three parts of each target. The background included also beam particles that were not rejected by the anticoincidence circuits and positrons originating from muons stopping in the targets. The latter contribute an asymmetric part to the background. However, owing to depolarization of the muons in the counter, the effect is small. In order to check the method, the pion-beam polarization was measured in the same manner as that of the muons. As expected, this measurement showed no significant asymmetry [i.e., $\Delta(x)=-0.059\pm0.113$ at $x=0.453$ and $\Delta(x)=-0.029\pm0.100$ at $x=0.866$].

If high-energy muons strike the spectrometer vacuum chamber wall, some inelastically scattered electrons are counted. These were found as distortions in the unpolarized spectrum at the low-energy point, and the first 80° sector of the vacuum chamber was lined with a baffle counter. The output of this counter was placed in anticoincidence with the events.

Figure 2 shows the data corrected for background, ionization loss, and radiation straggling in the targets and counters as well as for virtual photon processes and inner bremsstrahlung.[9] The other resolution effects do not contribute uncertainties outside the accuracies of the applied corrections.[10] The solid line drawn in Fig. 2 represents the polarization expected on the basis of the two-component neutrino theory for a value of $R\xi=0.89$. Inspection of Fig. 2 shows all measurements to be consistent with this curve except for two points. The low-energy one of these points, drawn with broken error flags, represents an asymmetry measurement when the anticoincidence counter lining the spectrometer vacuum chamber was not on its voltage plateau and hence not sufficiently sensitive for an efficient rejection of particles inelastically scattered on the vacuum chamber walls.

With these qualifications, we conclude from the data that (a) $R\xi=0.89\pm0.09$ for our pion beam, this value being the error-weighted mean based on all data for $x>0.5$ (the error is its external standard deviation; its internal standard deviation is ±0.03); (b) the asymmetry changes rapidly in going from $x=0.5$ to $x=1.0$; and (c) the asymmetry for $x=0.5$ is small, and our data are not sufficiently accurate to establish a sign reversal. Further investigations of the polarization at low energies with spectrometer and counter methods are planned.

ACKNOWLEDGMENTS

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This work was performed under the auspices of the U. S. Atomic Energy Commission.

[9] T. Kinoshita and A. Sirlin, Phys. Rev. **107**, 593 (1957). Because of the limited accuracy of these measurements we have not made comparison with the theoretical results obtained by T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1611 (1957), and S. Bludman and A. Klein, Phys. Rev. **109**, 550 (1958).

[10] Calculations of resolution effects are being made and will be reported in future discussions of this work.

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Variations in the Cosmic-Ray Rigidity Spectrum*

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Variations in the counting rates of two different high-latitude neutron monitors, a high-latitude meson telescope, and a low-latitude neutron monitor are studied for the period August, 1956, to January, 1958. A long-term decrease in counting rate was observed at all stations, superposed on which there were numerous short-term variations of from 3 to 30 days duration. The long-term variation in neutron counting rate at high latitudes was four times greater than that at low latitudes, indicating that the change in the cosmic-ray spectrum was most pronounced at low rigidities. The high-latitude short-term variations in neutron counting rate were about 2.5 times greater than those at low latitudes, the ratio varying from event to event. This is interpreted as evidence that the spectrum changes during short-term variations are less strongly dependent upon rigidity than in the case of the long-term variation, and that they are of a variable character. Comparison of the neutron data with simultaneous meson data supports this view. It is concluded that the long- and short-term variations in intensity are produced by different mechanisms.

INTRODUCTION

THE geomagnetic field prevents primary cosmic radiation of rigidity <14 Bv from reaching the top of the atmosphere near the equator. Thus a low-latitude neutron monitor is sensitive to primaries of rigidity >14 Bv. The geomagnetic cutoff decreases with increasing latitude, until at high geomagnetic latitudes ($\lambda>50°$), particles of rigidity >2 Bv can be detected by a sea level neutron monitor. The limiting factor for $\lambda>50°$ is atmospheric absorption, not geomagnetic cutoff.

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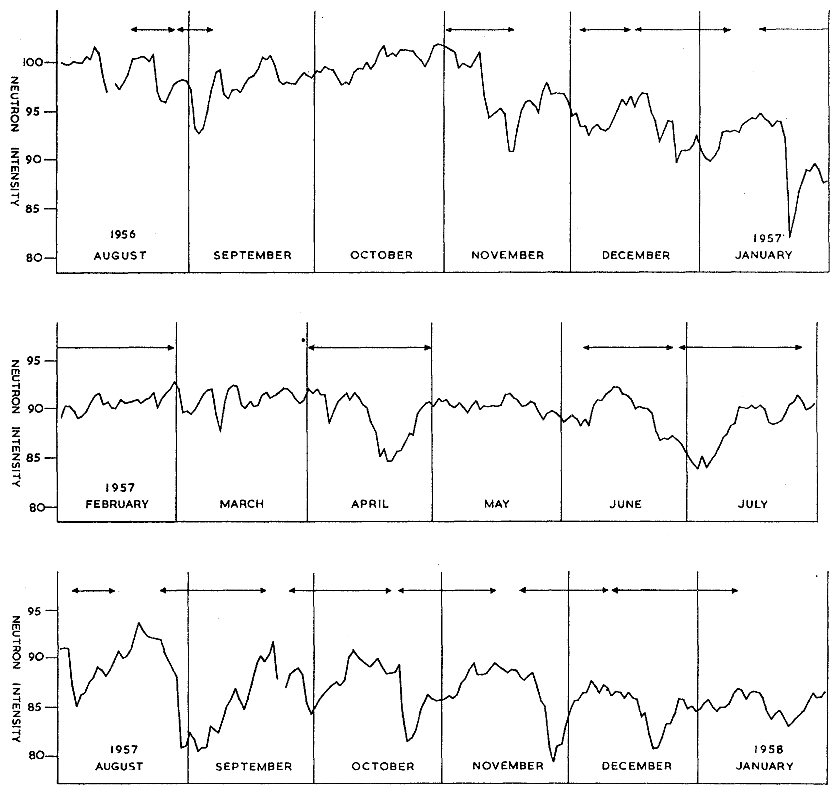

FIG. 1. Daily mean neutron intensities at Hobart for the period August 1, 1956, to January 31, 1958. The double-headed arrows indicate the subintervals considered.

It has been shown[1] that a neutron monitor is more sensitive than a meson telescope to low-rigidity primary radiation. Thus at $\lambda > 50°$, approximately 45% of the neutron, and 10% of the meson counting rates at sea level are due to primaries of rigidity <14 Bv.[2]

By comparing the variations in the counting rates of (1) two neutron monitors, one near the equator and the other at a high latitude, and (2) a neutron monitor and a meson telescope, both at the same high latitude, the variations in the intensity of low-rigidity (<14 Bv) and high-rigidity (>14 Bv) primary cosmic rays can be compared. The results of such a comparison are presented.

EQUIPMENT

The instruments from which the data were derived are listed in Table I. The geometries of the neutron monitors are similar to those recommended for use during the International Geophysical Year.[3] All neutron data have been adjusted for atmospheric change using an absorption mean free path of 145 g cm^{-2}. The meson data have been adjusted for changes in pressure and the height of the 125-mb level using a mass coefficient of −1.63% per cm of mercury and a decay coefficient of −4.88% per km.

The Mawson detector is operated by the Australian National Antarctic Research Expeditions for the con-

TABLE I. Details of instruments, their geomagnetic latitudes, and the periods for which they were operating. The Hobart neutron monitor is 725 meters above sea level. All other instruments are at sea level.

Instrument	Location	Geomagnetic latitude	Period of operation
Meson telescope 10-cm Pb absorber: 1 m×1 m×1.5 m	Hobart, Tasmania	52°S	August 1, 1953–May 5, 1957
Meson telescope 10-cm Pb absorber: 1 m×1 m×1 m			Subsequent to May 5, 1957
Neutron monitor: 4-counter	near Hobart, Tasmania		June 10, 1956–December 20, 1956
Neutron monitor: 8-counter			Subsequent to December 21, 1956
6-counter neutron monitor	Lae, New Guinea	16°S	Subsequent to May 25, 1957
12-counter neutron monitor	Mawson, Antarctica	73°S	Subsequent to March 10, 1957

[1] W. H. Fonger, Phys. Rev. **91**, 351 (1953).
[2] Derived from the sea level determinations reported by Rose, Fenton, Katzman, and Simpson, Can. J. Phys. **34**, 968 (1956).
[3] J. A. Simpson, *Annals of the International Geophysical Year* (Pergamon Press, Inc., New York, 1956), Vol. **4**, p. 351.

duct of whose cosmic-ray program the University of Tasmania is responsible.

RESULTS

The daily mean neutron intensity at Hobart is plotted as a function of time in Fig. 1 for the period from August 1, 1956, to January 31, 1958. At the time of the change of instruments on December 20, 1956, an additional two-counter monitor was in operation at Hobart. This enabled accurate normalization of the data obtained prior and subsequent to the change.

A large number of variations in intensity are evident. The most striking feature of the data is the manner in which the intensity suffered a permanent change during the months of November and December, 1956. The fact that during the greater part of March and May, 1957, the intensity was constant, and not showing any tendency to return to the October, 1956, value suggests that a drastic, long-lived change occurred in the primary intensity. This is identified as part of the 11-year cycle of cosmic-ray intensity.[4]

There are a large number of variations of from 3 to 30 days duration superposed on the long-term intensity change. By consideration of the manner in which the intensity changed with time these variations have been identified as Forbush decreases, 27-day variations and combinations of these events. It was not possible to consider the two types of events separately, and they have been considered together under the broad title of "short-term variations."

For each month a selection was made of those days on which the intensity was unaffected by short-term variations. For each month, the mean of all such days was calculated. This mean is called the "undisturbed" intensity for the month.

In Fig. 3(A), the undisturbed intensity is plotted as a function of time. As the effects of short-term fluctuations have been eliminated, this graph indicates the manner in which the long-term change affected the neutron intensity. It can be seen that the intensity decreased during November and December, 1956, and January, 1957, remained practically constant from February, 1957, until September, 1957, and then decreased slowly until January, 1958.

Nomenclature

The data were split up into a number of groups for analysis. For each group of data, the intensities were expressed as percentage deviations from the mean of the group.

The neutron intensities at Hobart, Mawson, and Lae, and the meson intensity at Hobart will be written H, M, L, and T, respectively. The relative changes in two intensities, that is, quantities of the type $\Delta H/\Delta L$ will be determined. A subscript "long" or "short" will indicate whether the ratio applies to a long- or short-term variation. Thus $(\Delta H/\Delta T)_{\text{long}}$ and $(\Delta H/\Delta T)_{\text{short}}$ apply to long- and short-term variations, respectively.

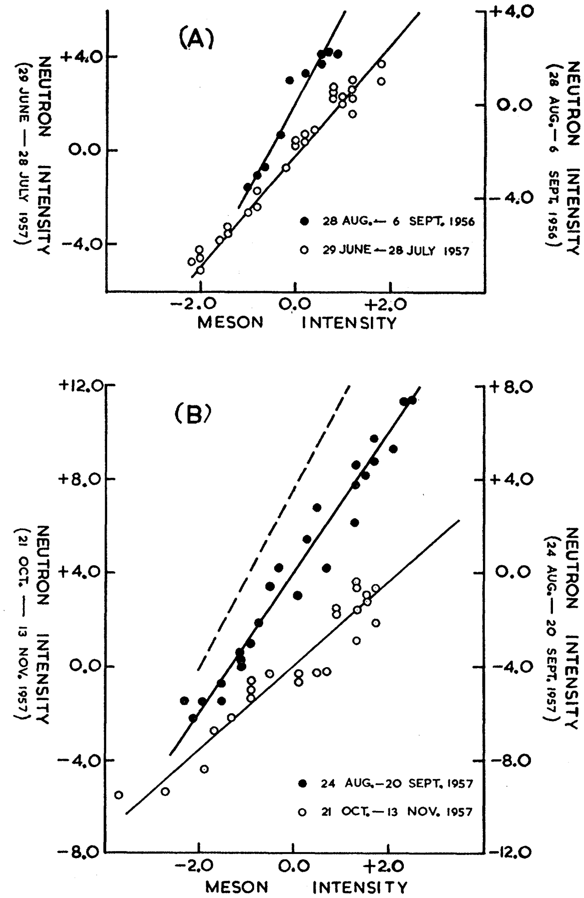

FIG. 2. Scatter diagrams of Hobart neutron intensity against Hobart meson intensity for four short-term variations. Percentage deviations from the group mean are plotted. The standard errors of the neutron and meson intensities are 0.12% and 0.06%, respectively. The gradient of each line is the mean of the appropriate values of b_{12} and $1/b_{21}$ given in Table II. (A) Comparing events prior and subsequent to November, 1956. (B) The events occurring after November, 1956, for which the lines of best fit had the greatest and least gradient. The gradient of an event occurring prior to November, 1956, is shown for comparison.

Comparison of Short-Term Variations

The whole interval was split up, as far as possible, into subintervals containing only one major intensity fluctuation. On some occasions superposition of two events made this impossible. The subintervals are indicated in Fig. 1.

For each subinterval, scatter diagrams of (H,L), (H,M), and (H,T) were prepared. Daily means have been used throughout. The (H,T) diagrams for four events are given in Figs. 2(A) and 2(B). It is clear from these figures that the gradients of the lines of best fit are different from event to event. Inspection of all the diagrams indicated that the gradients subsequent to

[4] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).

TABLE II. The observed relative responses to short-term variations of the Hobart neutron monitor (H), the Hobart telescope (T), the Lae neutron monitor (L), and the Mawson neutron monitor (M). b_{12} and b_{21} are the regression coefficients between the two variables. The standard errors of b_{12} and $1/b_{21}$ are given.

Period	$(\Delta H/\Delta T)_{\text{short}}$		$(\Delta H/\Delta L)_{\text{short}}$		$(\Delta H/\Delta M)_{\text{short}}$	
	b_{12}	$1/b_{21}$	b_{12}	$1/b_{21}$	b_{12}	$1/b_{21}$
18.8 —Aug. 28, 1956	3.2±0.4	3.6±0.4				
29.8 —Sept. 6, 1956	3.4±0.4	3.7±0.4				
1.11—Nov. 17, 1956	3.5±0.3	3.9±0.3				
3.12—Dec. 15, 1956	2.4±0.4	3.0±0.4				
16.12—Jan. 8, 1957	2.2±0.3	3.0±0.4				
15.1 —Feb. 28, 1957	2.0±0.2	2.5±0.2				
1.4 —April 30, 1957	2.4±0.2	2.8±0.2			0.93±0.04	0.98±0.05
6.6 —June 27, 1957	1.7±0.1	1.8±0.1	1.7±0.2	1.9±0.2	0.96±0.06	1.03±0.07
29.6 —July 28, 1957	2.3±0.1	2.3±0.1	2.4±0.2	2.7±0.2	1.12±0.04	1.15±0.04
4.8 —Aug. 14, 1957	1.3±0.2	1.4±0.2	2.2±0.3	2.6±0.4	0.79±0.08	0.86±0.09
24.8 —Sept. 19, 1957	2.9±0.1	3.0±0.1	2.6±0.2	3.0±0.2	1.01±0.03	1.02±0.03
25.9 —Oct. 19, 1957	2.5±0.2	2.8±0.2			1.02±0.07	1.12±0.08
21.10—Nov. 13, 1957	1.7±0.1	1.9±0.1	2.0±0.2	2.3±0.2	1.06±0.04	1.10±0.05
19.11—Dec. 10, 1957	2.2±0.2	2.5±0.2	2.7±0.2	2.9±0.2	1.10±0.05	1.15±0.05
11.12—Jan. 10, 1958	1.8±0.3	2.7±0.4	1.6±0.2	2.2±0.3	0.90±0.07	1.05±0.08

November, 1956, were never as great as those prior to, or during that month. This can be seen quite clearly in Fig. 2(B), where the scatter diagrams of (H,T) showing the greatest and least gradient observed after November, 1956, are compared with the gradient found for the event occurring during the period from August 28 to September 6, 1956.

For each scatter diagram, the two linear regression coefficients b_{12} and b_{21} were calculated. Since both variates are subject to error, neither b_{12} nor b_{21} can be preferred as defining the line of "best fit." However, it has been shown[5] that b_{12} and b_{21} define the limiting values of the gradient of the line of "best fit," and they will be used to define these limits rather than go to the added complexity of considering the problem rigorously.

In Table II are tabulated the values of b_{12} and $1/b_{21}$ calculated for all the subintervals shown in Fig. 1.

The limiting values of $(\Delta H/\Delta T)_{\text{short}}$, $(\Delta H/\Delta L)_{\text{short}}$ and $(\Delta H/\Delta M)_{\text{short}}$ are plotted in Figs. 3(B), 3(C), and 3(D). The solid black rectangles extend between the appropriate values of b_{12} and $1/b_{21}$. The standard errors of b_{12} and $1/b_{21}$ are shown.

The change in the neutron to meson relative response after November, 1956, can be seen quite clearly in Fig. 3(B). It can be seen from Fig. 3(A) that this change occurred at the same time as the marked change in the undisturbed intensity. The change in meson telescope geometry on May 5, 1957, (Table I) does not appear to have affected $(\Delta H/\Delta T)_{\text{short}}$.

TABLE III. Summary of the relative responses of the Hobart neutron monitor (H), the Hobart telescope (T), the Lae neutron monitor (L), and the Mawson neutron monitor (M) to short- and long-term primary variations.

Relative response	Period of observation	Short-term variation	Long-term variation
$\Delta H/\Delta T$	Forbush decreases prior to Nov., 1956	3.4 to 3.7	
	after Nov., 1956	1.4 to 2.9	4.0
$\Delta H/\Delta L$	after May, 1957	1.8 to 2.8	4.0
$\Delta H/\Delta M$	after Feb., 1957	1.0	1.0

[5] H. E. Jones, Metron 13, 21 (1937).

The variations in $(\Delta H/\Delta T)_{\text{short}}$ and $(\Delta H/\Delta L)_{\text{short}}$ appear to be in phase, and the correlation coefficient between the two quantities is 0.7. This is significant at the 90% level.

A fault in the Hobart neutron monitor might produce correlated changes in $(\Delta H/\Delta T)_{\text{short}}$, $(\Delta H/\Delta L)_{\text{short}}$, and $(\Delta H/\Delta M)_{\text{short}}$. The values of $(\Delta H/\Delta T)_{\text{short}}$ and $(\Delta H/\Delta L)_{\text{short}}$ for the period June 6–27, 1957, are 40% less than those for the period from August 24 to September 20, 1957. If this difference were due to a fault in the Hobart monitor, the values of $(\Delta H/\Delta M)_{\text{short}}$ would likewise differ by 40%. The observed difference of 2% indicates that the changes in $(\Delta H/\Delta T)_{\text{short}}$ and $(\Delta H/\Delta L)_{\text{short}}$ are not instrumental and it will be shown that they are probably due to changes in the primary spectrum.

Comparison of Long-Term Variations

The "undisturbed" intensity decreased during the period October, 1957, to January, 1958, during which period the Lae monitor was in operation. To determine $(\Delta H/\Delta L)_{\text{long}}$, the mean neutron intensity at Lae was determined for each of the periods used in the derivation of the undisturbed intensity at Hobart. In Fig. 4 the Hobart values of the "undisturbed" intensity are plotted against the corresponding values for Lae. The four points are very nearly colinear. The line in the figure, which was fitted by eye, has a slope of 4.0. Thus $(\Delta H/\Delta L)_{\text{long}} > (\Delta H/\Delta L)_{\text{short}}$.

In a similar manner, a value of 1.0 was found for $(\Delta H/\Delta M)_{\text{long}}$.

A comparison of the neutron and meson variations at Hobart is more difficult owing to the incomplete correction of the meson data for change in atmospheric structure. The period during which the rate of change of undisturbed neutron intensity was greatest, namely November–December, 1956, is consequently the most likely to provide an accurate value of $(\Delta H/\Delta T)_{\text{long}}$, as errors due to the seasonal changes in atmospheric structure are minimized.

While the two periods November 1, 1956, to November 9, 1956, and November 21, 1956, to November 30, 1956, were relatively free of short-term variations, the two mean neutron intensities differ by 4%. Figure 1 shows that this decrease was part of the long-term change in intensity. The difference in mean meson intensity was calculated, giving a value of 3.8 for $(\Delta H/\Delta T)_{\text{long}}$. The magnitude of the error introduced into this value by incomplete correction for change in atmospheric structure is not known. A recent determination using data from high-latitude stations in the Northern hemisphere[6] yielded a figure of from 4 to 5. The authors quote the monthly mean intensities for their recorders, and as October, 1956, and May, 1957, were both practically

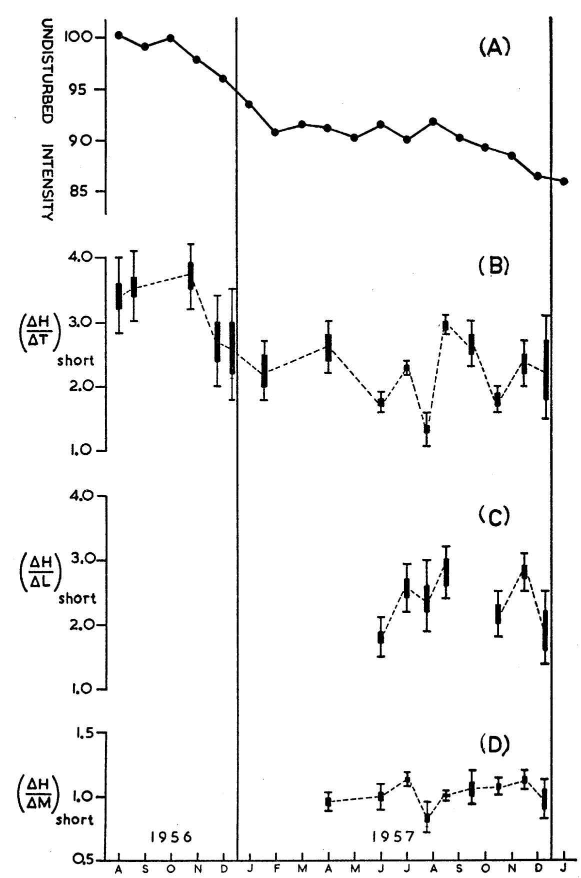

FIG. 3. (A) Monthly mean undisturbed neutron intensity at Hobart for the period August, 1956, to January, 1958. The standard errors are all less than 0.06%. (B), (C), and (D) show the values of $(\Delta H/\Delta T)_{\text{short}}$, $(\Delta H/\Delta L)_{\text{short}}$, and $(\Delta H/\Delta M)_{\text{short}}$, respectively, for a number of short-term variations.

[6] Fenton, Fenton, and Rose, Can. J. Phys. **36**, 824 (1958).

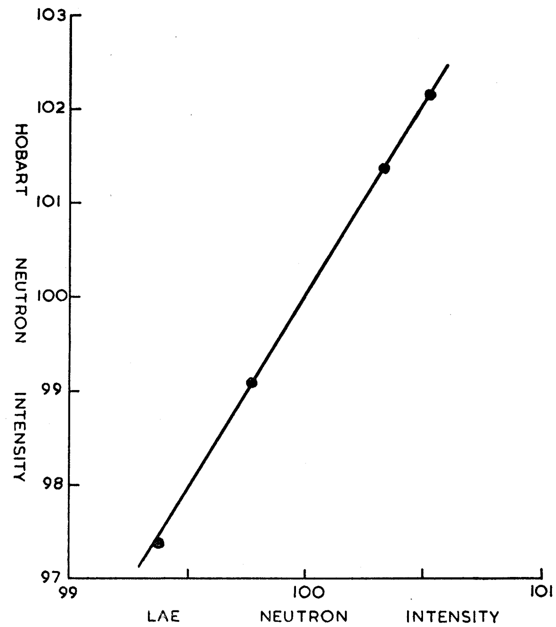

FIG. 4. The relation between the undisturbed neutron intensity at Hobart and Lae. Intensity is expressed as the percentage deviation from the mean of the four values. The standard errors of the Hobart and Lae intensities are 0.04% and 0.08%, respectively.

"undisturbed" months, the method used in the present paper can be used to determine the relative neutron-meson response. The result is a value of 2.8 for Ottawa and 4.4 for Resolute. As the neutron variations at both stations are very similar to those at Hobart, it is suggested that the lack of agreement is due to inadequate correction of the meson data for meteorological effects.

From the data available the relative neutron-meson response appears to have a value of about 4. That is, $(\Delta H/\Delta T)_{\text{long}} > (\Delta H/\Delta T)_{\text{short}}$. Even the lowest value of the relative response, 2.8, is greater than the majority of the $(\Delta H/\Delta T)_{\text{short}}$ values, and although the actual value of $(\Delta H/\Delta T)_{\text{long}}$ is in doubt, there is little doubt that the above relationship is true.

DISCUSSION

Table III summarizes the experimental results. A number of conclusions can be drawn from these.

(1) The high values of $(\Delta H/\Delta T)_{\text{long}}$ and $(\Delta H/\Delta L)_{\text{long}}$ indicate that the low-rigidity end of the primary spectrum suffers the greatest change during the solar cycle. The result $(\Delta H/\Delta L)_{\text{long}}=4$ can be shown to indicate that the percentage change in the counting rate due to primaries in the rigidity range 2–14 Bv is approximately eight times greater than that due to primaries of rigidity >14 Bv. The decreased values of $(\Delta H/\Delta T)_{\text{short}}$ after November, 1956, when the long-term change of intensity became very pronounced [Figs. 3(A) and (B)] can be explained, at least in part, in terms of this hardening of the primary spectrum.

Observations at aircraft[7] and balloon[8] altitudes also show that the long-term spectral changes are greatest at low rigidities.

(2) The fact that $(\Delta H/\Delta L)_{\text{long}} > (\Delta H/\Delta L)_{\text{short}}$ for superposed long- and short-term fluctuations suggests that the mechanisms responsible are not identical. For if the long-term decrease were due to a long-lived mechanism of the same type that produces short-term variations, the spectrum changes during the two types of event would be the same, and $(\Delta H/\Delta L)_{\text{long}}$ would be equal to $(\Delta H/\Delta L)_{\text{short}}$. The fact that $(\Delta H/\Delta T)_{\text{long}} > (\Delta H/\Delta T)_{\text{short}}$ also leads to the same conclusion.

(3) Consider the result $(\Delta H/\Delta M)_{\text{short}} = (\Delta H/\Delta M)_{\text{long}} = 1$. The "knee" in the neutron intensity against latitude curve is in the vicinity of Hobart. Thus although Mawson is at a higher latitude than Hobart, the additional primaries admitted by the change in geomagnetic cutoff are not detected by the sea level neutron monitor, and the same rigidity spectrum is observed by the two neutron monitors. Consequently, any change in rigidity spectrum would be expected to produce the same percentage change in neutron counting rate at both stations, as is observed.

The preceding remarks apply only if the change in rigidity spectrum is the same for primary radiation reaching the earth from all directions in space. For if the change in spectrum were a function of asymptotic latitude, the counting-rate variations at the two monitors would be different, that is, $(\Delta H/\Delta M) \neq 1$. Thus the observed result indicates that neither the long- nor the short-term variations in the spectrum are strongly dependent upon asymptotic latitude.

(4) The variability of $(\Delta H/\Delta L)_{\text{short}}$ and $(\Delta H/\Delta T)_{\text{short}}$ could be due to (a) the rigidity spectrum of the primary radiation prior to passage through the depressive mechanism being different from event to event, or (b) the efficiency of the mechanism being a variable function of asymptotic latitude, or (c) the dependence of spectral changes on rigidity varying from event to event. These three possibilities will be considered in turn.

(a) A variable rigidity spectrum would result in correlated changes in $(\Delta H/\Delta L)_{\text{short}}$ and $(\Delta H/\Delta T)_{\text{short}}$. Consider the events occurring on June 23, August 4, and October 22, 1957. The values of $(\Delta H/\Delta T)_{\text{short}}$ for these events are quite different, being 1.8, 1.4 and 2.6, respectively. Yet for every recorder, the intensities prior to the three events were practically the same (for example, Fig. 1). Since any change in the rigidity spectrum would alter the intensity recorded by at least one of the detectors, the spectra prior to these three events must have been identical.

(b) Consider a mechanism situated outside the geomagnetic field. Reference to published data[9,10] on the deflection of cosmic-ray particles in the earth's magnetic field shows that the majority of the particles detected by the Lae and Hobart monitors come from asymptotic geographic latitudes within the ranges (20°N to 15°S) and (20°N to 20°S), respectively. These ranges are so similar that the efficiency of the mechanism would have to be very strongly dependent upon asymptotic latitude to produce the observed effect. This would result in $(\Delta H/\Delta M)_{\text{short}} \neq 1$, contrary to observation.

(c) The remaining alternative is that the manner in which the mechanism affects the spectrum varies from event to event. Thus for some events, the percentage change at the low-rigidity end of the spectrum would be much greater than that for the high-rigidity end, resulting in high values of $(\Delta H/\Delta T)_{\text{short}}$ and $(\Delta H/\Delta L)_{\text{short}}$. For other events, the high and low ends of the spectrum would be affected to roughly the same extent, and $(\Delta H/\Delta T)_{\text{short}}$ and $(\Delta H/\Delta L)_{\text{short}}$ would have values close to one.

Possibilities (a) and (b) are not consistent with all the observations. As none of the data discredit possibility (c), it is concluded that the dependence of percentage decrease of intensity upon rigidity varies from event to event.

Any model proposed to explain short-term variations must predict the observed variations in $(\Delta H/\Delta L)_{\text{short}}$ and $(\Delta H/\Delta T)_{\text{short}}$. Thus any geoelectric hypothesis[11] wherein a large decelerating voltage alters the primary spectrum prior to the entry of the radiation into the earth's magnetic field may be excluded, for the change in spectrum is a definite function of the decelerating potential.[1] Thus fixing the potential so as to give the correct amplitude for the decrease at one recorder fixes the amplitude at any other recorder, and no variability such as reported here is possible.

ACKNOWLEDGMENTS

My thanks go to Professor A. L. McAulay and my colleagues in the Hobart cosmic-ray group for many helpful discussions. The assistance of the Department of Civil Aviation, and especially Mr. C. Ozorio, in the operation of the Lae station is gratefully acknowledged.

[7] P. Meyer and J. A. Simpson, Phys. Rev. **99**, 1517 (1955).
[8] H. V. Neher and H. Anderson, Phys. Rev. **109**, 608 (1958).
[9] E. A. Brunberg, Tellus **5**, 135 (1953); E. A. Brunberg and A. Dattner, Tellus **5**, 269 (1953).
[10] F. S. Jory, Phys. Rev. **103**, 1068 (1956).
[11] K. Nagashima, J. Geomag. Geoelec. **5**, 141 (1953).