Present Status of Solar and Sidereal Time Variation of Cosmic Rays

E. O. WOLLAN
University of Chicago and Chicago Tumor Institute, Chicago, Illinois

MOST of the investigations and speculations in connection with cosmic rays are concerned with an attempt to answer the following questions: (1) What is the nature of the radiation? (2) From where do the rays come?

If we consider "cosmic" rays as embracing all the radiations (exclusive of local radioactivity) which we record in our instruments at sea level, a great deal has been learned about their nature during the last decade. We have learned that the radiation consists primarily of charged particles, we know something about the types of particles, about their energy distribution, their absorbability in matter and how these particles interchange energy with the matter through which they pass; but we have also learned that most of the radiation which our instruments record at sea level consists of secondaries which are excited at high altitudes by the primary radiation which we postulate to be of cosmic origin. Regarding this primary radiation we are not so well informed. The discovery of the latitude effect has shown us that most of the primary radiation consists of charged particles. Balloon experiments at high altitudes when taken together with theoretical knowledge about the effects of the earth's magnetic field have given some information about the intensity, the energy distribution and the sign of the charge of the incoming cosmic rays. The more information we obtain regarding the nature of the primary cosmic rays the more able will we be to make intelligent speculations regarding the question as to the origin of the cosmic rays.

One type of experiment from which it has been hoped that information regarding the origin of the cosmic rays might be obtainable is that involving measurements of the periodic time variation of their intensity. There are several kinds of variations which might be expected, some of which have been definitely proved to exist. Periods of one solar day, twenty-seven days (rotation of the sun) and one year might be expected to arise from the changes which our solar system undergoes during these periods. A diurnal variation of intensity according to sidereal time, if present, might have a bearing on the remote origin of the radiation in the universe.

In this paper the experimental side of the problem associated with measurements of the variations of intensity and the analysis of the data for the solar and sidereal diurnal periods will be considered. Since these periodic variations are not greater than a few tenths of a percent, they become difficult to detect in the presence of fluctuations in intensity due to a number of other causes.

There are the purely random statistical fluctuations which arise from the fact that a finite number of cosmic-ray particles traverse the apparatus per unit time. The relative effect of these fluctuations becomes less as the time of observation is increased. Phenomena such as bursts which occur infrequently and cause much larger changes may also be disturbing factors when systematic variations of the intensity are sought.

Changes of intensity due to differences in the barometric pressure which cause alterations in

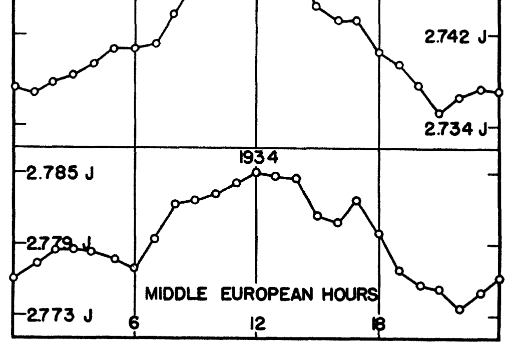


FIG. 1. Diurnal variation of ionization for 1932, 1933, and 1934, with "Vollpanzer" (10 cm of lead on all sides).

the absorbing layer through which the rays must pass amount to about two percent for each cm change of pressure. One might at first think that the correction for this effect should be as accurate as the readings of the barometer. Since, however, the atmosphere is not static, one can realize that the readings of a barometer at sea level are not always a true measure of the mass of air above the apparatus. Another effect associated with changes of barometric pressure which has been brought to light in the past year is connected with the decay of the mesotrons. When the atmosphere is expanded the place of production and decay of the mesotrons is altered, with corresponding changes in intensity.

The fact, which has been known for several years, that the temperature of the outside air has an effect on the observed cosmic-ray intensity has also been accounted for in a similar way on the basis of the production and decay of mesotrons and hence also introduces disturbing fluctuations.

Another type of fluctuation is that associated with magnetic storms.

In spite of all the factors (of which the above-mentioned are only a part) which cause more or less random fluctuations of intensity, it is found that when these are systematically corrected for, and observations are extended over a period of a year or more, some types of periodic variations with amplitudes of a tenth of a percent or less can be observed. The smaller these variations are the more important it is to apply proper statistical methods in determining the size and also the probable reality of such variations.

The Solar Diurnal Variation of Intensity

The variation of cosmic-ray intensity with a period of one solar day has been observed by many investigators and the results accord in giving a maximum of intensity around noon with an amplitude of about 0.2 percent.

The measurements of Hess and Graziadei[1] on the Hafelekar (2300 m) during the years 1932, 1933, and 1934 taken with a Steinke type of apparatus under a shield of 10 cm of lead are shown in Fig. 1. The similarity of the curves for the three years shows beyond doubt the existence of a diurnal variation with a maximum at about noon and a minimum at night. The difference between the noon and night values amounts to 0.4 percent.

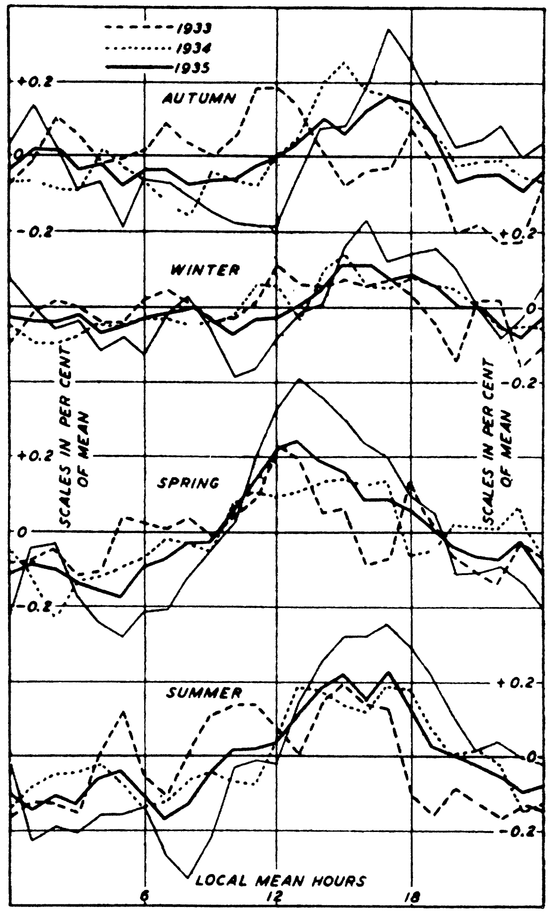


Fig. 2. Seasonal diurnal variation cosmic-radiation intensity, Vollpanzer, Capetown.

Results obtained by Schonland and his collaborators[2] for 1933, 1934, and 1935 in the Southern Hemisphere with the same type equipment are shown in Fig. 2. The data have been plotted separately for each season of the year, the average amplitude being again about 0.2 percent but the time of maximum falls in this case at about 3 P.M. These data also show a seasonal variation of the amplitude with a maximum value in the summer and a minimum in the winter. The data obtained by Compton and Turner[3] over a period of a year on the Pacific

[1] V. F. Hess and H. T. Graziadei, Terr. Mag. and Atmos. Elec. **41**, 9 (1936).

[2] Schonland, Delatizky and Gaskell, Terr. Mag. and Atmos. Elec. **42**, 137 (1937).

[3] A. H. Compton and Turner, Phys. Rev. **52**, 799 (1937).

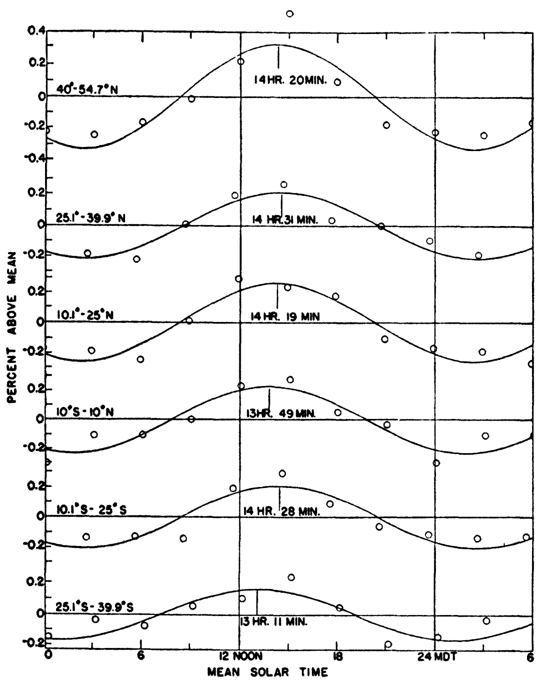


FIG. 3. Diurnal variation. Data of Compton and Turner, reference 3, analyzed by Thompson, reference 4.

Ocean between Vancouver and Sydney have been analyzed by Thompson[4] and the results are shown in Fig. 3, each curve representing the diurnal variation for a particular range of latitude. The solid lines show the calculated first harmonic of the twenty-four-hour wave. It is apparent from these data that both the amplitude and phase are approximately independent of the latitude.

The data which have been discussed above give only the average value of the diurnal variation. A method of analysis which is well suited to give also an idea of the variability in the data has been applied to this problem by Forbush.[5] In this method the daily values of the amplitude and phase of the first harmonic of the twenty-four-hour wave after the necessary corrections for barometric pressure, bursts, etc. have been made are represented by a vector on a twenty-four-hour dial. Fig. 4 shows such a harmonic dial for the observed cosmic-ray intensity for 273 single days during 1935 and 1936 at Cheltenham. The large scatter in the cloud of points makes one realize why it is necessary to make measurements over a long period of time before a reliable value of the diurnal variation can be obtained. The large circle represents the probable limits to be expected for a single day's readings. The small circle represents the same quantity for the 273-day period. It will be noticed that the time of maximum which he obtains falls at about 11 A.M. which is earlier than the values obtained by the other observers.

It has been suggested by Hess that the diurnal variation may be due to rays coming directly from the sun. Gunn has suggested that it is most likely a secondary effect associated with the known diurnal variation of the earth's magnetic field. In the accompanying paper of Vallarta and Godart a more complete theory of the various factors which give rise to the diurnal variation of intensity is given. According to their analysis the magnetic field of the sun is responsible for the diurnal variation of intensity at latitudes greater than 40° and by a proper choice of the relative number of positively and negatively charged particles in the primary cosmic rays, they obtain calculated values of the amplitude and phase which are in good agreement with the measurements. For latitudes lower than 40° the effect of the sun's field becomes negligible and the cause of the diurnal variation is sought in the changes in ring currents in the ionosphere. By adjusting a variable in the calculated formula so that the diurnal variation of the magnetic field is accounted for they obtain again results which are in good accord with the experiments.

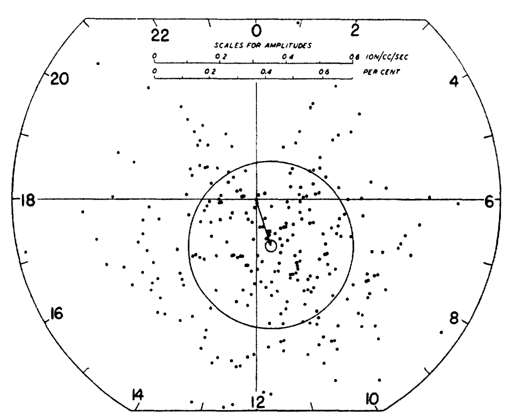


FIG. 4. 24-hour harmonic dial, apparent cosmic-ray intensity, 273 single days during April 20, 1935 to October 27, 1936, Cheltenham, Maryland (times of maximum in 75° west meridian mean hours).

[4] J. L. Thompson, Phys. Rev. 54, 93 (1938).
[5] S. E. Forbush, Terr. Mag. 42, 1–16 (1937).

THE SIDEREAL DIURNAL VARIATION OF INTENSITY

Compton and Getting[6] suggested that a variation in the intensity of cosmic rays according to sidereal time should be expected, from the fact that because of the rotation of our galaxy the earth is moving through space with a velocity of about 0.001 that of light. This has stimulated a search for a sidereal diurnal variation. The motion caused by the galactic rotation carries us toward the constellation Cygnus at about 47° north. If the cosmic rays come from outside our galaxy and do not share its motion the effects on the observed cosmic-ray intensity should be to give a slight excess in the Northern as compared

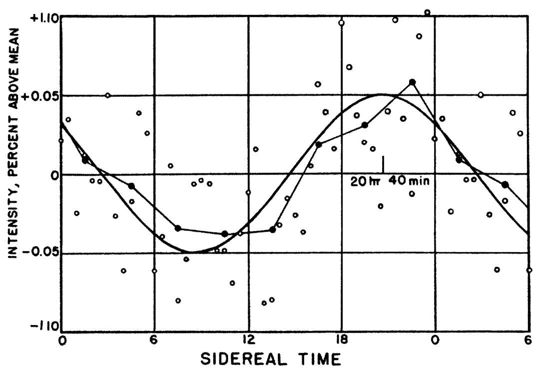


FIG. 5. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

with the Southern Hemisphere and to produce a sidereal diurnal variation with a maximum at 20 hr. 40′ sidereal time, i.e., when the observer is on the forward side of the earth. Although the theory of the effect is straight forward for a neutral type of radiation, difficulties are introduced for charged particles by the presence of the earth's magnetic field and the uncertainty of the relative number of positively and negatively charged primary rays. In the theory of Compton and Getting the effect was first calculated for a neutral radiation and then an attempt was made to correct for the effect of the earth's field. Their comparison of the theoretical predictions with the measurements of Hess for 1932 is reproduced in Fig. 5. The agreement between experiment and

[6] A. H. Compton and I. A. Getting, Phys. Rev. **47**, 817 (1935).

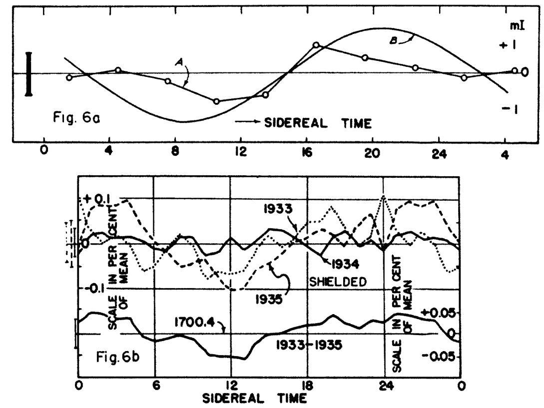


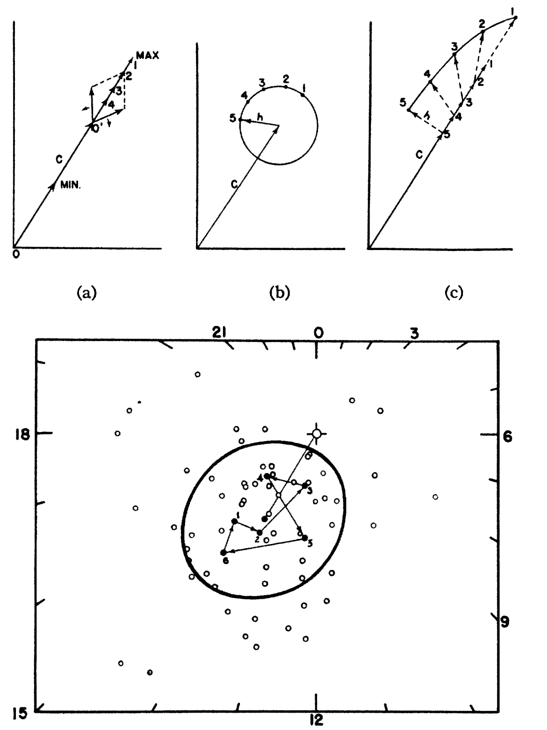
FIG. 6. (a) Curve *A*, average of data of Illing for three years. Curve *B*, theoretical curve of Compton and Getting. (b) Data of Schonland, Delatizky and Gaskell for 1933–35.

theory was justifiably taken at that time as strong evidence for the existence of the predicted effect. Although there have since been single years of observation which, taken alone, apparently give as good agreement with their theory as the original data of Hess, there have also been years in which either the observed amplitude has been zero or in which the measurements have given an apparent effect which is as much as 180° out of phase with the predictions.

Measurements which have been analyzed by the method of averaging the hourly or bi-hourly values of the deviations from the mean intensity according to sidereal time are brought together in Fig. 6. Fig. 6(a) represents the average of the data of Illing[7] for three years. The curves of Fig. 6(b) are from measurements of Schonland *et al.*[2] for 1933–35; the upper curves are for each year and the lower curve represents the average for all three years. The observed amplitude and the time of maximum are in qualitative agreement with the predictions of Compton and Getting. The observed effect is, however, of the same order as the probable error of the individual points, which is represented by the vertical line to the left of each figure.

It is to be noted that if, as seems not unlikely from the measurements (Fig. 2), there exists an annual variation in the amplitude of the solar diurnal variation, a period of one sidereal day will be introduced. If then an annual variation of the solar diurnal wave is present, the above

[7] W. Illing, Terr. Mag. and Atmos. Elec. **41**, 185 (1936).



(d)

Fig. 7. (a) Annual variation alone. (b) No annual variation. (c) Annual and sidereal component. (d) Solar time dial for 1936 cosmic-ray data from the Pacific Ocean. Light circles, 3–4 day means; heavy circles, all data combined to show chronological order. (Data from Compton and Turner.)

method of handling the data will not be capable of determining the existence of a real sidereal diurnal period.

A harmonic dial method of analysis[8] which should overcome this difficulty has been used by Thompson[9] in analyzing the data of Compton and Turner. The principle of the method can be understood from Fig. 7. The vector **c** represents as previously the amplitude and phase on a twenty-four-hour dial. An annual periodic variation of this vector can be represented by two vectors (Fig. 7(a)) which move in opposite directions about the point O' completing a rotation once a year. The period of one of these vectors with respect to point O is 365/366 solar days or one sidereal day.

In the presence of no annual variation of intensity one can understand from Fig. 7(b) that the combination of a constant sidereal diurnal vector **h** with a constant solar vector **c** would give rise to datum points which fall in progressive order on a circle. For the annual variation alone, the points lie on a line as in Fig. 7(a). If an annual variation of the solar component is present together with a sidereal component the points will be arranged in orderly fashion on an ellipse as shown in Fig. 7(c). Fig. 7(d) shows the result of Thompson's analysis of Compton and Turner's Pacific Ocean data, and from these results Thompson concludes that no sidereal variation greater than experimental error is present. This method has also been applied to other data by Forbush.

In order to give a picture of the experimental status of the problem at the present time the amplitude and phase of each available year's observations has been represented by a block in Fig. 8. The solid blocks correspond to measure-

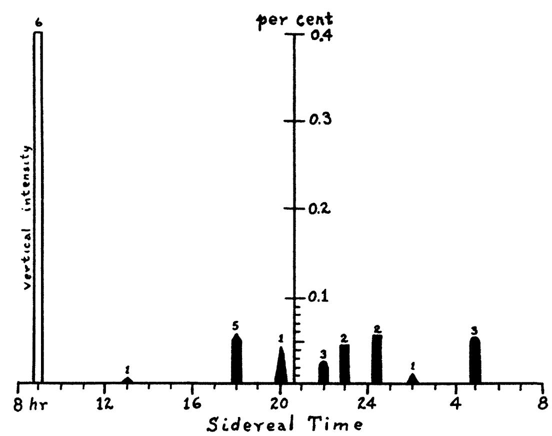


Fig. 8. Summary of data. With ionization chambers: (1) Illing (Hess) (1932–34) 47°N; (2) Schonland, Delatizky, Gaskell (1933–35) 34°S; (3) Forbush (1935–37) 39°N and 12°S; (4) Thompson (1936) *No effect* 49°N to 34°S; (5) Gill (Phys. Rev. **55**, 429 (1939)) 29°N. With G-M counters: (6) Barnóthy and Forró, (Phys. Rev. **55**, 868 (1939)) 47°N.

ments taken with ionization chambers and the open block represents measurements taken with a vertical arrangement of coincidence counters. In view of the fact that the 3,000,000 counts which these latter data represent give a small statistical accuracy as compared with a year's observations with a large ionization chamber, it would seem

[8] This method has been used very successfully by Bartels [Terr. Mag. **40**, 1–60 (1935); **37**, 291 (1932)] in connection with the analysis of magnetic phenomena and is discussed in detail by him.

[9] J. L. Thompson, Phys. Rev. **55**, 11 (1939).

that very little weight should be given to this point. In viewing the ionization chamber data as a whole one might consider that although the spread in phase is large, an amplitude of the sidereal diurnal variation of about 0.04 percent with an average phase of about twenty-three hours sidereal time is at least indicated. This value of amplitude and phase would be in good accord with the predictions of Compton and Getting. Before drawing any conclusions let us consider more carefully the ability of the methods of analysis to detect a sidereal variation of about this amount.

We have considered above an harmonic dial method of analysis which theoretically permits of the detection of a sidereal variation in the presence of a seasonal variation in amplitude of the solar diurnal wave. One method of investigating this point is that of introducing a sidereal wave of known amplitude and phase into a set of data and seeing whether it can be brought out again in the analysis. To do this a set of data was manufactured which had random fluctuations in phase and amplitude of the solar wave of about the same amount as that of a real set. The data of Forbush shown in Fig. 4 were taken as a fair sample, and from a study of the daily distribution of phase and amplitude of these data an artificial set of data of similar type was made up,[10] but which was entirely random except for the presence of the diurnal wave. The monthly means of the phases and amplitudes were then obtained. On these monthly means a sidereal wave having an amplitude of 0.05 percent was superimposed by finding the vector sum of the solar vector and the sidereal vector for each month. The points so obtained are shown in Fig. 9. A set of data free from random fluctuations should give a set of points arranged in order on a circle of radius 0.05 percent with its center at the end of the solar vector **c**. One sees some tendency towards such an arrangement and a conclusion could probably be drawn that either a seasonal variation of the solar vector exists or a sidereal diurnal variation is present. If both existed the circle would become an ellipse and a determination of the phase of the sidereal component would depend on fixing the major and minor axes of this ellipse. This certainly does not seem possible from such a set of points. It would seem then that in view of the uncertainty in the analysis of the data for a sidereal diurnal variation one is not at present in a position to say that such a variation does or does not exist.

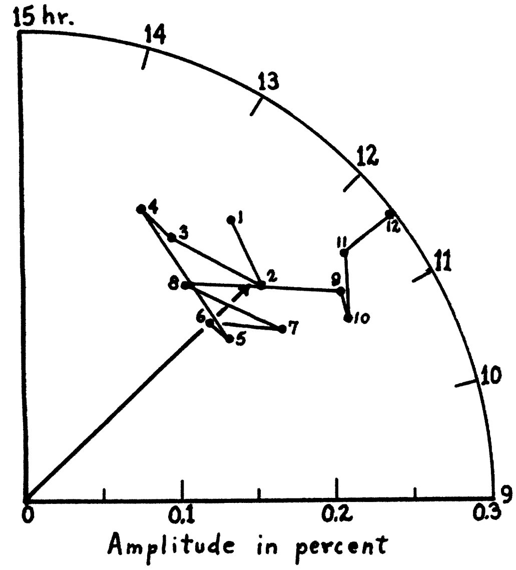


FIG. 9. Monthly means from an artificial set of data having random fluctuations in amplitude and phase of solar wave plus a sidereal wave of constant amplitude and phase.

[10] This set of data was made by writing down on small pieces of paper 360 phase hours distributed according to a Gaussian error curve the shape of which represented approximately the phase distribution of the real data and then these numbers were chosen at random to represent the phase for each day in the 360. A similar procedure was used to obtain the daily amplitudes. The maximum of the diurnal wave was taken at 12:00 and the amplitude as 0.2 percent.