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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-4-2. Anisotropy and Changes of Energy Spectrum During Cosmic Ray Storms

V. A. SARABHAI and G. L. PAI
Physical Research Laboratory, Ahmedabad, India

AND

U. R. RAO*
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Mass., U.S.A.

§1. Introduction

Many studies have been conducted primarily from measurements with detectors at intermediate and low latitudes, of cosmic ray storms or Forbush decreases at the minimum of intensity which occurs on the first or second day after the onset of a storm. McCracken[1], McDonald and Webber[2], Lockwood[3] and others have suggested from observations made with neutron monitors that the global changes during cosmic ray storms can be explained by a spectrum of variation

$$\frac{\delta D(E)}{D(E)}=aE^{-x} \tag{1}$$

where 'x' has a value ranging from 0.7 to 1.0. This model with an exponent significantly different from zero and with no other constraints on the spectrum of variation, is referred to as Model 1 in this communication. On the other hand, from a comparison of data from neutron monitors and meson detectors at latitudes $\lambda=0°$ and $\lambda=50°$ during a large number of storms, Dorman[4], Blokh *et al*[5] and others have pointed out that an exponent 'x' different from zero does not explain the observed relative decreases. Their proposal which we designate as Model 2 involves a spectrum of variation

$$\begin{aligned}\frac{\delta D(E)}{D(E)}&=-a \text{ for } E\leq E_{\max}\\ &=\ \ 0 \text{ for } E>E_{\max}\end{aligned} \tag{2}$$

where $E_{\max}$ differs from storm to storm, but has a value approximately equal to 40 GV. They have, moreover, related $E_{\max}$ and 'a' to the physical characteristics of the solar plasma stream responsible for the storm and to the position of the earth with respect to the stream.

In seeking to explain a change of cosmic ray intensity in terms of a physical model, it is important to have information not only on the spectrum of the primary intensity during the change, but also on the position and the symmetry of the modulating mechanism with respect to the sun, the earth and the plane of the ecliptic. For estimating the spectrum of variation, it is desirable to have data from detectors with as large as possible difference in primary energy response. Moreover, the detectors which are compared should sample cosmic ray primaries from essentially the same region of the celestial sphere. For studying the symmetry of the modulating mechanism, the detectors should sample restricted regions of space. These considerations imply that unless the modulation is isotropic, we cannot use the latitude effect of a change to determine the spectrum of variation. Generally we should rather compare pairs of detectors with differing energy response characteristics, both located at appropriate positions on the earth so that the information which is derived can be related to one and the same region of the celestial sphere.

A meson and a neutron monitor at a station such as Resolute, very close to the geomagnetic pole, satisfy our requirements rather well. A similar pair of detectors at the geomagnetic equator at a place such as Huancayo or Lae or Trivandrum furnishes information concerning a belt of the celestial sphere in the range of declinations ±30°. On the other hand, for stations at intermediate latitudes, the spatial response is very sensitive to the spectrum of variation and only under certain conditions it is appropriate to compare neutron and meson intensities to

* On leave of absence from the Physical Research Laboratory, Ahmedabad, India.

Table I. Particulars of stations giving the geographic and geomagnetic coordinates, the magnetic cut-off rigidities, mean energy of response for mesons (M) and neutrons (N) and the name of the principal investigator.

Station	Altitude (meters)	Geographic Lat. o	Geographic Long. o	Geomagnetic Lat. o	Geomagnetic Long. o	Magnetic cut-off rigidity Q & W (BeV)	Component.	Mean energy of response (BeV)	Investigator
I. *Equatorial Region*									
Trivandrum	S.L.	8.48	76.95	-1.13	147.5	17.48	M	59.9	Dr. V. Sarabhai.
Lae	S.L.	-6.72	147.0	-15.72	218.6	14.89	N M	41.8 50.7	Dr. A. G. Fenton.
Huancayo	3400	-12.05	284.6	-0.69	354.7	14.18	N	38.3	Dr. J. A. Simpson.
II. *High Latitude Region*									
Chicago	S.L.	41.83	272.3	52.56	338.2	1.54	N	11.6	Dr. J. A. Simpson.
Leeds	100	53.82	358.5	56.45	84.7	1.71	N	11.6	Dr. P. L. Marsden
Ottawa	101	45.40	284.40	56.70	352.57	0.68	N M	11.2 43.7	Dr. D. C. Rose.
Mt. Wellington	725	-42.87	147.33	-51.40	225.78	1.47	N M	11.6 43.7	Dr. A. G. Fenton.
Sulphur Mt.	2283	56.10	244.40	58.18	301.86	0.80	N M	11.2 43.7	Dr. D. C. Rose.
Climax	3400	39.37	253.8	48.17	317.0	2.77	N	10.3	Dr. J. A. Simpson.
III. *Polar Region*									
Mawson	S.L.	-67.60	62.8	-73.22	104.5	0.57	N	10.9	Dr. A. G. Fenton.
Resolute	17	74.68	265.05	82.99	291.3	0.00	N M	10.9 43.7	Dr. D. C. Rose.
Churchill	39	58.80	265.9	68.71	324.3	0.11	N M	10.9 43.7	Dr. D. C. Rose.

derive the spectrum.

We have applied considerations discussed above to study 6 major cosmic ray storms using the superposed epoch method. The storms that have been analysed occurred on 28-9-1957, 21-10-1957, 25-11-1957, 19-12-1957,

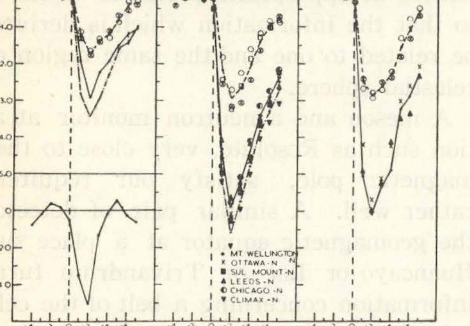

Fig. 1. Results of Chree analysis of the neutron and meson intensity changes for 6 cosmic ray storms studied together. The values indicated are percent deviations from the mean value on -2, -1 and 0 day with respect to the epoch.

25-3-1958 and 16-8-1958. Data from 3 equatorial stations, 6 stations in geomagnetic latitude range $50\pm5°$ and 3 polar stations which are indicated in Table I have been used. Results of the Chree analysis are shown in Fig. 1 for equatorial, high latitude and polar stations; separately for neutron monitors and meson telescopes. We are grateful to Dr. A.G. Fenton, Dr. J.A. Simpson, Dr. P. L. Marsden and Dr. D. C. Rose for furnishing the data for our analysis.

§ 2. Relative changes during cosmic ray storms

For studying the modulation of cosmic ray primaries incident almost perpendicular to the plane of the ecliptic, we consider the ratio of neutron intensity change at Resolute and the mean change of meson intensity at Resolute and Churchill. We disregard the neutron intensity change at Churchill since, due to deflection in the geomagnetic field, this detector responds to low declinations in the celestial sphere. For studying the modulation of primaries travelling along the plane of the ecliptic we consider the ratio of neutron intensity change at Lae or at Huancayo with the mean decrease of meson intensity at Trivandrum and Lae, both the latter intensities having been corrected for upper air temperature effects using radiosonde data. For stations at high latitudes, we consider the ratio of the mean decrease of neutron monitors at Ottawa, Chicago, Mt. Wellington and Leeds and the mean decrease of the meson intensity at Ottawa and Hobart.

Fig. 2 indicates the ratios of changes in neutron and meson intensity for equatorial, high latitude and polar stations. It will be observed that at all places the ratio remains fairly constant from +1 to +5 day, but thereafter the ratio increases significantly on +6 and +7 days. Thus the characteristics of the spectrum of variation undergo systematic changes after the intensity has recovered by about 50 per cent. This coincides with the complete recovery of the horizontal component of the geomagnetic field at the equator.

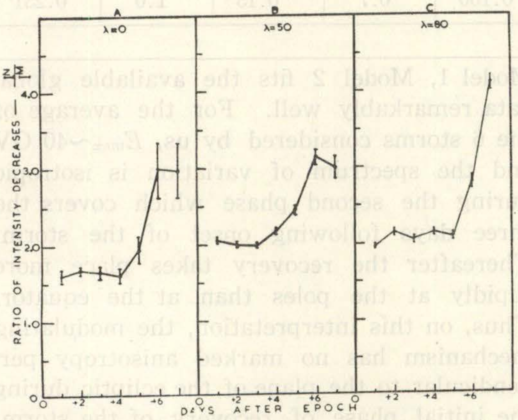

Fig. 2. Ratio of intensity decreases from +1 to +7 day for neutron and meson detectors at the same latitude and same elevation. (a) Equatorial region ($\lambda=0$), (b) High latitude region ($\lambda=50$) and (c) Polar region ($\lambda=80$).

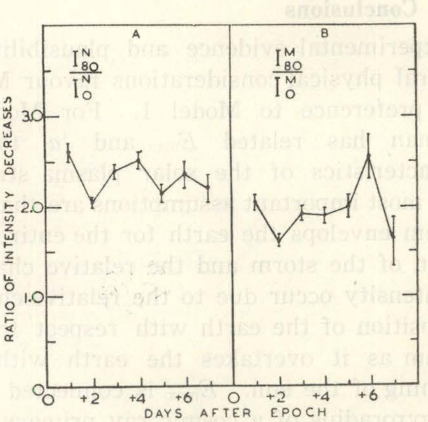

Fig. 3. The ratios of intensity decreases $\frac{I_{80}{}^N}{I_0{}^N}$ and $\frac{I_{80}{}^M}{I_0{}^M}$ for stations at the same elevation from +1 to +7 day of with respect to the epoch.

The latitude effect of changes for sea level stations for neutron monitors and meson detectors is shown in Fig. 3. It will be observed that the ratios $I_{80}{}^N/I_0{}^N$ and $I_{80}{}^M/I_0{}^M$ are fairly constant from +1 to +7 days in contrast to the marked increase in the ratios $I_0{}^N/I_0{}^M$ and $I_{80}{}^N/I_{80}{}^M$ on +6 and +7 days. This indicates that the recovery of the cosmic ray storm at the poles takes place proportionately quicker than at the equator. In other words, the effect on cosmic ray primaries travelling along the plane of the ecliptic is longer lived than for primaries arriving from perpendicular directions.

§ 3. The spectrum of variation

Using geomagnetic cut offs according to Quenby and Webber[6] and the coupling coefficient as given by Dorman[7], the spectrum of variation has been derived for Model 1 and for Model 2 for each latitude belt for seven successive days following epoch. The characteristics of the spectrum are indicated in Tables II (a) and (b) for the two models respectively.

For Model 1, it is difficult to reconcile the decrease at mountain elevations with the decreases observed at sea level stations at a comparable latitude unless we assume that coupling coefficients for stations at mountain elevations are in error. Using coupling coefficients derived by Dorman[7] or the yield functions derived by Quenby and Webber[6] no satisfactory spectrum of variation can explain the relative changes in neutron intensities at Climax and Chicago or the relative changes in the neutron intensity at Huancayo and the meson intensity at Trivandrum or Lae. Even if we disregard this discrepancy for stations at mountain elevations and confine our study to sea level stations, we find that for Model 1, 'x' and 'a' in the spectrum of variation on any particular day significantly differ for cosmic ray primaries incident along the plane of the ecliptic and perpendi-

Table II.a The exponent 'x' and the strength of the source 'a' calculated from neutron and meson intensity changes at $\lambda=0$, $\lambda=50$ and $\lambda=80$ according to Model 1 when the spectrum of variation is $\frac{\delta(DE)}{D(E)}=aE^{-x}$

Day	$\lambda=0$				$\lambda=50$		$\lambda=80$	
	Lae (N) / ½ (Lae+TVM) (M)		Ottawa (N) / Ottawa (M)		Mt. Wellington (N) / Hobbert (M)		Res. (N) / ½ (Res.+Chur.) (M)	
	x	a	x	a	x	a	x	a
+1	1.4	2.92	0.4	0.135	0.6	0.20	0.5	0.180
+2	1.4	4.43	0.5	0.224	0.6	0.29	0.5	0.209
+3	1.4	3.39	0.4	0.160	0.6	0.25	0.5	0.187
+4	1.4	2.93	0.4	1.133	0.8	0.34	0.5	0.168
+5	1.8	8.04	0.6	0.170	0.8	0.25	0.5	0.112
+6	2.8	132.50	0.8	0.218	0.9	0.25	0.7	0.152
+7	2.8	113.90	0.8	0.160	0.7	0.13	1.0	0.231

Table II. b The value of $E_{\max}$ and the corresponding value of 'a' calculated from neutron and meson intensity changes at $\lambda=0$, $\lambda=50$ and $\lambda=80$ according to Model 2, where the spectrum of variation is $\frac{\delta D(E)}{D(E)}=-a$ for $E\leq E_{\max}$ and $\frac{\delta D(E)}{D(E)}=0$ for $E>E_{\max}$.

Day	$\lambda=0$		$\lambda=50$		$\lambda=80$	
	$E_{\max}$ Bev	a	$E_{\max}$ Bev	a	$E_{\max}$ Bev	a
+1	37.5	0.050	40	0.062	45	0.065
+2	37.5	0.074	40	0.083	40	0.082
+3	37.5	0.057	40	0.075	40	0.074
+4	37.5	0.050	35	0.066	40	0.066
+5	32.5	0.043	30	0.055	40	0.042
+6	25.0	0.046	25	0.050	30	0.043
+7	25.0	0.039	30	0.035	22.5	0.038

cular to it. This would mean that the plasma cloud in interplanetary space, which is believed to screen galactic cosmic rays, produces a steeper variational spectrum along the plane of the ecliptic than along a perpendicular direction. The exponent of the spectrum increases for all directions after the initial partial recovery of the intensity.

For Model 2, on +1 day, $E_{\max}$ is greater at the poles than at equator. During the second phase extending from +2 to +4 days, an almost identical $E_{\max}$ can explain changes at mountain elevations and at sea level, at equatorial, high latitude and polar regions. Thus, unlike the discrepancy which arises in attempting to explain on the basis of Model 1, Model 2 fits the available global data remarkably well. For the average of the 6 storms considered by us, $E_{\max}\sim$40 GV and the spectrum of variation is isotropic during the second phase which covers the three days following onset of the storm. Thereafter the recovery takes place more rapidly at the poles than at the equator. Thus, on this interpretation, the modulating mechanism has no marked anisotropy perpendicular to the plane of the ecliptic during the initial phase of recovery of the storm. An anisotropy for directions of arrival along and perpendicular to the plane of the ecliptic is indicated only during onset on +1 day and during the second stage of the recovery.

§ 4. Conclusions

Experimental evidence and plausibility on general physical considerations favour Model 2 in preference to Model 1. For Model 2, Dorman has related $E_{\max}$ and 'a' to the characteristics of the solar plasma stream. The most important assumptions are that the stream envelops the earth for the entire duration of the storm and the relative changes of intensity occur due to the relative change of position of the earth with respect to the stream as it overtakes the earth with the spinning of the sun. $E_{\max}$ is connected with the gyroradius of a cosmic ray primary in a stream with magnetic field H_1 and a minimum distance l_1 of the edge of the stream from the earth.

Experimentally we find that $E_{\max}$ is nearly constant for the first five days. This would mean that $H_1 l_1$ is constant and does not vary with the relative motion of the stream with respect to the earth during this period. It seems plausible that this constancy arises from the stream originating in the sun and from l_1 being incapable of exceeding the earth sun distance.

Gold[8] has pointed out how a stream ejected from the sun would get disconnected from the sun in a time of the order of 3 to 5 days. This must represent a point of time at which a major change in the effective length 'l' would occur. If during the first five days, we assume that 'l' is the earth sun distance, the average value of the trapped magnetic field would be 1.78×10^{-5} gauss.

An interesting implication arises in the interpretation of cosmic ray storms in the manner suggested above. We would require for $E_{\max} \sim 40$ GV at the poles, a beam perpendicular to the ecliptic of extent comparable to an astronomical unit. On these considerations, it would appear that during a major storm, plasma is ejected or a shock front travels outwards over a wide cone such that it changes magnetic fields in a substantial part of interplanetary space. This is in conformity with recent evidence from space probes concerning cosmic ray decreases at great distances from the earth.

Acknowledgments

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4) L. I. Dorman: Proc. Cosmic Ray Conference, Moscow, **4**, (1960) 111.
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6) J. J. Quenby and W. R. Webber: Phil. Mag. **4** (1959) 654.
7) L. I. Dorman: English Translations of his book "Cosmic Ray Variations" (1957).
8) T. Gold: Paper presented at the COSPAR meeting, Florence, April 1961.

Discussion

Roederer, J.G.: Were the recovery times of the six storms comparable value? We found similar results with yours, but the numerical values and characteristics differ from storm to storm.

Sarabhai, V.A.: The values would differ from storm to storm.

Marsden, P.L.: What effect does likely arise from the movement of earth relative to the beam?

Does day +4 correspond to position of earth in centre of beam?

Sarabhai: This depends on the model we take. We have made a calculation of the type conducted by Bloch and Dorman. I, however, find this rather artificial. I suggest that the cosmic ray changes are produced not only by the isorotation of the beam but also by the radial motion outwards.

Ehmert, A.: I agree that it is useful to start from neutron and meson research. But diurnal variation within such storms has another energy response and for storms with strong and without diurnal variations you come near to model 2 and 1 respectively.

Sarabhai: It is clear that apart from the large storms where Model 2 seems applicable, there are longer lasting streams, where Model 1 type spectrum is applicable to smaller modulation effects.

Sandström, A. E.: Concerning Dr. Marsden's remarks on the diurnal variation on days following closely upon an F, d. I wish to point out the following; The variations on days following closely upon an F, d. often have an $U, T.$ variation and the daily variation.