Energy Dependence of Transient Changes in the Primary Cosmic-Ray Spectrum*

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(Received June 12, 1959)

Quantitative comparisons are made between the cosmic-ray intensity variations observed by a Geiger counter telescope and ionization chamber at a high geomagnetic latitude, high latitude neutron monitors at sea level, and at two different mountain altitudes, Geiger counter telescopes situated 40 meters of water equivalent underground, and a neutron monitor and Geiger counter telescopes at a low geomagnetic latitude. Long-term and short-term variations are considered. As the intensity variations were large, and as the instruments were all of good statistical accuracy, considerable reliance can be placed in the determinations. It is shown that similar comparisons published by other investigators are in agreement with these determinations, provided adequate allowance is made for the altitudes at which the data were obtained. Writing the differential energy spectrum of the primary cosmic radiation as $j(E)$, and measuring E in Bev, the inter-instrument comparisons are used to show that the average spectral changes approximate to the law $\delta j(E)=\text{const}\,(1+E)^{-\beta}j(E)$; where $\beta\approx 0.9$ for short-term variations, and $\beta\approx 1.2$ for long-term variations.

It is shown that the amplitude of the long-term variation is markedly dependent upon altitude. Some evidence is presented that there might be a north-south asymmetry in the long-term variation, the amplitude being greater in southerly directions.

INTRODUCTION

In an earlier paper[1] neutron data obtained near Hobart (geomagnetic latitude $(\lambda)=52°$S) were compared with neutron data from Mawson ($\lambda=73°$S) and Lae ($\lambda=16°$S), and with meson data from Hobart. From these comparisons, a number of qualitative conclusions were reached regarding the changes which occur in the rigidity spectrum of the primary cosmic radiation during short- and long-term variations.

Other cosmic-ray detectors are operated by the University of Tasmania, and the present paper presents further inter-instrument comparisons based upon the data from these detectors. Comparisons with data obtained by other investigators are also made. On the basis of these, and the earlier inter-instrument comparisons,[1] the average functional dependence of spectral change upon energy is determined for long- and short-term events.

EQUIPMENT

The University of Tasmania's instruments from which the data considered in this paper were obtained are listed in Table I. The geometries of the neutron monitors are similar to those recommended for use during the International Geophysical Year.[2] The Mawson monitor is operated by the Australian Antarctic Research Expeditions, for the conduct of whose cosmic-ray program the University of Tasmania is responsible.

The Geiger counter telescopes have been described elsewhere.[3] Briefly, they consist of three square, equally spaced trays of Geiger counters. For the period considered here, the separation of the extreme trays was equal to the sensitive length of the counters (that is, a cubical geometry). There is 10 cm of lead absorber between the bottom two trays.

A description of the underground observatory, and a detailed report of the intensity variations observed by the semicubical telescopes will be given in another paper. In brief, the telescopes comprise three trays of Geiger counters, the sensitive area of each tray being of dimensions 1 m×1 m, the extreme tray separation being 0.5 m.

The ionization chamber is similar to the well-known Carnegie Type C instrument.[4] It is filled with commercial nitrogen to a pressure of 60 atmospheres, and is shielded at the top, and on the four sides, by 10 cm of lead. Figure 1 is a simplified block diagram of the re-

TABLE I. Some details of the University of Tasmania's observational program, summarizing the station locations, the instruments from which the data used in this paper were obtained, and the mean hourly counting rates of the instruments. These particulars apply to the period subsequent to June 1, 1957. The Hobart neutron monitor is 725 meters above sea level. All the other detectors are within 100 meters of sea level.

Location	Geomagnetic latitude	Instrument	Mean hourly counting rate
Lae, New Guinea	16°S	Duplex neutron monitor	8000
		Two cubical telescopes	48 000 each
Hobart, Tasmania and environs	52°S	Duplex neutron monitor	35 000
		Cubical telescope	130 000
		23-liter ionization chamber	
		Two semicubical telescopes 40 m.w.e. (meters water equivalent) underground	34 000 each
Mawson, Antarctica	73°S	Duplex neutron monitor	33 000

* This work was carried out during tenure of an Australian Atomic Energy Commission studentship, and later, a General Motors Holden Research Fellowship.

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[1] K. G. McCracken, Phys. Rev. **113**, 343 (1959).

[2] J. A. Simpson, *Annals of the International Geophysical Year* (Pergamon Press, New York, 1956), Vol. 4, p. 351.

[3] N. R. Parsons, Australian National Antarctic Research Expedition Interim Report, No. 17, 1957 (unpublished).

[4] A. H. Compton, E. O. Wollan, and R. D. Bennett, Rev. Sci. Instr. **5**, 415 (1934).

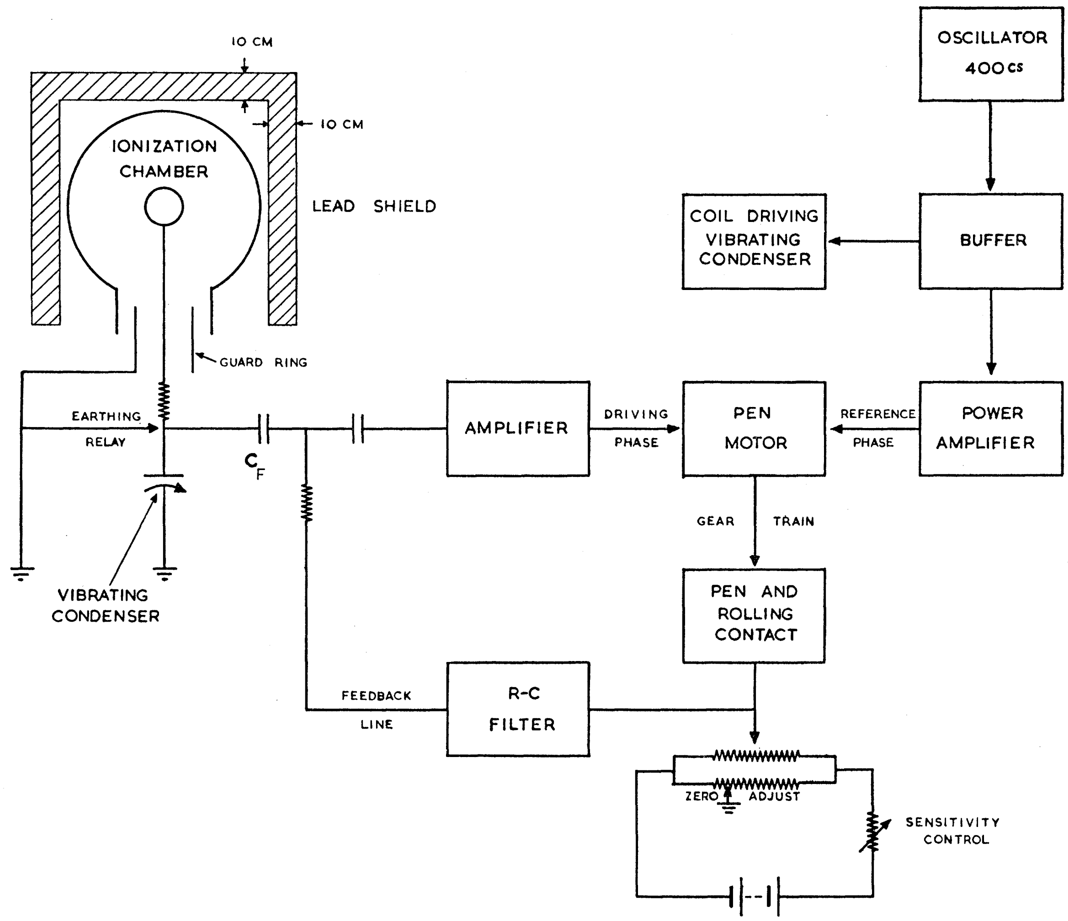

FIG. 1. Simplified block diagram of the Hobart ionization chamber. The chart deflection produced by a given change in cosmic-ray intensity is determined by the setting of the sensitivity control.

cording apparatus used in conjunction with the ionization chamber. The collection electrode is connected to a vibrating condenser, the ac signal from which, after amplification, energizes one coil of an induction motor, a reference signal 90° out of phase being fed to the other coil. The motor drives a pen across the recording chart, and, at the same time, a roller on the pen carriage picks a dc voltage off a precision wound resistance strip. A fixed fraction of this dc voltage is fed back to the ionization chamber collection electrode via the feedback condenser, C_F. The circuits have been so arranged that the pen always moves to the point where the feedback voltage cancels out the voltage across the vibrating condenser. Thus the voltage across the insulator between the collection electrode and the earthed guard ring is always very small, and consequently leakage currents are negligible. By using air as the dielectric, and wide spacing of the plates, leakage across C_F is also reduced to a negligible figure.

Radioactive contamination of the chamber and its surroundings contributes to the total ionization current. By comparing the ionization currents observed at ground level and 40 m.w.e. underground, and from a knowledge of the ratio of the meson intensities at the two locations (calculated from observations made with the semicubical telescopes), the contribution due to radioactive contamination was calculated. This has enabled observed variations in chart deflection to be converted into percentage changes in the cosmic-ray ionization current.

CORRECTION FOR ATMOSPHERIC CHANGE

The neutron data have been corrected using an attenuation length of 145 g cm^{-2}. It has been shown recently that this value is about 5% in error[5]; however, it was not deemed necessary to recalculate the results presented in this paper, as the neutron variations observed at high latitudes during the periods considered were in excess of 7%, and therefore the residual variations of atmospheric origin (of the order of $\pm 0.5\%$) were relatively unimportant.

[5] K. G. McCracken and D. H. Johns, Nuovo cimento **13**, 96 (1959).

TABLE II. Correction coefficients for the Hobart meson detectors. The negative decay coefficients refer to the height of the 125-millibar level.

Hobart cubical telescope	
Mass coefficient:	−1.63% per cm of mercury
Negative decay coefficient:	−4.88% per km
Hobart ionization chamber	
Mass coefficient:	−1.80% per cm of mercury
Negative decay coefficient:	−5.02% per km
Hobart underground telescopes	
Mass coefficient[a]:	−0.85% per cm of mercury
Positive decay coefficient[a]:	+0.07% per °C (temperature of 100 to 200 millibar stratum)

[a] See reference 7.

Radiosonde information indicates that the day-to-day changes in the temperature of the atmosphere at Lae are small, and a simple correction of the meson data for barometric change was deemed adequate. For the present analyses, the Lae meson data were corrected using the Trefall's theoretical coefficient of −2.31% per cm of mercury.[6]

The coefficients used in the correction of the Hobart cubical telescope, ionization chamber, and underground telescope[7] data are summarized in Table II. They were all obtained from correlation analyses of the cosmic-ray and atmospheric data observed during 1957 and early 1958. As primary intensity variations introduce errors into such analyses, only those days on which the Hobart neutron counting rate lay within a range of 4 % were employed, thereby limiting the non-meteorological variations in the meson data.

SHORT-TERM VARIATIONS

Let R_i be the daily mean counting rates observed by the ith recorder. The measure of relative amplitude $(\sigma_1/\bar{R}_1)(\bar{R}_2/\sigma_2)$ defined in an earlier paper[5] will be used to compare the percentage variations observed by recorders 1 and 2, and will be called the recorder 1-recorder 2 relative amplitude. $[\sigma_i=\sum(X_i-\bar{X}_i)^2/(N-1).]$ This measure is used in preference to the simpler measure $(\delta R_1/\bar{R}_1)(\bar{R}_2/\delta R_2)$, where δR_i is the difference between the minimum value of R_i and the value prior to the event, for the following reasons:

(1) On plotting scatter diagrams of the data obtained at two widely separated stations during the onset and recovery of Forbush-type decreases, it is sometimes found that the point corresponding to the day of minimum intensity deviates considerably from the line defined by the general trend of all the points. This is believed to be due to the marked, quickly changing asymmetries which occur in the Forbush decrease mechanism during the first one or two days of the event.[8] The $(\delta R_1/\bar{R}_1)(\bar{R}_2/\delta R_2)$ measure, being based on these anomalous points, therefore includes a contribution produced by the asymmetry, and is not a good indication of the relative changes in the counting rates produced by the average change in the energy spectrum. The $(\sigma_1/\bar{R}_1)(\bar{R}_2/\sigma_2)$ measure, being based on the general trend, which is predominantly that of the data obtained after the disappearance of the asymmetries, is therefore to be preferred.

(2) There are small meteorological variations remaining in the corrected data. The meteorological conditions at Hobart exhibit a rough periodicity of about 5 to 7 days. While the meteorological contributions will broaden the scatter diagrams of data 1 against data 2, they will not seriously affect the general trend, as the recovery of all the events considered occupied considerably longer periods, namely, from 10 to 20 days. Thus the $(\sigma_1/\bar{R}_1)(\bar{R}_2/\sigma_2)$ measure will not be very sensitive to the residual meteorological contributions. No such compensation for meteorological conditions occurs when using the $(\delta R_1/\bar{R}_1)(\bar{R}_2/\delta R_2)$ measure.

Using the $(\sigma_1/\bar{R}_1)(\bar{R}_2/\sigma_2)$ definition, the relative amplitudes appropriate to a number of instruments were calculated for a number of the subintervals used in reference 1. The results are listed in Table III. In the case of the neutron monitor-underground meson relative amplitude, the fragmentary nature of the data from the underground observatory prevented the above measure from being used, and the less accurate $(\delta R_1/\bar{R}_1)\times(\bar{R}_2/\delta R_2)$ measure was employed.

An earlier series of inter-instrument analyses[5] has shown that, in the case of the neutron component, short-term event amplitude is a function of altitude. Figure 2 reproduces the average dependence found.

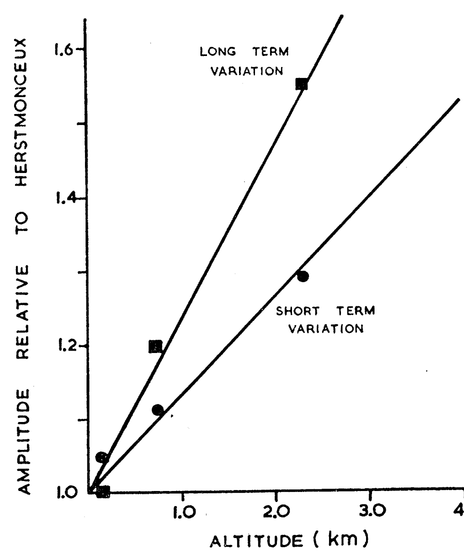

FIG. 2. The amplitude of variations in the counting rate of a neutron monitor as a function of altitude. Short-term variations (black circles) and the long-term variation (black squares) are considered. Event amplitudes are expressed relative to those observed at Herstmonceux (altitude=20 meters). The data were obtained at observatories at approximately the same geomagnetic latitude (52°<|λ|<49°).

[6] H. Trefall, Proc. Phys. Soc. (London) **A68**, 953 (1955).
[7] R. B. Taylor (unpublished).
[8] A. G. Fenton, K. G. McCracken, D. C. Rose, and B. G. Wilson, Can. J. Phys. **37**, 970 (1959).

TABLE III. The relative amplitudes (R.A.) of the variations observed by a number of the recorders operated by the University of Tasmania. Standard errors are given. The correlation coefficients (r_{12}) between the data used to derive the various values of the relative amplitudes are listed (year—1957).

Relative amplitude \ Period		June 1– June 28	June 29– July 28	July 29– Aug. 24	Aug. 24– Sept. 20	Sept. 21– Oct. 19	Oct. 20– Nov. 13	Nov. 14– Dec. 10	Mean value
Mawson neutron–	R.A.	1.93±0.21	2.03±0.11	3.45±0.40	2.80±0.24	poor	2.07±0.17	2.66±0.25	2.49
Lae neutron	r_{12}	0.89	0.96	0.88	0.91	correlation	0.92	0.88	
Hobart telescope–	R.A.	1.43±0.14	1.48±0.04	1.37±0.08	1.43±0.09	1.57±0.32	1.50±0.10	1.83±0.17	1.52
Lae telescope	r_{12}	0.91	0.99	0.97	0.96	0.78	0.97	0.94	
Hobart neutron–	R.A.	1.76±0.10	2.30±0.07	2.16±0.20	2.94±0.12	2.67±0.21	1.79±0.13	2.32±0.19	2.28
Hobart telescope	r_{12}	0.98	0.99	0.92	0.98	0.95	0.95	0.95	
Hobart neutron–	R.A.	1.72±0.10	2.46±0.17	2.12+0.19	3.08±0.25	2.48±0.30	2.52±0.18	2.49±0.16	2.41
Hobart ion	r_{12}	0.97	0.93	0.91	0.92	0.87	0.94	0.95	
Lae neutron–	R.A.	1.30±0.13	1.36±0.09	1.10±0.11	1.38±0.06	1.31+0.16	1.30±0.10	1.58±0.23	1.33
Lae telescope	r_{12}	0.93	0.95	0.91	0.98	0.87	0.94	0.89	
Hobart ion–	R.A.	1.09±0.06	0.92±0.05	0.96±0.09	1.07±0.08	0.98±0.08	0.74±0.05	0.90±0.07	0.95
Hobart telescope	r_{12}	0.97	0.96	0.92	0.95	0.93	0.95	0.95	
Hobart neutron– Underground telescope	R.A.				7.3 ±0.6		7.3 ±0.7		7.3

COMPARISON WITH THE LITERATURE (SHORT-TERM VARIATIONS)

A number of investigators have published the results of relative amplitude determinations. However, these results do not all agree with those presented in Table III. In particular, the values of the Hobart telescope–Lae telescope relative amplitude are considerably greater than the well-established value of 1.1 for the Cheltenham ion–Huancayo ion relative amplitude,[9,10] and further, the values of the Hobart neutron–Hobart ion relative amplitude are about half those found by Fonger for the Climax neutron-Freiburg ion relative amplitude.[11]

Various measures of relative amplitude have been used by earlier investigators. Thus writing the regression coefficients between the percentage variations in data 1 and 2 as b_{12} and b_{21}, the measures b_{12}, $1/b_{21}$, $\frac{1}{2}(b_{12}+1/b_{21})$, $(\delta R_1/\bar{R}_1)(\bar{R}_2/\delta R_2)$ (defined in previous section) and regression coefficients derived by assigning weights[12] to the data have all been used in addition to the measure $(\sigma_1/\bar{R}_1)(\bar{R}_2/\sigma_2)$ employed in this paper. It has been shown[13] that when the correlation coefficient $r_{12}>0.8$, the three measures $\frac{1}{2}(b_{12}+1/b_{21})$, $(\sigma_1/\bar{R}_2)\times(\bar{R}_2/\sigma_2)$ and a weighted regression coefficient based on weights applicable to the data from the University of Tasmania's recorders[12] are in reasonable agreement, while the agreement with either b_{12} or $1/b_{21}$ is poor for $r_{12}<0.9$. Thus for comparison purposes, whenever an author has listed either b_{12} or $1/b_{21}$, and has also given the correlation coefficient r_{12}, then σ_1/σ_2 has been calculated ($b_{12}=r_{12}\sigma_1/\sigma_2$), and used in the following discussion.

Altitude Effect

As the relative amplitudes reported in the literature have been based upon data obtained at various altitudes, an examination must be made of the dependence of event amplitude upon altitude. This has been done already for the neutron component[5] (Fig. 2).

Table IV summarizes the published data on the altitude effect in the case of the meson component at high geomagnetic latitudes. From this table it appears that the event amplitude is greater at the Hafelekar than at sea level, and the extrapolation of this meager data suggests that the percentage variations observed by a shielded ionization chamber at 3350 m will be about 1.6 to 2.0 times those observed at sea level.

To determine the altitude effect at a low latitude the ionization chamber data from Mt. Norikura[14] (2840-m altitude, $\lambda=26°$N) were compared with those from Tokyo[14] (20-m altitude, $\lambda=26°$N) the relative amplitude averaged over seven of the short-term events occurring during 1957 being found to be 1.7. Unfortunately, while both chambers were shielded with 10 cm of lead, the Tokyo chamber was situated under a

TABLE IV. Comparison of ionization chamber variations observed at various altitudes with those observed at sea level. All observatories are at geomagnetic latitudes between 45° and 50°.

Detector 1 Location	Altitude (meters)	Detector 2	1–2 Relative amplitude	Reference
Christchurch	8	Cheltenham	0.81±0.21	a
Freiburg	240	Cheltenham	0.77	b
Canberra	800	Cheltenham	1.01±0.15	a
Hafelekar	2300	Cheltenham	1.40±0.03	a

a S. Yoshida and Y. Kamiya, J. Geomag. Geoelect. 5, 136 (1953).
b W. H. Fonger, Phys. Rev. 91, 351 (1953).

9 S. E. Forbush, Phys. Rev. 54, 975 (1938).

10 S. E. Forbush, J. Geophys. Research 59, 525 (1954).

11 W. H. Fonger, Phys. Rev. 91, 351 (1953).

12 Using weights which reflect the errors in the corrected data. It has been shown[13] that for the high counting rate neutron monitors and telescopes operated by the University of Tasmania, the standard deviations of the daily means of the corrected data are all between 0.2% and 0.4%, regardless of the figure to be expected from statistical fluctuations alone. This is believed to be due to the presence of uncorrected meteorological effects, and to a lesser extent, equipment variations.

13 K. G. McCracken, Ph.D. thesis, University of Tasmania (unpublished).

14 I am indebted to Dr. Miyazaki for providing me with these data.

TABLE V. The dependence of event amplitude upon latitude for ionization chamber data. The figures apply to short-term events. Only a few events were used to obtain the Teoloyucan and Hafelekar comparisons.

Detector 1 Location	λ	Detector 2 Location	λ	1–2 Relative amplitude	Reference
Cheltenham	50°	Huancayo (3350 m)	1°	1.11, 1.06, 1.1	a, b, c
Teoloyucan (2285 m)	30°	Huancayo (3350 m)	1°	1.58	a
Hafelekar (2300 m)	48°	Huancayo (3350 m)	1°	1.59	a

[a] S. E. Forbush, Phys. Rev. **54**, 975 (1938).
[b] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).
[c] W. H. Fonger, Phys. Rev. **91**, 351 (1953).

further 40 cm of concrete (1.1 meters water equivalent). As a rough estimate, taking the concrete shield to be the equivalent of 1.1 m.w.e. of the atmosphere, the percentage variations observed by an ionization chamber shielded with 10 cm of lead at 3350 m would be about 1.6 times those observed by a similar instrument at sea level.

Latitude Effect

The published data on the dependence of event amplitude upon latitude are given in Table V. The most reliable of these determinations is the Cheltenham–Huancayo relative amplitude, and this has led a number of investigators to conclude that event amplitude is only slightly latitude dependent.

From the altitude effect for ionization chamber data deduced earlier, and taking the Cheltenham–Huancayo relative amplitude to be 1.1, the high latitude variations at 3350 m are estimated to be between 1.7 and 2.2 times those at Huancayo. Thus the value of 1.58 for the Teoloyucan–Huancayo relative amplitude is reasonable, whereas earlier investigators have regarded it with suspicion.[9,11]

As there is still a marked altitude effect at low latitudes ($\lambda=26°$), the variations at sea level at the equator will be less than those at Huancayo. Assuming that the value of 1.6 estimated to be the altitude effect between 3350 m and sea level at $\lambda=26°$ also applies at the equator, and using the observed value of 1.1 for the Cheltenham–Huancayo relative amplitude, the high latitude-low latitude relative amplitude at sea level is estimated to be about $1.1\times1.6\approx1.7$. Bearing in mind the uncertainties in the derivation of this result, it is not inconsistent with the value of 1.5 found for the Hobart–Lae relative amplitude applicable to the cubical meson telescope data (Table III).

Neutron-Meson Relative Amplitude

Table VI lists the various values which have been published for the high latitude neutron-meson relative amplitude. While all the meson detectors were situated near sea level, a number of the determinations were based upon neutron data obtained at mountain altitudes. To permit comparison, the values of the relative amplitudes which would have been obtained if the neutron monitors had been at sea level have been estimated using Fig. 2.

There is a reasonable agreement between the values found using the meson telescope data from Manchester, Ottawa, Resolute, Hobart, and Herstmonceux. The majority of the values found using ionization chamber data are somewhat higher, but can be reconciled to the values found using the telescope data by taking into account the value of 0.95 found for the average ionization chamber-cubical telescope relative amplitude at Hobart, and the fact that this is somewhat variable (Table III).

The high value of 3.8 derived from the Climax-Freiburg determination for a period during 1951 suggests that the neutron monitor-ionization chamber relative amplitude has changed with time.[15] While this hypothesis is supported by the data presented in reference 1, it must be accepted with some caution, as the Climax-Cheltenham (1951) and the Manchester (1953) determinations listed in Table VI are not inconsistent with the 1957 values.

In the majority of cases then, the results reported in the literature can be reconciled to those presented in Table III if allowance is made for the altitudes at which the data were obtained. Further, in view of the fact

TABLE VI. Average values of the short-term neutron-meson relative amplitude (R.A.). When neutron data have been obtained at mountain altitudes the relative amplitude which would have been observed if the monitor had been at sea level has been estimated [written $(\text{R.A.})_S$]. All data have been obtained at geomagnetic latitudes >48°.

Detector 1 (neutron)	Detector 2 (meson)	R.A.	$(\text{R.A.})_S$	Reference
Manchester	Manchester telescope	2.3	2.3	a
Ottawa	Ottawa telescope	1.9	1.9	b
Resolute	Resolute telescope	2.2	2.2	b
Hobart	Hobart telescope	2.3	2.1	c
Herstmonceux	Herstmonceux telescope	2.3	2.3	d
Climax	Freiburg ion	5.5	3.8	e
Climax	Cheltenham ion	4.0	2.8	e
Syowa	Syowa ion	2.8	2.8	f
Climax	Cheltenham ion	3.0	2.1	g
Hobart	Hobart ion	2.4	2.2	c

[a] I. J. van Heerden and T. Thambyahpillai, Phil. Mag. **46**, 1238 (1955).
[b] A. G. Fenton, K. B. Fenton, and D. C. Rose, Can. J. Phys. **36**, 824 (1958).
[c] Table III of this paper.
[d] Derived from data supplied by the Astronomer Royal and Mr. D. R. Palmer. The same subintervals were used for the analysis of the Herstmonceux and the Hobart data.
[e] W. H. Fonger, Phys. Rev. **91**, 351 (1953).
[f] M. Kodama and Y. Miyazaki, Rept. Ionosphere Res. Japan **11**, 99 (1957).
[g] H. V. Neher and S. E. Forbush, Phys. Rev. **87**, 889 (1952).

[15] An alternative explanation would be that too small a correction has been made for the radioactive contamination of the Freiburg chamber. This would result in the derived percentage variations being smaller than those in the cosmic-ray ionization current, and thus the Climax-Freiburg relative amplitude would be too big. This would explain why the Climax-Freiburg and the Climax-Cheltenham determinations, while referring to the same period during 1951, are substantially different.

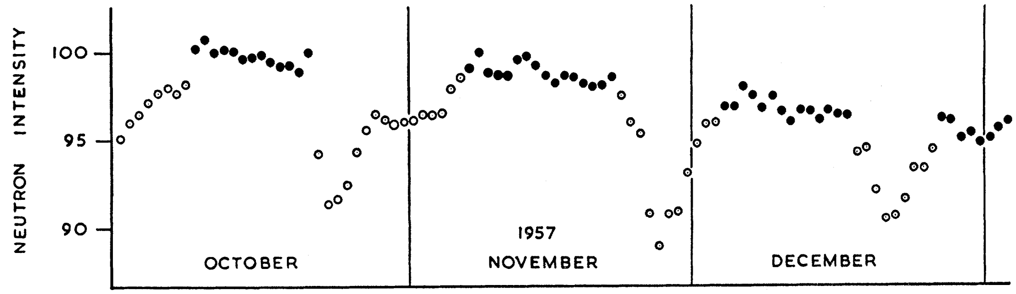

FIG. 3. Illustrating the selection of disturbed days (open circles) and undisturbed days (filled in circles). The Hobart daily mean, pressure corrected neutron intensities for the period October-December, 1957, are plotted.

that the variations during 1957 were large, and since the instruments operated by the University of Tasmania provide data of good statistical accuracy, it is considered that considerable reliance can be placed in the results given in Table III.

LONG-TERM VARIATIONS

The monthly mean undistrubed neutron intensity was defined in reference 1. Recapitulating, a selection was made of those days on which the Hobart neutron intensity was unaffected by short-term variations. In the selection, the view was taken that disturbed days were (1) those during the onset and recovery from Forbush-type decreases, (2) those during which the intensity was showing a systematic trend which resulted in intensity changes in excess of 3% within a period of 3 days, and (3) those on which the intensity was depressed below adjacent maxima by more than 3%. Figure 3 indicates the class to which each day during the period October 1 to December 31, 1957, was assigned.

The dependence of undisturbed intensity upon time was plotted in reference 1. This graph indicates the manner in which the long-term change affected the neutron intensity.

Using the same days as were used in the case of Hobart, the monthly mean undisturbed neutron intensities for the period August, 1957, to January, 1958, were determined for Mawson, Lae, Uppsala, Ottawa, Sulphur Mountain, Resolute, and Herstmonceux.[16] Plotting the values for all other stations against the values found for Herstmonceux, and fitting straight lines to the points so found by eye, the amplitudes of the long-term changes observed at various observatories relative to those observed at Herstmonceux were found. In Fig. 4, the diagrams yielding the Sulphur Mountain, Hobart, Uppsala, and Lae relative amplitudes are plotted. In Table VII, the various relative amplitudes are listed.

It can be seen that (1) with the exception of Mawson, the amplitudes of the long-term changes in the data obtained at high latitude, sea level stations were the same; (2) plotting the Sulphur Mountain, Hobart, and Uppsala relative amplitudes against altitude on Fig. 2 yields points which can be fitted reasonably well by a straight line. The long-term variation is clearly more dependent upon altitude than is the short-term variation.

Consider the fact that the Mawson-Herstmonceux relative amplitude is greater than the relative amplitudes applicable to other high latitude, sea level stations. This could be due to an undetected instrumental drift at Mawson.[17] There is, however, an alternative possibility, namely, that the primary intensity changes were greater in the asymptotic directions[18] scanned by Mawson. Although such a situation would augment the variation at Hobart, the fact that Hobart scans asymptotic directions which are close to the equatorial plane, as do Herstmonceux, Uppsala, Ottawa, and Sulphur Mountain, would result in the Hobart changes being little greater than those which would have been observed by an identically situated northern hemisphere station. Consequently, the deviation from a straight line in Fig. 2 would be small, and hard to detect. The existence of a north-south asymmetry in the long-term variation must therefore remain an open question until further data are accumulated.

TABLE VII. The amplitudes of long-term changes in the neutron component at a number of stations relative to those at Herstmonceux. Station altitude and geomagnetic latitude are listed. Herstmonceux is at geomagnetic latitude 54°N, and 20 m above sea level.

Station	Sulphur Mt.	Hobart	Mawson	Ottawa	Resolute	Uppsala	Lae
Altitude	2280 m	725 m	15 m	101 m	17 m	<100 m	4 m
Latitude	58°N	52°S	73°S	57°N	83°N	58°N	16°S
Relative amplitude	1.55	1.20	1.2	1.0	1.0	1.0	0.30

[16] Data kindly supplied by Dr. A. E. Sandström, Dr. D. C. Rose, the Astronomer Royal, and Mr. D. R. Palmer.

[17] If such were the case, equal drifts must have occurred in both sections of the duplex monitor, as the ratio of the two counting rates did not change. Further, regular determinations of the counting rates using a neutron source revealed no systematic changes in instrumental efficiency greater than 0.5%. The existence of an equipment drift therefore seems unlikely.

[18] The asymptotic direction of arrival of a cosmic-ray particle is that direction from which the particle is coming before it enters the geomagnetic field.

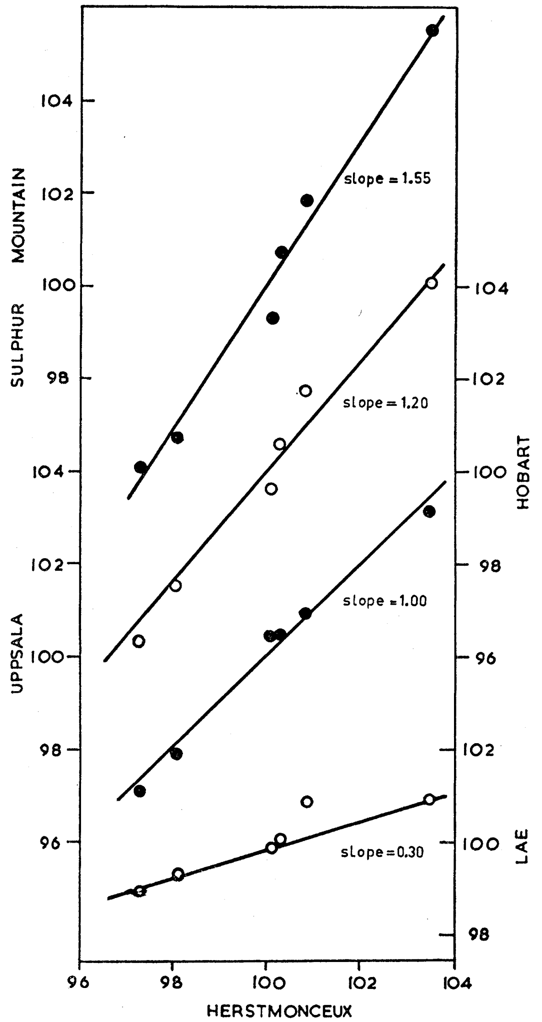

FIG. 4. Comparing the long-term variations in neutron intensity observed at Sulphur Mountain, Hobart, Uppsala, and Lae with those observed at Herstmonceux. Data obtained during the period August, 1957–January, 1958, are plotted.

The Resolute neutron monitor responds to primaries from asymptotic directions making a considerable angle to the equatorial plane, while the stations such as Herstmonceux respond to primaries from asymptotic directions close to this plane. Hence the value of 1.0 for the Resolute-Herstmonceux relative amplitude indicates, that, in the northern sky at least, the long-term change is independent of asymptotic direction.

Consider now the neutron monitor-ionization chamber relative amplitude. Forbush[19] has shown that during 1956 and 1957, the changes in the Ottawa neutron and the Huancayo ionization data were well correlated, the percentage variations in the former being 4.7 times those in the latter. In earlier analyses,[9,10] values of 1.11 and 0.98 were obtained for the Cheltenham ionization–Huancayo ionization relative amplitude (long term). From the mean, 1.045, the Ottawa neutron–Cheltenham ionization relative amplitude is estimated to be 4.7/1.045≈4.50. Ottawa and Cheltenham, both being near sea level, and both being in the vicinity of the cosmic-ray "knee," are suitable for such a comparison.

DERIVATION OF THE ENERGY DEPENDENCE OF VARIATIONS

A critical test of any theory which is advanced to explain cosmic-ray variations is that it must be able to predict the correct dependence of intensity change upon primary energy. The most satisfactory method for determining this dependence experimentally for energies less than 15 Bev is a comparison of the variations observed by a series of neutron monitors, situated such that their primary cutoff rigidities are evenly distributed throughout the range from 2 to 16 Bv. Until such a comparison has been made, a more approximate determination is of value, as it permits a preliminary test of the various theories. Such a determination is now made using the relative amplitude data presented in this paper.

For simplicity, the alpha and heavy particle components of the primary radiation are neglected unless there is a statement to the contrary. Let E be the primary energy in Bev, and $j(E)$ the differential energy spectrum of the primary radiation.

In reference 1, it was shown by comparison of the neutron counting rate variations at Mawson and Hobart, that the short-term changes in the primary spectrum during a cosmic-ray variation are approximately independent of asymptotic latitude. As shown in the previous section, this is at least approximately true for the long-term variation also. Hence, apart from a small longitude dependence which will be neglected, spectral change during a cosmic-ray variation is independent of asymptotic direction, merely being a function of energy. The change in spectrum at energy E will be written $\delta j(E)$.

Dorman has shown that the change in the counting rate C produced by a change in the primary spectrum is given by[20]

$$\frac{\delta C}{C}=\int_{\text{cutoff}}^{\infty} W(E)\frac{\delta j(E)}{j(E)}dE, \tag{1}$$

where $W(E)$ is the coupling constant applicable to the recorder. In the Appendix, it is pointed out that $W(E)$ is not invariant with respect to primary spectral change, and that, consequently, the values of $W(E)$ applicable

[19] S. E. Forbush, J. Geophys. Research **63**, 651 (1958).

[20] L. I. Dorman, *Cosmic-Ray Variations* (State Publishing House for Technical and Theoretical Literature, Moscow, 1957). Translation by U. S. Technical Documents Liaison Office. This method is similar in principle to the specific yield function method developed by the Chicago group [for example, J. A. Simpson, W. Forger, and S. B. Treiman, Phys. Rev. **90**, 934 (1953)]. Dorman's method has the advantage that a detailed knowledge of the primary spectrum is not required.

to any given recorder change throughout the solar cycle. Dorman[20] lists coupling constants which are applicable to a period of minimum solar activity, that is, they apply to the period 1953–55. In the Appendix, the coupling constants applicable during 1957 are estimated from these values.

Dorman[20] points out that, as the energy dependence of $W(E)$ is different for different recorders, and further, as the vertical cutoff energy is different at different latitudes, it is possible to determine $\delta j(E)/j(F)$ occurring during a primary variation from a comparison of the values of $\delta C/C$ observed by a number of different recorders. Consider a spectral variation prescribed by

$$\delta j(E)/j(E) = \text{const}(1+E)^{-\beta}, \qquad (2)$$

where β is a parameter characterizing the energy dependence of the variation. Using both the 1954 and 1957 values of $W(E)$, and integrating Eq. (1) graphically, the values of $\delta C/C$ corresponding to spectral variations given by Eq. (2) were calculated for a number of values of β in the range $0.6<\beta<2.0$. The instruments for which these calculations were made were (1) a high latitude neutron monitor at an atmospheric depth of 680 g cm^{-2}; (2) a high latitude, sea level neutron monitor; (3) the Lae neutron monitor. (The vertical cutoff used, 13 Bev, was derived from the map given by Kodama et al.[21]); (4) a high latitude and (5) a low latitude (vertical cutoff 13 Bev) ionization chamber; (6) a meson detector under 50 m.w.e. of absorber (40 m.w.e. earth plus 10 m.w.e. of atmosphere). The meson coupling constants were those calculated from latitude effect curves which had been corrected for the influence of meteorological factors.[20] From these values of $\delta C/C$, various relative amplitudes were calculated for each value of β considered. In Fig. 5, two of the relative amplitudes are plotted as functions of β. The observed, or estimated mean values of the quantities are shown.

Consider the short-term variation. As the relative amplitudes were derived from 1957 data, the 1957 curves for the relative amplitudes in Fig. 5 are applicable. It is clear that a value of β of about 0.9 describes the average energy dependence of the variations reasonably well.

Now consider the long-term variation. Assuming that the spectrum outside the mechanism producing the long-term variation is that which was observed during 1954–55, the energy dependence of the long-term variation relative to this spectrum is desired. Hence the 1954 curves in Fig. 5 are used. If anything, the high latitude-low latitude relative amplitude of the long-term variation in the neutron component will have decreased with time (as a result of the progressive depletion of the low-energy end of the spectrum), and so 3.3 can be taken as a lower limit for the relative amplitude of the total changes during the period 1954–57. There was no

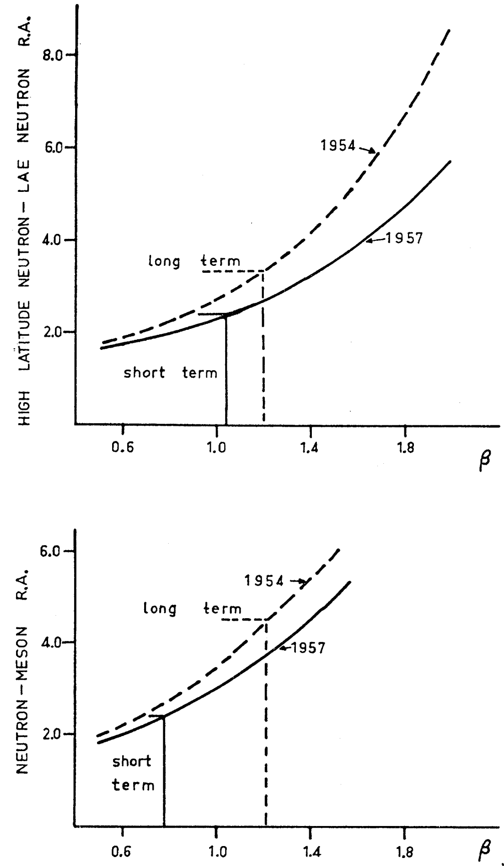

FIG. 5. The dependence of relative amplitude (R.A.) upon β [where β is the exponent in Eq. (2)], calculated for a period of minimum solar activity (labelled 1954), and a period of great solar activity (labelled 1957). The observed relative amplitudes are indicated.

noticeable change in the Ottawa neutron–Huancayo ion relative amplitude during 1956–1957,[19] so the value of 4.50 for the Ottawa neutron–Cheltenham ion relative amplitude will be taken as being applicable to the major part of the long-term change. From Fig. 5, it is seen that these relative amplitudes indicate a value of 1.2, or greater, for β.

In Table III a number of relative amplitudes based upon cubical telescope data were presented and these are now considered. Dorman's coupling constants for the meson component were calculated from latitude surveys using ionization chambers, and as yet, no surveys have been reported using cubical telescopes. However, Rathgeber[22] reports that while a very wide angle telescope revealed a latitude effect of 13%, in reasonable agreement with ionization chamber surveys,[23] a simultaneous determination using a vertical pointing telescope of opening angle 26°×33° yielded a value of 20%. It therefore appears that the coupling constants

[21] M. Kodama, I. Kondo, and M. Wada, J. Sci. Research Inst. (Tokyo **51**, 138 (1957).

[22] H. D. Rathgeber, Australian J. Phys. **3**, 183 (1950).

[23] D. J. X. Montgomery, *Cosmic-Ray Physics* (Princeton University Press, Princeton, 1949), p. 137.

TABLE VIII. Comparison of the values of relative amplitudes calculated for a spectral variation of the form $\delta j(E)=\text{const}\,(1+E)^{-\beta}j(E)$ with those observed in practice. The observed data apply to the short term variation.

Relative amplitude \ β	0.6	0.8	1.0	1.2	2.0	Observed
High latitude neutron-underground	6.9	13.9	26.1	51.8	1000	7.3
High latitude meson-low latitude meson (ion chambers)	1.2	1.3	1.3	1.4		1.5 (telescope)
Low latitude neutron-low latitude meson (ion chambers)	1.3	1.4	1.4	1.5		1.3 (telescope)

applicable to a narrow angle, vertical pointing telescope are different from those applicable to an ionization chamber, the narrow angle telescope, and therefore a cubical telescope being the more sensitive to low-energy primaries. Consequently, the percentage variations in cubical telescope counting rate at high latitudes will be greater than those for an ionization chamber (as is observed), and the high latitude-low latitude relative amplitude will be greater than that applicable to ionization chambers. The intensity variations calculated using ionization chamber coupling constants are therefore taken as lower limits of the variations observed using cubical telescopes.

In the calculations reported here, it was assumed that primaries with energies <150 Bev do not contribute to the counting rate 40 m.w.e. underground. This limit could be considerably in error. Furthermore, there are considerable uncertainties in the coupling constants which are applicable to an underground telescope. For these reasons, it is believed that an agreement within a factor of about 2 or 3 between observed, and predicted relative amplitudes employing underground data must be regarded as being satisfactory.

In Table VIII, relative amplitudes calculated using Eqs. (1) and (2) are compared with the means of those observed using Geiger counter telescopes (Table III). All values refer to the short-term variation. Bearing in mind the remarks made in the preceding paragraphs, the agreement between the observations, and the predictions made using $\beta=0.8$ or 1.0 is fairly satisfactory.

Extrapolating in Fig. 2, the relative amplitudes of the neutron variations at an atmospheric depth of 680 g cm^{-2} ($\approx$3.4 km) and sea level during short- and long-term variations are estimated to be 1.45 and 1.8, respectively. Using the 1957 values of the coupling constants requires unreasonable high values of β in order to yield such relative amplitudes. This may possibly indicate that the variations at low energies deviate considerably from the energy dependences deduced earlier.

DISCUSSION

Parker[24] has proposed that the cosmic-ray intensity is depressed by clouds of solar matter which cluster around the earth. He calculates from his model the spectrum which would be observed at the earth. Thus, writing the spectrum of the primary radiation outside the cloud cluster as $j_\infty(E)$, he derives

$$j(E)=j_\infty(E)\frac{E(E+2)}{C+E(E+2)}, \tag{3}$$

where C is a quantity determined by the properties and number of the clouds in the vicinity of the earth. Consider a change in C produced by the arrival of more clouds from the sun. Then for $C_0<3$, and $E>3$

$$\frac{\delta j(E)}{j(E)}\approx -\frac{\delta C}{C_0+E(E+2)}$$
$$\approx -\delta C(1+E)^{-2.0}.$$

Reference to Fig. 5 shows that the relative amplitudes calculated using an exponent of -2.0 fit neither the short-term, nor the long-term variations. An independent calculation of the high latitude neutron-Lae neutron relative amplitude using Eq. (3), and taking into account the alpha and heavy particle spectra,[25] yielded a value of 8.1, whereas the observed values are 2.5 and 3.3. A specific yield function[11] calculated from the latitude survey reported by Rose et al.[26] was used in this calculation.

Thus the mechanism originally proposed by Parker does not fit the facts. A similar conclusion has been reached recently by Brown.[27]

Fonger[10] shows that for an electric field outside the geomagnetic field

$$\frac{\delta j(E)}{j(E)}\sim\frac{1}{1+E}\left\{\frac{2}{1-1/(1+E)^2}+\text{const}\right\},$$

where const$\approx$2.0. For $E>3$, this approximates to a $(1+E)^{-1.0}$ energy dependence, which is in good agreement with the observed short-term dependence. It was pointed out in reference 1 that a geocentric electric field situated outside the geomagnetic field will not result in the observed event to event variability of inter-instrument relative amplitude. However, an electric field in the same region as the geomagnetic field will alter the distribution of cutoff energies upon the surface of the earth, and thereby alter the latitude dependence of the relative amplitude. A study of this type of mechanism,[28] on the assumption of one special electric field distribution, has shown that a field at a distance of about four earth radii from the earth does result in a smaller latitude dependence of relative amplitude than

[24] E. N. Parker, Phys. Rev. **103**, 1518 (1956).

[25] M. F. Kaplon, B. Peters, H. L. Reynolds, and D. M. Ritson, Phys. Rev. **85**, 295 (1952).

[26] D. C. Rose, K. B. Fenton, J. Katzman, and J. A. Simpson, Can. J. Phys. **34**, 968 (1956).

[27] R. R. Brown, Nuovo cimento **9**, 197 (1958).

[28] J. A. Simpson, Phys. Rev. **94**, 426 (1954).

when the field is either closer to, or further from the earth. Thus an electric field whose distance from the earth varies from event to event might predict both the variability of relative amplitude, and the correct dependence of intensity variation upon energy. It appears that further investigation of this type of mechanism might be worthwhile, despite the fact that the high electrical conductivity of interplanetary space would appear to preclude the existence of such fields. If the cosmic-ray effects can be shown to be consistent with such fields, we may have to re-examine our theories of interplanetary electromagnetic processes.

ACKNOWLEDGMENTS

I am indebted to Dr. A. G. Fenton, under whose guidance this work was performed. I also wish to thank my colleagues of the Hobart cosmic-ray research group for many valuable discussions. Mrs. P. S. James, and the other members of the computing staff assisted greatly in the reduction of the raw data. The assistance of the Department of Civil Aviation, and especially Mr. C. Ozorio in the operation of the Lae station is gratefully acknowledged.

Mr. R. B. Taylor graciously made available the data he obtained with the underground telescopes. I am also indebted to Dr. D. C. Rose, Dr. B. G. Wilson, Dr. A. E. Sandström, Dr. Y. Miyazaki, the Astronomer Royal, and Mr. D. R. Palmer for supplying me with the data from their observatories.

APPENDIX

By definition,[20] the coupling constant $W(E)$ of a recorder is given by

$$W(E)=m(E)j(E)/C,$$

where C is the total counting rate of the recorder, and $m(E)$ is defined by $C=\int_{\text{cutoff}}^{\infty} m(E)j(E)dE$. For data from which all variations of an atmospheric nature have been removed, $m(E)$ is invariant with respect to time. If $j(E)$ changes to $j(E)+\delta j(E)$, and as a consequence C changes to $C+\delta C$, then the coupling constant applicable to the recorder is now

$$W'(E)=\frac{m(E)[j(E)+\delta j(E)]}{C+\delta C}$$

$$=\frac{C}{C+\delta C}[1+\delta j(E)/j(E)]W(E), \quad (4)$$

that is, the coupling constants are not invariant with respect to spectral change.

As marked changes occur in the cosmic-ray spectrum during the solar cycle, values of $W(E)$ obtained experimentally during the period of minimum solar activity do not apply during a period of intense solar activity. Consequently, the neutron and meson coupling constants derived by Dorman[20] from observations made during 1952–54[29] (neutron data) and 1936[30] (meson data), that is, periods of minimal solar activity, are not applicable during 1957, a period of very great solar activity.

A preliminary investigation[18] showed that the long-term spectral changes occurring during the period 1954–57 could be expressed approximately by $\delta j(E)=\alpha j(E)\times(1+E)^{-1.2}$. From the requirement that this expression, when inserted in Eq. (1), should predict the observed 20% change in high latitude neutron intensity,[31] α was determined to be -3.7. [The 1954 values of $W(E)$ were used in this calculation.] From $\delta j(E)=-3.7j(E)\times(1+E)^{-1.2}$, and Eq. (4), the neutron coupling constants during 1957 [written $W_{57}(E)$], were estimated from the 1954 values [$W_{54}(E)$] thus

$$W_{57}(E)=(100/80)\{1-3.7(1+E)^{-1.2}\}W_{54}(E).$$

In a similar manner, the values of the meson coupling constants applicable during 1957 were estimated from the 1936 values.

[29] D. C. Rose and J. Katzman, Can. J. Phys. **34**, 1 (1956); J. A. Simpson, W. Fonger, and S. B. Treiman. Phys. Rev. **90**, 934 (1953).

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

[31] A. G. Fenton, K. B. Fenton, and D. C. Rose, Can. J. Phys. **36**, 824 (1958).