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Hysteresis of Primary Cosmic Rays Associated with Forbush Decreases

R. S. Rajan

727 Fifteenth Avenue, SE, Minneapolis, Minn. 55414, U.S.A.

Abstract

Regression analysis of primary cosmic ray intensities during Forbush decreases indicates the existence of a differential modulation between high and low rigidity primaries.

Introduction

The 11 year variation of primary cosmic ray intensities is known to exhibit a hysteresis as a function of sunspot numbers. A similar effect is reported in this paper in the case of the quasistationary primary intensities during a Forbush event. It is shown that a regression plot of high and low rigidity primaries exhibits a loop during a Forbush event, indicating a differential modulation between the two. It is also shown that this effect is superposed on the 11 year variation.

Experimental Details

Method

Neutron monitors and satellite-borne ion chambers provide an almost continuous record of primary cosmic ray intensities. For the present study, data from the Deep River neutron monitor and Ogo-I and Ogo-III ion chambers have been combined with the daily observations of the upper atmosphere intensities recorded with standardized Geiger–Mueller counters over Murmansk, U.S.S.R. (Ageshin and Charakhchyan 1966). The choice of these three detectors was made because they cover different rigidity regions of the primary spectrum. The response characteristics of these detectors are shown in Fig. 1. To eliminate very short-term variations, all the available data were reduced to 10-day moving averages. Using the reduced data, an extensive regression analysis was made. The events considered in this paper have periods much longer than 10 days.

Observations

A number of results yielded from these data have already been reported by others and they are summarized here:

(1) All the instruments recorded their solar-cycle maxima at about the same date (14 May 1965) even though they responded to different rigidities.

(2) The data points tended to accumulate, and to deviate very little from definite values during certain periods which correspond to equilibrium conditions in the modulation region (Lezniak and Webber 1971).

(3) A plot of the equilibrium intensities between the Murmansk Geiger–Mueller counter data and the Churchill neutron monitor data indicates that the intensities from May 1965 to May 1966 had a different spectral index, i.e. there were fewer high rigidity particles. A similar observation during 1969 has been discussed by a number of authors (e.g. Iucci *et al.* 1973*a*). Also, in the ascending phase of cycle 20 many step-like changes were observed (Iucci *et al.* 1973*b*). Combining this result with the observations of the present analysis, we find that such step-like changes most frequently occur close to the turn-around points in the solar cycle, e.g. between October–November 1964 and April 1965.

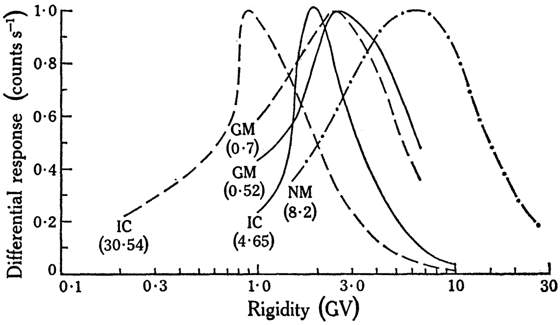


Fig. 1. Response characteristics of the detectors used to collect the data:
IC, Ogo-I and Ogo-III ionization chambers (dashed curve, solar minimum; continuous curve, solar maximum).
GM, Murmansk Geiger–Mueller counter (dashed curve, solar minimum; continuous curve, solar maximum).
NM, Deep River neutron monitor (dot–dash curve).
The IC curves were constructed using ionization response curves and primary cosmic ray spectra, while the GM and NM curves were constructed from latitude surveys. The multiplication factors which convert the curves to actual counting rates are given in parentheses.

(4) The spectral index of primary cosmic rays underwent considerable change during certain periods, the spectrum being steeper during September 1965 and November–December 1966. The spectrum occasionally became flatter also, e.g. in April 1967. The plot of the equilibrium intensities, mentioned in point (3), indicates a constant spectral index except during May–September 1965 (Verschell *et al.* 1973).

(5) Forbush events mix up the intensities of primary cosmic rays relative to their 11 year values. The regression plot (Fig. 2) between the Murmansk Geiger–Mueller counter data and the Deep River neutron monitor data shows some of the 1968

Fig. 2 (*opposite*). Regression plot between 10-day averaged counts from the Murmansk Geiger–Mueller counter and the Deep River neutron monitor. Points corresponding to different periods are indicated as shown in the legend, while the circled regions correspond to equilibrium counting rates (see text). The numbered data correspond to the following dates:

1, Oct.–Nov. 1964; **2**, 13 Mar. 1965; **3**, Mar. 1965; **4**, 11 Apr. 1965; **5**, 14 May 1965; **6**, May 1965. **7**, 1 Dec. 1965; **8**, 1 Apr. 1966; **9**, 11 Apr. 1966; **10**, 9 May 1966; **11**, 22 Aug. 1966; **12**, 25 Sept; 1966; **13**, 8 Oct. 1966; **14**, 26 Oct. 1966; **15**, 30 Nov. 1966; **16**, Nov.–Dec. 1966; **17**, 12 Mar. 1967; **18**, 26 Mar. 1967; **19**, 25 Aug. 1967; **20**, 12 Sept. 1967; **21**, 10 Oct. 1967; **22**, 21 Oct. 1967; **23**, 1 Jan. 1968; **24**, 16 Mar. 1968; **25**, 10 May 1968; **26**, 27 Sept. 1968; **27**, 7 Oct. 1968; **28**, 23 Oct. 1968; **29**, 4 Nov. 1968; **30**, 11 Nov. 1968; **31**, 26 Nov. 1968.

The data group associated with points **19** and **20** has been shifted to the left by $50\,\mathrm{s}^{-1}$.

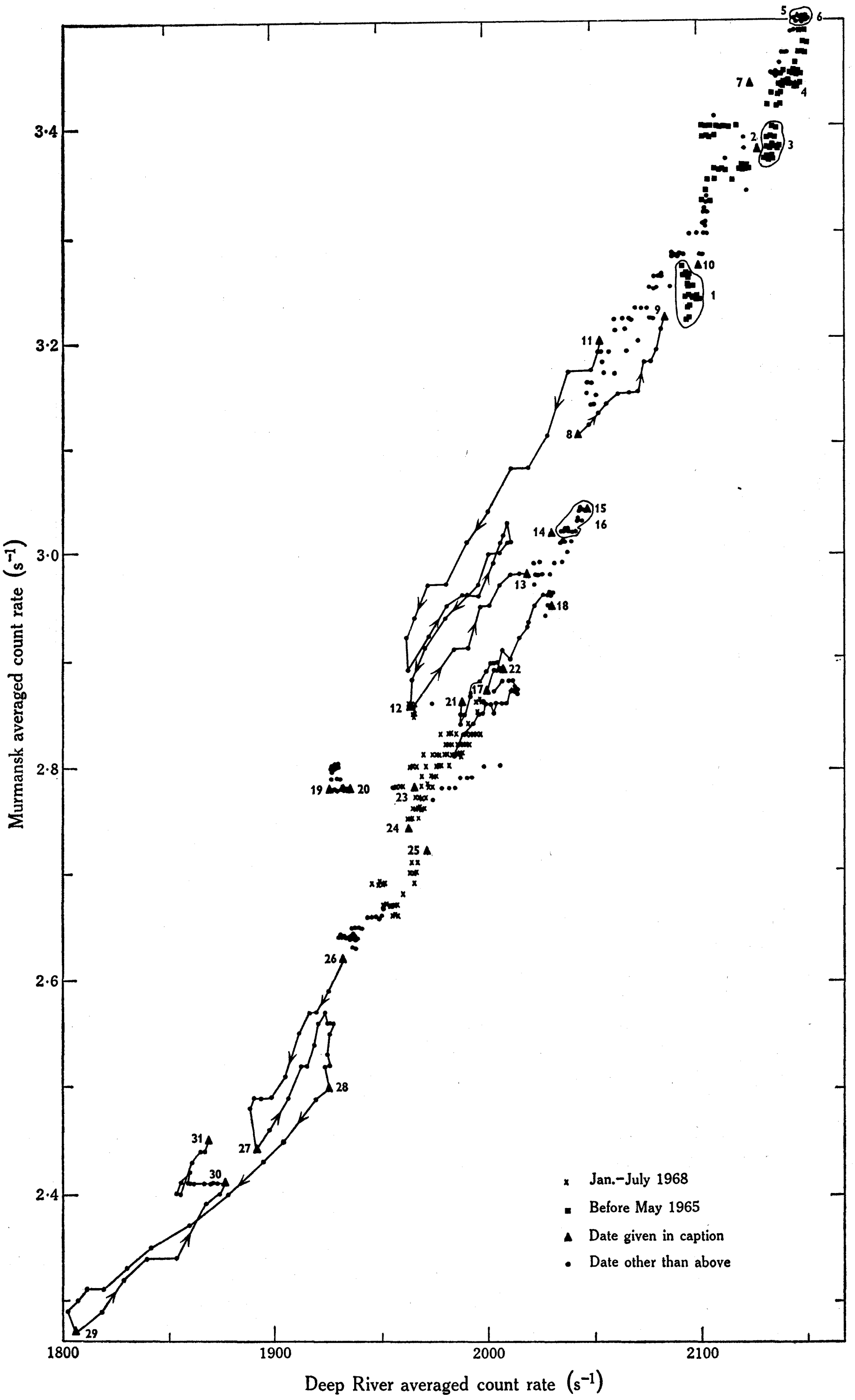

Murmansk averaged count rate (s^{-1})
Deep River averaged count rate (s^{-1})
3·4
3·2
3·0
2·8
2·6
2·4
1800
1900
2000
2100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
x Jan.–July 1968
■ Before May 1965
▲ Date given in caption
● Date other than above

Fig. 2.

points lying close to 1966 points and some 1967 points lying lower than 1968 points. Thus Forbush events prevent the primary intensities from decreasing monotonically from sunspot minimum to maximum.

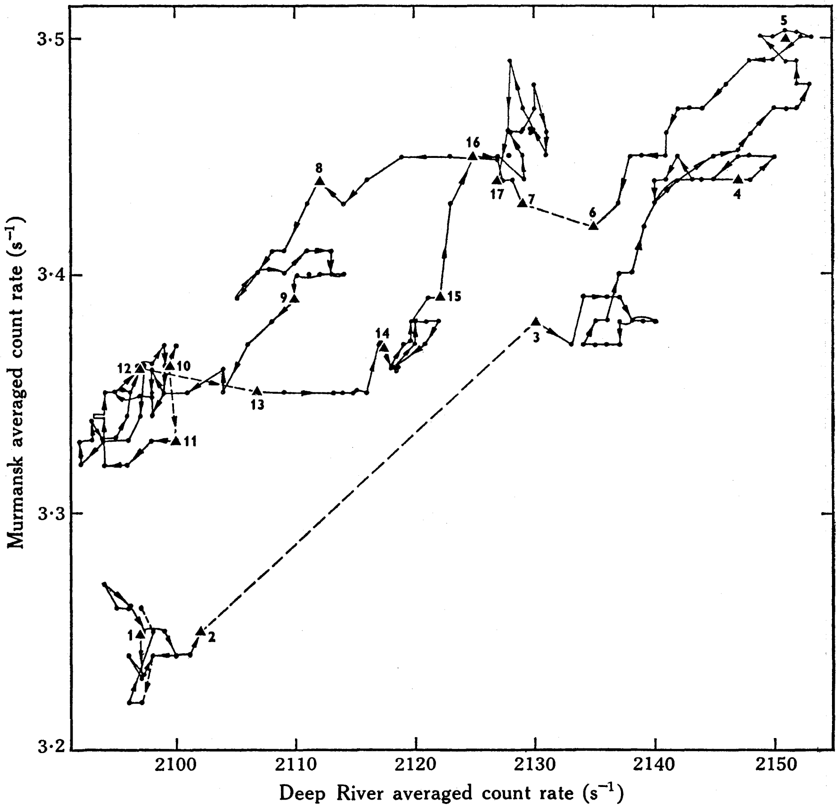


Fig. 3. Regression plot between 10-day averaged counts from the Murmansk Geiger–Mueller counter and the Deep River neutron monitor (supplementing Fig. 2). The solid triangles correspond to data for the following dates:

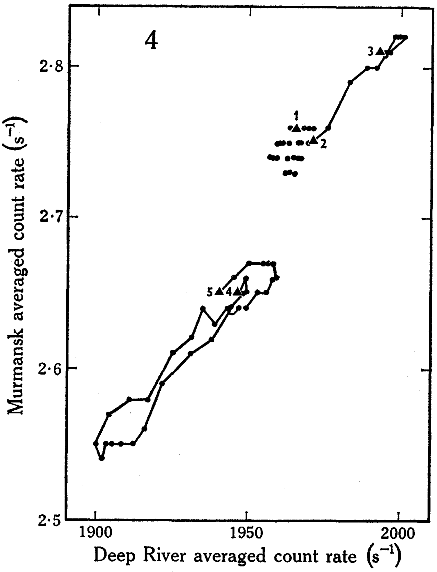
1, 10 Oct. 1964; **2**, 25 Nov. 1964; **3**, 13 Mar. 1965; **4**, 11 Apr. 1965; **5**, 14 May 1965; **6**, 1 June 1965; **7**, 6 June 1965; **8**, 16 June 1965; **9**, 3 July 1965; **10**, 10 Aug. 1965; **11**, 14 Sept. 1965; **12**, 26 Sept. 1965; **13**, 13 Oct. 1965; **14**, 23 Oct. 1965; **15**, 9 Nov. 1965; **16**, 11 Nov. 1965; **17**, 1 Dec. 1965.

The hysteresis after the solar minimum is clearly seen.

Figs 3, 4 and 5 indicate the behaviour of low and high rigidity particles during typical Forbush events. Hysteresis is clearly evident. This indicates that high and low rigidity particles are modulated differently during a Forbush event. High rigidity particles are removed faster in the early phase of the decrease and they recover faster. A similar observation has been reported by Verschell *et al.* (1973) for type I Forbush decreases, but the effect reported in the present paper is much more general.

The relative modulation between the high and low rigidity particles can be measured by a parameter of the form

$$\mu = \frac{\Delta N_g/N_g}{\Delta N_n/N_n} \approx \frac{\Delta(\ln N_g)}{\Delta(\ln N_n)},$$



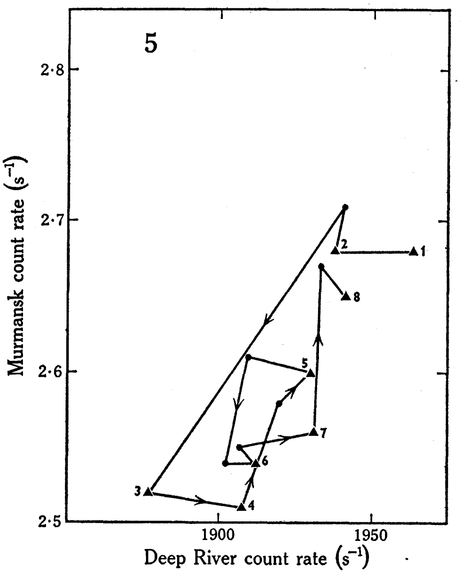


Fig. 4. Regression plot between 10-day averaged counts from the Murmansk Geiger–Mueller counter and the Deep River neutron monitor for the Forbush decrease from 3 July to 5 Aug. 1968. The solid triangles correspond to data for the following dates:

1, 20 Mar.; **2**, 12 Apr.; **3**, 26 Apr.; **4**, 3 July; **5**, 5 Aug.

The equilibrium region during Mar.–Apr. 1968 is evident.

Fig. 5. Regression plot of unaveraged counts from the Murmansk Geiger–Mueller counter and the Deep River neutron monitor for the Forbush decrease from 7 June to 25 June 1968. The solid triangles correspond to data for the following dates:

1, 7 June; **2**, 9 June; **3**, 11 June; **4**, 13 June; **5**, 16 June; **6**, 20 June; **7**, 23 June; **8**, 25 June.

Table 1. Count rates and relative modulation during Forbush decreases

The errors in the count rates are 2·5%

Start of Forbush decrease	N_g (s^{-1}) Start	N_g (s^{-1}) Minimum	N_n (s^{-1}) Start	N_n (s^{-1}) Minimum	Modulation μ
20 Jan. 1966	3·43	3·28	2137	2092	1·89
23 Mar. 1966	3·38	3·08	2109	2032	2·40
30 Aug. 1966	3·19	2·89	2055	1911	1·44
15 Sept. 1966	3·03	2·85	2013	1964	2·43
24 May 1967	2·92	2·69	2039	1952	1·82
10 June 1968	2·67	2·56	1946	1905	2·03
11 July 1968	2·65	2·54	1948	1902	1·63
3 Sept. 1968	2·66	2·54	1950	1904	1·78
1 Oct. 1968	2·61	2·44	1943	1892	2·58
29 Oct. 1968	2·52	2·27	1926	1804	1·50

where N_g and N_n denote the counting rates of the Geiger–Mueller counter over Murmansk and the neutron monitor at Churchill respectively, and Δ signifies the maximal change in the counting rates caused by the Forbush decrease. In Table 1, the relative modulation parameter is evaluated for some Forbush events. The fact that there is no correlation between μ and the corresponding values of N_g

and N_n indicates that the modulation region is affected differently during different Forbush events. The parameter μ has a constant value of $2 \cdot 33 \pm 0 \cdot 01$ for the long term variation. Plots of the raw data (i.e. without averaging) confirm these observations. In many cases the Forbush event is characterized by a decrease, a small increase and a final decrease, as some authors have reported. But this is not found to be true in all cases (Ables 1967).

Conclusions

The existence of loops during Forbush events can be explained by assuming the presence of a long range order for the magnetic inhomogeneities in the modulation region. The existence of the quadrant structures supports this (Wolcox and Ness 1965). Assuming that interplanetary space is made up of inhomogeneities of varying scale sizes with frozen-in magnetic fields pointing in random directions, but with a long range ordering, the high rigidity particles which have a longer mean free path would spiral along the effective field lines and reach the Earth. The low rigidity particles with shorter mean free paths would not experience the long range order and would be scattered effectively. During a Forbush event caused by a flare, a shock is generated in the interplanetary space. The shock is characterized by an increase in the magnetic field, the particle density and the temperature (Wilcox 1969). These in turn, mean a lower gyroradius, a higher number of scattering centres and more fluctuation in the field direction. Also, since the ambient interplanetary magnetic field points along the 'garden-hose' direction, either towards or away from the Sun, the shock resolves itself into one component propagating along the field direction and on other propagating transverse to it. Thus it could act as a switch-on or switch-off shock generating fields in other directions.

Theoretical studies of modulation using Boltzmann's kinetic equation show that the magnetic field has to satisfy the condition $|\delta B|^2 \ll |B|^2$ for the validity of the solutions obtained (Jokipii 1971, 1972). From the above analysis, it would seem that such an approximation is valid for high rigidity particles, i.e. those above 5 GV, but not for low rigidity particles. The correlation length is strongly a function of the particle's rigidity. It seems that, immediately after a shock, the conditions in interplanetary space favour a higher number of collisions for the high rigidity particles, removing them first. The early recovery of high rigidity particles indicates that the long range order of the magnetic inhomogeneities occurs prior to a return of the interplanetary space to its quiescent conditions. A switch-on or a switch-off shock, while creating fields in transverse directions, does not destroy the longitudinal field and thereby maintains the long range order. So when the magnetic field intensity, the density and the temperature recover, the long range order enables the recovery of high rigidity particles ahead of low rigidity particles.

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