Relation of the Cosmic Radiation to Sunspot Magnetic Moments*

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A function (SS-MM) designed to represent the arithmetical sum of the magnetic moments of all visible sunspots has been compared statistically with the intensity of the cosmic radiation (C-R). Large pulses (20 to 30 percent) in SS-MM were found to occur out of phase with primary pulses in C-R. SS-MM pulses of comparable magnitude bore different phase relations to subsidiary pulses in C-R. For subsidiary pulses preceding the primaries, the C-R was generally high when the SS-MM was increasing and low when it was decreasing. For subsidiary pulses following the primaries, the C-R was generally high when the SS-MM was decreasing and low when it was increasing. The analysis was carried out for intervals of 60 days preceding and following the selected days of high or low C-R. Some consideration was given to the e.m.f. generated in connection with an imaginary but in some respects representative sunspot by electromagnetic induction.

THE writer[1] has already introduced a function (SS-MM) designed to represent approximately the arithmetical sum of the magnitudes of the magnetic moments of all sunspots visible on a particular day, irrespective of polarity or location.

Analysis of the data for an eighteen-month period by Chree's method of superposed epochs provided evidence of recurrence of fluctuations in the magnitude of SS-MM at intervals of about 27 days, corresponding to recurrence phenomena displayed by intensity of the cosmic radiation[2] during the same period. Statistical treatment has also brought out a relation between primary pulses in cosmic-ray intensity and total sunspot area,[3] even though the latter did not display recurrence features at intervals approximating 27 days. These facts, combined with the further fact that the SS-MM includes recognition of a physical characteristic of sunspots which conceivably might affect the intensity of the cosmic radiation measured at a particular location on the Earth, led the writer to investigate the possibility that the SS-MM might display a closer relation to subsidiary pulses or minor fluctuations in cosmic-ray intensity than did total sunspot area.

The same period of investigation, May 25, 1938, to December 1, 1939, inclusive, and the same cosmic-ray data employed in the earlier investigations[2,3] were utilized again in this. As discussed more fully in the earlier papers, the cosmic-ray intensity was measured by means of a heavily shielded, high pressure ionization chamber and recording equipment, and was corrected for bursts and for variations in barometric pressure. Because, for purposes of comparison, the zero-days required for the Chree analysis were the identical days selected earlier on the basis of cosmic-ray intensity, the cosmic-ray curves appearing in this paper are the same (or sections of the same) cosmic-ray curves appearing in the earlier papers, with somewhat different scales. The SS-MM data were the same as heretofore employed,[1] of course.

The first step was to investigate what variations in SS-MM might be associated with the primary pulses in C-R. (C-R will be used hereinafter to designate cosmic-ray intensity.) Figures 1 and 2 show the results obtained. Figure 1 shows the primary positive pulse in C-R (dotted line) from day number -15 to $+15$ and the accompanying curve (solid line) for SS-MM. The ninety zero-days selected for this diagram were the five with highest C-R in each of the 18 months, June 1938 to November 1939, inclusive. Figure 2 shows the primary negative pulse in C-R with the corresponding curve for SS-MM.

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[1] J. W. Broxon, Phys. Rev. **75**, 606 (1949).

[2] J. W. Broxon, Phys. Rev. **59**, 773 (1941). This paper provides details of the method of measurement of the cosmic-ray intensity at Boulder, Colorado (lat. 40° N; long. 105°16′ W; alt. 5440 ft.); its diagrams provide an indication of the statistical variations in the intensity, and the paper includes a brief description of Chree's method of analysis.

[3] J. W. Broxon, Phys. Rev. **62**, 508 (1942).

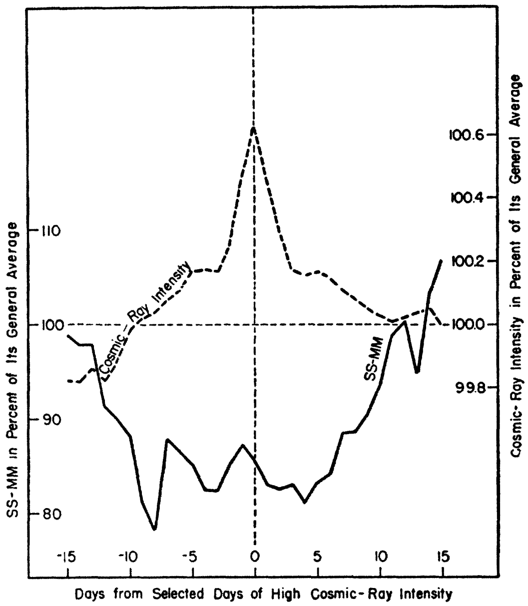

FIG. 1. The solid line represents SS-MM pulse corresponding to primary positive pulse in cosmic-ray intensity. The dotted line represents the cosmic-ray intensity. For both these curves the selected zero-days are the five days in each month with *highest* cosmic-ray intensity; included are all 90 zero-days for the 18 months.

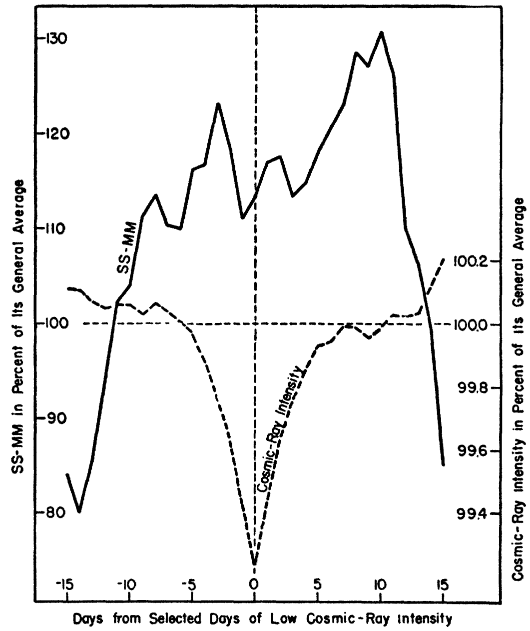

FIG. 2. SS-MM pulse with corresponding primary negative pulse in cosmic-ray intensity. This corresponds to Fig. 1 except that here the selected zero-days are the five days with *lowest* cosmic-ray intensity in each month; again, 90 zero-days are employed.

For this diagram the selected zero-days were the five of lowest C-R in each of the 18 months.

The SS-MM resembles total sunspot area somewhat in that it displays large pulses in approximate phase opposition to the primary pulses in C-R. As is seen upon comparison of Figs. 1 and 2 with Figs. 6 and 7 of reference 3, however, the pulses in SS-MM and in sunspot area associated in the same way with the primary pulses in C-R are strikingly different in detail. (It should be recalled that the C-R curves of references 2 and 3 were drawn 0.09 percent too high.) The associated pulses in sunspot area have quite definite peaks opposed to the sharp peaks of the C-R primary pulses and preceding the latter by three or four days. The correspondingly associated pulses in SS-MM display no such definite peaks. With the exception of the rather unsymmetrically high portion of the curve of Fig. 2 in the region of day numbers 6 to 11, the SS-MM curves appear to have rather broad minimum and maximum, respectively, and to be rather well centered about day-number zero, indicating that they are almost exactly out of phase with the C-R primary pulses, or perhaps there is a lag in Fig. 2. In spite of the blunt form of the associated pulses in SS-MM, their bases (their widths in day numbers at the level where the average is attained) do not appear to be much broader than the bases of the pulses in sunspot area. The departures from the average are somewhat greater in the SS-MM pulses, extending to some 20 to 30 percent as compared with extreme variations of 14 to 21 percent in the case of the sunspot-area pulses. It seems really rather remarkable that such large variations in any variable should be disclosed in connection with the selection of days on the basis of variations in C-R whose primary peak values represent departures of less than 0.7 percent from the average C-R.

The next step was to investigate whether the SS-MM might also display any correlation with the minor variations or subsidiary pulses in C-R, such correlation not having been apparent in the other variables heretofore investigated. Accordingly, the Chree analysis was run from day number -5 (or -15 in some cases) to $+60$ for zero-days selected from the first 15 of the 18 months, and from -60 to $+5$ (or $+15$ in

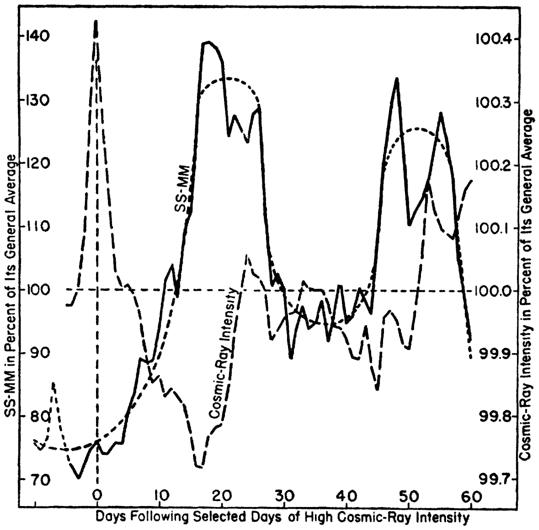

FIG. 3. The solid line represents SS-MM pulses corresponding to the primary positive pulse and subsequent subsidiary pulses in the cosmic-ray intensity. The dotted line is one drawn arbitrarily to represent the salient features of the SS-MM pulses while minimizing irregularities of relatively short duration. The broken line represents cosmic-ray intensity. The 75 zero-days for these curves are the five with *highest* cosmic-ray intensity in each of the *first* 15 months.

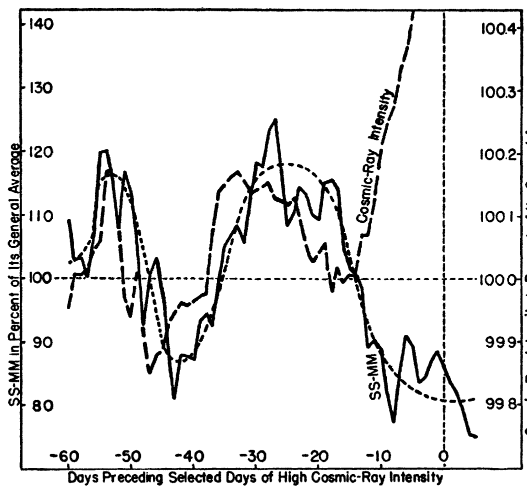

FIG. 5. SS-MM pulses with corresponding primary positive pulse and preceding subsidiary pulses in cosmic-ray intensity. This corresponds to Fig. 3 except that here the zero-days are the five with *highest* cosmic-ray intensity in each of the *last* 15 months.

some cases) for zero-days selected from the last 15 months of the period of the investigation.

The results are shown in Figs. 3, 4, 5, and 6. In each of these (as well as in subsequent diagrams) the broken line represents the C-R pulses obtained earlier.[2] The solid lines represent the corresponding pulses in SS-MM obtained with the *identical* zero-days employed in obtaining the C-R curves. For Fig. 3 the selected zero-

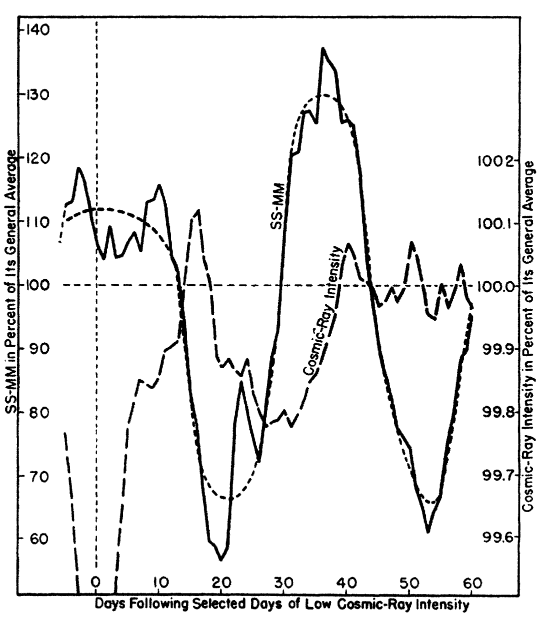

FIG. 4. SS-MM pulses with corresponding primary negative pulse and subsequent subsidiary pulses in cosmic-ray intensity. This corresponds to Fig. 3 except that here the selected zero-days are the five with *lowest* cosmic-ray intensity in each of the *first* 15 months.

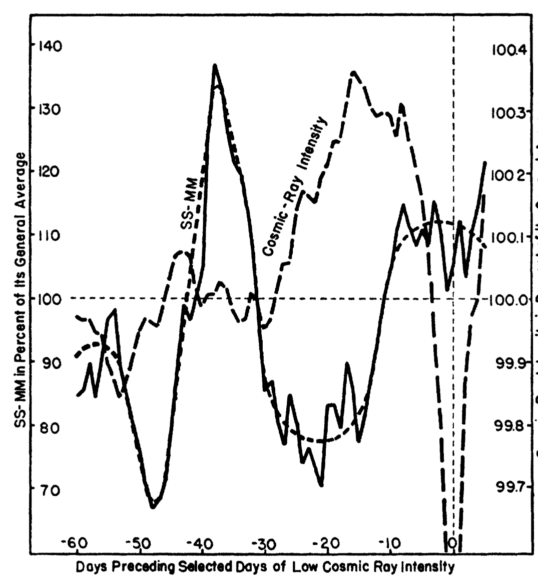

FIG. 6. SS-MM pulses with corresponding primary negative pulse and preceding subsidiary pulses in cosmic-ray intensity. This corresponds to Fig. 3 except that here the zero-days are the five with *lowest* cosmic-ray intensity in each of the *last* 15 months.

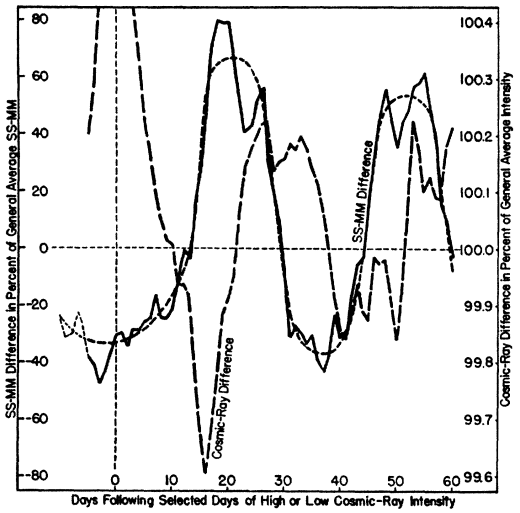

FIG. 7. The solid line represents SS-MM primary and subsequent difference pulses obtained by subtracting the SS-MM values of Fig. 4 from the corresponding ones of Fig. 3. As in Figs. 3, 4, 5, and 6, the dotted line is drawn arbitrarily to represent the salient features of the SS-MM difference pulses while minimizing minor irregularities. The corresponding difference pulses in cosmic-ray intensity are shown by the broken line.

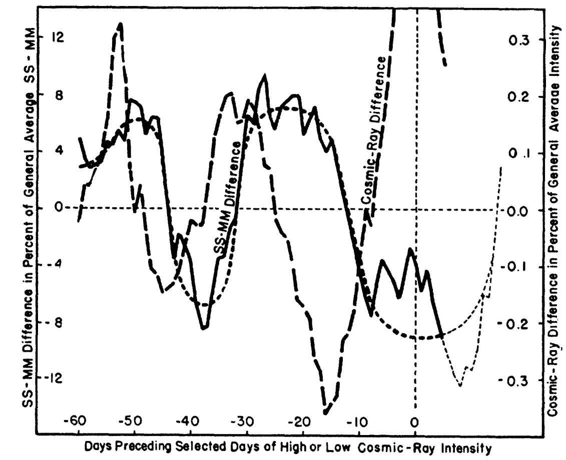

FIG. 8. SS-MM and cosmic-ray primary and preceding difference pulses obtained by subtracting values in Fig. 6 from corresponding values in Fig. 5. Otherwise, this corresponds to Fig. 7.

days were the five with highest C-R in each of the months, June, 1938, to August, 1939, inclusive. For Fig. 4 the selected zero-days were the five of lowest C-R in each of these same months. For Fig. 5 the selected zero-days were the five with highest C-R in each of the months, September, 1938, to November, 1939, inclusive. For Fig. 6 the selected zero-days were the five of lowest C-R in these same months.

In each of these four diagrams the dotted line is drawn arbitrarily to represent what appears to the writer to be the principal features of the SS-MM pulses associated with the C-R pulses. While it appears that any attempt to represent these pulses by a smoothed-out curve must be rather arbitrary, it may be noted that the principal variations of SS-MM on either side of the mean, and the day numbers where the mean is attained, are quite well represented by the dotted lines. The smaller fluctuations near the troughs and crests of the pulses, presumably largely due to statistical variations and perhaps to inaccuracies in the data as well as in the mode of approximation in determining the SS-MM, were rather generally ignored in drawing the dotted curves. In considering irregularities it may be well to keep in mind not only the several approximations employed in obtaining the SS-MM, but also the facts that the date of determination of the maximum H for a particular sunspot group and the particular position in the group in which it was determined are not known, that this value is given only in integral multiples of 100 gauss, and that the sunspot areas are determined at widely different hours on different days.

In Figs. 7 and 8 are shown the difference pulses in SS-MM and C-R obtained in the usual way from the preceding four diagrams. The curves of Fig. 7 were obtained by subtracting ordinates of the curves of Fig. 4 from the corresponding ordinates of Fig. 3. The curves of Fig. 8 were obtained similarly by subtracting ordinates of Fig. 6 from the corresponding ones of Fig. 5. These difference curves in at least one respect are more satisfactory than the originals from which they were obtained, for the very considerable seasonal effect in C-R is largely eliminated in these. As in the preceding four diagrams, dotted lines have been drawn to represent the principal features of the SS-MM difference curves while smoothing out their minor fluctuations. The C-R difference curves are sections of those published earlier.[2]

Inspection of Figs. 3 to 6 shows that the secondary pulses in SS-MM are generally (though not always) quite as large or larger than those associated with the primary pulses in C-R, deviating in some cases by approximately 40

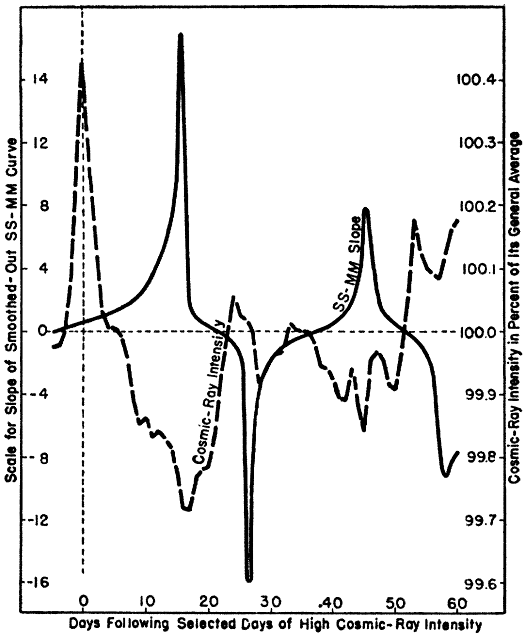

FIG. 9. The solid line represents the slope of the dotted line of Fig. 3. The broken line is the same as that in Fig. 3, and represents cosmic-ray intensity.

percent from the mean. They appear to be quite as large or rather larger than the secondary pulses obtained[1] with zero-days selected on the basis of large or small SS-MM. A similar statement holds for the SS-MM difference pulses in Figs. 7 and 8.

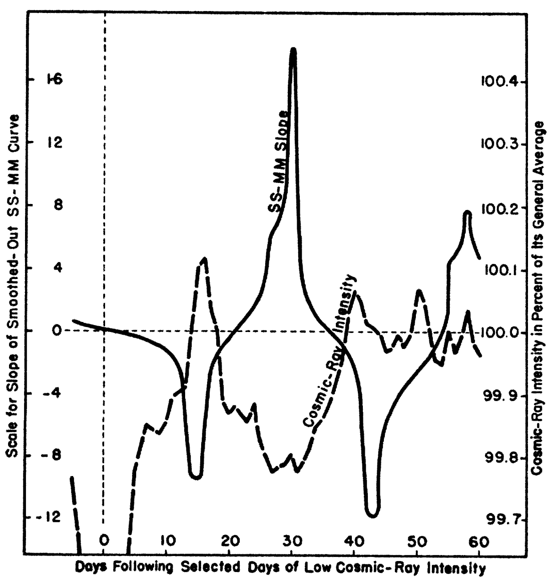

FIG. 10. These curves bear the same relation to Fig. 4, as do those of Fig. 9 to Fig. 3.

Although the pulses in SS-MM associated with the primary pulses in C-R appear to be almost exactly out of phase with them in each instance, the remaining pulses in SS-MM do not generally appear to be either in phase nor directly opposed in phase to the subsidiary pulses in C-R in any of the diagrams, Figs. 3 to 8, inclusive. Insofar as one can speak of "phase" in the case of such irregular pulses, there appear to be many cases where the difference in phase is about 90°. That is, the departure of the SS-MM from its mean is often near zero when that of the C-R from its mean is very large, and vice versa. This condition is particularly apparent in the difference curves of Figs. 7 and 8.

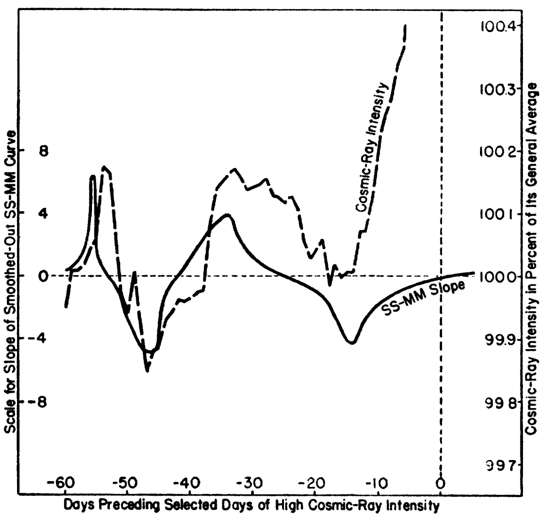

FIG. 11. These curves bear the same relation to Fig. 5, as do those of Fig. 9 to Fig. 3.

This situation suggests that there might be a close relation between the subsidiary pulses in C-R and the *rate of change* of SS-MM. It was this observation which led the writer to draw the smooth (dotted) curves to approximate the principal features of the SS-MM curves in Figs. 3 to 8, inclusive. In one instance the slopes of the jagged SS-MM curve were obtained directly and plotted against day numbers. As expected, the curve obtained was quite meaningless, because the slope is so highly susceptible to minor variations. Consequently, the smooth curves were drawn for all the SS-MM curves determined statistically, and the slope of the smooth curve was determined at each day number by a tangent meter. These slopes were then plotted as ordinates with day numbers as abscissae. The curves so obtained are shown in Figs. 9 to 14, inclusive, which give the slopes of the smooth (dotted) curves for SS-MM in Figs. 3 to 8 in that order. In Figs. 9 to 14 are also included the identical C-R curves given in the corresponding diagrams of Figs. 3 to 8.

It is seen that the SS-MM slope curves do appear to bear a rather definite relation to the subsidiary pulses in C-R, at least for the first two subsidiary pulses on either side of the primary which have been investigated here. In all cases the SS-MM slopes appear to be almost directly out of phase with the subsidiary pulses

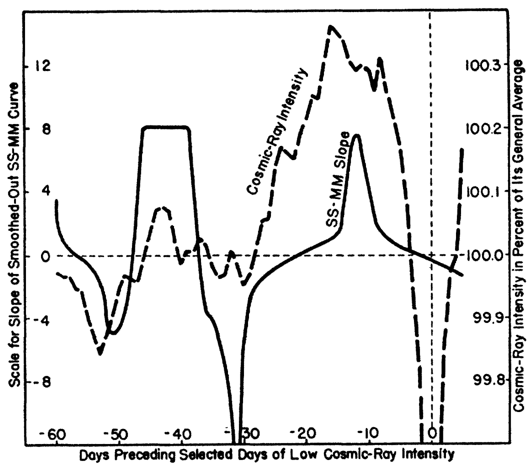

FIG. 12. These curves bear the same relation to Fig. 6, as do those of Fig. 9 to Fig. 3.

in C-R following their primary pulses. On the other hand, the SS-MM slopes appear to be almost directly in phase with the subsidiary pulses in C-R preceding their primary pulses. That is, if we neglect the minor fluctuations in SS-MM but consider only the general trends represented by the smoothed-out SS-MM curves, then it appears that previous to the primary pulses, the C-R is generally high when the SS-MM is increasing and low when the SS-MM is decreasing; while subsequent to the primary pulses, the C-R is generally high when the SS-MM is decreasing and low when the SS-MM is increasing. As in the case of the primary pulses with zero-days selected from all 18 months, the SS-MM exhibits a pulse in approximate phase

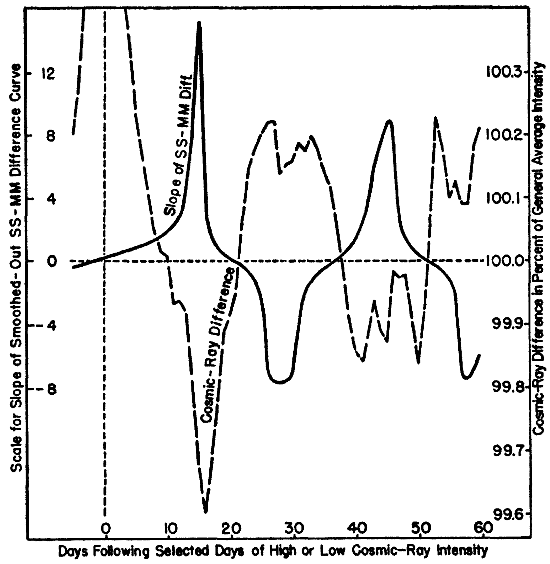

FIG. 13. These curves bear the same relation to Fig. 7, as do those of Fig. 9 to Fig. 3.

opposition to the primary pulse in C-R in every case, thus providing a slope of approximately zero at day number zero in each instance. It should be pointed out that the writer was influenced somewhat by the form of the eighteen-month curves in drawing the smooth curves for the several fifteen-month curves in the neighborhood of day-number zero. The pulse in SS-MM associated with the primary positive pulse in C-R in Fig. 1 is certainly quite symmetrical

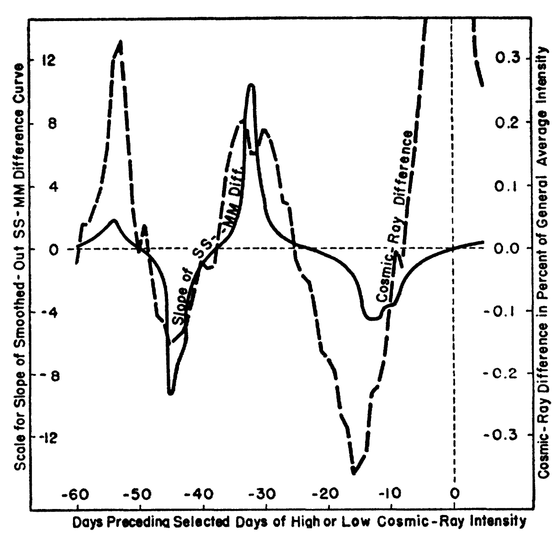

FIG. 14. These curves bear the same relation to Fig. 8, as do those of Fig. 9 to Fig. 3.

relative to day-number zero, and it appears that practically zero slope should certainly be assigned to any smoothed-out representation here. In the case of the pulse in SS-MM associated with the primary negative pulse in C-R in Fig. 2, there may be some argument in favor of a small positive slope in SS-MM at day-number zero. The base of this pulse appears to be fairly well centered relative to day-number zero, however, and it appears that the slope here must be rather small. This appears to be substantiated particularly in the case of the primary negative pulse in C-R in Fig. 4.

In contemplating the relations between the SS-MM slopes and the subsidiary pulses in C-R, it should be borne in mind that the latter represent deviations of generally less than one-fifth of one percent from the mean. These pulses are quite irregular, perhaps in part because there is a limit to the accuracy of measurement, and very likely because the C-R data have been corrected only for bursts and for variations in barometric pressure, while they are doubtless subject to variations associated with other phenomena. Moreover, they are brought out in each instance by statistical treatment of data extending over intervals of only 15 months. In view of these limitations, the relations indicated by the last six diagrams seem rather striking.

The unit of the scale for the SS-MM slope curves of Figs. 9 to 14, inclusive, represents a rate of change of SS-MM equal to 0.99 percent of its mean value of 2.5×10^{31} e.m.u. (ring-current representation) per day or 2.8×10^{24} e.m.u./sec. According to the definition[1] of SS-MM, its (ring-current) value for a single sunspot in terms of its area, A, is $M_c=0.0460H_mA^2/(A_m)^{\frac{1}{2}}$ on the assumption that its central magnetic field intensity is given by $H_c=H_m(A/A_m)^{\frac{1}{2}}$. A_m is the maximum value of A during the history of the sunspot (while it remains on the visible portion of the Sun) and H_m is the maximum value of H_c ever associated with it. Chapman[4] has shown that the magnetic flux leaving or entering the sunspot is approximately $N=AH_c/3$. On the above assumption regarding H_c, this becomes $N=H_mA^{\frac{3}{2}}/(3(A_m)^{\frac{1}{2}})$. There was a single unipolar sunspot group, M.W. 6618, which attained its maximum area during the period of this investigation (September 23, 1939), which was visible for thirteen days, whose maximum SS-MM was three times as great as the daily average for the total of all sunspots during the period, and whose maximum area was about three percent greater than the daily average value (1889 millionths of the Sun's visible hemisphere, or 5.82×10^{19} cm^2) of the total area of all sunspots observed during the period. Consequently, it may be of some interest to consider the magnetic flux that would be associated with a single sunspot with an area and corresponding SS-MM equal to the average values of these for all the sunspots for the whole period, according to the relations just stated.

Proceeding thus, the flux to be associated with the sunspot is found by dividing its SS-MM$(=M_c)$ by $3\times0.0460(A)^{\frac{1}{2}}=1.05\times10^9$ cm. This gives $N=2.4\times10^{22}$ e.m.u. The ratio of the rate of change of flux to the rate of change of its SS-MM$(=M_c)$ equals the product of the ratio of the respective functions, themselves, by the ratio of the corresponding powers of A occurring in these functions. Thus $(dN/dt)/(dM_c/dt)=0.75N/M_c$. Supposing the SS-MM of the imaginary representative sunspot to be changing at the rate corresponding to the unit of the scale for the SS-MM slope curves of Figs. 9 to 14, we obtain for its rate of change of flux, $dN/dt=0.75(2.8\times10^{24})/(1.05\times10^9)=2.0\times10^{15}$ e.m.u./sec. In Figs. 9 to 14, slopes of 8 units are not infrequently attained. On the basis of the foregoing assumptions, these would correspond to rates of change of flux associated with the representative sunspot which, according to Faraday's law, would produce an e.m.f. of 1.6×10^8 volts in a circuit linking the flux.

While these contemplations have dealt with a situation rather far removed from the actual physical situation, the magnitude of the e.m.f. obtained is at least interesting. It seems not unlikely that considerably larger e.m.f.'s may actually be produced in sunspots by electromagnetic induction. Several years ago Swann[5] deduced that stellar magnetic fields such as occur in sunspots can by electromagnetic induction

[4] S. Chapman, Mon. Not. R. Astr. Soc. **103**, 117 (1943).

[5] W. F. G. Swann, Phys. Rev. **43**, 217 (1933); J. Franklin Inst. **215**, 273 (1933).

impart to electrons energies corresponding to 10^{10} volts in a time interval of the order of one second without great magnetic field intensities, and that the rate of acquiring energy may reasonably be expected to be greater than the rate of loss by collision. He appears to have considered that 10^9 ev might approximate the upper limit in the case of the sun.

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The Radioactivities of Some High Mass Isotopes of Cobalt

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By neutron bombardments of samples of Ni enriched in isotopes 61, 62, and 64, respectively, the following radioactivities have been identified:

Co^{61}, β^- 1.3 Mev, no γ, half-life 1.75 hours,
Co^{62}, β^- 2.3 Mev, γ1.3 Mev, half-life 13.9 min.

Evidence is also presented for a 1.6-minute β- and γ-activity associated with Co^{62}, and for a 4- to 5-minute activity possibly of Co^{64}.

I. INTRODUCTION

THE availability of isotopically enriched nickel samples in milligram amounts has made possible the study of radiations from cobalt nuclei in the region of a few mass units above the well-known Co^{60}.

The nickel samples employed in this investigation were prepared by the calutron process here at the Radiation Laboratory. Only the sample enriched in Ni^{64} has been isotopically analyzed. The relative abundances for this sample were found to be:

Ni^{64}	Ni^{62}	Ni^{61}	Ni^{60}	Ni^{58}
61.6%	2.8%	1.0%	13.6%	21.0%

This article presents data on activities assigned to Co^{61} and Co^{62}, and also on an activity which is tentatively assigned to Co^{64}.

II. RADIOACTIVITY OF COBALT 61

In a letter to the editor of the Physical Review[1] a 1.75±0.05-hour half-life, β-activity was reported as a result of Co^{61}. Here we wish to present more complete evidence of this assignment, and data on the energy of the β-particle.

To help determine the isotope responsible for this activity, samples of nickel 61, 62, and 64 were placed one in front of the other, separated by paper, within a 0.035-in. cadmium shield in the neutron beam produced by 22-Mev deuteron bombardment of beryllium in the Crocker Laboratory 60-inch cyclotron. In all neutron bombardments of the nickel isotopes, the cadmium covering was used to minimize the $Ni^{64}(n,\gamma)Ni^{65}$ reaction yielding the 2.64-hour activity. The 1.75-hour activity appeared in each sample but much more strongly in connection with the Ni^{61} isotope than in the others.

Chemical identification was made as follows: A small sample of approximately 2-mg weight enriched in the isotope 61 was bombarded with neutrons as described above. The activated metal was dissolved in HNO_3, the nitrates were converted to chlorides, and 2 mg of cobalt and 2 mg of iron as chlorides were added. An iron fraction was separated by precipitation with NH_4OH and purified by solution in HCl and additional NH_4OH precipitations. The filtrate was acidified slightly with HCl, saturated with NH_4SCN, and cobalt was extracted with an

* Department of Physics, University of Utah, Salt Lake City, Utah.
[1] T. J. Parmley and B. J. Moyer, Phys. Rev. 72, 82 (1947).