge curves taken in the air compare in accuracy quite favorably with those taken on the ground. The various rates of discharge were standardized by comparing the values with the rate of discharge caused by a radium standard of about 0.01 mg which could be clamped at a fixed distance of about 12 cm from the center of the electroscope. When not in use it was removed to a distance of at least 150 cm from the electroscope and placed inside a lead shield 5 cm thick. About half the measurements were made with visual observations of the fibers; the rest, with a simple photographic arrangement which recorded the position of the fibers on a photographic film. Both methods yielded about the same accuracy.

It was of course necessary to know the atmospheric pressure at the altitude at which the measurement was being made with considerable precision on account of the rapid increase in intensity with altitude. (A one percent change in pressure changes the intensity about 2.5 percent at 20,000 feet). After obtaining some widely discordant results with inferior instruments, ordinary aneroid altimeters, recording barographs, etc., a so-called Bureau of Standards-type sensitive altimeter was obtained. In this instrument one of the important sources of error in ordinary aneroids, namely the shift of the zero due to plastic deformation of the soft metal bellows is avoided by use of a bellows made of springy material. It was calibrated with a mercury barometer and also tested for temperature compensation. The errors were not greater than 0.5 percent and it could be read to twenty feet (about one part in a thousand in pressure) so that the atmospheric pressure can be assumed to be known to 0.5 percent.

Some troublesome factors in making measurements in an airplane are: Vibrations set up by the motor, varying tilts of the plane from the level position and the presence of radioactive instrument dials. The disadvantages of vibrations and tilts can be overcome largely by a properly designed suspension and measuring electroscope. It was found necessary to remove the luminous dials from the instrument board. Even with the radium paint removed a small and almost negligible correction for the radioactivity of the plane was made by taking the difference of the rates of discharge of the electroscope in the plane

[6] A. H. Compton and J. J. Hopfield, Phys. Rev. **41**, 539 (1932).

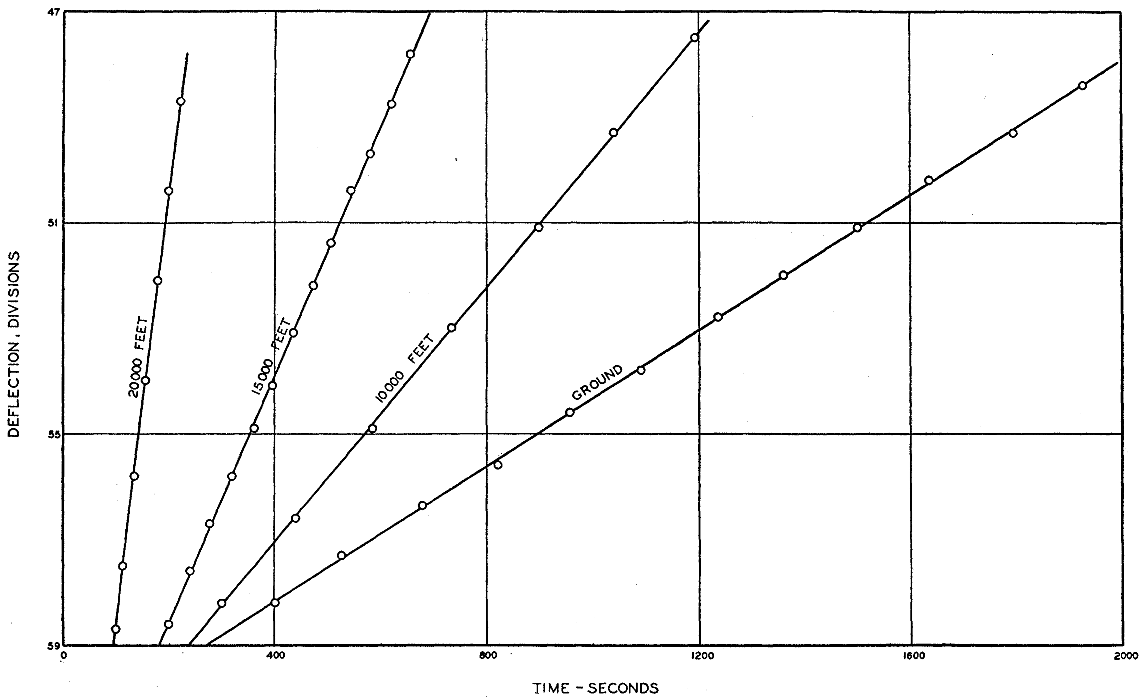


FIG. 1. Sample discharge curves.

on the ground and at the same point with the plane removed.

## EXPERIMENTAL RESULTS

The following cosmic-ray measurements have been made: The cosmic-ray intensity curve from 1000 to about 26,000 feet with various thicknesses of lead shielding, taken in the daytime (between 10 A.M. and 2 P.M.: also several points taken around midnight to test for a possible large diurnal effect at very high altitudes. Finally, we had the opportunity of taking a set of readings at an elevation of about 24,000 feet during the recent solar eclipse (that of August 31, 1932).

The altitude curves were taken in the vicinity of Dayton, Ohio, geomagnetic latitude 51°N except the two low-altitude points at 1000 and 3000 feet which were determined enroute from Boston to Washington at an average geomagnetic latitude about the same as that of Dayton. The eclipse observation was made near Biddeford, Maine, at a magnetic latitude of about 54°N.

All the determinations taken with the unshielded electroscope are shown in the curves of Fig. 2 where the abscissas are the atmospheric pressure in cm of mercury and the ordinates the rate of discharge in divisions per second. Values of the intensity taken from a carefully drawn smooth curve through the observed points are presented in Table I. The rate of discharge has

TABLE I. *Cosmic-ray intensities taken from the smooth curve of Fig. 2.*

Values in the third column are determined by using Millikan's value of 2.63 ions/cc per sec. at 74.0 cm pressure.

| Barometric pressure, cm Hg | Intensity, division/sec. $\times 10^3$ | Intensity, ions/cc/sec. |
|---|---|---|
| 75 | 3.76 | 2.53 |
| 70 | 4.53 | 3.15 |
| 65 | 5.60 | 3.77 |
| 60 | 7.12 | 4.79 |
| 55 | 9.42 | 6.34 |
| 50 | 12.8 | 8.62 |
| 45 | 18.4 | 12.4 |
| 40 | 27.8 | 18.7 |
| 35 | 42.9 | 28.8 |
| 30 | 66.3 | 44.6 |
| 25 | 104. | 70.1 |

not been converted into absolute units, such as ions per cc per second in air under standard conditions, on account of the difficulty in making the conversion. As far as the shape of the curve,

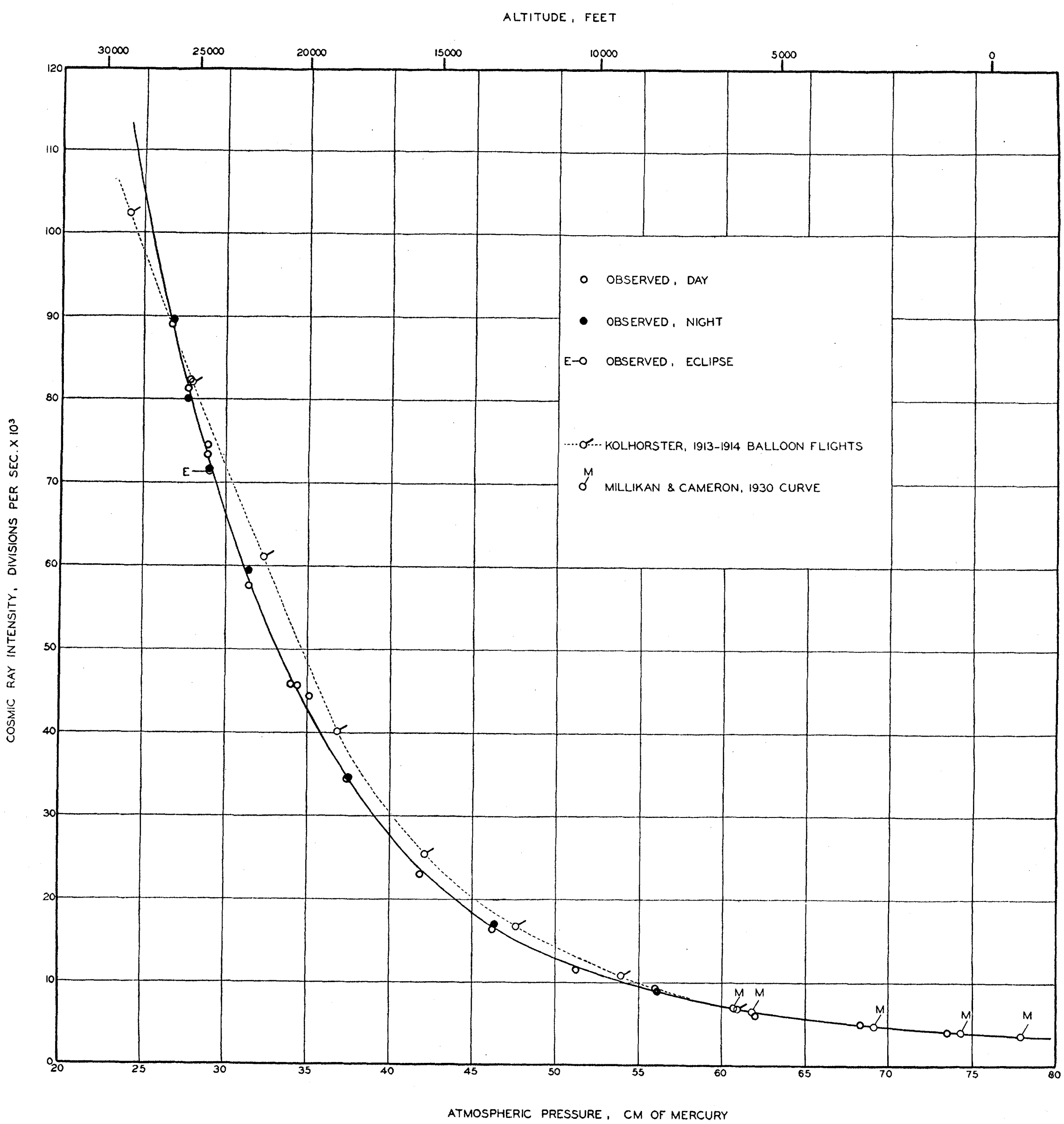


FIG. 2. Observed cosmic-ray intensities at different altitudes.

diurnal changes, etc., are concerned, knowledge of only the rate of discharge is sufficient. However, in order to render the present observations at least roughly comparable with those of other observers we have converted the rate of discharge into ions per cc per second in air by using the value 2.63 ions/cc/second obtained by Millikan[7] at 74.0 cm pressure at Pasadena. These data form column three of the table. From the observed quantities have been subtracted the zero of the electroscope, amounting to 0.00035 divisions per second and the rate of discharge due to the radioactivity of the airplane, 0.00012 divisions per second.

A word must be said about the observations at 1000 and 3000 feet. It was expected that, especially at 1000 feet, an appreciable amount of ground radiation would be picked up. Accordingly these two points were taken over the ocean several miles from shore where the local radiation must be very small.

Measurements were also made with various thicknesses of lead shielding the electroscope. These are shown in Fig. 3, where the unshielded curve has been repeated to allow comparison with the others. Curve one represents the rate of discharge of the unshielded electroscope; curve two, the electroscope shielded with 1.25 cm of lead; curve three, the electroscope shielded with 2.5 cm of lead; and curve four, the electroscope shielded with 4.7 cm of lead. From these curves and the data of Table II showing the fractions of the cosmic-ray intensities absorbed by the different thicknesses of lead at various levels, it is evident that the absorption in lead does not follow an exponential law but represents the type of absorption resulting from the "uebergangs" effect.[8]

TABLE II. *Absorption by the shields.*

$I_1$ is the intensity with 1.25 cm lead shield, $I_2$ with 2.5 cm shield, and $I_3$ with 4.7 cm shield.

| Barometric pressure, cm Hg | $\frac{I_0-I_1}{I_0}$ | $\frac{I_0-I_2}{I_0}$ | $\frac{I_0-I_3}{I_0}$ |
|---|---|---|---|
| 65 | 0.15 | 0.31 | —— |
| 60 | 0.17 | 0.33 | 0.45 |
| 55 | 0.17 | 0.35 | 0.49 |
| 50 | 0.15 | 0.36 | 0.51 |
| 45 | 0.14 | 0.38 | 0.54 |
| 40 | 0.13 | 0.40 | —— |
| 35 | 0.12 | 0.41 | —— |
| 30 | 0.11 | 0.40 | —— |

It will be noted that the character of this effect changes with altitude. According to Johnson's[9] interpretation this means that the absorption coefficients of the secondary radiation produced in air and in lead and the "production coefficient" of the secondary radiation are undergoing a change. In order to determine the nature of this change we use the relation,

$$I/I_0=[e^{-\mu_1 x}+Ae^{-\nu x}(1-e^{-\mu_2 x})].$$

Here $I/I_0$, the fractional reduction in ionization produced by a shield of $x$ cm of lead, is the sum of two terms, the first representing the decay in the lead of the secondary radiation accompanying the primary radiation in air, the second giving the growth of the secondary radiation produced in the lead. The factor $e^{-\nu x}$ takes into account the absorption of the primary radiation in passing through the shields. The quantity $A$ determines the relative amounts of ionization produced by the secondary particles from the two media. With this relation, the quantities $\mu_1$, $\mu_2$ and $A$ have been computed from the observed values of the ionization at the altitudes corresponding to atmospheric pressures of 60 and 45 cm of mercury. (The three experimental values of $I/I_0$ suffice to determine $\mu_1$, $\mu_2$ and $A$ since the value of $e^{-\nu x}$ can be computed by using the air absorption coefficient at the elevation in question.) The computed values of these constants are shown in Table III

TABLE III. *Uebergangs-effect constants.*

| Barometric pressure, cm Hg | $\mu_1$ | $\mu_2$ | $A$ |
|---|---|---|---|
| 76 | 0.50 | 0.98 | 0.65 |
| 60 | 0.70 | 1.2 | 0.54 |
| 45 | 0.66 | 2. | 0.45 |

where the values at 76 cm have been taken from Johnson's paper.[9] The absorption curves calculated with these constants are shown in Fig. 4 together with the observed points. The observed ionizations at 30 cm are also shown, the dotted curve being sketched in to show the probable be-

[7] R. A. Millikan, Phys. Rev. **39**, 397 (1932).

[8] Heinz Schindler, Zeits. f. Physik **72**, 625 (1931).

[9] Thomas H. Johnson, Phys. Rev. **41**, 545 (1932).

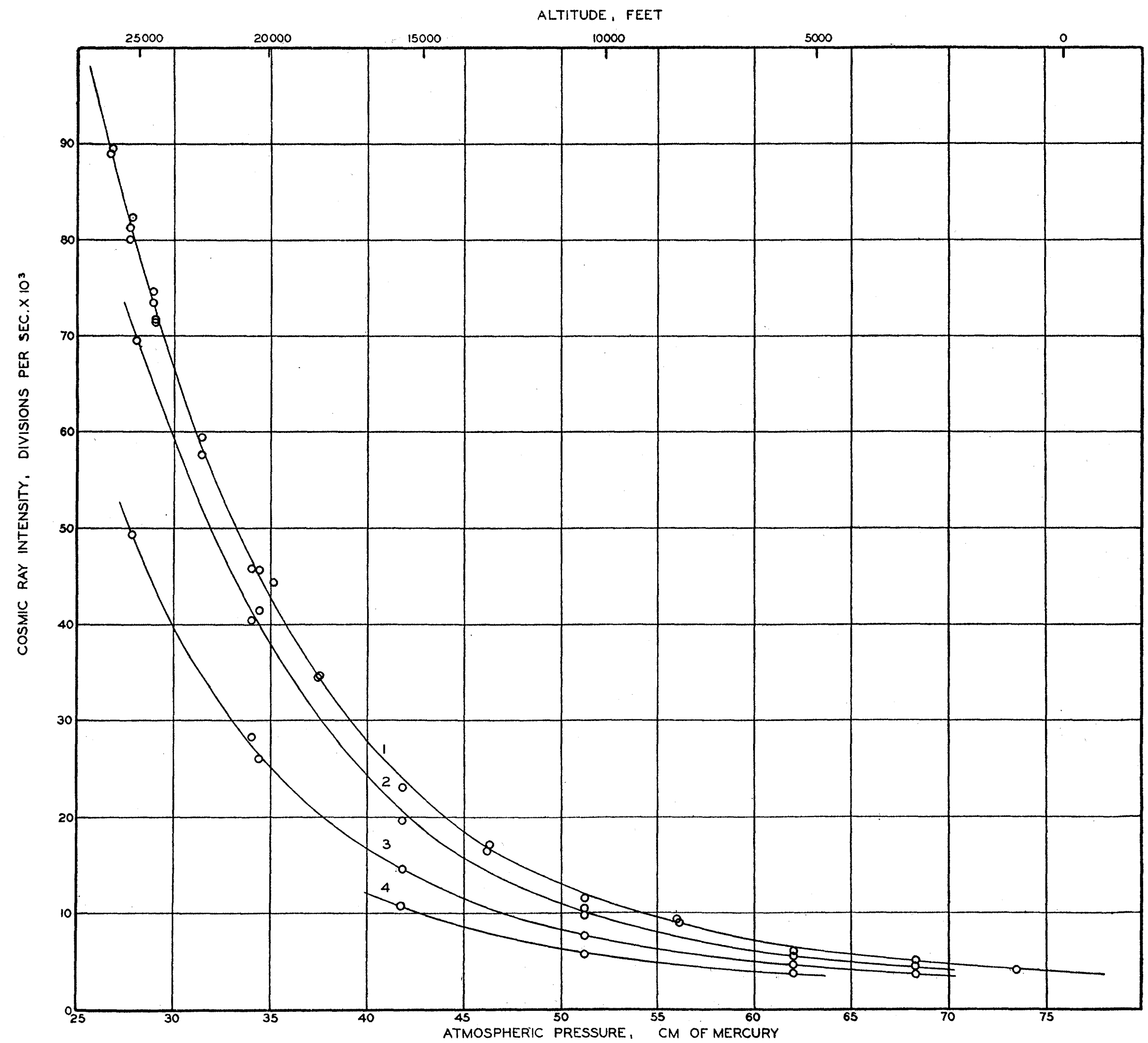


FIG. 3. Effect of various thicknesses of lead shielding on the cosmic-ray ionization at different altitudes.

havior of the curve at this elevation. (Here the computation of the constants was not possible since the datum at 4.7 cm shielding is lacking.) These calculations are necessarily very rough, not only on account of the limited amount of data but also since the uebergangs effect in the walls of the electroscope has not been taken into account. They do, however, seem to indicate that the penetrating power of the secondary radiation, particularly that produced in lead, decreases with increasing altitude. They also show that the amount of secondary radiation in lead becomes less relative to that in air. One conclusion which may be drawn from these observations is that the ionization at different altitudes in any electroscope except one with extremely thin walls will not be proportional to the intensity of the radiation, though the deviation from proportionality does not appear to be very large with any reasonable wall thickness.

Concerning the night observations, it was felt that there might be an appreciable diurnal effect at 25,000 feet since there is some evidence for the existence of a small diurnal effect at low elevations. It will be noted that any diurnal change existing is less than the errors of observation.

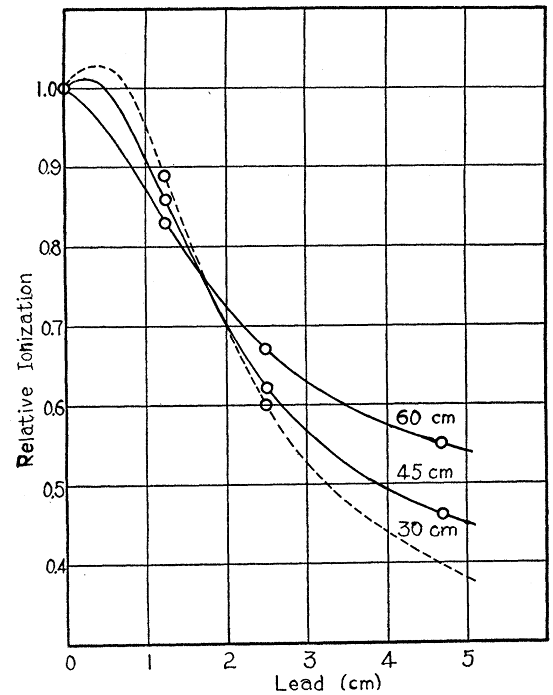


FIG. 4. Calculated absorption curves in lead at different altitudes.

These are estimated to be about three percent.

With regard to the eclipse measurement, since Captain Stevens was to be flying at a high altitude in the path of totality, it was thought worth while again to test whether there is a solar component of the cosmic radiation (coming in rectilinear paths from the sun). Eight discharges of fibers were recorded, just before, during, and just after totality, during which time at least 80 percent of the disk of the sun was obscured by the moon. The result is to be compared with the other points obtained at about the same elevation. It will be noted that no effect was found, again outside of a probable uncertainty of about 3 percent. This is in accord with the result of eclipse measurements made at lower altitudes by other observers, none of whom have found a diminution in intensity during a solar eclipse.

We have compared our results with Kolhoerster's balloon flight data recently recomputed by him and Tuwim (the dotted curve of Fig. 2). There is rough agreement between the two curves, probably within the observational errors of the two sets of observations, for Kolhoerster gives his accuracy as about 10 percent. The difference in the slopes at the top, however, causes a large difference in the computed values of the absorption coefficients. Kolhoerster and Tuwim[10] computed the average absorption coefficient over one kilometer stretches of Kolhoerster's curve from 2 to 9 kilometers and found a sharp maximum at 6 kilometers. We have computed absorption coefficients[11] for our curve in the same manner, and with the same intervals. The two sets of values are compared in the curves of Fig. 5

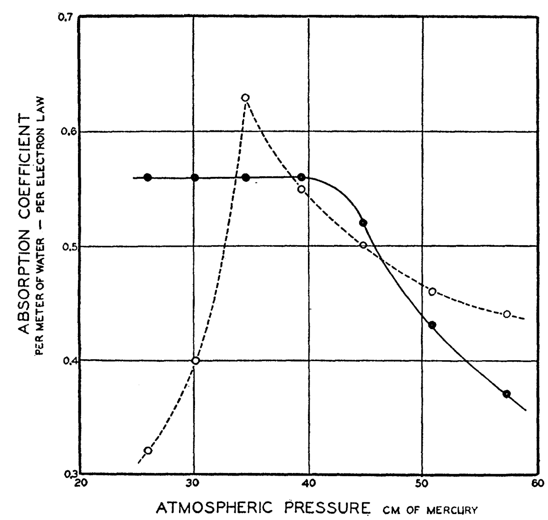


FIG. 5. Variation of absorption coefficients with altitude.

where the dotted curve represents Kolhoerster's values. We find, instead of a sharp maximum, that the absorption coefficient reaches a constant value of 0.56 per meter of water above 17,000 feet. This behavior seems to us to be the more reasonable since it is difficult to see how to account for such a sudden change. It must however be borne in mind that absorption coefficients computed in this manner are purely formal quantities since they are derived by assuming that the elementary rays are exponentially absorbed, a very questionable procedure on account of the complex nature of the radiation.

[10] W. Kolhoerster, Naturwiss. **19**, 574 (1931).

[11] The coefficients have been computed under the assumption that the absorption is proportional to the number of extranuclear electrons per cc.

### Acknowledgments

This work would not have been possible without the cooperation of Captain Albert W. Stevens of the United States Air Corps, who was responsible for making the arrangements for the flights and who assisted in making many of the observations. We are also indebted to the authorities at Wright Field for their cooperation in the project and to Lieutenants Phillips and MacCallister and to Captain Moffat, who served as pilots. We wish to thank Major T. W. Blackburn of the Texas National Guard and his men for the opportunity of making several preliminary flights, and also Mr. J. E. Hanes of the Morton Salt Company for permission to make the measurements in the salt-mine.