Cosmic-Ray Intensity Fluctuations at Sea Level*

ROBERT L. CHASSON†
Department of Physics, University of California, Berkeley, California
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Geomagnetic and atmospheric influences on sea-level cosmic radiation have been studied at Berkeley, California (95-m elevation, 44° N geomagnetic latitude). The hard (20-cm lead absorber) and total intensities were measured with wide-angle triple-coincidence counter telescopes, and fluctuations of intensity were compared statistically with changes of barometric pressure, pressure-altitude, and temperature of the lower stratosphere. The atmospheric coefficients found by Duperier were verified for the 100-millibar region, but radiosonde data were not complete enough to permit calculations for higher strata of the atmosphere. The hard and total intensity data, corrected to constant barometric pressure, were examined for fluctuations that could be correlated with geomagnetic disturbances. No apparent cosmic-ray changes accompanied any of seven geomagnetic sudden commencements. Of eighteen magnetic storm periods occurring over eight months, only four appeared definitely to be accompanied by cosmic-ray intensity decreases. No increases of intensity occurred during these periods. Of the four decreases observed, two were unusual in that the decrease occurred an appreciable time before the measurable geomagnetic disturbance (May 27 and June 25, 1951). These two events occurred during times of very great sunspot activity, but only a loose genetic relationship could be established between the sunspot behavior and the prestorm cosmic-ray decreases.

I. INTRODUCTION

FLUCTUATIONS of cosmic-ray intensity observed at sea level may arise partly from changes of the primary flux of charged particles resulting from alterations of the geomagnetic field.[1,2] Other fluctuations may be caused by changes in the distribution of atmospheric mass. By means of multiple correlation and regression analysis of intensity data, Duperier[3,4] has shown that it is possible to separate three main atmospheric effects. They are the barometric effect (mass absorption of muons), the pressure-altitude effect (decay of muons), and the upper-air temperature effect (attributed by Duperier to competition between the decay and nuclear interaction processes for charged pions).

The purpose of the work reported here was to obtain further statistics regarding the time and magnitude of cosmic-ray changes associated with magnetic storms.[5–17] It was also desired to investigate further the atmospheric effects described by Duperier.

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† Now at the Department of Physics, University of Nebraska, Lincoln, Nebraska.
[1] G. Lemaitre and M. S. Vallarta, Phys. Rev. **43**, 87 (1933).
[2] G. Lemaitre and M. S. Vallarta, Phys. Rev. **50**, 493 (1936).
[3] A. Duperier, Proc. Phys. Soc. (London) **A62**, 684 (1949).
[4] A. Duperier, J. Atm. Terrest. Phys. **1**, 296 (1951).
[5] Altman, Walker, and Hess, Phys. Rev. **58**, 1011 (1940).
[6] T. H. Johnson, Revs. Modern Phys. **10**, 193 (1938). Contains an extensive list of references to earlier work.
[7] D. H. Loughridge and P. Gast, Phys. Rev. **57**, 938 (1940).
[8] K. Sittkus, Z. Naturforsch. **1**, 204 (1946).
[9] V. F. Hess and E. B. Berry, Phys. Rev. **60**, 746 (1941).
[10] S. Korff, Terrestrial Magnetism and Atm. Elec. **48**, 217 (1943).
[11] I. Lange and S. E. Forbush, Terrestrial Magnetism and Atm. Elec. **47**, 185 (1942).
[12] I. Lange and S. E. Forbush, Terrestrial Magnetism and Atm. Elec. **47**, 331 (1942).
[13] E. B. Berry and V. F. Hess, Terrestrial Magnetism and Atm. Elec. **47**, 251 (1942).
[14] A. Duperier, Nature **149**, 579 (1942).
[15] D. W. N. Dolbear and H. Elliot, Nature **159**, 58 (1947).
[16] H. Elliot and D. W. N. Dolbear, J. Atm. and Terrest. Phys. **1**, 205 (1951).
[17] B. Trumpy, Univ. Bergen Skrifter No. 3, 3 (1949).

II. EXPERIMENTAL PROCEDURE

The apparatus used to monitor the hard and total sea-level cosmic radiation was of simple conventional design. It consisted of two separate Geiger counter triple-coincidence telescopes having wide acceptance angle. The geometrical features of these two counter arrays were made as close to identical as possible. One of them (the "soft" telescope) had no absorber other than the counter walls and the thin pressed-wood material used to make the counter trays. The other (the "hard" telescope) contained 20 cm of lead and 1.25 cm of iron absorber. Figure 1 gives the dimensions of the telescopes and the disposition of the absorber in the hard telescope. The lower limits of momentum for the hard telescope were approximately 370 Mev/c for muons and 1 Bev/c for protons.[18]

Each tray contained 7 external-cathode Geiger counters[19] of $1\frac{1}{2}$-inch diameter and 24-inch length, yielding an effective tray area of about 1600 cm^2. Triple coincidences were selected by Rossi-type circuits, followed by scales-of-eight, which actuated mechanical registers. Photographic records were made of the scaled hard and total counts every 14.4 minutes (1/100 day). The approximate triple-coincidence rates were

$$\text{hard: } 2.4\times10^4/\text{hr}$$

and

$$\text{total: } 3.5\times10^4/\text{hr}.$$

These rates were such that the statistical probable error was less than 1 percent over the 14.4-minute recording interval. It is believed that such precision makes it

[18] D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, 1949), Appendix E.
[19] M. L. MacKnight and R. L. Chasson, Rev. Sci. Instr. **9**, 700 (1951).

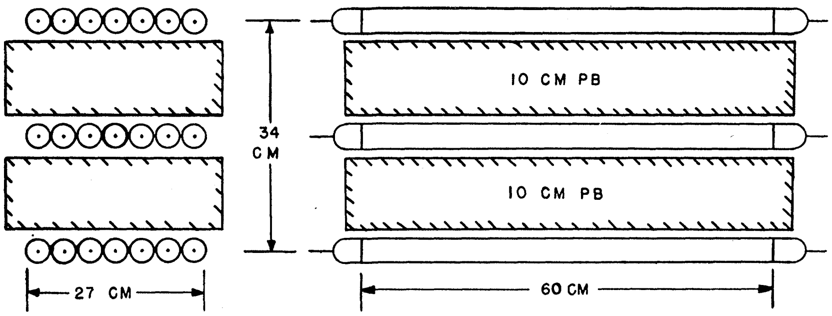

FIG. 1. Counter telescope geometry, showing disposition of 20 cm of lead in the hard telescope. Telescope opening angle is 75°×120°. Effective absorber is approximately 240 g/cm² for hard telescope and approximately 3 g/cm² for total telescope.

possible to study sudden intensity variations and their time relationship with other geophysical phenomena with considerable confidence in the statistics.

The resolving time of the coincidence input circuits (measured with a pulse-pair generator having a provision for varying the time interval between pulses) was 3.5 microseconds; thus the accidental coincidence rate was completely negligible.

Meteorological data for Oakland, California, were obtained from the United States Department of Commerce Weather Bureau and the United States Navy. Reports of geomagnetic activity were received regularly from the Instituto Geofísico de Huancayo, Peru (1° S geomagnetic latitude). The choice of an equatorial magnetic observatory as a reference for geomagnetic activity was made upon the recommendation of Forbush.[20] In considering the world-wide nature of cosmic-ray changes accompanying geomagnetic field variations, Forbush concluded that the principal changes of intensity follow the time changes in the dipole component of the magnetic storm field. Variations in the dipole component affect the magnetic records over the whole world, but such changes are superimposed upon the diurnal variation; also, such storms result in what Chapman calls the disturbance daily variation.[21] The latter is especially troublesome at high latitudes since it means that one cannot obtain a very sensible picture for the dipole component by subtracting the ordinary diurnal variation, which itself varies considerably in magnitude from day to day. Thus Forbush recommended that the records from low-latitude magnetic observatories would be of greatest significance in the consideration of cosmic-ray magnetic-storm effects.

One complete intensity unit, consisting of a pair of counter telescopes and associated electronic and recording equipment, went into operation on November 22, 1950. Its location was the Cosmic Ray Deck, Le Conte Hall, University of California, Berkeley, California (95-m elevation, 44° N geomagnetic latitude). The apparatus lay under a thin aluminum roof (0.3 g/cm²).

A similar complete unit went into operation on March 31, 1951. It was located about one mile from the Le Conte Hall site, and was housed under a $\frac{1}{8}$-inch pressed wood roof.

III. METHOD OF ANALYSIS OF DATA

Intensity and atmospheric relationships were examined statistically by use of standard methods of correlation and regression analysis. All errors quoted are statistical probable errors, based upon least-squares. The qualitative estimates of levels of significance of correlation were determined by a method developed by Fisher.[22]

The atmospheric dependence of intensity was assumed to fit linear regression relationships used in similar work;[3,23] that is,

$$\delta I=\beta(\delta B) \qquad (1)$$

for the simple barometric correlation, and

$$\delta I=\mu(\delta B)+\mu'(\delta H)+\alpha(\delta T) \qquad (2)$$

for the complete atmospheric correlation. δ represents the deviation of a variable from its mean value, and the symbols used are I = intensity, B = barometric pressure, H = pressure altitude (100-millibar level), T = average temperature between 100- and 200-millibar levels, β = simple barometric coefficient, μ = mass absorption (barometric) coefficient, μ' = decay (pressure altitude) coefficient, and α = temperature coefficient (referred to T defined above). Subscripts: t refers to total intensity, h refers to hard intensity, and s refers to soft intensity.

Data taken during periods of appreciable geomagnetic disturbance were not used in the calculation of atmospheric coefficients. This precaution insures the exclusion of significant intensity fluctuations not resulting primarily from atmospheric effects, although it seems that most magnetic storms are not accompanied by appreciable cosmic-ray disturbances.

The atmospheric coefficients obtained were used to correct the raw intensity data to a standard atmosphere, chosen to correspond with the International Standard

[20] S. E. Forbush (private communication).

[21] S. Chapman and J. Bartels, *Geomagnetism* (Clarendon Press, Oxford, 1940), Vol. 2.

[22] R. A. Fisher, *Statistical Methods for Research Workers* (Oliver and Boyd, Edinburgh, 1946).

[23] D. W. N. Dolbear and H. Elliot, J. Atm. Terrest. Phys. 1, 215 (1951).

Atmosphere, so that other work of a similar nature could be readily and unambiguously compared with the results presented below. The International Standard Atmosphere gives $B=1013.2$ millibars (sea level), $H=16\,250$ m (100-millibar level), and $T=-55.0$°C (average between 100- and 200-millibar levels).

Corrected intensity values were then compared with a standard intensity. The standard intensity was chosen on the basis of the average intensity, corrected to standard atmosphere, for the period of data used in the atmospheric calculations. It is believed that such a standard reference intensity is more useful in the study of trends of intensity changes. Although magnetic-storm effects may appear to be more dramatic when the intensities are plotted with respect to some arbitrary prestorm average intensity, as has been usual, such a technique might easily separate the magnetic-storm period from the true context of surrounding periods. It is believed that the examination of the whole period of data gives a much more reliable picture and leads to more fruitful results. This procedure is followed in Figs. 3, 4, and 5.

IV. RESULTS AND DISCUSSION

1. Inter-unit Correlation

It was immediately apparent that the records of the two separate intensity units were almost completely parallel. A statistical comparison was made between the two separate records of both hard and total intensity for a three-month period of joint operation. The daily average hard intensity for the Le Conte Hall unit was about 0.7 percent lower than that for the second unit, whereas the average total intensity was about 0.8 percent higher for the Le Conte Hall unit. These small discrepancies are undoubtedly due to slightly different sensitivities of the coincidence input units and to small differences of effective telescope geometry.

Most important, however, is the generally excellent parallelism existing between the records. The inter-unit correlation coefficients bear this out, having been found to be

$$r_h=0.94 \quad \text{(hard)},$$

and

$$r_t=0.96 \quad \text{(total)}.$$

Both values are highly significant, according to the criterion of Fisher,[22] indicating that, for the period of observation and the distance involved, there were no sensible major spatial differences in the magnitude of cosmic-ray fluctuations. As a whole, the results indicate a striking degree of homogeneity of sea-level radiation, taken over a small but significant horizontal distance. This is in agreement with the more general observations (between New York and Maryland) of Altman, Walker, and Hess.[5]

2. Simple Barometric Effect for Hard, Total, and Soft Intensities

The simple barometric coefficient β is calculated from regression Eq. (1) under the assumption that all intensity fluctuations are due to barometric changes. As shown by Duperier,[3] such an assumption leads to overemphasis of the contribution of pressure changes, but it is a matter of considerable practical interest to calculate the value of the simple barometric coefficient. The results will be applied later to the intensity data as what may be considered a first order correction.

Daily mean values of pressure and of hard and total intensity were calculated. The data covered a six-month period of operation, with the exclusion of days of marked geomagnetic activity or when the intensity data were not reliable because of equipment failure. The following values were found for the simple barometric regression and correlation coefficients:

$$\beta_h=-(2.07\pm0.14) \text{ percent/cm Hg},$$
$$(r_{IB})_h=-0.63 \text{ (highly significant)} \quad \text{(108 days)},$$
$$\beta_t=-(2.87\pm0.21) \text{ percent/cm Hg},$$
$$(r_{IB})_t=-0.68 \text{ (highly significant)} \quad \text{(100 days)}.$$

The regression coefficients are expressed in percent of the mean value of the daily mean intensity.

The value for β_h is in close agreement with that found for long periods of observation by other workers.[3,23,24] The value of β_t agrees substantially with other determinations.[25,26]

Clearly β_t is numerically larger than β_h. The difference could be accounted for by the excess of electronic component at sea level arising from cascade processes generated by the decay of neutral pions. Greisen[27] has pointed out that radiation thus born could make it appear that there is not muon-electron equilibrium at sea level. The electronic component would be especially sensitive to barometric pressure changes since the absorption coefficient for low energy electrons is approximately 0.025 cm^2/g, whereas the absorption coefficient for muons is of the order of 10^{-3} cm^2/g. Thus the electronic component could well account for the large barometric dependence of the total intensity. In partial support of this contention is the barometric coefficient of approximately -10 percent/cm Hg found by Daudin and Daudin[28] for extensive air showers.

From the values of the simple barometric coefficients for hard and total intensity, it is possible to derive the coefficient for the soft. Returning to the definition of β given by Eq. (1), one may write for the total intensity

[24] D. C. Rose, Can. J. Phys. **29**, 97 (1951).
[25] F. Lindholm, Arkiv. Mat. Astron. Fysik. **A30**, No. 3 (1944).
[26] Caro, Law, and Rathgeber, Australian J. Sci. Research **A1**, 261 (1948).
[27] K. Greisen, Phys. Rev. **73**, 521 (1948).
[28] A. Daudin and J. Daudin, J. phys. et radium **10**, 394 (1949); **14**, 169 (1953).

(hard plus soft)

$$\delta I_t = (\beta_h + \beta_s)\delta B, \quad (3)$$

where β is in terms of counts/(pressure×time). Thus

$$\beta_t = \beta_h + \beta_s. \quad (4)$$

If the β's are to be expressed in terms of percent intensity change per unit pressure change, it is necessary to weight each term of Eq. (4) by the respective fraction of the total intensity included in each intensity component. Equation (4) becomes, by using average values of intensity to construct the weighting factors,

$$\beta_t = \frac{\langle I_t \rangle_{\text{Av}} - \langle I_h \rangle_{\text{Av}}}{\langle I_t \rangle_{\text{Av}}} \beta_s + \frac{\langle I_h \rangle_{\text{Av}}}{\langle I_t \rangle_{\text{Av}}} \beta_h. \quad (5)$$

In Eq. (5) each β is in units of percent/pressure.

From the data used to calculate β_h and β_t, it was found that $\langle I_h \rangle_{\text{Av}} / \langle I_t \rangle_{\text{Av}} = 0.6918$. Thus the simple barometric coefficient for the soft intensity is

$$\beta_s = -(4.67 \pm 0.65) \text{ percent/cm Hg}.$$

The value of β_s compared with the value of β_h shows very clearly how much more barometrically sensitive the soft component is when compared with the hard. Only a few percent of the soft sea-level radiation is composed of slow mesons;[29] hence most of the contribution to the soft barometric effect is due to electron absorption. Since, however, most electrons at sea level result from muon decay and knock-on processes,[30] the apparent barometric dependence of these electrons will rest considerably on that of the muons. Thus β_s will be numerically smaller than might be expected if one considered simply the absorption of electrons in air.[31]

3. Complete Atmospheric Correlation

It is now assumed that the intensity fluctuations caused by atmospheric changes are expressed by the multiple linear regression equation (2). Duperier[3,4] has shown that this relationship assumes greater validity as higher levels in the atmosphere are considered for the temperature term. His analysis shows that the height of the 100-millibar level gives the best correlation for the pressure altitude (decay) effect. He found better correlation for the temperature effect if the mean temperature between 50 and 200 millibars (T_{52}) is used rather than that between 100 and 200 millibars (T_{12}). The result was that the temperature coefficient α_{52} is twice as large as α_{12}, indicating that a large fraction of primary interactions take place in the first 50 g/cm^2 of the atmosphere. The high-altitude balloon observations of Winckler and Stroud[32] more directly confirm this.

In the present work the lack of much radiosonde data above the 100-millibar level made it impossible to consider in detail the effect upon the intensity of the fluctuations of T_{52}. Furthermore, since only two radiosonde flights were made per day (0300 and 1500 hr GMT) at Oakland, California, it was not possible to calculate daily average values of H and T for comparison with the available daily average of B and I. The best that could be done was to use the average intensity and sea-level barometric pressure for the 3-hour period of the day bracketing each radiosonde flight period. To avoid complications possibly arising from the diurnal variation and random fluctuations of H and T, the calculations of atmospheric coefficients were made using either morning or afternoon flight periods, but not mixing them in a single calculation. Missing atmospheric data could not be interpolated, as judged from unsuccessful attempts to interpolate and reproduce known values of H and T.

For six months of operation, during which there were 78 afternoon radiosonde flights that reached 100 millibars, the calculation of the atmospheric coefficients gave

$$\mu = -(1.56 \pm 0.23) \text{ percent/cm Hg},$$

$$\mu' = -(3.22 \pm 0.49) \text{ percent/km},$$

and

$$\alpha_{12} = (0.068 \pm 0.018) \text{ percent/°C}.$$

The multiple correlation coefficient was

$$R_{I.BHT} = 0.61 \quad \text{(highly significant)}.$$

The acceptance angle and general geometry of the telescopes used in the present work were essentially the same as those used by Duperier in his more recent determinations of the atmospheric coefficients.[4] The over-all agreement with Duperier is excellent.[33]

4. Correction of Intensity Data for Atmospheric Effects

Before comparing intensity fluctuations with geomagnetic data, it is necessary to eliminate, as far as possible, the effects of atmospheric changes. In the present experiment only about one-fourth of the intensity data for one day could be reliably corrected for the three atmospheric effects, assuming that both daily radiosondes reached 100 mb. Actually, only about two-thirds of the flights reached the requisite altitude. It would be a very undesirable procedure with regard to the study of geomagnetic effects if one were forced to

[29] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

[30] Bernardini, Cacciapuoti, and Querzoli, Phys. Rev. **73**, 335 (1948).

[31] D. I. Dawton and H. Elliot, J. Atm. Terrest. Phys. **3**, 295 (1953), have directly calculated the absorption coefficient for the soft intensity using regression Eq. (2). They obtained a value of $-(4.70 \pm 0.23)$ percent/cm Hg. This agreement with the simple β_s in the present work indicates that the soft intensity fluctuations most strongly reflect barometric pressure changes alone.

[32] J. Winckler and J. R. Stroud, Phys. Rev. **76**, 1012 (1949).

[33] Duperier (to be published) finds a value of the barometric coefficient, using 40 cm of lead absorber, of $-(1.21 \pm 0.06)$ percent/cm Hg, which is in perfect agreement with the presently determined value and the value from the absorption curve in water.

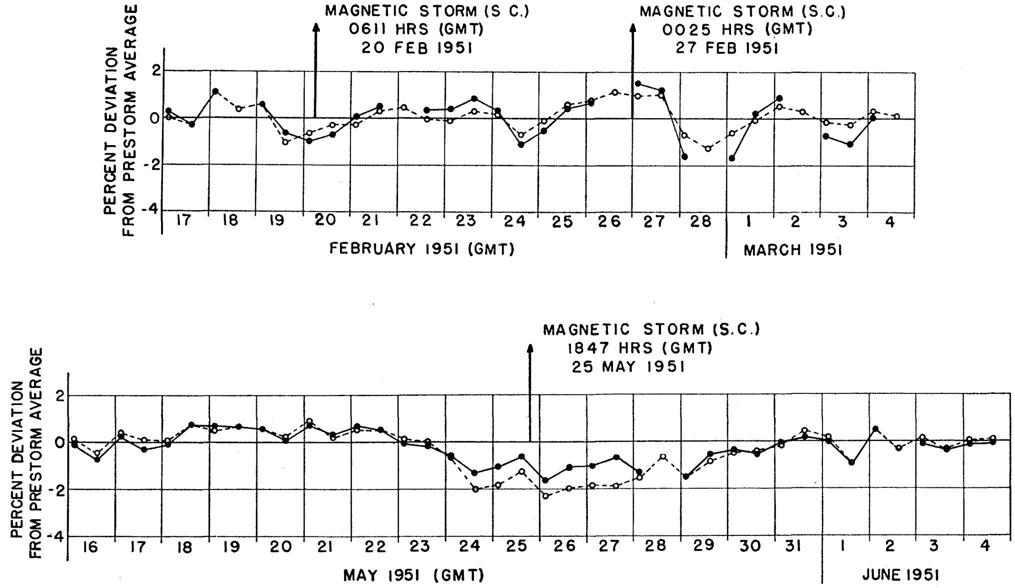

FIG. 2. Variations of hard cosmic-ray intensity when corrected for both barometric pressure and altitude of 100-millibar isobar (solid curve) and for barometric pressure alone (dashed curve). Radiosonde ascents made at 0300 and 1500 hr GMT. Points on curves represent intensity means for approximately $\frac{1}{8}$ day, centered about the time of radiosonde ascent. Missing points on solid curves indicate absence of 100-millibar radiosonde data. (S.C. = sudden commencement.)

rely upon intensity data corrected only for such restricted periods. Thus it was necessary to test whether or not a simple barometric correction, which could be done for a whole day of data, would give a set of corrected intensity values reliable enough to be used in examining the geomagnetic effects. The following procedure was carried out: two different periods of intensity data (16 and 20 consecutive days) were chosen, and the portions of data corresponding to the times of the morning and afternoon radiosonde flight periods were corrected according to the three atmospheric regression coefficients. (The net positive temperature effect was much smaller than that of barometric pressure and pressure-altitude.) The same raw data were also corrected using only the simple barometric coefficient. The data adjusted in the two different ways are plotted together in Fig. 2. It is seen that it is adequate to correct the intensity data by means of the simple barometric coefficient without seriously altering the sense of the results. Although this was certainly the less desirable alternative, it was the only way, under the circumstances, that the whole day of intensity data could be effectively used. The magnitude of the simple barometric correction seems, fortuitously, almost equivalent to the combined barometric and pressure-altitude corrections. Thus all intensity data shown graphically, with the exception of solid portions of Fig. 2, were corrected only for the simple barometric effect.

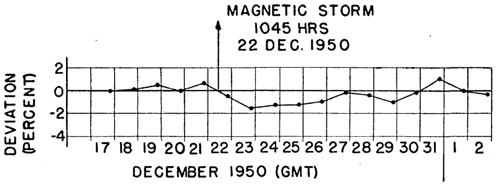

FIG. 3. Variations of hard cosmic-ray intensity during geomagnetic storm of December 22, 1950. Ordinate is daily mean percent deviation from standard intensity. For convenience, points are centered upon 2200 hr GMT.

5. Analysis of Sudden Commencements

The intensity trend for several 14.4-minute intervals, surrounding each of seven different geomagnetic sudden commencement periods, was examined for significant fluctuations that could be considered coherent with the sudden commencement. The amplitudes of the sudden commencements ranged from +14 to +101 gamma, but no significant cosmic-ray intensity changes were found that could be associated with any of the seven events.

It is evident, under the statistical limitations of the counting experiment, that any alteration of the allowed cone of radiation or change of incident primary flux occurring during sudden commencements would not produce large enough effects to be resolved.

6. Intensity Variations during Geomagnetic Storm Periods

Counting data for the hard component were corrected (simple barometric) for 18 of 19 magnetic storms that occurred between November 22, 1950, and July 9, 1951. No intensity data were available for the magnetic storm of December 12, 1950. Examination of the in-

tensity trends over the storm and surrounding periods indicates the following general distribution of results: (The amplitudes of maximum horizontal field disturbance at Huancayo are given. Greenwich dates are used throughout.)

(a) No clear magnetic-storm effect (14 storms):
November 24, 1950 (−250 gamma),
January 22 and 29, 1951 (−322 and −364 gamma),
February 4, 21, and 27, 1951 (−319, −320, and −284 gamma),
March 6 and 13, 1951 (−268 and −234 gamma),
April 2 and 18, 1951 (−249 and −436 gamma),
May 1 and 9, 1951 (−402 and −307 gamma),
June 25, 1951 (−167 gamma),
July 1, 1951 (−292 gamma).

(b) Probable magnetic-storm effects (4 storms):
December 22, 1950 (−282 gamma),
January 26, 1951 (−405 gamma),
May 25, 1951 (−375 gamma; prestorm cosmic-ray decrease),
June 17, 1951 (−393 gamma; prestorm cosmic-ray decrease).

The daily mean percent deviation from standard hard intensity is plotted for these latter four periods in Figs. 3, 4, and 5. Missing points are for days when the cosmic-ray data were not reliable because of equipment failure. For convenience, means are centered on 2000 hr GMT. The fluctuations of total intensity closely paralleled those of the hard.

Altman, Walker, and Hess[5] examined 20 magnetic storms over an interval of eleven months and reported that 16 lowered the cosmic-ray intensity and 4 raised it. They remarked that the positive effects were for small storms (250 gamma or less), while the negative effects were for storms ranging to 850 gamma. Their technique of looking at the data consisted of a comparison of the corrected intensities for the day of maximal magnetic disturbance with the intensities for the preceding undisturbed or little-disturbed day. There are serious objections to such a technique since application of simple atmospheric corrections to short intervals of data is not very reliable, and the separation from the context of surrounding periods of data can be quite misleading. For example, if one considers only the data for February 26, 27, and 28, 1951, in Fig. 2, he may conclude that the magnetic storm of February 27 definitely caused an intensity decrease. But examination of the general intensity record for the periods immediately preceding and following indicates that the negative fluctuation starting on February 27 may well have been only a part of the normal fluctuation pattern that applies to the whole period. One cannot say that the decrease of February 27 is uniquely associated with the magnetic storm. In view of this interpretation of the

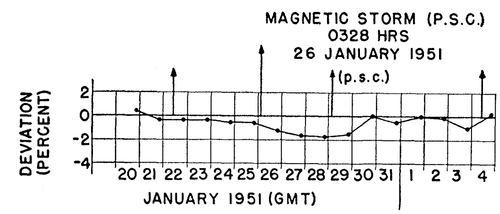

FIG. 4. Variations of hard cosmic-ray intensity during geomagnetic storm of January 26, 1951. Unlabelled arrows are for commencements of magnetic storms not accompanied by apparent cosmic-ray changes. (P.S.C.=pulsating sudden commencement.)

records, it is doubtful that the storm-effect statistics of Altman, Walker, and Hess can be considered as reliable.

7. Prestorm Effect

Two events of unusual interest were noted; namely, the marked intensity decreases that preceded the advent of the geomagnetic storms of May 25 and June 17, 1951.[34] Records from both independent intensity units were the same throughout. Records of hard and total intensity for these periods at Manchester, England, are in excellent agreement with the Berkeley results.[35] Also, the high altitude neutron records show even larger negative fluctuations during these periods.[36] A considerable decrease of intensity started on May 23, followed by the moderate magnetic storm of May 25, which lasted for about $1\frac{1}{2}$ days. The intensity slowly returned to its "prestorm" value after the end of the magnetic disturbance, as is characteristic when cosmic-

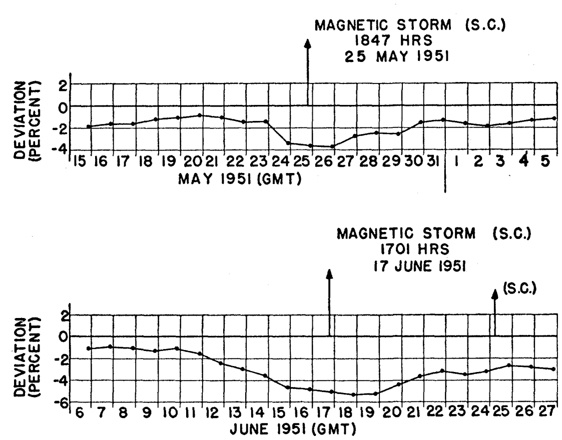

FIG. 5. Variations of hard cosmic-ray intensity for geomagnetic storms of May 25 and June 17, 1951, showing prestorm cosmic-ray decreases. Sunspot group Mt. Wilson 10662 disappeared around the west limb of the sun on May 23, 1951, and sunspot group Mt. Wilson 10692 passed across the solar disk during June 12–25, 1951.

[34] Reported to the American Physical Society at Chicago, Illinois, October 24–27, 1951. See R. L. Chasson, Phys. Rev. **85**, 719(A) (1952).
[35] H. Elliot (private communication).
[36] Reported to the American Physical Society at Chicago, Illinois, October 24–27, 1951. See Simpson, Fonger, and Wilcox, Phys. Rev. **85**, 720(A) (1952).

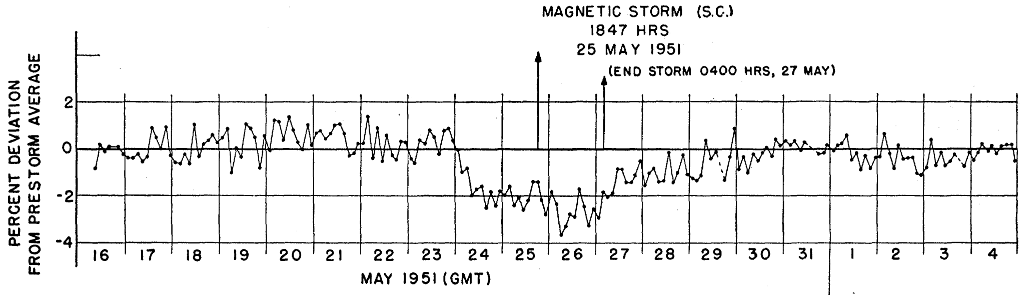

FIG. 6. Variations ($\frac{1}{10}$-day means) of hard cosmic-ray intensity for geomagnetic storm of May 25, 1951, showing details of prestorm cosmic-ray decrease. Sunspot group Mt. Wilson 10662 disappeared around west limb of sun on May 23, 1951.

ray decreases accompany magnetic storms. The fine structure of the hard intensity variations ($\frac{1}{10}$ day intervals) for this period may be seen in Fig. 6. There is remarkable agreement between the amplitudes for hard and total intensity.

The second prestorm decrease was of considerably larger amplitude, but it displayed entirely different characteristics at the beginning. The intensity drop started on about June 11, 1951, and the intensity kept dropping slowly for several days. A moderate magnetic storm started on June 17 and lasted about one day. The intensity remained very low for several days and then slowly began to increase. The intensity had not quite re-attained its normal value by the beginning of August, 1951.

These prestorm decreases were somewhat associated in time with unusual sunspot activity. A great sunspot group (Mt. Wilson 10662), one of the largest ever recorded, completed its passage across the disk of the sun and disappeared around the West Limb on May 23, 1951, the date of onset of the sharp cosmic-ray decrease. Another great sunspot group (Mt. Wilson 10692) made its passage across the disk during the period June 12–25, 1951, which time almost exactly encompasses the period of the persistent intensity decrease noted to start on June 11.

It is noteworthy that such a prestorm decrease and slow return to normal intensity has been reported by Duperier and McCaig[37] in connection with unusual sunspot activity accompanied by magnetic storms. The event reported is unique in the cosmic-ray literature.

It is difficult to suppose that these prestorm decreases of cosmic-ray intensity, considered by Duperier and McCaig to be the logical counterpart of storms accompanied by no intensity decrease at all, are not in some way associated with the large-scale sunspot activity. It seems impossible, however, to establish any other than a loose genetic relationship. Hogg[38] has made a five-year study of the relation between cosmic rays and various solar phenomena. Correlation with formation and central meridian passage of sunspots and with solar flare activity failed to show any significant effect with respect to cosmic rays unless geomagnetic disturbances were also observed. Hogg gave no information with regard to any particular event, however.

Solar flare activity was normal during the period of the unusual events discussed above, and it cannot be said that there is any unique relationship between the sunspot passages and the time of the cosmic-ray decreases. The occurrence of geomagnetic disturbances at the time fits in with the general conclusions of Hogg.

Also, there were no unusual fluctuation trends in the pressure-altitude or upper-air temperature during these periods. Therefore it is believed that the unusual decreases cannot be explained in terms of measurable atmospheric influences. Figure 2 also contains the storm period of May 25, 1951. It is seen that the intensity trends are well preserved when the complete atmospheric correction is applied to a restricted amount of data.

V. CONCLUSIONS

1. Atmospheric Effects

The atmospheric regression coefficients of Duperier have been confirmed up to the 100-millibar level of the atmosphere. Duperier has originally interpreted the positive temperature effect as a strict consequence of the competition between decay and nuclear interaction processes, depending upon upper air density, as the ultimate fate of pions. According to the theoretical calculations made by Olbert[39] for the vertical intensity, however, all of the atmospheric effects could be explained satisfactorily in terms of the barometric pressure, pressure-altitude, and a mean temperature of part of the troposphere. According to this theory the temperature coefficient is negative, and it arises as a result of considering ionization losses by muons during their traversal of the atmosphere. It is apparent that the Duperier positive temperature coefficient is much too large to be consistent with the known mean life and nuclear collision cross section for muons.

[37] A. Duperier and M. McCaig, Nature **157**, 477 (1946).
[38] A. R. Hogg, J. Atm. Terrest. Phys. **1**, 56 (1950).

[39] S. Olbert, Phys. Rev. **92**, 454 (1953). The author is deeply indebted to Dr. Olbert for supplying a prepublication copy of his paper and for several very enlightening discussions regarding the problem.

There seems to be no doubt that the positive temperature effect is statistically real, but the degree of its physical reality is an open question. It may be only a reflection, as Olbert has suggested, of the strong negative correlation that exists between temperature changes of the troposphere and the lower stratosphere.

A possible indicator of the significance of the positive temperature effect is the observation that the regression coefficient decreases as the opening angle of the cosmic-ray telescope is increased.[4] Duperier explained this effect in terms of the fact that only the most energetic muons would penetrate the very great amount of atmosphere presented to them at large zenith angles. Such muons would have come from the decay of pions of such extremely high energy that they would not show any dependence upon density changes of the lower stratosphere. Duperier correctly predicted the ratio of the two positive temperature coefficients that he found in his experiments, but he failed to predict the magnitude of the individual coefficients. He ascribed this failure to the possible existence of intermediate particles of extremely short lifetime. The trouble may lie, in part, in the Duperier interpretation of the positive temperature coefficient. The observed zenith-angle dependence may be largely consistent with the sign reversal of temperature changes discussed above, coupled with the change of average muon survival probability as the telescope opening angle is altered and longer paths through the atmosphere are included.

If, however, one could determine the degree of physical reality of the positive temperature effect, he could, by using the zenith-angle dependence of the temperature coefficient, calculate the relative-number spectrum for high energy pions at creation. Direct upper-air cosmic-ray data are difficult to interpret in this respect because of the extremely short duration of balloon flights, the great number of complex multiplicative events taking place in the region, and the limitations on the amounts of absorber that can be balloon-borne to great altitudes.[40]

[40] A counting experiment is presently in progress at the University of Nebraska, from which a precise test of the Olbert theory will be made. Two more points on the opening-angle *vs* temperature coefficient curve will also be obtained from this work.

2. Geomagnetic Effects

It now appears that there are four cosmic-ray effects associated with magnetic storms; they are, namely, the simultaneous decrease, the delayed decrease,[15,16] the prestorm decrease, and the null effect. As yet no theory has been successful in explaining cosmic-ray behavior during periods of magnetic disturbance. No exhaustive calculations have been made on the basis of the ring-current hypothesis of Chapman,[41,42] and special calculations based upon the ring-current theory gave results which were opposite to those expected from qualitative argument.[43,44]

No precise test of any theory of the relationship of cosmic-ray intensity to geomagnetic field disturbances will be possible until more reliable magnetic storm statistics are available. It is evident that such statistics will not be available until the problem of atmospheric influences has been rather completely solved.

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[41] S. Chapman, Nature **140**, 423 (1937).
[42] S. Chapman and V. Ferraro, Terrestrial Magnetism and Atm. Elec. **45**, 245 (1940).
[43] S. B. Treiman, Phys. Rev. **89**, 130 (1953).
[44] Hayakawa, Nishimura, Nagata, and Sugiura, J. Sci. Research Inst. (Tokyo) **44**, 121 (1950).