

STEPLIKE CHANGES IN THE LONG-TERM MODULATION OF COSMIC RAYS*

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ABSTRACT

An experimental investigation is reported of the rigidity dependence of the solar modulation of relativistic cosmic-ray particles at the orbit of Earth by comparison of the monthly averages of the neutron monitor at Deep River at geomagnetic cutoff rigidity 1 GV with those of the neutron monitor at Kula at cutoff 13 GV during the period of increasing solar activity which began in 1964-1965. The constancy with time of the efficiency of each monitor was confirmed to better than 0.5 percent by comparisons with other monitors near the same respective cutoffs. The regression curve expected between the monitor at Deep River and the monitor at Kula was calculated from the results of latitude survey by the method of coupling constants assuming that the modulating parameter $\eta(r, t)$ was independent of rigidity P and that the form of the modulation function was $f(P, \beta) = P^\alpha$. The monthly experimental points fitted the regression line calculated for $\alpha = 1$ until December 1966; but thereafter they suddenly (between successive months) formed, for periods varying from 6 to 18 months, new regression lines which appeared to have about the same slope as the $\alpha = 1$ line but were strongly displaced laterally. The $\alpha = 1$ slope of the separate successive segments of the regression is attributed to the local modulation in the vicinity of the Sun associated with Forbush decreases and 27-day variations. The steplike long-lasting changes between the successive segments of the regression are believed to be demonstrated here for the first time. They are probably associated with the state of the interplanetary medium far beyond the orbit of Earth. Statements in the literature that the form of the modulation function is independent of time and that the modulating parameter is independent of rigidity appear to have been premature.

I. INTRODUCTION

The solar modulation of galactic cosmic radiation has been extensively studied both theoretically and experimentally since the concept of the solar wind was introduced by Parker (1958). A comprehensive list of references to the theoretical work accompanies a new contribution from Jokipii and Parker (1970). The present situation on the experimental side as regards the lower-energy particles detectable only in space or at balloon altitudes (helium nuclei and protons of magnetic rigidity less than ~ 3 GV and electrons of rigidity less than ~ 10 GV) has been discussed with references by Lezniak and Webber (1971). For the cosmic-ray particles of magnetic rigidity greater than ~ 2 GV which affect neutron monitors, Simpson and Wang (1970) have recently drawn definitive conclusions from comparisons of the intensity variations at three recording stations at geomagnetic rigidity cutoffs, 1.7, 3, and 13 GV. Their neutron-monitor data are continuous from the year 1952. In particular, Simpson and Wang (1970) have concluded that "the form of the modulation function . . . is independent of time" for extended periods on either side of the solar minima in 1954 and 1965 and through the 1958 solar maximum.

* This work was reported (Carmichael and Stoker 1970) at the National Fall Meeting of the American Geophysical Union, San Francisco, 1970 December 10.

In this paper we have used data from neutron monitors installed near the time of the IQSY (1964–1965) at different latitudes and altitudes; and we have found, making use of the generally accepted form of the modulation function, that the form did change several times, and irreversibly in the short term, during the interval from 1965 to 1970. The same steplike changes have also been disclosed in the original data of Simpson and Wang (1970) by a more detailed analysis than had been carried out by them.

The form of the modulation function, defined more precisely below, is generally understood to mean the dependence of the relative variations of intensity throughout the cosmic-ray spectrum near the Earth on the magnetic rigidity of the particles. To demonstrate that the form of this dependence was constant with time it would suffice to show that the relative variations of any detector sensitive in a particular rigidity range of the galactic spectrum made a single-valued regression curve with the relative variations of another detector sensitive in a different rigidity range. Even if a particular detector such as a neutron monitor was shielded by the atmosphere, this demonstration would still be valid because the fractional effect of the atmosphere on the various rigidities does not change with time.

On the other hand, if any such regression curve exhibited a discontinuity or a “hysteresis” loop, it would indicate, as proved by Simpson and Wang (1970, Appendix B), that a change in the form of the modulation function had occurred.

Hitherto only Ormes and Webber (1968) seem to have given evidence that the form of the modulation function of particles of moderately high rigidity might change with time. They used on the one hand measurements made at different times between 1959 and 1965 at balloon altitudes and on the other the intensity as recorded by a neutron monitor at a geomagnetic cutoff of 1.4 GV. The rigidity range was between particles of 0.4–4 GV measured by the balloon spectrometers and the rigidity of the mean response of the neutron monitor, about 16 GV. The rigidity dependence of the modulation was estimated for 1959, 1961, 1963, and 1965. They say, “Taken in this manner, the data suggest that the rigidity dependence of the modulation is increasing with increasing solar activity.”

Ormes and Webber (1968) also say, “While our intention has been to study the long-term (11 year) modulation of cosmic rays, it is possible that the short-term modulations, which are included in our measurements, may be significant. It is not certain that the long-term and the shorter-term modulations have the same functional form, although no good evidence has been found to the contrary. The assumption will be made that this study is of a single phenomenon only and not a superposition of several different ones.” In the present investigation no such assumption has been made; indeed, evidence is presented that the 11-year and the shorter-term modulations have very different characteristics.

II. FORM OF THE MODULATION FUNCTION

Both the diffusion-convection model of solar modulation (Parker 1963) and the equivalent model based on the power spectrum of magnetic-field irregularities (Jokipii 1966) relate the local differential cosmic-ray particle flux $J_{r_E}(P, \beta, t)$ at orbit of Earth to the galactic differential flux $J_\infty(P, \beta)$ by

$$J_{r_E}(P, \beta, t) = J_\infty(P, \beta) \exp \left[- \int_{r_E}^{L(t)} \frac{v(r, t)}{\kappa(P, \beta, r, t)} dr \right], \quad (1)$$

where v is the velocity of the solar wind at distance r from the Sun at time t , P is the charged-particle magnetic rigidity, β is the ratio of the particle velocity to the velocity of light, $L(t)$ is the distance from the Sun over which the modulation is effective, r_E is the distance of the Earth from the Sun, and $\kappa(P, \beta, r, t)$ is the isotropic diffusion coefficient of the particles in the interplanetary magnetic field.

It has been generally assumed that the dependence of $\kappa(P, \beta, r, t)$ on the spatial coordinate r and on the rigidity P is separable, and experimental evidence in support of this has been given by O'Gallagher (1967) for the period of time around solar minimum in 1965. He says (p. 695), "Since $\kappa(P, \beta, r, t)$ is observed to have the same dependence on P and β for time and spatial changes of intensity, $\kappa(P, \beta, r, t) \dots$ must be the same function of P and β throughout the modulating region as it is at Earth \dots thus implying approximate separability." Then, after also putting $\beta \simeq 1$ for the particles ($P > 2$ GV) capable of affecting a neutron monitor, equation (1) has been written as

$$J(P, t) = J_{\infty}(P) \exp \left[- \frac{\eta(r, t)}{f(P)} \right]. \quad (2)$$

Here $\eta(r, t)$ has been called the *modulating parameter* which has been written $\eta(t)$ for neutron monitors taking $r = \text{constant}$ at Earth, and $f(P)$ has been called the *modulation function*.

The diffusion coefficient κ may be written

$$\kappa = \frac{1}{3} \lambda w, \quad (3)$$

where w is the speed of the particles ($=c\beta$) and $\lambda(P, r, t)$ is the mean free path between scattering centers of interplanetary magnetic-field irregularities transported by the solar-wind plasma. Only λ_{\parallel} , the component parallel to the magnetic-field lines, has to be considered because diffusion of cosmic-ray particles is much larger in this direction than perpendicular to the field lines. As shown by Jokipii (1966, 1968) λ_{\parallel} is related to the exponent σ of the frequency power spectrum of interplanetary magnetic-field irregularities by

$$\lambda_{\parallel} \propto P^{2-\sigma}. \quad (4)$$

Hence in equation (2) we can write

$$f(P) = P^{2-\sigma} \equiv P^{\alpha}. \quad (5)$$

In 1962 (Coleman 1966) the exponent σ of the power spectrum was very nearly unity in the range of frequencies greater than 10^{-5} Hz corresponding to particles of $P \leq 5$ GV. Therefore, for this time and these rigidities, $\alpha \simeq 1$. If this power spectrum could be extrapolated unchanged to lower frequencies corresponding, say, to $P \leq 50$ GV, then for neutron monitors at this time the form of the modulation function would be given by

$$f(P) = P. \quad (6)$$

III. CALCULATIONS FOR NEUTRON MONITORS

Mathews, Stoker, and Wilson (1970) have demonstrated that the fractional changes of counting rates of neutron monitors [with time as represented by $\eta(t)$] can now be calculated with considerable accuracy from the results of surveys with a mobile overland neutron monitor made near cosmic-ray maximum in 1965 (Carmichael, Bercovitch, Steljes, and Magidin 1969) and more extensively in 1966 (Carmichael, Shea, and Peterson 1969), by using the modulation function (5) and the relation (2). The measurements of the latitude survey were corrected to the time of cosmic-ray maximum (May 1965) and tabulated by Carmichael and Bercovitch (1969).

The calculation is essentially that of the method of coupling constants first described rigorously by Dorman (1957). The calculation depends upon the establishment of the differential counting rate dN/dP of the monitor for the time of cosmic-ray maximum (solar minimum) as a function of magnetic rigidity of the particles incident on the atmosphere for the particular depth of the monitor within the atmosphere. For the rigidity cutoffs of 2–13 GV provided by the geomagnetic field the differential counting

rates dN/dP were obtained from the latitude survey; and the differential response above 13 GV was assumed, in conformity with previous authors (Dorman 1957; Webber and Quenby 1959; Lockwood and Webber 1967), to be

$$\frac{dN}{dP} = AP^{-\gamma}(13 \text{ GV} < P < \infty), \quad (7)$$

where A and γ are constants dependent upon the atmospheric depth of the monitor. Mathews *et al.* (1970) drew a smooth curve through values of γ estimated by extrapolation of the latitude-survey data for different atmospheric depths and used that curve to provide γ for each particular station.

We have elaborated the calculation by including the assumption that the modulation of cosmic rays may be effective only to a maximum rigidity P_m . The counting rate at a location at atmospheric depth x and cutoff geomagnetic rigidity P_c becomes

$$N(P_c, x, t) = \sum_{P_c}^{13} \frac{dN}{dP} \exp[-\eta(t)/P^\alpha] \Delta P + A \int_{13}^P P^{-\gamma} \exp[-\eta(t)/P^\alpha] dP \\ + A \int_{P_m}^{\infty} P^{-\gamma} dP, \quad (8)$$

where $\eta(t)$ is now the modulating parameter at time t , reckoned from zero for the residual modulation of galactic cosmic rays at cosmic-ray maximum (May 1965). When $\eta(t) = 0$, the counting rate is

$$N_0(P_c, x) = \sum_{P_c}^{13} \frac{dN}{dP} \Delta P + A \int_{13}^{\infty} P^{-\gamma} dP. \quad (9)$$

The fractional rate $N(t)/N_0$ at a time when the modulating parameter is $\eta(t)$ is given by dividing equation (8) by equation (9). It is to be understood that a change of α or a change of P_m with time is an alteration of the form of the modulation function $f(P)$. Also, the initial assumption that the diffusion coefficient is a separable function of P and r must not be forgotten: this may not be true, or it may be true only for limited periods of time.

IV. REGRESSION CURVES BETWEEN PAIRS OF STATIONS

A regression curve for the fractional rates at any one station calculated by means of equation (8) for different values of $\eta(t)$ plotted against the rates at any other station calculated for the same values of $\eta(t)$ will be a continuous single-valued function. This calculated curve can be compared directly with the regression curve between the observed fractional rates at the two stations. Then, as already stated, if the observed regression curve has discontinuities or "hysteresis" loops or is not a single-valued relationship, it must be concluded that the form of the modulation function is *not* independent of time.

V. STATIONS AT DIFFERENT ATMOSPHERIC DEPTHS

In Figure 1 fractional monthly average counting rates for the high-latitude stations, Inuvik at 758 mm Hg, Calgary at 662 mm Hg, and Sulphur Mountain at 576 mm Hg, have been plotted against Deep River (747 mm Hg) for the years 1965–1969. Particulars for all the stations discussed are listed in Table 1. The Inuvik–Deep River regression (which includes some points for 1970) indicates equal fractional time variations, as would be expected for stations above the knee of the latitude effect and at the same atmospheric depth. Furthermore, after more than 5 years the two stations agree to within better than 0.5 percent. In Figure 1 a different symbol has been used for each successive year so that the progress of the modulation with time can be followed.

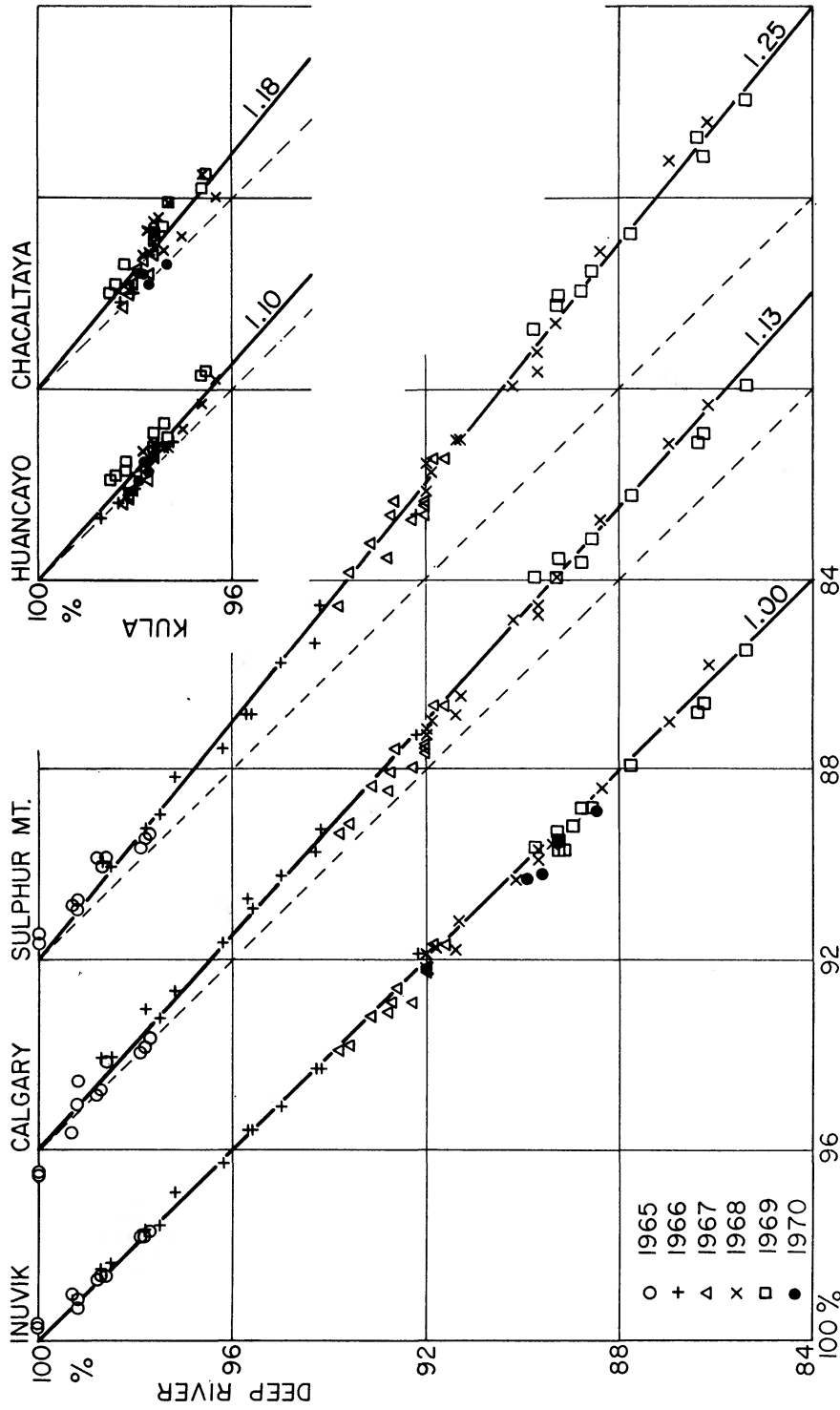


FIG. 1.—Correlation of changes in neutron-monitor intensity for pairs of stations at the same magnetic rigidity cutoff but at different altitudes during 5 years of increasing solar activity from 1965 to 1970. The points represent monthly averages. The curves are regression lines calculated as described in the text for $P_m = \infty$ and $\alpha = 1$. The numerical value of the calculated regression coefficient for each pair of stations is given. Regression lines for other values of P_m and α may be seen in Fig. 2.

TABLE 1
SUMMARY OF NUMERICAL DATA

LOCATION	mm Hg	GV	γ	$\eta(t)=1.6; P_m = \infty$ (percent)		
				$\alpha=0.7$	$\alpha=1.0$	$\alpha=1.3$
Deep River.....	747	1.0	1.57	79.0	87.9	92.8
Inuvik.....	758	0.2	1.57	79.0	87.9	92.8
Sulphur Mountain.....	576	1.0	1.70	75.0	84.9	90.6
Calgary.....	662	1.1	1.63
Climax.....	507	3.0	1.75
Kula.....	686	13.3	1.62	88.7	95.6	98.2
Huancayo.....	518	13.4	1.74	87.8	95.1	98.1
Chacaltaya.....	406	13.1	1.84	86.7	94.6	97.8

The regression lines for the fractional variations of the neutron monitors at Calgary and at Sulphur Mountain with respect to Deep River in Figure 1 are calculated curves that use the quotient (eq. [8]/eq. [9]) with $\alpha = 1$ and $P_m = \infty$. The agreement of the calculated curves with the experimental values is excellent, the fractional variations at Calgary being 13 percent and at Sulphur Mountain 25 percent larger than the variations at Deep River.

In Figure 2 calculated regression curves for Sulphur Mountain-Deep River are shown over a range of variation of the modulating parameter from 0.0 to 1.6 (for P in GV) and for various values of α and P_m as indicated. As already stated, the curve calculated for $\alpha = 1.0$ and $P_m = \infty$ is the curve drawn through the experimental points for Sulphur Mountain-Deep River in Figure 1. It is apparent that the sensitivity of the altitude

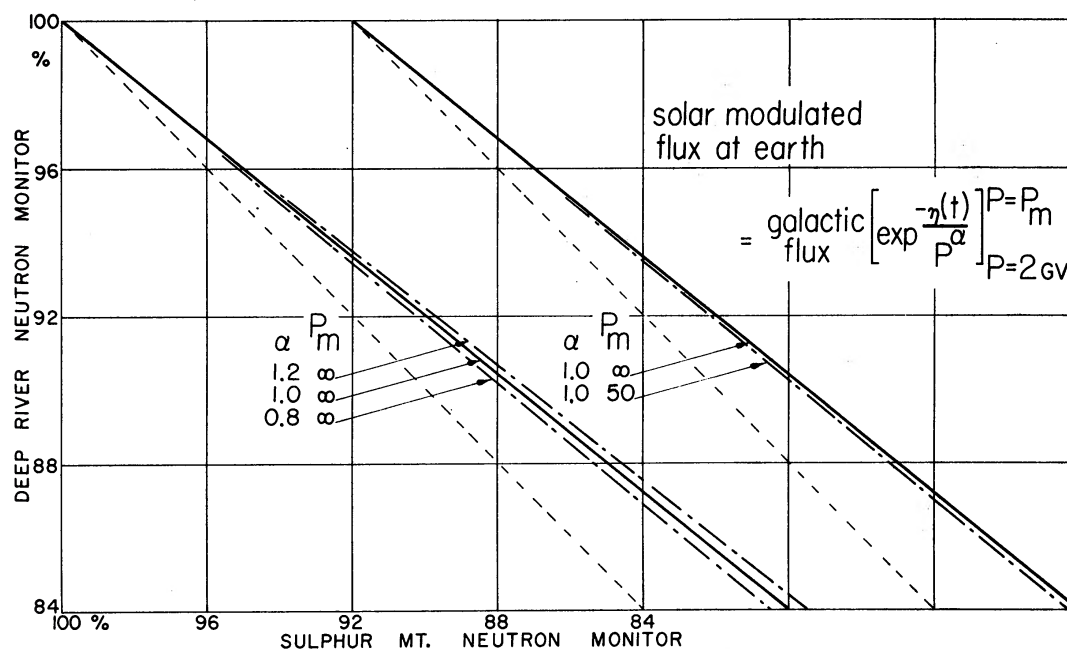


FIG. 2.—Calculated regression curves between relative changes of intensity as measured by the high-altitude neutron monitor at Sulphur Mountain (pressure 576 mm Hg) and the “sea level” neutron monitor at Deep River (pressure 747 mm Hg) for different values of α and P_m and variation of $\eta(t)$ from 0 to 1.6 GV.

effect to alteration of α or P_m is insufficiently large to indicate that $\alpha = 1.0$ and $P_m = \infty$ are the only possible assignments or whether any significant change in either of these with time has taken place.

Also shown in Figure 1 are regression curves similarly calculated for the low-latitude stations Huancayo at 518 mm Hg and Chacaltaya at 406 mm Hg plotted against Kula at 686 mm Hg. All three of these stations have geomagnetic rigidity cutoffs near 13 GV. Again, use of different values of α and P_m would have had little effect on the calculated regression lines.

Since the monitors at Kula and at Chacaltaya only began to operate late in 1966, it was necessary to determine the 100 percent counting rates for both stations for mid-1965 by means of the Huancayo data which were normalized to 100 percent for May 1965. Rates were chosen which made the experimental points fit the calculated regression lines as shown in Figure 1.

It may be mentioned here that satisfactory agreement of the neutron-monitor observations with the calculated regression curves does not exist unless corrections (the so-called normalization factors) are applied to the tabulated data. At each of the stations Deep River, Inuvik, and Kula the digital servobarometers have been slowly drifting with time. The direction and magnitude of the drift at each station could only be determined with precision from comparisons with meteorological barometers extending over several years. Hence the necessary normalization factors have only recently been published for Deep River and Inuvik (Steljes 1970) and for Kula (Carmichael, Steljes, and Kowalski 1970). It may also be mentioned that many other neutron monitors have been operating at high latitudes and have been used to confirm Deep River, but no data from neutron monitors at low latitudes other than Huancayo and Chacaltaya were available for comparison with Kula.

VI. STATIONS AT DIFFERENT GEOMAGNETIC CUTOFFS

In Figure 3, on the left-hand side and in the center, calculated regression curves are shown over a range of the modulating parameter $\eta(t)$ from 0.0 to 1.6 GV for Deep River (1 GV) plotted against Kula (13 GV) for the values of α and P_m indicated. The lines are slightly curved; for $\alpha = 1.0$, $P_m = \infty$, and $\eta(t) = 1.6$, the fractional decrease at Kula is 0.37 that at Deep River. In Figure 3 on the right-hand side are shown the monthly totals at Deep River plotted against the corresponding totals at Kula from August 1966 when the station started. There is good agreement with the regression line for $\alpha = 1.0$ and $P_m = \infty$ until December 1966 (see list of dates on Fig. 4). After that there are successive steplike changes between each of which the variations seem to follow a new regression line.

We have chosen to delineate each new regression by a similarly curved line "parallel" to the calculated curve. Despite the considerable scatter of the individual points, this seems to be a distinctly better choice than a series of regression lines all intersecting 100 percent, such as would result from calculations that used successively increasing values of α . The lines have been drawn by hand since at this stage automatic fitting procedures seem superfluous. Our choice of the 100 percent value for Kula for 1965, before the monitor was in operation, was based as stated above upon the regression with Huancayo (Fig. 1).

The 100 percent value chosen for the Kula data is, of course, of critical importance. It is evident that the value adopted strongly prohibits the use of one single regression line to represent all the experimental points in Figure 3. It may be mentioned here that independent confirmation of the 100 percent value chosen for Kula, based on muon monitor data, exists and will be reported later.

In Figure 4 the sequence of the experimental points is shown in detail. The different symbols used represent successive intervals of time as listed. Arrows show the steps from one interval to the next. Except for the sequence of square points, July to December

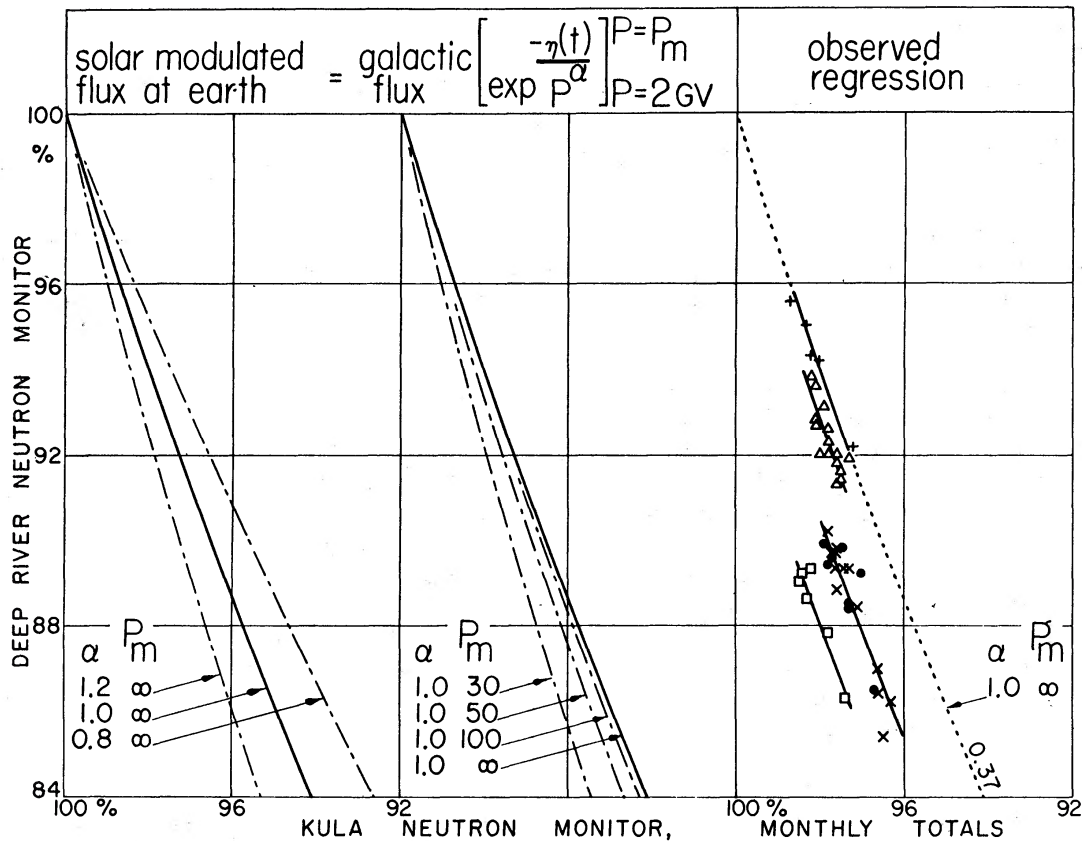


FIG. 3.—*Left*, the calculated regression curves between relative changes of intensity as measured by the low-latitude neutron monitor at Kula (geomagnetic rigidity cutoff ~ 13 GV) and the high-latitude neutron monitor at Deep River (cutoff ~ 1 GV) for constant P_m and three different values of α . *Middle*, the calculated curves for constant α and four different values of P_m . *Right*, the calculated regression curve for $\alpha = 1.0$ and $P_m = \infty$ shown again as a broken curve. The monthly observations follow this curve only from August 1966 when the Kula monitor started till December 1966. The regression lines are calculated for variation of $\eta(t)$ from 0 to 1.6 GV and are curved; for $\alpha = 1.0$, $P_m = \infty$, and $\eta(t) = 1.6$ GV, the relative variations at Kula are 0.37 of those at Deep River (for list of dates see Fig. 4).

1969, the points for successive months travel backward and forward once or twice on each successive regression line. This behavior strengthens the feeling that the variations behave as if the form of the modulation function remained unchanged for periods of duration 6–18 months and then changed within about 1 month.

As in Figure 3 we have drawn the successive slightly curved regression lines “parallel” to each other. They could also have been drawn with little alteration so that, reckoning from the respective points of intersection with the ordinate as 100 percent for each monitor, the regressions between the relative monthly variations of the two monitors were always similar and numerically equal for the different regression lines. This implies that, as a first approximation, the short-term (monthly) variations may be said to maintain a P^{-1} rigidity dependence regardless of the depth of the 11-year modulation as measured by either of the two monitors.

Although we have already demonstrated that the four stations at high latitude and also the three stations at low latitude track consistently with each other so that it is very unlikely that the steps are due to instrumental error, it is expedient to examine directly the other pairs of stations similarly separated in latitude.

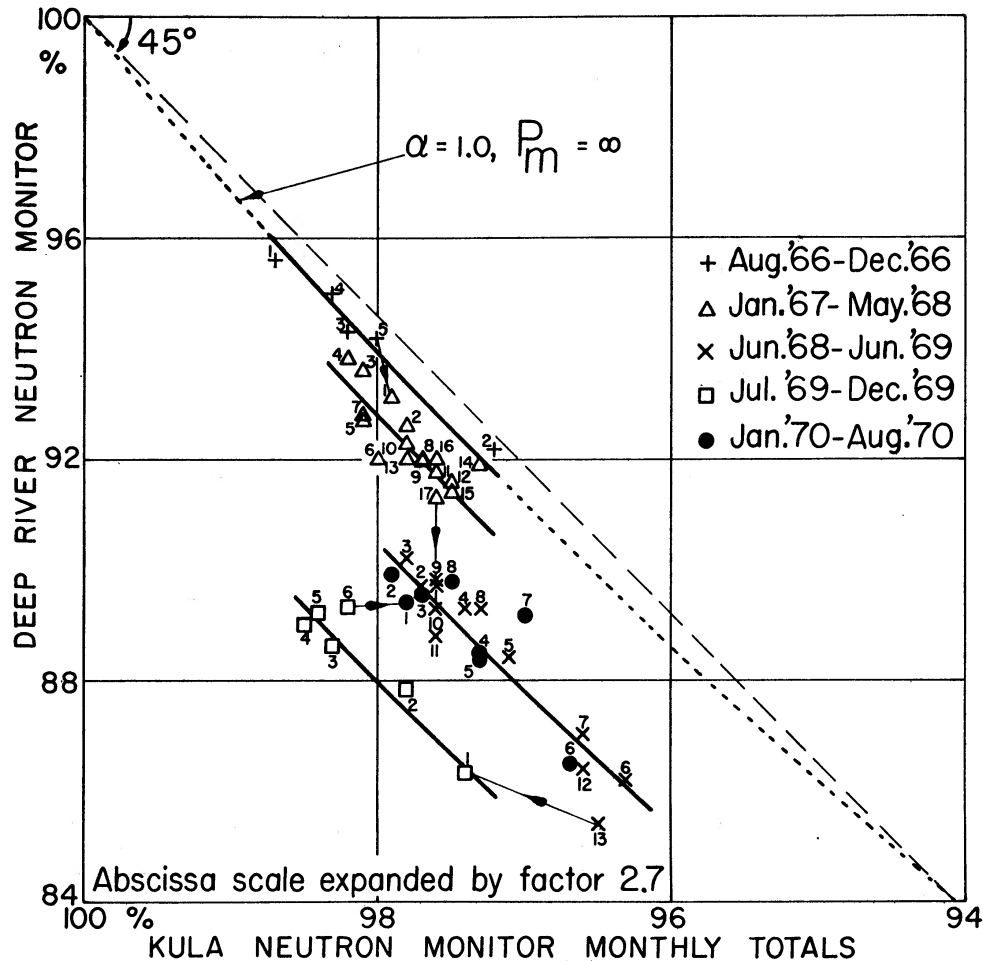


FIG. 4.—Observed and calculated regressions between the relative variations of the Kula and the Deep River neutron monitors in more detail. The monthly experimental points have been numbered in sequence.

In Figure 5 on the left hand we see observations from Climax (3 GV) and Huancayo (13 GV), two of the stations used by Simpson and Wang (1970). Simpson and Wang (1970) used the data in the form of 3-month totals and concluded that “the regression curves leading into and out of the periods of minimum solar modulation are consistent with single-valued functions.” Using the monthly totals, we feel that for this particular period the data should properly be represented by a series of disjointed regression lines as shown in Figure 5 almost identical with the lines already used for the completely independent pair of monitors in Figure 4. We feel that Simpson and Wang have grossly underestimated the precision of their monitors. The calculated regression curve for $\alpha = 1.0$ and $P_m = \infty$ (consistent with the figures given in Table 1) has been included in Figure 5 and again agrees quite well with the observations until December 1966 (in this case from June 1965).

On the right-hand side of Figure 5 another pair of stations, Sulphur Mountain and Chacaltaya at latitudes near 1 and 13 GV, are shown with the same result. In this case, however, several of the monthly totals at Chacaltaya appear to be abnormally low. This is believed to be instrumental error due to absorption by snow which falls occasionally during their summer season (December and January).

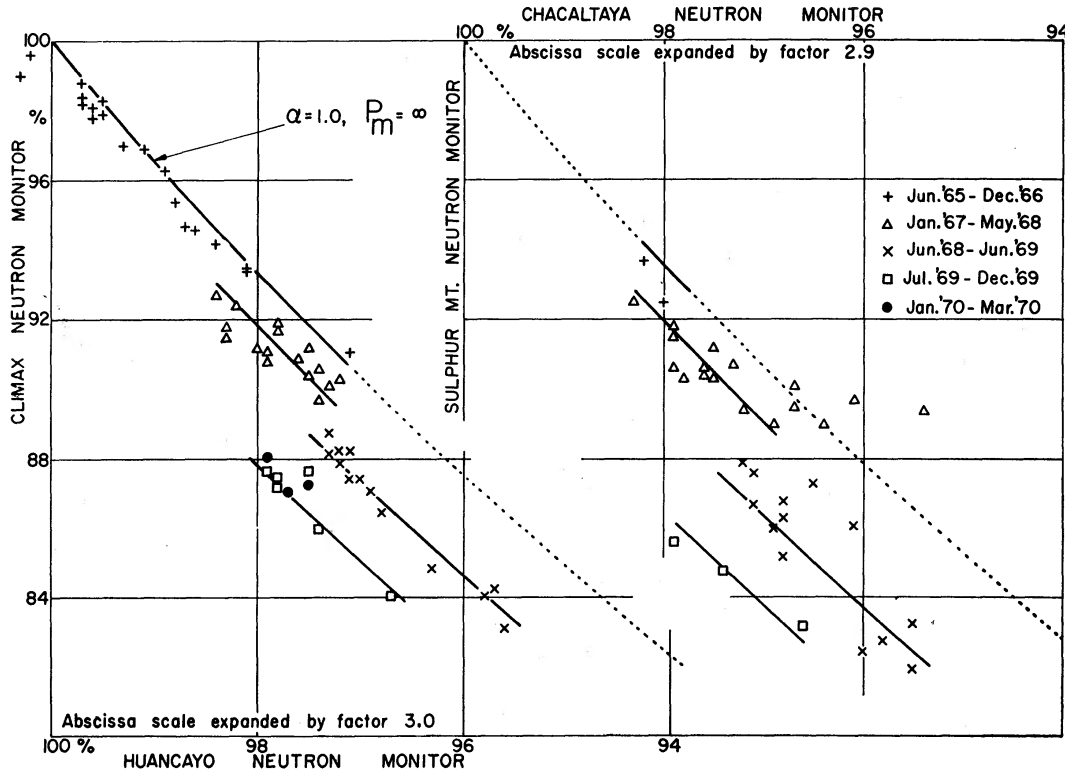


FIG. 5.—Correlation of the relative variations of the neutron monitors at Huancayo (cutoff ~ 13 GV) and Climax (~ 3 GV) and also at Chacaltaya (13 GV) and Sulphur Mountain (1 GV). *Broken curves*, the calculated regression curves for these pairs of stations on the assumption that $\alpha = 1.0$ and $P_m = \infty$. The experimental points are monthly averages. At Chacaltaya several months appear to be abnormally low; this is probably caused by occasional snowstorms at this station.

In comparing the experimental points and regression lines of Figure 4 with the two sets of completely independent data plotted in Figure 5 it should be noted, in addition to the general similarity of the tracking, that the symbols have been switched on the same dates in all cases. In other words, the steps in the long-term modulation occur at exactly the same times, and once a step has occurred, all the following experimental points remain within about 0.5 percent of the new regression line (except for a few points associated with Chacaltaya).

VII. DISCUSSION

It is evident from these experimental observations with neutron monitors involving a range of magnetic rigidity from 2 to 100 GV or more that the form of the modulation function has changed suddenly at least three times since 1965 (a fourth alteration indicated at Kula in January 1970 and not confirmed by the data from Huancayo must await confirmation; it should be noted that the neutron monitor at Kula was used for an altitude survey in January 1970; this may have introduced an instrumental change).

Comparison with the calculated curves indicates that only utterly unreasonable changes of P_m could have caused the observed effects. The observed effects could be fitted by substantial increases of α , but the gradients for the relative fractional changes of counting rates at a particular value of α would then be altered, which is not borne out by the experimental data. However, the requirement for increased values to α to provide new theoretical regression curves passing through the origin and approximately fitting the experimental data after each steplike change suggests that the average rigidity

dependence of the long-term modulation increases with increasing solar activity, as was observed by Ormes and Webber (1968).

The kind of alteration of the modulation required is one that can produce a long-lasting decrease in the intensity of the lower-rigidity particles without much change of the average intensity of the higher-rigidity particles. At the same time it must not much affect the short-term variations of the monthly averages which are presumably closely associated with the well-known Forbush decreases and fluctuating 27-day variations produced by sporadic local influences of the Sun on the interplanetary plasma. Additionally, it should be possible for the average modulation at higher rigidities to suffer a persistent change without much alteration at low rigidities. This seems to have occurred in July 1969 when at the bottom of Figure 4 the fractional intensity at Kula recovered without a proportionate increase of the fractional intensity at Deep River.

In this first paper on this effect our main concern has been to report the discovery of the steplike nature of the form of the long-term modulation on a sound experimental basis and to give the dates (see inset Fig. 4) of the steps. Detailed study of the steps and their possible correlations with individual cosmic-ray events such as Forbush decreases or emissions of high-energy particles by the Sun has not been attempted. We have looked for the same steps using data from stations at intermediate latitudes and have satisfied ourselves that they are present, but we considered that a detailed study of the intermediate stations should not be allowed to delay the present report.

These observations may conceivably be explained by alterations in the shape of the power spectrum of the irregularities of the interplanetary magnetic field (Jokipii 1966). This would mean that the power in the smaller irregularities relative to the larger irregularities could be altered in a relatively short time interval of several weeks, the approximate time required for a steplike change to take place. It follows that the simple and unchanging dependence on rigidity of the power spectrum of the irregularities of the interplanetary magnetic field expressed by relation (5) with constant α would no longer apply. The time of several weeks for these changes to take place is suggestive of an overall change in features of the interplanetary magnetic field, up to its outer boundary.

Another possible explanation is that the effective modulation distance $L(t)$ in equation (1) is dependent on the rigidity of the particles, i.e., that lower-rigidity galactic cosmic-ray particles are scattered randomly farther out from the Sun than higher-rigidity particles, and that this rigidity dependence of $L(t)$ is increased stepwise with increasing solar activity. This would mean that $\eta(t)$ is also a function of rigidity, changing stepwise in time.

It is certainly of considerable interest to try to identify these sudden and persistent changes of the interplanetary medium with events observed on the Sun which might bring about such changes. A solar observational approach such as this seems to be needed because, even with no knowledge of the steplike features reported above, Mathews, Quenby, and Sear (1971) have recently argued that the cosmic-ray modulation over the cycle of solar activity cannot be explained by observed variations in solar-wind and interplanetary magnetic-field parameters.

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these three stations is processed, and published in a long series of reports, by Mr. J. F. Steljes whom we also thank. The latest of these reports, AECL-3562 for Kula and AECL-3736 for Deep River, Inuvik, Alert, and Goose Bay, contain references to all earlier reports.

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