II-4. Modulation

Chairmen:	H. V. Neher (Sept. 4, 5 and 6)	
	V. A. Sarabhai (Sept. 7, 8 and 13)	
	J. A. Simpson (Sept. 9)	
Secretaries:	Y. Kamiya (Sept. 4, 5, 6 and 9)	
	M. Wada (Sept. 7, 8 and 13)	

Date	Time	Paper Numbers
Sept. 4	11 : 30 – 13 : 30	from II-4-1 to II-4-4
Sept. 5	15 : 30 – 17 : 30	from II-4-5 to II-4-13
Sept. 6	11 : 30 – 13 : 30	from II-4-14 to II-4-17
Sept. 7	15 : 30 – 17 : 30	from II-4-18 to II-4-24
Sept. 8	15 : 30 – 17 : 30	from II-4-25 to II-4-29
Sept. 9	09 : 00 – 11 : 00	from II-4-30 to II-4-33
Sept. 13	15 : 30 – 17 : 30	from II-4-34 to II-4-38

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II-4-1. Fine Structure of Forbush Decreases

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Chree analysis of neutron monitor data (15-minute epochs) showed specific recurrent behavior following time of onset of geomagnetic storms clearly accompanied by Forbush effects. Of specific interest is a recurrent oscillation of intensity ($1\frac{1}{2}$-hour period, $1\frac{1}{2}$-2% peak-to-peak relative amplitude) observed for a narrow band of mid-latitude, sea-level stations during IGY. (The effect is not noted for IGC-59, a difference ascribed to a lower degree of solar activity.) Parallel analysis of horizontal geomagnetic intensity at Koror shows no resemblance between detailed cosmic-ray changes and the field variations. Arguments are presented to eliminate geocentric mechanisms controlling the effect, *e.g.* fluctuations of cut-off rigidity or variable modulation due to magnetized solar plasma being entrained in terrestrial radiation belts. Heliocentric particle-injection models are examined which have some satisfactory features to explain the oscillatory recurrence tendency: (1) clusters of trapped protons of solar origin moving in a distended solar magnetic field are considered with regard to their azimuthal drift around the sun and periodic encounters with the earth, and (2) "ringing" within the plasma behind the hydromagnetic shock front is considered with regard to resulting quasi-periodicity of intensity of trapped fields and the consequently different maximum rigidities of protons trapped within the travelling field regions, which successively encounter the earth.

§ 1. Introduction

We have heard much about the general structure of the Forbush effect and the spectrum of the participating particles[1),2),3)], but for these considerations it has been usually sufficient to study long-term variations (datum periods$\geq$1 hour long); such treatment could, however, conceal short-time features of the decrease which are indicative of part of the disturbance mechanism connecting sun and earth. The following study is concerned with this fine structure, being limited to the first few hours before and after the Forbush decrease.

Certain familiar features of some Forbush decreases are evidently related to finer details of mechanism: (1) the "increase-before-the-drop" of Yoshida and Wada[4)], which Dorman and others[5)] believe to result from the reflection of galactic radiation from the approaching hard-magnetized front of the approaching solar corpuscular stream, and (2) the "peak-in-the-trough" thought to result from guiding of low-energy particles of solar origin into the region of the earth along hydromagnetically-extended solar field lines[6)]. These are large-amplitude effects of relatively long duration and are not concealed by averaging over periods of an hour or more.

Our analysis is that of 15-minute variations of nucleonic intensity; the amplitudes of these variations are often not strongly outside those of statistical fluctuations, but they seem to be large enough to be worthy of detailed investigation.

§ 2. Initial Procedure and Subsequent Analyses

Geomagnetic storms were selected that were reported by at least five observatories (including Huancayo) and were accompanied by Forbush decreases in the daily average low-energy nucleonic intensity. Results of Chree analysis of pressure-corrected 15-minute Lincoln nucleonic data for sudden commencement (s.c.) and gradual commencement (g.c.) groups of storms have been previously reported[7)]. The two sets of variations found are remarkably alike if the s.c. zero epoch is superimposed over the minus-one epoch of the g.c. plot, indicating that the best reference epoch is not an s.c. epoch but the one containing the start of the first phase of the main disturbance[8)]. The 15-minute adjustment is a good approximation to the average duration of the s.c. preceding the first phase of the ensuing storm. (The time distribution of our 33 storm beginnings is quite flat over the 24-hour day, eliminating concern about systematic fluctuations related to daily variations.) Fig. 1 contains the results of this combination over the two species of storms.

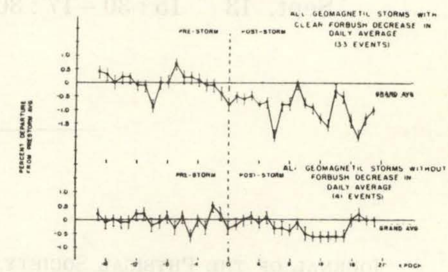

Fig. 1. Chree analysis of 15-minute nucleonic data (Lincoln) for IGY storms having clear Forbush decrease in daily average intensity. Standard error of total counts ($\sqrt{n}$) is shown.

Results of similar treatment of data from several other IGY stations for the group of events used in the Lincoln analysis are shown in Fig. 2. A latitude effect is evident. Thule and College show a definite rise of intensity during the second post-storm epoch. Mt. Washington shows a very quiet but persistent decrease tendency, but Mt. Washington (800 mb.) is the only station shown that is not near sea level, and there is a considerable low-energy particle dilution in the spectrum which would be present at the base of Mt. Washington. Middle-latitude stations (Kiel, Chicago, Lincoln) display considerable similarity, particularly in the first main decrease (at about the sixth epoch);

Kiel somewhat resembles Lincoln near the 14th epoch, where there seems to be a persistent increase. Lincoln and Chicago show the strongest recurrent pulsing, with a periodicity of about $1^1/_2$ hours, but Berkeley and Weissenau are very quiet for the events covered. There is some similarity between these oscillatory effects and those noted for low-energy particles in the outer radiation

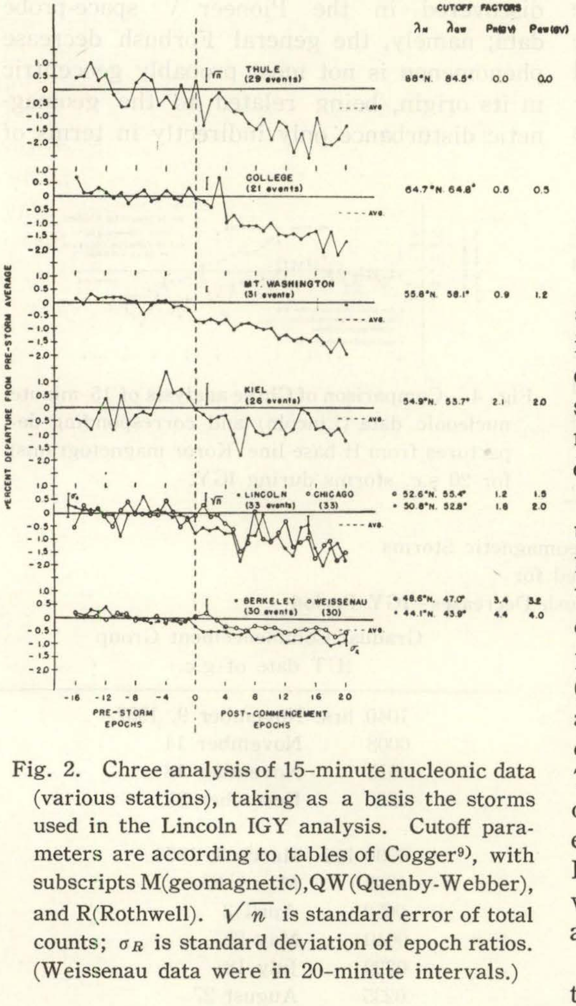

Fig. 2. Chree analysis of 15-minute nucleonic data (various stations), taking as a basis the storms used in the Lincoln IGY analysis. Cutoff parameters are according to tables of Cogger[9], with subscripts M(geomagnetic), QW(Quenby-Webber), and R(Rothwell). $\sqrt{n}$ is standard error of total counts; σ_R is standard deviation of epoch ratios. (Weissenau data were in 20-minute intervals.)

belt during a geomagnetic storm observed by scintillation counters aboard Explorer VI[10], where a fluctuation with a period of approximately 40 minutes was observed. Not shown, but calculated, were Climax and Huancayo, which had smooth trends, as Mt. Washington and Berkeley.

We now examine these oscillations to see if they are real, and if so, what might cause them and their sharp latitude dependence.

§ 3. Extended Analysis and Critique of Error

Fig. 3 contains the results of extending the Lincoln calculations beyond the 20 epochs previously used. The oscillation pattern persists for perhaps 4 cycles, and then the fluctuations begin to resemble "normal" ones[7]. Also seen in Fig. 3 are results for

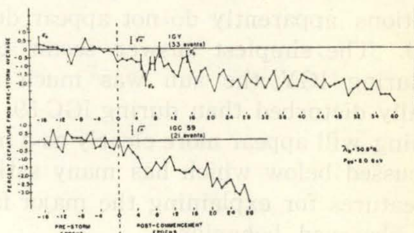

Fig. 3. Extended Chree analysis of 15-minute nucleonic data (Lincoln) for IGY and IGC-59 storms.

storms occurring during IGC-59, where there is no oscillatory phenomenon; there is, however, a strong coincidence with the first substantial dip of intensity in the IGY recurrence pattern. Also, the IGC-59 average decrease seems considerably deeper.

Two different error indicators have been used: (1) unmarked error bars which are proportional to the statistical standard errors $\sqrt{n}$ (where n is the total number of counts contributing to each point), and (2) some representative values of the standard deviation (σ_R) of epoch ratios. Epoch ratios are defined as follows: for each event the average value of intensity over all epochs was calculated. Then, for each epoch of each event, the ratio of the value of the epochal intensity to the event average was computed. Thus, for Lincoln, 33 ratios of uncorrected intensity were found for each epoch. σ_R is the standard deviation of these ratios for the epoch.

The use of epoch ratios tends to eliminate the effect of different intensity levels generally found for the events, differences due, for example, to seasonal variations and to the occurrence of some Forbush effects during recovery from a previous decrease. Not eliminated, however, are effects due to rapidly-changing barometric pressure over the 9 hours spanned for each event. The use of epoch ratios of uncorrected intensity thus should give the least favorable estimate of uncertainty.

The σ_R for Lincoln are about 50% larger than the $\sqrt{n}$. For Berkeley the two values are almost indistinguishable. The σ_R are approximately equal for all Lincoln points (not all shown) and from peak to trough there are easily $3\sigma_R$.

We thus conclude that our IGY recurrence effect is real, but we must explain why the oscillations apparently do not appear during IGC-59. The simplest answer seems to be that during IGY the sun was much more generally disturbed than during IGC-59. The reasoning will appear more clearly as a model is discussed below which has many satisfactory features for explaining the major facets of the observed behavior.

§ 4. Models for the Phenomenon

Two geocentric and two heliocentric models are considered to explain the observed fine-structure recurrence tendency.

A Chree analysis of deviations from pre-storm average departure from the horizontal geomagnetic field base-line value (Koror) is shown in Fig. 4 with the Lincoln nucleonic results (s.c. storms). The geomagnetic field, where disturbance daily variation and other localized fluctuations are quite negligible, did not show the fluctuation pattern seen in the cosmic rays. Clearly, the cosmic-ray recurrent behavior does not have any parallel in the details of the superimposed geomagnetic disturbances. Thus in fine structure we tend to confirm what Lockwood[3] has concluded for the Forbush decrease spectrum and what Simpson and co-workers[11] have discovered in the Pioneer V space-probe data; namely, the general Forbush decrease phenomenon is not most probably geocentric in its origin, being related to the geomagnetic disturbance only indirectly in terms of

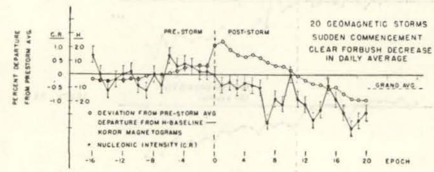

Fig. 4. Comparison of Chree analysis of 15-minute nucleonic data (Lincoln) and corresponding departures from H-base line (Koror magnetograms) for 20 s.c. storms during IGY.

Key List of Geomagnetic Storms
used for
Chree Analysis of Forbush Decreases—IGY Period

Sudden Commencement Group (UT date of s.c.)

1557 hrs.	August 3, 1957
1930	August 29
0314	September 2
2154	September 12
0235	September 23
0016	September 29
2241	October 21
0155	November 26
0937	December 19
0125 hrs.	February 11, 1958
1642	February 16
1212	March 14
0747	July 8
1636	July 21
0622	August 17
0227	August 22
0843	September 3
1003	September 30
0315	October 22
0035	December 4
1546	December 17

Gradual Commencement Group (UT date of g.c.)

1040 hrs.	November 9, 1957
0008	November 14
0615	November 18
0200	December 31
0930 hrs.	March 3, 1958
1203	March 25
0652	April 2
0040	May 29
0220	July 18
0235	August 27
1020	September 4
0930	September 16

a common cause. Thus our oscillation effect with its 1.5 hour period and amplitude of 1.5% to 2% cannot easily be ascribed to changing geomagnetic field values which result in alterations of cut-off rigidity.

A geocentric modulation model is next considered. Akasofu and Chapman[12] have proposed the peeling-off of quantities of the solar plasma stream, forming a third radiation belt to yield a suitable equatorial ring current to account properly for various phases of geomagnetic storms. If these quantities of magnetized matter are scattered from the stream in such a way that they form a variable modulation screen as they drift around the earth, then similar fluctuations (with amplitudes of several gamma) should appear in the values of local geomagnetic fields. Analysis of the Koror data (Fig. 4) shows that such fluctuations are not observable, indicating that the suggested ring current is *not* distributed piecewise during the beginning of the geomagnetic storm when our oscillatory recurrence tendency prevails.

Next, we consider the possible effect of solar Van Allen belts[13]. One description of the storm-producing mechanism is that the solar corpuscular stream carries solar magnetic field lines deep into the interplanetary space, eventually enveloping the earth's orbit[14]. Let there be injected onto these distended field lines bursts of energetic protons from the sun and assume that these trapped particles eventually have very steep pitch angles in the field, with mirror points very near the ecliptic plane. There is also azimuthal drift of these groups of particles as they spiral around their solar field line. A drift frequency of one revolution per 1.5 hours (our observed periodicity) is assumed for the group as it recurrently strikes the region of the earth. The first encounter essentially took place when the storm began, the second 1.5 hours later, etc. The cyclotron radii at 1 A.U. from the sun for such drifting protons in a plasma-trapped field of 10^{-5} gauss is approx. 1/3 A.U.[15] (These calculations are for a pure dipole field which our distended solar field approximates very poorly. But the actual field gradient will be smaller and thus the orbits tighter than given by the dipole approximation.) Particles with this cyclotron radius and 90° pitch angles have a rigidity of approx. 17 GeV/c, a lower limit for the trapped particles, this can produce a latitude effect for the oscillation property. The usual geomagnetic cutoff will prevail in the lower latitudes, and in the higher latitudes and altitudes the low-energy particle dilution would tend to obscure the oscillations. (The early brief maximum at Thule and College could result from early guiding-in of low-energy particles directly from the sun, along distended field lines, while the small cutoff is temporarily overcome by deep penetration of the body of the magnetic storm cloud into the earth's field[16].)

We have found a reasonable momentum for the particles orbiting in such solar radiation belts, after forcing them to display the proper drift frequencies. The main oscillatory effect seems to last for four cycles (approximately 7 hours), the time required for the thickness of the main cluster of particles to pass the 1 A.U. sphere centered at the sun. Diffusion of the clusters into shells also takes place. The radial distance travelled by the cluster in this time is approx. 1/5 A.U., a value consistent with the cyclotron radii of the particles with steep pitch angles, especially as the field is not truly dipole.

The smoothed trend of Fig. 3 probably represents the exclusion of galactic radiation by the general plasma modulation mechanism as it is diluted with solar particles of different energies trapped in the corpuscular stream at various times[17]. The particles of rigidity <10 GeV, say, compose a variable but non-periodic dilution component. This heliocentric model should also explain the IGC-59 behavior, which shows similar starting features as the IGY but no oscillations. We say that the sun was not sufficiently active during IGC-59 to inject high-energy particles often enough to give rise to the oscillatory recurrence tendency. This is not to imply that the oscillations *happened every time* there was a Forbush decrease during IGY, but we are discussing a recurrence tendency and its marked difference for periods of differing degrees of solar activity.

Fourth, we consider the possibility of "ringing" within the plasma behind the hydromagnetic shock front[18], which causes quasi-periodic fluctuations of the magnetic field trapped in the impinging plasma. The range of rigidities of protons trapped in these fields would be 1.6 to 16 GeV/c for fields 10^{-5} to 10^{-4} gauss, respectively, where the ringing period is 1.5 hours and the stream velocity is 1000 km/sec.

This second heliocentric model is less satisfactory in explaining the difference between the IGY and IGC-59 results, but it is more plausible for the latitude effect. The first model seems to demand a highly-peaked rigidity and pitch-angle distribution to explain the observed latitude dependence, causing a major objection, although the electrodynamics of the expanding field lines, coupled with less selective conditions for injection and loss of particles, could conceivably give rise to these special distributions near the orbit of the earth.

Acknowledgments

We are grateful to our colleagues in the many IGY stations (particularly Professors Pomerantz, Korff, Lockwood, Bagge, Simpson, and Brown) who sent us the detailed neutron-monitor data used in this study. Thanks are also due to Richard Altrock, David B. Gustavson and Tomoshige Suda for patient help with the calculations. This work has been performed with support of National Science Foundation Grant G 14040.

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Discussion

Sarabhai, V.A.: (1) Did Chasson consider geomagnetic data from higher latitude stations than Koror?

(2) Suggested that station (like as Chicago) would show possible fluctuations more strongly than at the poles or equator if an effect due to geomagnetic cut off changes is involved.

Chasson, R.L.: (1) We considered that Tucson did not show any more fluctuations than Koror.

(2) Agreed.