HIGH ENERGY COSMIC RAY OBSERVATIONS DURING AUGUST 1972

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Abstract. A series of spectacular cosmic ray events which included two relativistic solar particle enhancements and three major Forbush decreases were registered by ground-based cosmic ray monitoring stations beginning 4 August, 1972. These were associated with four major proton flare events on the Sun and with large interplanetary magnetic field disturbances and high velocity shock waves. This review attempts to discuss and interpret the high energy cosmic ray phenomena observed during this period in the light of the known behaviour of low energy particulate flux, interplanetary plasma and field observations and other associated solar and terrestrial effects recorded during this period.

The first Forbush decrease event FD-1 occurred in the early hours of 4 August, exhibiting very strong north–south and east–west anisotropies. Immediately following the onset of FD-1, the first ground level solar particle enhancement occurred. This event, which had its onset almost 6 h after the flare event on 4 August, had a very steep rigidity spectrum. The major Forbush event of the series which had its onset at ~2200 UT on 4 August, exhibited extremely interesting and complex behaviour, the prominent features of which are a precursory increase prior to the onset (PI-1), a large decrease (FD-2), the largest observed to date, followed immediately by an abrupt square wave like enhancement (PI-2). Interplanetary space during this entire period was highly disturbed by the presence of large low energy particulate fluxes and shock waves, at least one of which had a velocity exceeding 2000 km s^{-1}. Large north–south and east–west anisotropies existed throughout the event. Both FD-2 and PI-2 were characterized by almost the same rigidity spectrum, with a power law index of -1.2 ± 0.2, and a predominant anisotropy along the sunward direction. The square wave-like spike PI-2 during the recovery of FD-2 was associated with a similar abrupt change in low energy particle flux in space, as well as an abrupt decrease in the interplanetary magnetic field value from $\sim 50\,\gamma$ to $\sim 10\,\gamma$.

Based on the available particle, field and plasma observations, an unified model is presented to explain the Forbush event in terms of a transient modulating region associated with the passage of a narrow magnetic shock front. In this model, the reflection of particles from the approaching shock front account for the precursory increase PI-1. The main Forbush event is caused when the magnetic barrier at the shock front sweeps past the Earth. The square wave increase is due to the enhanced flux contained in the 'magnetic well' just behind the shock front and bounded by magnetic discontinuities, which is explained as due to the transverse diffusion of particles into this region from the interplanetary space which have easy access to this region. *In situ* plasma, field and low energy particle observations are reviewed to support the model.

1. Introduction

The spectacular cosmic ray and the associated solar terrestrial events which occurred during the first half of August 1972 easily form the most significant set of events of solar cycle 20. The active center in McMath Plage Region 11976 was undoubtedly responsible for the intense solar flares, severe cosmic ray disturbances and all the associated solar terrestrial effect such as spectacular visual aurorae, geomagnetic storms, radio blackouts and a host of other terrestrial effects observed during this

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period. Two relativistic solar particle enhancements and three major Forbush decrease events, some of them exhibiting abnormal features were the major highlights of the cosmic ray behaviour during this period. Of these, the Forbush decrease event of 4 August, 1972 was the greatest recorded in more than 3 decades of continuous monitoring by ground based cosmic ray monitoring stations. In spite of the large amount of observations made so far, the detailed mechanism responsible for Forbush decrease events is still not clear.

Recently Barouch and Burlaga (1975) have made a detailed analysis of neutron monitor intensity changes and their relationship with interplanetary field variations. They have shown that identifiable cosmic ray intensity depressions are usually associated with magnetic field enhancements in interplanetary space. Barnden (1973) has concluded that the Forbush decreases are not directly produced by shocks but are caused by the large scale irregularities of the magnetic field in the shock fronts. In view of the availability of a variety of solar terrestrial observations, both from ground-based and from spacecraft instrumentation, the August event lends itself to a detailed study for obtaining a clearer understanding of the electromagnetic phenomena in the interplanetary space.

In this article, we essentially review the high energy cosmic ray observations during this period in an effort to understand the complex interplanetary phenomena that occurred during this event and arrive at an acceptable picture for explaining the high energy cosmic ray observations recorded by ground-based monitors. After briefly summarizing the general solar activity associated with these events, the detailed features of high energy cosmic ray disturbances, as observed by ground-based monitors are discussed in relation to the interplanetary field and plasma disturbances observed during the same period. The detailed anisotropy and energy spectral characteristics of both relativistic particle enhancements and of Forbush decrease events are presented. A unified model for the major Forbush decrease event is presented to explain all the observed features of this event, some of which are unique. Collateral evidence from direct *in situ* interplanetary field measurements is presented in support of this model.

2. General Solar Activity During August 1972

The McMath Plage Region 11976 located at 13°N latitude and Carrington longitude 14° started developing active centers only late in solar cycle 20. The first appearance of the pronounced large scale elliptical patterns in the magnetic field distribution, which extended for nearly 70° in heliographic longitude and to both hemispheres was seen only five rotations prior to the onset of August events. However, it was only in rotation 1590 that the activity became very intense producing a striking polarity distribution in the Sun-spot field activity (Bumba, 1973). This 'δ' Sun spot configuration having a steep magnetic field gradient produced as many as 70 Hα flares during the first 10 days of August 1972 (Hakura, 1974) of which four were major proton flares. Even though the McMath Region 11976 was overwhelmingly bright in K-line, and from the associated soft X-ray and microwave bursts could be classified as outstanding, it was by no means unique (Dodson and Hedeman, 1973) except when considered from the magnetic complexity point of view and from the frequency of large flares that occurred in this region.

This period was also characterized by intense radio activity from the Sun. Major radio bursts of Type I, Type II and Type IV, a strong and persistent metre-wave continuum emission for many days after 2 August (Cole, 1973) were observed at all the stations during this period. The Type II burst around 2040 UT on 2 August indicates the passage of a shock wave with a velocity of the order of 1100 km s^{-1} through the outer corona (Maxwell, 1973). An hour later, on the same day, intense microwave radio bursts and hard X-ray fluxes were registered. The largest solar radio burst (at 8800 MHz) and the X-ray event of cycle 20, however, occurred at 0621 UT on 4 August in association with the 3B flare at N14, E09 (Castelli *et al.*, 1973). The velocity of the shock wave inferred from Type II bursts for this event is as high as 3950 km s^{-1}. The largest particle event of the series occurred in association with this event. During the same time, instrumentation onboard the OSO-7 satellite (Chupp *et al.*, 1973) observed emission of gamma ray lines. On 7 August, Maxwell (1973) reports Type II bursts with at least two different velocities corresponding to shock waves at $\sim$1000 km s^{-1} and $\sim$3000 km s^{-1} respectively. The time evolution of the active region responsible for these disturbances and a very useful compilation of all the associated solar terrestrial observations during this period are now available in the literature (Lincoln and Leighton, 1972; McKinnon, 1972; Coffey, 1973). In Table I, some of the important characteristics of the four major proton flares which occurred during this period are listed.

The most striking feature from the particle acceleration point of view is the occurrence of these intense events approximately 3.7 yr after the maximum of the solar activity. The fact that relativistic ion events appear to avoid years of high Sun-spot activity has been noticed (Carmichael, 1962; Obayashi, 1964) even during solar cycles 17, 18 and 19. For example, the intense flares producing ground level cosmic ray enhancements (GLEs) occurred 4.8 yr after the solar maximum in cycle 17 and 3.3 yr after the solar maximum in cycle 19. Figure 1 shows the frequency of energetic solar particle events as a function of solar cycle of activity. It is clear from the figure that practically all the important GLE events seem to occur during either the rising or the decay phase of solar cycle of activity.

The tendency for the acceleration of cosmic ray particles to relativistic energies to avoid maximum solar activity period seems to be confirmed by all radio observations as well, made during both solar cycle 19 and 20. Boorman *et al.* (1961) and Takakura and Ono (1962) considered the microwave radio bursts observed during cycle 19 and noted that the most intense events ($>10^{-18}$ W m^{-2} Hz^{-1} at $\sim$8 cm and 3 cm) exhibited the same avoidance tendency as relativistic ions. The observations in cycle 20 reinforce the view that high solar activity is not conducive to the most efficient acceleration of high energy ions and electrons. An explanation for this phenomena is

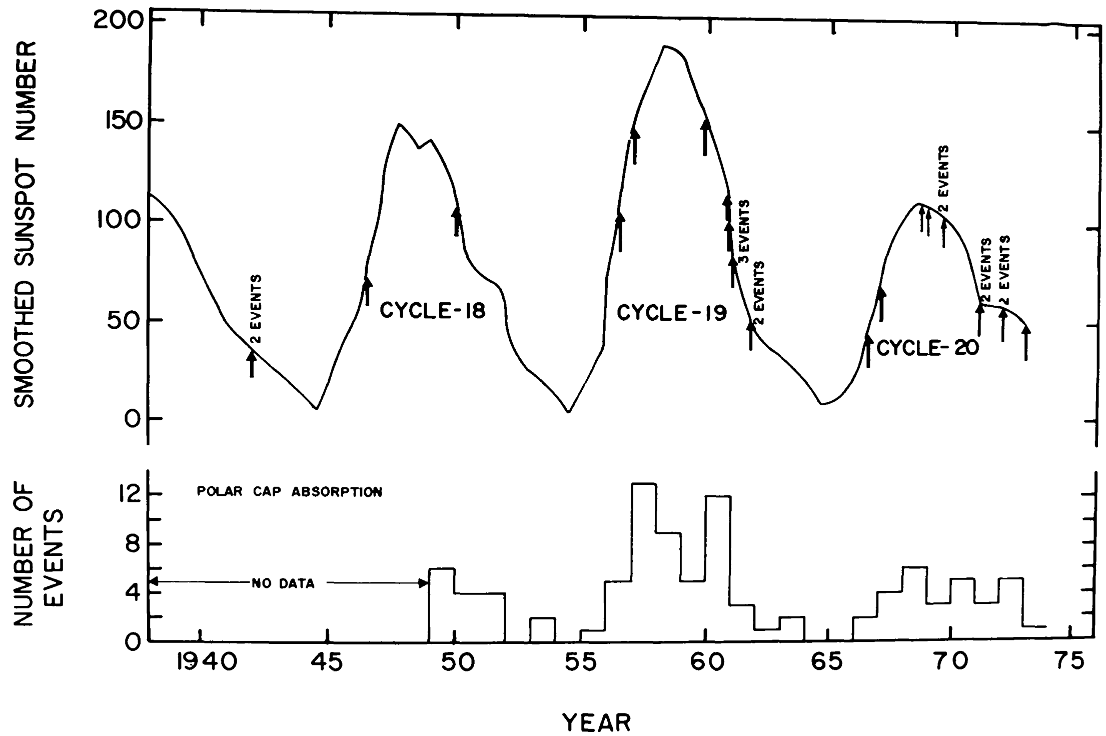

Fig. 1. The frequency of GLE events and polar cap absorption (PCA) events plotted as a function of the solar cycle of activity. The occurrence of proton events mainly during the rising and decay phase of solar cycle is clearly brought out in the figure.

perhaps to be found in Swestka and Simon's (1969) suggestion that the development of the acceleration of particles to relativistic energies ($>10^9$ eV) may be prevented during periods of maximum solar activity by premature initiation of a solar flare through outside influence such as sympathetic flares.

3. High Energy Cosmic Ray Events During August 1972

DISCUSSION OF GENERAL INTENSITY PROFILE

The electromagnetic condition in the interplanetary space was highly disturbed by the blast waves originating in the four major proton flare events and the energetic particles produced thereof. Large particle intensity enhancements, plasma and magnetic field disturbances were detected by various satellites and deep space probes that were operational during this period. In this article, however, we limit our discussion primarily to the high energy cosmic ray intensity disturbances and use the *in situ* particle, field and plasma observations only in support of the major conclusions that will be drawn based on the former.

Practically all the ground-based cosmic ray monitoring stations at high latitudes registered two prominent high energy particle enhancements of solar origin and three major Forbush decrease events during the period 2–9 August, 1972. Of these, even though the GLE enhancements and the third Forbush decrease event which occurred on 9 August, 1972 showed typical features characteristic of classical events of the

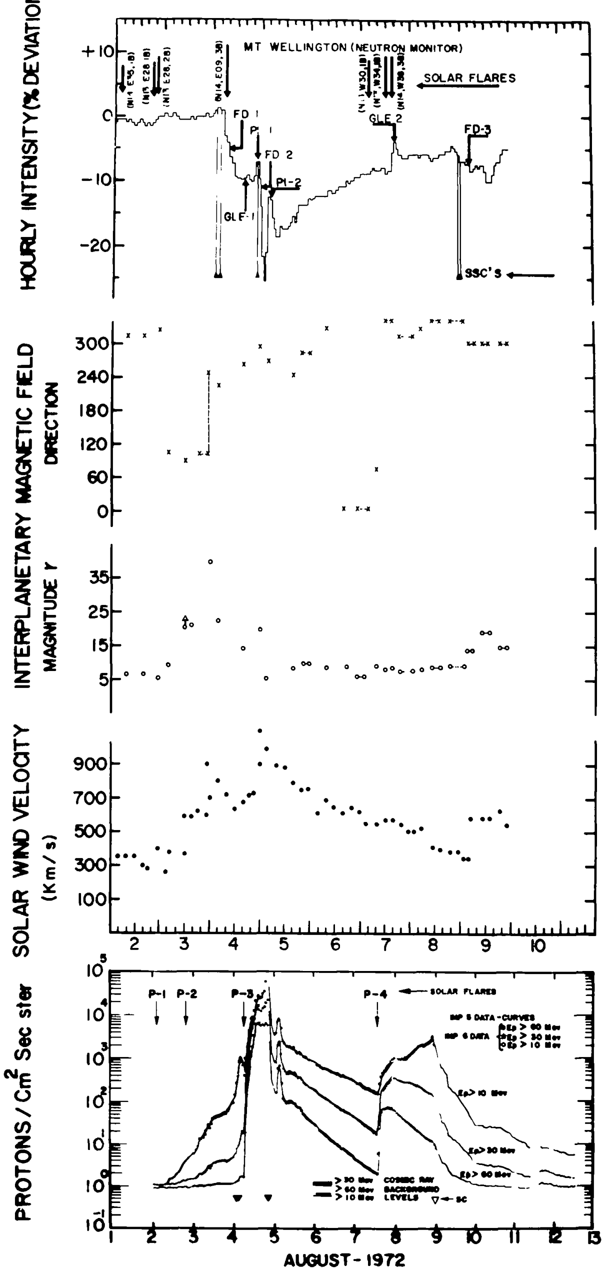

Fig. 2. The cosmic ray intensity profile during 2–9 August, 1972 observed by a typical high latitude neutron monitor. The time of occurrence of solar flare and SSCs along with the prominent features in the observed complex intensity profile are marked in the figure (after Agrawal *et al.*, 1974). The figure also shows the solar wind and interplanetary field observations on Pioneer-9, situated 45° west of the Earth–Sun line (after Hakura, 1974). The observed intensity enhancements at low energies on Explorer-34 and 41 satellites (after Bostrom *et al.*, 1972) are also shown in the figure.

above type, the Forbush decrease event which occurred on 4 August, exhibited very complex behaviour thus providing an unique opportunity to carry out intensive studies on Forbush decrease mechanism through a detailed analysis of the various solar terrestrial effects associated with the above complex features.

Figure 2 shows the typical high energy cosmic ray intensity profile observed during the period 2–9 August, 1972 by a ground based neutron monitor. The unusual complex features associated with relativistic particle intensity changes as well as their time association with solar and terrestrial disturbances are clearly marked in the figure. In the same figure are also shown the enhancement of low energy particles at energies 10, 30 and 60 MeV as observed by Explorer 34 and 41 satellites (Bostrom *et al.*, 1972) along with the solar wind and interplanetary field observations as observed on Pioneer-9 spacecraft located at 0.8 AU and at a heliolongitude of 45° West (Hakura, 1974).

Two large solar proton flares were observed on 2 August at 0315 UT (IMP-3N) and at 1958 UT (IMP-2B) which produced two Sudden Commencement geomagnetic storms (SSC) on 4 August at 0119 UT and 0220 UT respectively. Enhancements of low energy solar protons and electrons were observed on Explorer-34 and -41 satellites (Kohl *et al.*, 1973) commencing at about 1000 UT and 0300 UT on 2 August and 3 August respectively, following these proton flares. A noticeable feature of this low energy particle enhancement is its slow onset. In contrast, the third and fourth proton flare events caused enhancements of low energy particulate flux with very rapid rise time starting at about 0800 UT on 4 August and 1600 UT on 7 August respectively. The latter two proton events, in fact, were also responsible for the two energetic particle enhancements observed on the ground (GLE), causing a cosmic ray intensity increase of about 7% and 5% respectively at a typical high latitude neutron monitoring station.

The first disturbance in the neutron monitor cosmic ray intensity profile occurred as a Forbush decrease event (FD-1) at ~0200 UT on 4 August, which in all probability was caused by the second proton flare event at 1958 UT on 2 August. The time association of this Forbush event with the Sudden Commencement geomagnetic storm at 0220 UT on 4 August and the associated increase in the low energy particulate flux (> 10 MeV) in the interplanetary space is clearly evident from Figure 2.

FD-1 was followed by the first relativistic particle enhancement GLE-1 of the series which had its onset at ~1200 UT during the recovery phase of FD-1. The ground level increase thus occurred when the satellite proton event was already in progress (Kodama *et al.*, 1973). The time intensity profile of the ground level increase shows a gradual increase reaching a maximum at ~1500 UT, approximately 8 h after the major proton flare event of importance 3B which occurred at 0621 UT on 4 August. From the observed time delay between the occurrence of the optical flare and one of the most dramatic SSC observed during this cycle at 2054 UT on 4 August, the estimated average solar wind velocity is found to be as high as 2700 km s^{-1}. This may be compared with peak solar wind velocities of ~1700 km s^{-1} observed onboard

Prognoz-2 (Cambou *et al.*, 1974) and ~2000 km s^{-1} observed by instrumentation on HEOS-2 (Rosenbauer *et al.*, 1972).

The proton flare event on 4 August is undoubtedly responsible for the GLE-1 event, the sharp increase in the low energy particulate flux in space, the Sudden Commencement geomagnetic storm which occurred at 2054 UT on the same day and the major Forbush event of the series FD-2. The sharp decline in the intensity of low energy particles in space, immediately following the onset of SSC is noticeable in Figure 2. The low energy particle flux (> 10 MeV) reached a peak value of $\sim 1 \times 10^6$ protons cm^{-2} s^{-1} $ster^{-1}$ (Kohl *et al.*, 1973) at around 2200 UT on 4 August after which it declined rapidly till ~0300 UT on 5 August.

The Forbush event FD-2 exhibits complex and unique features. Just prior to the onset of the main phase, and even before the completion of the decay of GLE-1 event, a highly anisotropic pre-increase PI-1 in the intensity was recorded by both meson and neutron monitors. The onset of the main phase of FD-2 occurred around 21–22 UT on 4 August. This is the largest Forbush decrease event recorded so far, the amplitude of the maximum depression being 20–25% at a typical high latitude neutron monitor station.

During the recovery phase of FD-2, a very rapid increase PI-2 having almost a 'square wave' like structure with an amplitude of 10–15% was observed at all the ground stations. Apparently, this increase was not associated with any solar flare or significant radio emission. Interestingly, the low energy fluxes also show a similar increase commencing at ~0300 UT on 5 August and reaching a short plateau at ~0500 UT on the same day. The total ion detector deployed on the lunar surface on Apollos 12, 14 and 15 (Medrano *et al.*, 1975) also showed this remarkable square wave spike. Undoubtedly, this was the most conspicuous and interesting feature of this Forbush decrease event.

During the slow recovery of FD-2, the fourth proton flare event occurred (1500 UT on 7 August) which was responsible for the second GLE event. The low energy particle flux in space registered an abrupt increase at around 1530 UT. The relativistic particle enhancement which was almost classical in nature apparently had its onset at some ground stations between 1525 and 1530 UT (Mathews and Lanzerotti, 1973), earlier than the maximum (1534 UT) of the solar Hα-flare, clearly indicating that the accleration of particles to relativistic energies must have occurred before the flare reached its maximum. This is to be contrasted with the normal time delay of 5 min to 1 h usually observed between the maximum of the flare and the onset of GLE event. Several hard X-ray and millimeter radio bursts were detected during this period. From the time delay between the occurrence of the optical flare and the SSC at 2354 UT on 8 August, the average solar wind velocity is estimated to be ~1200 km s^{-1}.

The third Forbush decrease event FD-3 which had its onset around 0100 UT on 9 August, following the onset of SSC at 2354 UT on 8 August, completes the total scenario of this complex series of cosmic ray events. FD-3, even though short lived (~1 day) compared to many Forbush events, was almost classical in nature.

In the following sections, after a brief discussion of the propagation of shock waves in the interplanetary medium, we first describe the two GLE events and then discuss the two Forbush decrease events FD-1 and FD-3. The complex series of events associated with the major Forbush decrease event FD-2, namely the pre-increase PI-1, the main phase and the square wave increase PI-2 during its recovery, are dealt with later.

4. Interplanetary Shock Waves

To understand the basic Forbush decrease mechanism, a knowledge of the interplanetary shock waves and their propagation characteristics is essential. The occurrence of Sudden Commencement geomagnetic storms (SSC) is a positive indication of the existence of a shock wave and its interaction with the Earth's magnetosphere. The five major SSCs reported during this period (Lincoln and Leighton, 1972) at 0019 UT, 0220 UT and 2054 UT all on 4 August, 1972 and at 2354 UT on 8 August and at 0337 UT on 9 August are all marked in Figure 2. The SSC observed at 2054 UT on 4 August, 1972, which was apparently triggered by the 3B flare at 0621 UT on the same day was one of the most severe SSCs observed during this cycle. *In situ* observations with instrumentation onboard HEOS-2 measured peak plasma velocities as high as ~ 2000 km s^{-1} during this period. Interestingly, the corresponding interplanetary shocks were also detected by both Pioneer-9 and Pioneer-10 instruments as sudden changes in plasma parameters and interplanetary magnetic field (Mihalov *et al.*, 1974). Further, collaborative evidence from both interplanetary scintillation (Armstrong *et al.*, 1973; Watanabe *et al.*, 1973) as well as cometary observations are also available substantiating the existence of these interplanetary shocks.

Table I lists the velocities of shock fronts originating from the four major proton flare events during 2–9 August, 1972. The estimated value of velocities near earth and at the location of Pioneers-9 and -10 are also listed in the table. The average velocities listed in the table are essentially estimated from the transit time between the onset of the flare and the time of detection of the shock front and these are compared with actual *in situ* peak velocity observations. In all the cases, it is evident that the observed maximum solar wind velocity is considerably less than that obtained from transit time calculations. The evidence clearly points out to the deceleration of shock waves in the interplanetary medium consistent with what has been reported by Hundhausen (1970), Vernov *et al.* (1970) and Dryer *et al.* (1972).

On the basis of the data listed in Table I, Dryer *et al.* (1975) estimated the interplanetary shock trajectories for all the proton flares which occurred during this period. In Figure 3 is shown the approximate trajectory of the shock wave which caused the major Forbush event FD-2. The trajectory is approximate since the calculations assume spherical symmetry of shock wave propagation and neglect the deviations from this ideal situation due to non-inhomogeneities in solar wind. The shock velocity at 0.01 AU derived from Type II drift velocity and average shock velocities derived from the transit time between its arrival at the Earth, Pioneer-9 and Pioneer-10 and

TABLE I

The characteristics of interplanetary shock waves observed during 2–9 August, 1972 in association with the four major proton flares which occurred during this period

	P1	P2	P3	P4
Flare onset time	0315 UT/2 Aug	1958 UT/2 Aug	0621 UT/4 Aug	1500 UT/7 Aug
Flare	3N	2B	3B	3B
Flare coordinates	N 12, E 34	N 13, E 28	N 14, E 09	N 14, W38
10 cm radio peak flux 10^{-22} W M^{-2} H^{-1}	2600	9700	7600	4500
1–8 Å (X-ray) (10^{-2} erg cm^{-2} s^{-1})	18.0	14.8	45.6	45.6
Low energy particulate flux (10 MeV)[a]				
Proton cm^{-2} s^{-1} $ster^{-1}$	–	5.0×10^1	1×10^6	3.5×10^3
Drift velocity[b] (Type II radio observation)	1100 km s^{-1}	1000 km s^{-1}	3950 km s^{-1}	1500 km s^{-1}
Shock arrival time at Pioneer-9[c] (0.8 AU)	0440 UT/3 Aug	1117 UT/3 Aug	2323 UT/4 Aug	2354 UT/8 Aug
Average shock velocity:				
$\overline{V}$ P9	1300 km s^{-1}	2200 km s^{-1}	2000 km s^{-1}	840 km s^{-1}
Vmax P9	375 km s^{-1}	750 km s^{-1}	1150 km s^{-1}	600 km s^{-1}
SSC onset at Earth	0119 UT/4 Aug	0220 UT/4 Aug	2054 UT/4 Aug	0037 UT/9 Aug
Average shock velocity: $\overline{V}_E$	900 km s^{-1}	1400 km s^{-1}	2700 km s^{-1}	1200 km s^{-1}
Vmax HEOS	500 km s^{-1}	500 km s^{-1}	2000 km s^{-1}	–
Shock arrival time at Pioneer 10-(2.2 AU)	–	1506 UT/6 Aug	1506 UT/6 Aug	0245 UT/13 Aug
Average shock/velocity:				
$\overline{V}$ P10	–	–	1750 km s^{-1}	–

[a] Kohl *et al.* (1973).
[b] Pintér (1975), Maxwell (1973).
[c] Mihalov *et al.* (1974).

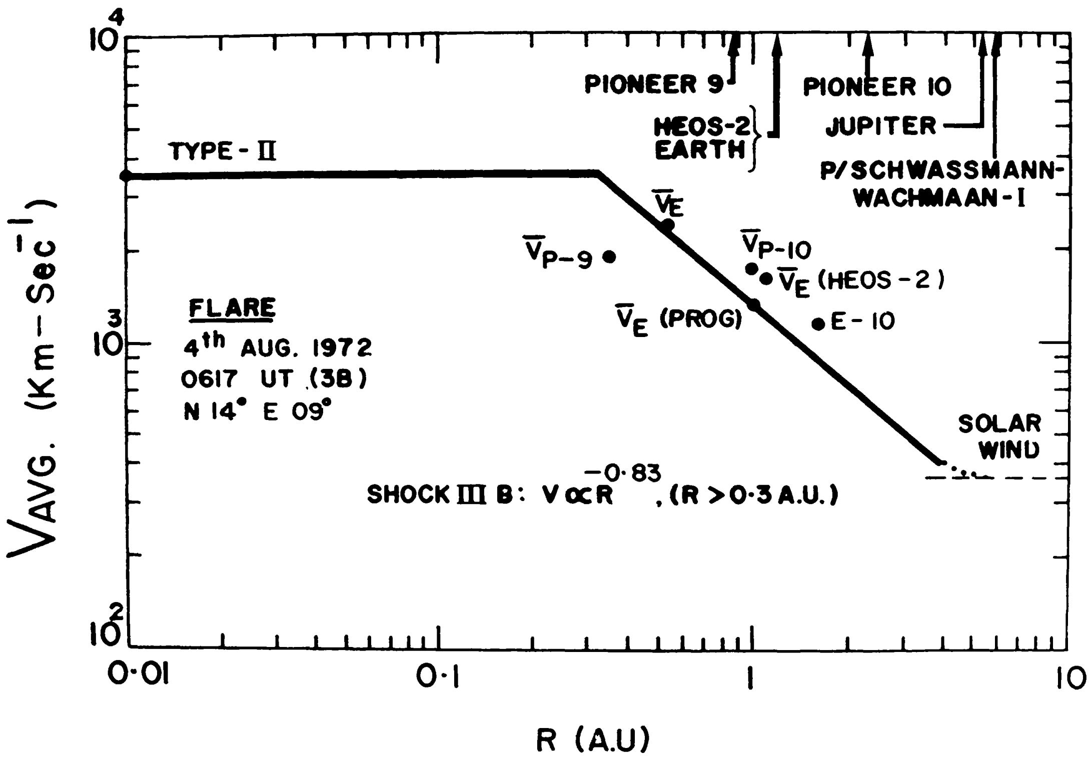

Fig. 3. Estimated shock velocities from the 3B flare on 4 August as a function of distance from the Sun. The average shock velocities computed from transit time calculations as well as peak velocities obtained from *in situ* observations are plotted in the figure. *In situ* observations include near Earth peak velocity measurements of $\sim$1700 km s^{-1} on Prognoz-2 (Cambou *et al.*, 1974) and of $\sim$2000 km s^{-1} on HEOS-2 (Rosenbauer *et al.*, 1972). (After Dryer *et al.*, 1975.)

the time of occurrence of flare event are plotted in the figure. The observed maximum velocity with instrumentation onboard HEOS-2 is also indicated. The absence of non I_0-related radio emission from Jupiter and the absence of the sudden brightening of comet P/Schwassmann-Wachmann I is indicative of the attenuation of shock waves at the orbit of Jupiter at $\sim$5 AU. The observations are consistent with the shock velocity V varying as $R^{-0.83}$, for $R > 0.3$ AU, where R is the distance from the Sun in AU.

Similar analysis was carried out by Dryer *et al.* (1975) on all the four shocks from which they have derived the functional relationship between the velocity of shock wave and distance in each case as follows:

Shock I: $V \propto R^{-1.1}$ ($R > 0.4$ AU)

Shock II: $V \propto R^{-1.3}$ ($R > 0.4$ AU)

Shock III: $V \propto R^{-0.83}$ ($R > 0.3$ AU)

Shock IV: $V \propto R^{-0.62}$ ($R > 0.4$ AU)

An interesting fact that emerges from the above analysis is that the deceleration of subsequent shocks is much slower compared to the deceleration of the first shock. The series of shock waves discussed above and their interaction with the interplanetary medium were responsible for the modulation of particle flux observed at the earth's orbit as well as in space. We describe the observed features of cosmic ray intensity profile in the light of the above discussion on interplanetary shocks.

5. High Energy Cosmic Ray Intensity Observations During 2–9 August 1972

5.1. Relativistic solar particle events during 2–9 August 1972

5.1.1. *GLE-1 Event*

The first relativistic solar proton event (GLE-1) due to the 3B proton flare which attained maximum brightness at 0639 UT on 4 August, was recorded by ground-based neutron monitors at ~1400 UT. As already stated in section 2, the relativistic particle enhancement at ground was associated with sharp increase in the low energy particulate flux in space. The integrated intensity of protons ($Ep > 10$ MeV) for this event from 0700 UT on 4 August to 1700 UT on 7 August, was greater than 2×10^{10} particles cm^{-2} (Kohl *et al.*, 1973), one of the largest in this decade. At most of the stations, the maximum intensity was reached 2–3 h after the onset and the event lasted approximately 8 h. Excepting at South Pole which registered a spectacular ~30% increase, the increase at most of the sea level polar stations was roughly 6%.

In order to identify the existence or otherwise of anisotropies during this event, the asymptotic directions of 'viewing' calculated for various cosmic ray stations using the trajectory calculations by McCracken *et al.* (1965) are plotted in Figure 4. The position of the Sun at the earliest onset for various events are also marked (Tanskanen *et al.*, 1973) in the same figure.

Comparison between the relativistic enhancements at a number of widely separated

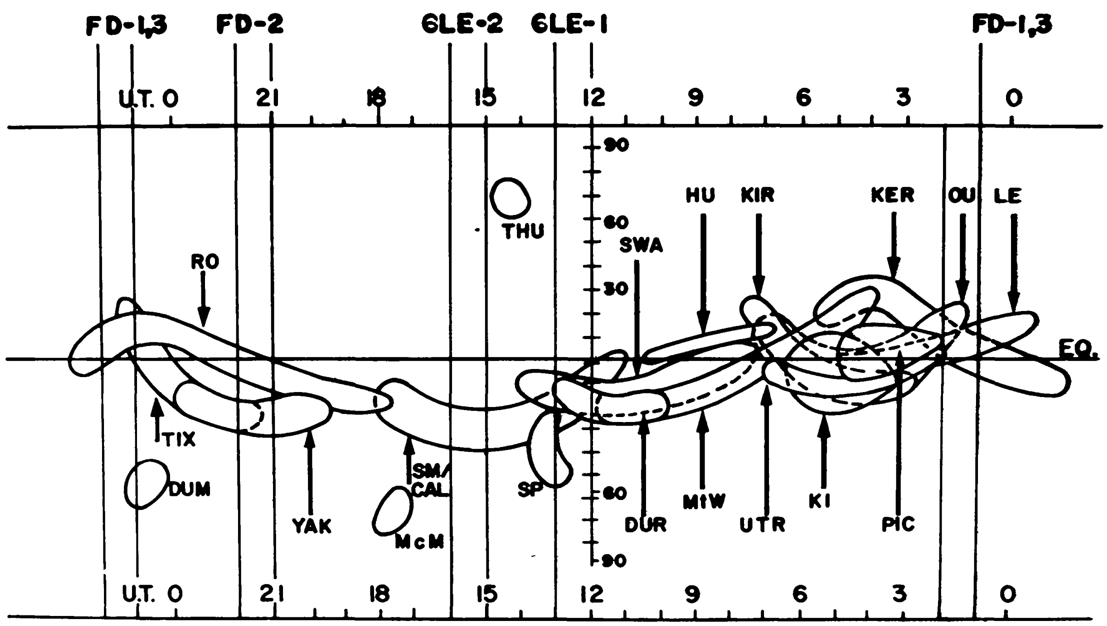

Fig. 4. Asymptotic directions of viewing calculated for various cosmic ray stations using the variational coefficients by McCracken *et al.* (1965). The positions of the Sun at the earliest onsets for various events are also marked in the figure (after Tanskanen *et al.*, 1973).

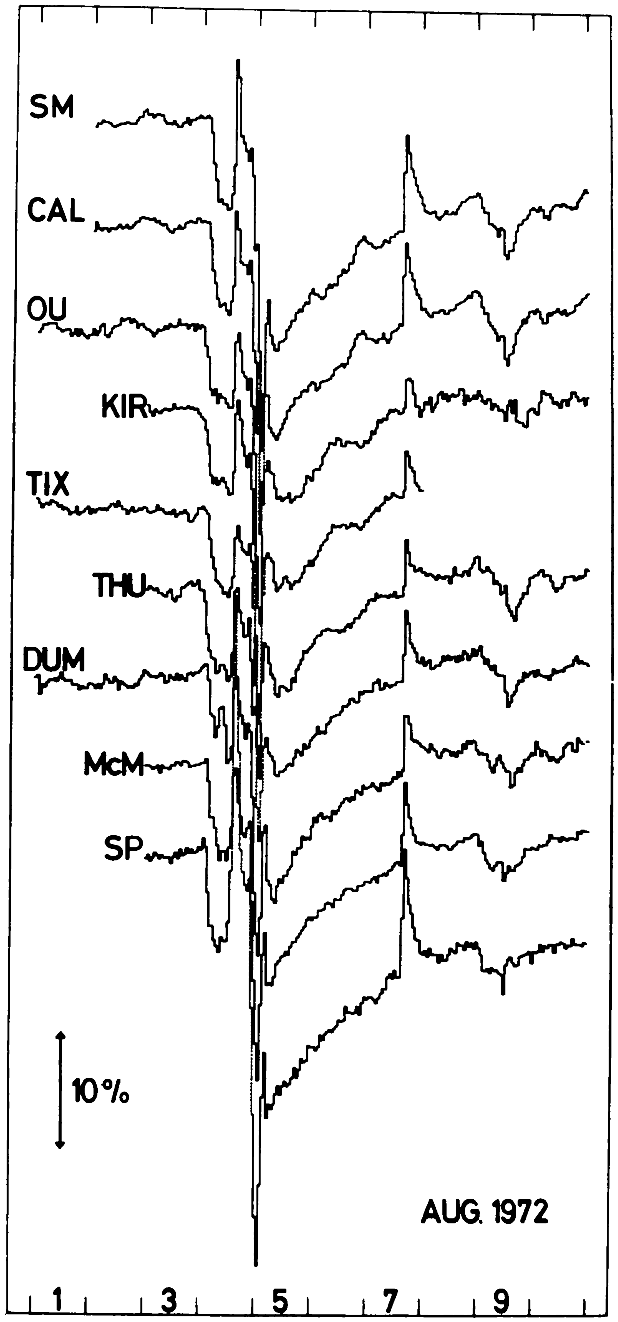

Fig. 5. Relativistic cosmic ray changes observed by various neutron monitors during 1–9 August, 1972 (after Tanskanen *et al.*, 1973).

stations are shown in Figure 5. The magnitude and the onset time of the GLE-1 event as recorded at a number of stations are also listed in Table II. Lockwood *et al.* (1975) have made a detailed analysis of the onset time as well as percent increase at various stations. The increases, after normalizing them to sea level, are also indicated in Table II in parentheses.

TABLE II

Particulars of GLE-1 event on 4 August, 1972 (after Lockwood *et al.*, 1975). The increases recorded at the mountain stations have been reduced to sea level using an absorption length of 85 g cm^{-2} and are shown in parentheses

Station	P_c, GV	Look direction at 1600 UT (°E of E–S line)	Onset, UT	Percent increase
Mt. Washington	1.24	broad	1345	3.0 (1.3)
Kerguelen	1.19	broad	1400	5.5
Sulphur Mountain	1.14	broad	1410	14.3 (4.4)
Calgary	1.09	broad	1410	10.0 (4.4)
Deep River	1.02	broad	1420	4.6
Oulu	0.81	150–200	$\geqslant$1400	4.2
Norilsk	0.60		1415	4.5
Kiruna	0.54	130–175	1400	5.6
Tixie Bay	0.53	190–205	1415	5.7
Goose Bay	0.52	130	~1400	4.9
Syowa	0.42	45–90	1200	4.2
Mawson	<0.22	105	$\gtrsim$1400	5.0
Inuvik	0.18	300	~1400	4.7
Thule	0.00	330	$\gtrsim$1400	5.4
McMurdo	0.01	330	$\gtrsim$1400	5.3
Dumont	0.01	215	1400	5.1
South Pole	0.00	60		~28.0 (5.3)
Alert	0.05	70	~1400	5.3

Even though there is some indication of an earlier onset at stations viewing in the direction of sun or close to the 'garden hose' direction, by and large, the onset time was independent of viewing direction. Stations having narrow asymptotic cones of acceptance registered almost same amount of increase irrespective of their location indicating that the particle enhancement during this event was more or less isotropic.

The ratio of intensity increases observed at high latitude mountain stations to that observed at low latitude stations is a good indicator of the hardness of the spectrum. The ratio of 3.8 observed between the increase at South Pole to that at McMurdo is the largest observed so far indicating that the energy spectrum for this event was very steep. Considering the data from a group of stations whose threshold rigidities exceed the atmospheric cut off (~1 GV), Pomerantz and Duggal (1974) and Lockwood *et al.* (1975) have calculated the actual rigidity spectrum applicable to this event. Figure 6

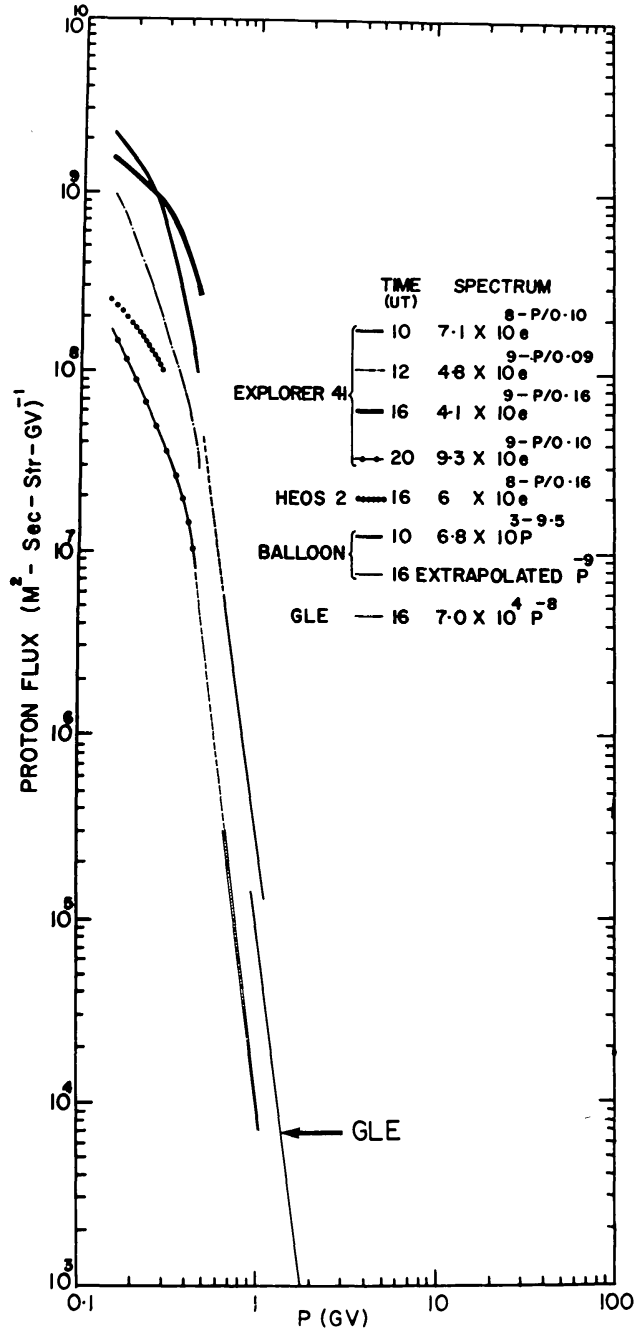

Fig. 6. Differential solar proton rigidity spectrum during GLE-1 event. Low energy proton increases at satellite (Bostrom *et al.*, 1972, Page, 1972) and balloon (Bazilevskaya *et al.*, 1973) altitudes are plotted along with the neutron monitor observations from a number of stations (after Lockwood *et al.*, 1975).

shows the rigidity dependence of the spectrum obtained from the latitude dependence of neutron intensity increases for the interval 1500–1600 UT. The observed increases at balloon and satellite altitudes during the interval 1000–2000 UT are also plotted in the same figure. The rigidity spectrum at high energies is consistent with a steep power low spectrum, with an index of 8.0 ± 0.5.

One of the unusual features of this event is the abnormal time delay between the onset of the particle increase and the parent flare. The earliest observed increases were during 1300–1400 UT, long after the optical flare maximum (0635 UT) was reached. Since it has not been possible to associate any other solar flare with this increase, it is difficult to explain GLE-1 enhancement as due to the injection of freshly accelerated particles. Delayed low energy solar particles events, also known as energetic storm particle events (ESP), have been observed in the past. The particle enhancement during these events have been generally attributed to the acceleration of particles within the interplanetary blast waves (Rao *et al.*, 1967; Bukata *et al.*, 1968; McCracken and Rao, 1970). The absence of an SSC associated with this event, however, rules out this possibility.

Pomerantz and Duggal (1974) have proposed that the acceleration of the particles to relativistic energies took place between the two shocks associated with the two SSCs which occurred at 0119–0220 UT and at 2054 UT on 4 August. Taking the individual transit times into consideration, the first shock was probably around 0.4 AU from the Earth on the night side and the later shock at almost the same distance on the day side of the Earth 1500 UT. Following Axford and Reid (1963), Pomerantz and Duggal propose that the particle enhancement associated with GLE-1 is due to the reflection of particles between the shocks moving relative to each other. The observed steep energy spectrum is consistent with this picture. From an examination of earlier GLE data, the above authors have shown that the GLE event which occurred on 19 July, 1959 having similar association with the SSCs can also be reasonably well explained with the above hypothesis.

An alternate explanation has been provided by Lockwood *et al.* (1975) who have invoked coronal spreading of the relativistic particle to magnetic flux tubes setting up a flux distribution in solar longitude. Since the Archimedean field line connecting the Earth is 60° away from the flare point ($\sim 9°$ East), the delayed increase is explained in terms of particle convection as the magnetic flux tubes move out behind the shock front (McCracken *et al.*, 1971; Roelof and Krimigis, 1973). As the flux tubes containing maximum particle flux density convect past the Earth, the peak intensity is registered at the ground stations. The interplanetary magnetic field data (Cattaneo *et al.*, 1973) shown in Figure 17 indicates a tangled magnetic filamentary structure for the field, thus supporting this hypothesis. Assuming reasonable values of $K_{\parallel}$ and $K_{\perp}/K_{\parallel}$ Lockwood *et al.* (1975) have been able to explain the observed time delay of almost 8 h.

From the presently available evidence, it is difficult to decide between the last two hypotheses. The acceleration of low energy particles in association with the shock fronts, both within the shock front and between the shock fronts, is not a well-understood phenomenon. To that extent, the coronal longitudinal spreading of relativistic particles onto flux tubes which, when they convect past the Earth, produce the observed relativistic particle enhancement, is a more attractive explanation, particularly in view of the position of the parent flare occurrence.

5.1.2. *GLE-2 Event*

The second GLE event starting around 1500–1600 UT on 7 August actually occurred during the slow recovery of the cosmic ray intensity from the great cosmic ray Forbush decrease FD-2. The fourth proton flare event of importance 3B which occurred at ~1500 UT (N14, W38) was responsible for this relativistic particle increase. The intensity profile for this event as observed at the Bartol network of neutron monitors is shown in Figure 7. The onset times and magnitudes of GLE-2 increase as well as of FD-1 and FD-3 events as observed at a number of stations are tabulated in Table III. Most of the high latitude stations registered an increase of 5–7%. The onset of the increase at South Pole took place within 45 min after the commencement of the flare whereas instrumentation onboard Explorers 41 and 43 observed another abrupt enhancement, beginning at about 1530 UT, about 30 min after the flare onset. The short time delay of 30 min between the optical flare enhancement and the flare particle increase is indicative of scatter free direct propagation of particles along the field lines. The favourable location of the flare region supports this hypothesis.

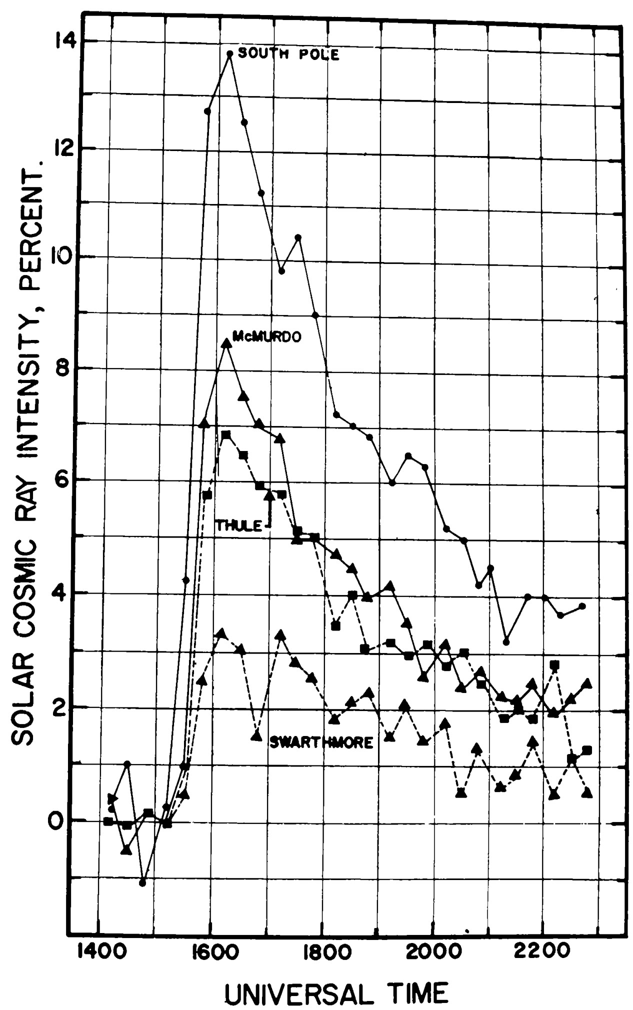

Fig. 7. The cosmic ray intensity profile of GLE-2 event as observed at the Bartol network of stations (after Pomerantz and Duggal, 1973).

Consistent with the direct scatter-free access of particles, anisotropies exceeding ~70% were observed during the onset phase of this GLE event. A small north–south asymmetry is also evident from Figure 7. Neutron monitoring stations having their cut off rigidity greater than 2.9 GV (Chasson 1973) did not register any appreciable increase during this event. This conclusion seems to be quite well substantiated by the lack of particle enhancement at Rome (6.3 CV), Brisbane (7.2 GV), Dallas (4 GV), Pic du Midi (5.4 GV), Mt. Norikura (11.4 GV) and Buenos Aires (10.6 GV). Table III

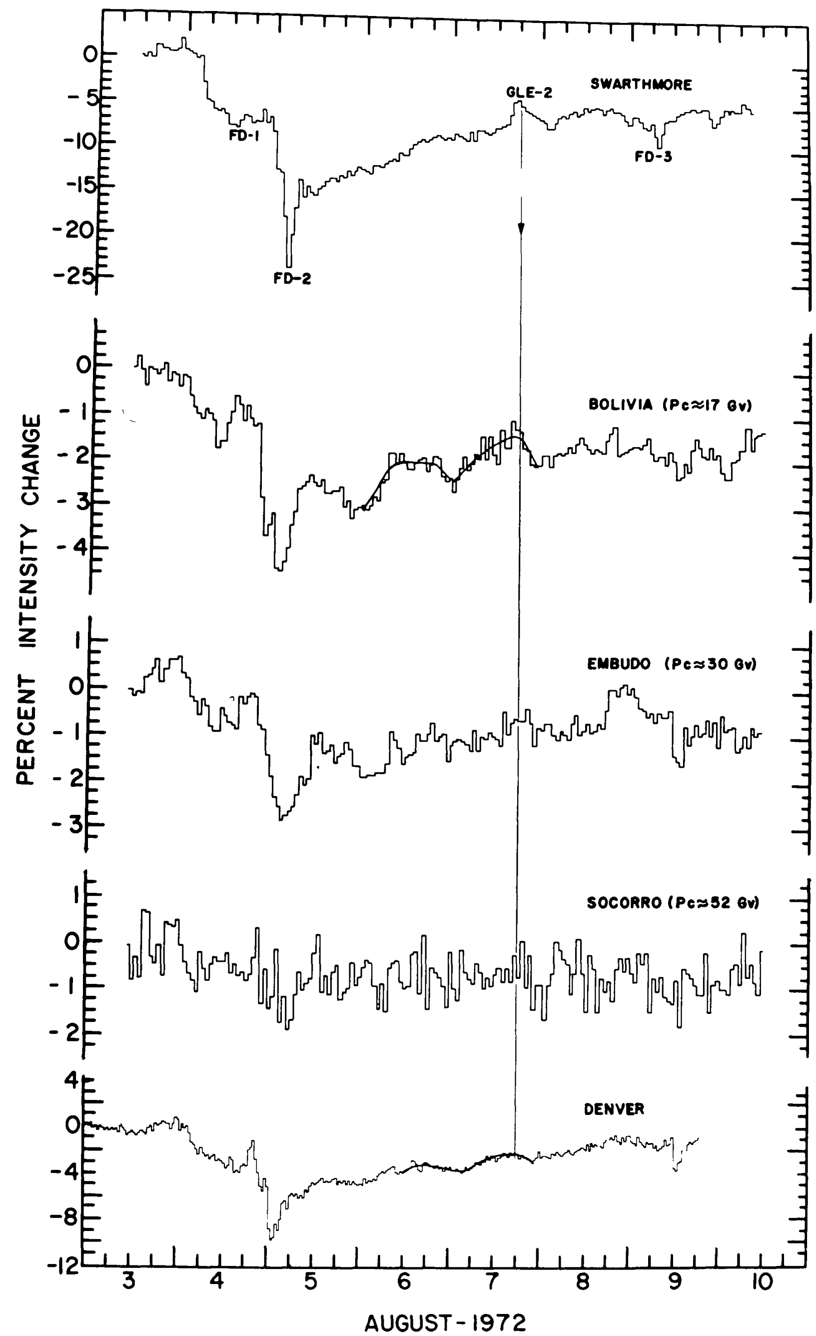

Fig. 8. The cosmic ray intensity profile as observed by the Swarthmore neutron monitor and the underground mu-meson telescopes at Bolivia, Embudo and Socorro (Swinson, 1973). The omnidirectional intensity observed at Denver is also shown (Chasson, 1973).

TABLE III

The magnitude and onset times of GLE-2, FD-1 and FD-3 events at different stations during 4–9 August, 1972

Station (R in GV)	Alt. (m)	4 Aug.		7 Aug.		9 Aug.	
		FD-1		GLE-2		FD-3	
		Onset (UT)	A (%) (approx.)	Onset (UT)	A (%) (approx.)	Onset (UT)	A (%) (approx.)
Huancayo (13.5)	3400	01–02	3.0	–	–	–	–
Rome (6.31)	60	01–02	4.5	–	–	–	–
Pic du Midi (5.36)	2860	01–02	4.5	–	–	–	–
Kiel (2.29)	54	01–02	5.5	16–17	1.7	–	–
Leeds (2.20)	100	~01–02	6.0	15–16	1.7	–	–
Swarthmore (1.92)	80	~03–04	6.5	15–16	2.5	02–03 gradual	4.0
Yakutsk (1.70)	105	~03–04	7.0	15–16	4.5	00–01 gradual	4.5
Durham (1.41)	Sl.	~02–03	7.0	15–16	3.5	00–01 gradual	5.0
Mt. Washington (1.24)	1900	~02–03	8.0	15–16	6.5	01–02 gradual	5.5
Kergulen (1.19)	Sl.	~01–02	6.5	15–16	4.0	04–05 gradual	2.0
Sulphur Mt. (1.14)	2283	~03–04	8.0	15–16	8.5	00–01 gradual	5.5
Calgary (1.09)	1128	03–04	7.5	15–16	7.0	00–01	6.0
Mt. Norikura (11.4)	2770	08–09	4.5	–	–	08–09 gradual	1.5
Oulu (0.81)	15	01–02	6.0	16–17	2.5	00–01 gradual	2.5

Table III (*continued*)

Kiruna (0.54)	400	01–02	6.5	16–17	4.0	–	–
Tixie Bay (0.53)	Sl.	03–04	7.5	15–16	5.0	00–01	4.5
Thule (0.04)	260	01–02	6.5	15–16	6.0	01–02	5.0
						gradual	
Dumon D'Urville (0.05)	45	03–04	6.0	16–17	5.0	00	3.5
						gradual	
McMurdo (0.05)	48	03–04	8.5	15–16	7.0	00	3.0
						gradual	
South Pole (0.11)	2820	02–03	9.5	15–16	11.0	00–01	4.5
						gradual	
Ahmedabad (15.94)	40	03–04	2.5	–	–	gradual	2.0

gives the details of the event as observed at a number of stations. Based on these data, Chasson (1973) has concluded that the upper limit of rigidity for acceleration of particles during this event was less than 10 GV. The apparent registration of a small increase by the mu-meson underground telescope at Bolivia (25 MWe) having a cut off rigidity of 17 GV (Swinson, 1973), however, if true, puts a much higher limit on the upper cut off rigidity (~25 GV) for the acceleration of the particles.

Figure 8 shows the comparison between the observed particle intensities at three muon telescopes at Bolivia, Embudo Cave (40 MWe) and Socorro (80 MWe) and at Swarthmore. In the same figure, the omni-directional intensity, as observed at Denver, is also shown, which clearly indicates the presence of an enhanced diurnal wave with a maximum along 1300 h direction (Chasson, 1973). The enhanced diurnal wave seems to be a high energy phenomenon observed only at stations whose cut off rigidity was above ~5 GV. Chasson has attributed the increase seen in Bolivia to this enhanced diurnal wave rather than to the presence of relativistic particles from the flare in view of the non-observation of particle enhancements at other high latitude neutron monitoring stations.

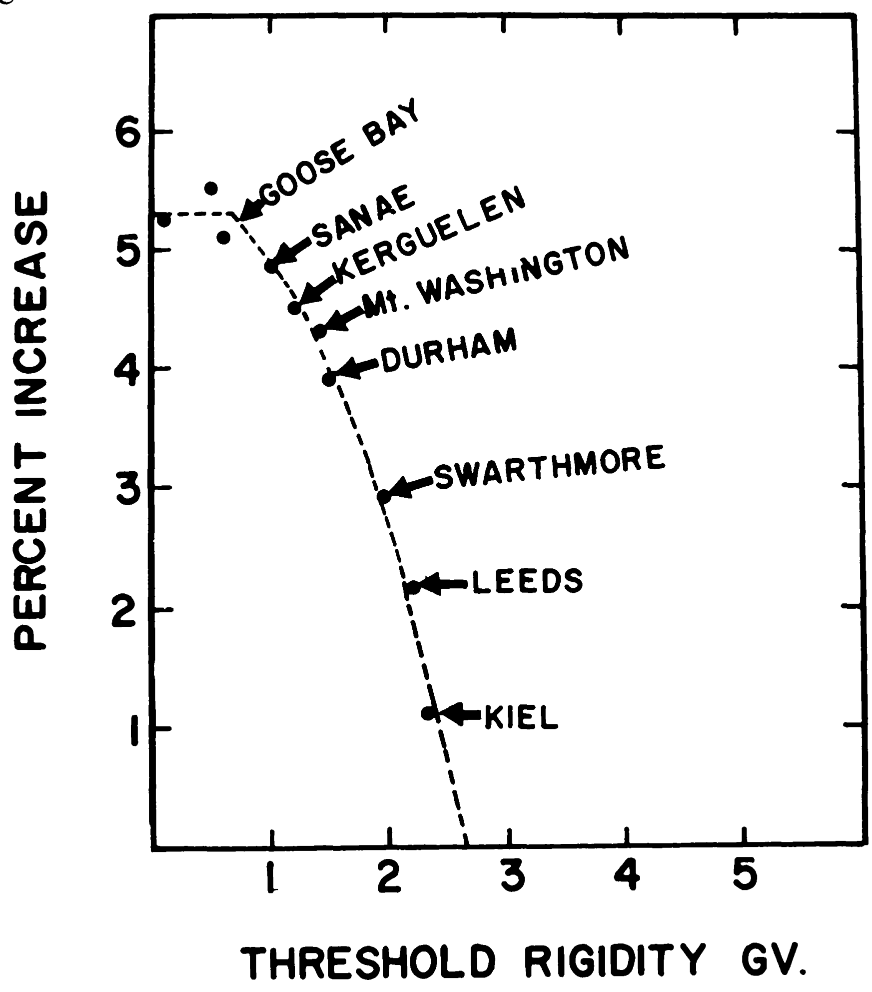

Fig. 9. The percentage increase in neutron intensity during GLE-2 event plotted as a function of the threshold rigidity of the station for the interval 1600–1700 UT on 7 August, 1972 (after Mathews, 1973).

TABLE IV

General characteristics of various cosmic ray events observed during 2–10 August, 1972

Characteristics	(a) Decreases			(b) Increases			
	FD-1	FD-2	FD-3	GLE-1	PI-1	PI-2	GLE-2
Date	4 Aug.	4 Aug.	9 Aug.	4 Aug.	4 Aug.	5 Aug.	7 Aug.
Onset time	0200 UT	21–22 UT	01–02 UT	12 UT	18–19 UT	2–3 UT	15–16 UT
Time of maximum variation	15 UT	01–02 UT	12–14 UT	15 UT	21–22 UT	5 UT	17 UT
Amplitude	~7%	~20%	~5%	~6%	~2%	12%	5%
Spectral exponent	−0.8±0.2	−1.2±0.2	−0.5±0.1	−8.0±0.5	−0.2±0.1	−1.2±0.2	−4.7±0.5
Amplitude of anisotropy in the equatorial plane	~4%	~7–8%	~3%	–	2%	5%	70%
Direction of anisotropy in space	9 h	5 h	18 h	–	12 h	12 h	garden hose
Amplitude of anisotropy in the north–south direction	~3%	~5%	~2%	–	~2%	~3%	~1.5%

The energy spectral characteristics during this flare event exhibited a much harder spectrum (see Table IV), having a power law spectrum with an index of $\gamma - 4.7 \pm 0.5$. The absolute increases observed on Explorer-41 satellite in various energy bands $E_p > 10$ MeV, $E_p > 30$ MeV and $E_p > 60$ MeV were approximately comparable (Kohl *et al.*, 1973) confirming the hard nature of the energy spectrum during this event. The same conclusion is brought out in Figure 9, in which the observed percentage increase of nucleonic intensity at 1600–1700 UT on 7 August is plotted as a function of the threshold rigidity (Mathews, 1973) of the station. The figure also clearly indicates that the upper threshold rigidity for particle acceleration during this event was around 3 GeV.

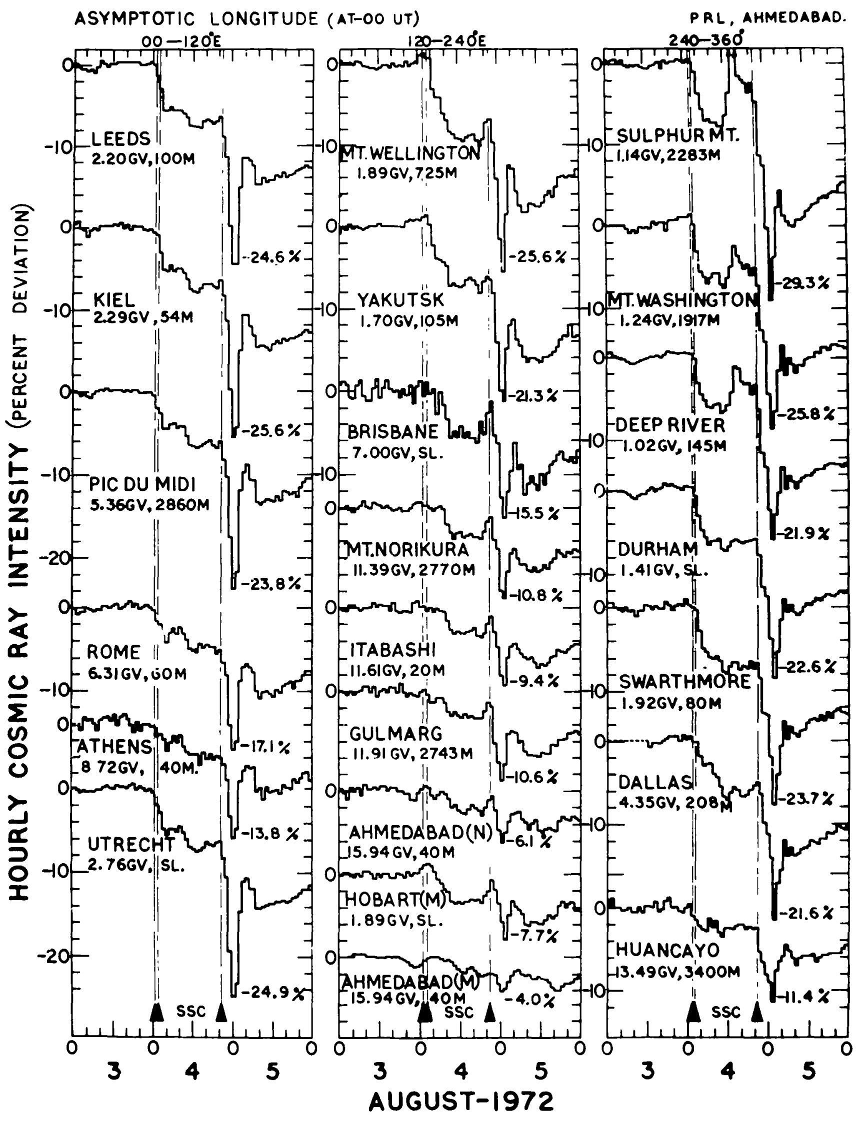

Fig. 10. Cosmic ray intensity profile during 3–5 August, 1972 observed by a number of selected neutron and meson monitors. The geomagnetic cut off rigidity of each station and its altitude in meters above sea level are marked in the figure. The stations have been grouped in three asymptotic longitude belts of width 120° each. The asymptotic directions correspond to 0 UT.

5.2. The Forbush decrease events during 2–9 August 1972

5.2.1. *The Forbush Decrease Event FD-1*

Even though the solar proton increases were observed on Explorers 41 and 43 (Bostrom *et al.*, 1972; Kohl *et al.*, 1973) and on the Pioneer-9 spacecraft around 2 August, the earliest onset of the Forbush decrease at stations viewing along the garden hose direction commenced only at 0100–0200 UT on 4 August, in time association with the sudden commencement geomagnetic storm which took place at 0119 UT on 4 August. The high latitude sea level monitors registered a maximum decrease of 7–8% at about 10–12 UT. The observation of a significant decrease by underground mu-meson telescopes (Figure 8) at Bolivia, Socorro and Embudo Cave (Swinson, 1973) is indicative of the extension of the Forbush event to very high energies. The amplitude of the decrease at Socorro ($P_c \sim 52$ GV) which exceeded $\sim 1.5\%$, shows that particles well above 52 GV suffered depression during this event. Figure 10 shows the cosmic ray intensity time profile as observed at various stations during 3–5 August, 1972. The selected stations have been grouped in three asymptotic longitude belts each having 120° width, to bring out the east–west anisotropy present during this period. Due to the presence of strong east–west anisotropy, the onset of the event at various stations

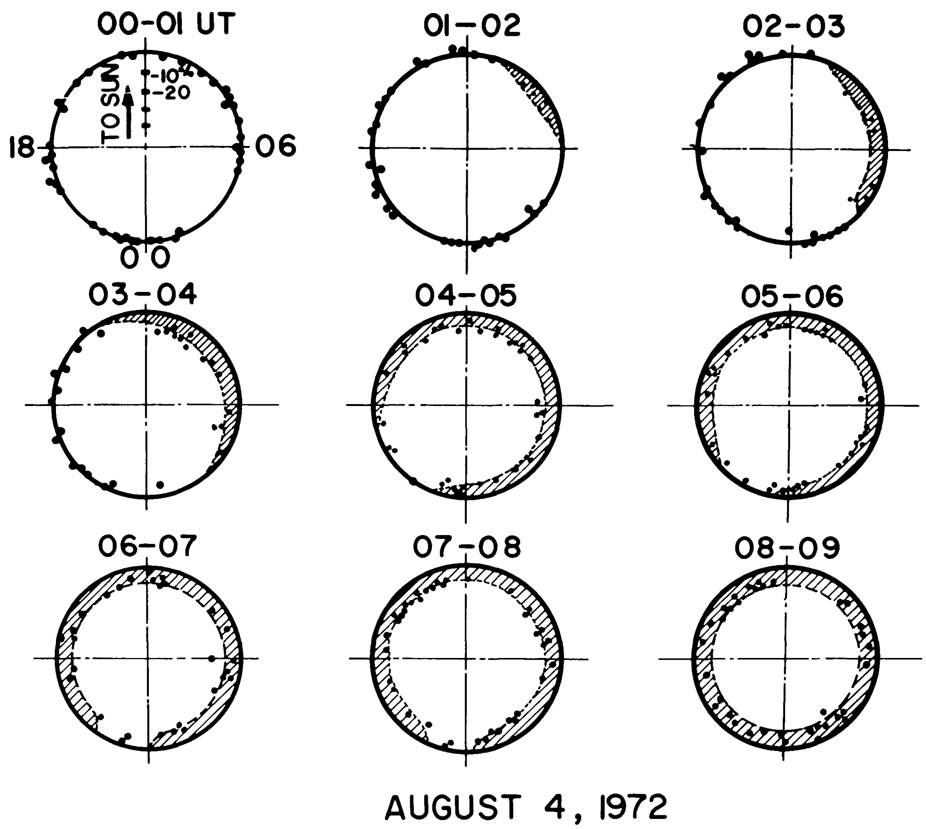

Fig. 11. The evolution of cosmic ray anisotropy in the equatorial plane on 4 August, 1972. The data from 42 ground-based neutron monitoring stations have been utilized in preparing this diagram. Hatched areas indicate regions in interplanetary space where significant depressions in cosmic ray intensity are observed (after Chiba *et al.*, 1973).

varied widely by as much as 3 h. The early onset of FD-1 at stations viewing along the garden hose direction and late onset at stations viewing along (120°–240°E) is very clearly brought out in Figure 10. Three dimensional analysis performed by Yoshida and Ogita (1974) has confirmed the existence of east–west anisotropies as large as ~4%, the minimum intensity being registered at stations viewing along the garden hose direction.

The time evolution of the east–west anisotropy during FD-1 is well brought out in Figure 11 (Chiba *et al.*, 1973) in which the observed intensity decreases at various

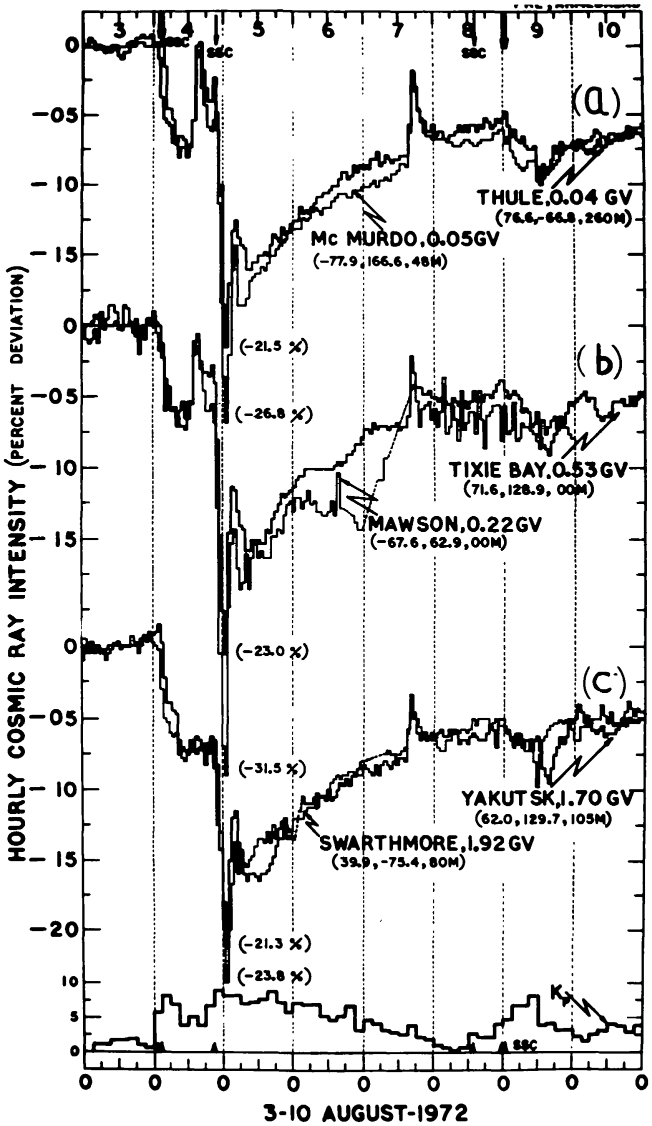

Fig. 12. Universal time hourly cosmic ray intensity during the period 3–10 August, 1972 recorded by three pairs of neutron monitors: (a) polar stations, Thule and McMurdo (Asymptotic latitude 72°N, and 79°S respectively), (b) High latitude stations, Tixie Bay and Mawson (Asymptotic latitude 37°N and 39°S), (c) Equatorial viewing stations, Yakutsk and Swarthmore (Asymptotic longitude at 00 UT, 170°E and 350°E). The geographic latitude, longitude and the altitude in metres above sea level for each station, along with their geomagnetic cut off rigidity, are shown in the figure. The Kp index representing geomagnetic disturbances is also plotted in the same figure (after Agrawal *et al.*, 1974).

stations are plotted as a function of time in a circular diagram. The intensity deviation at each station is normalized to that of a high latitude sea level station using an exponential rigidity spectrum with an exponent of -1.0 to remove the latitudinal or rigidity dependence of the decrease and also to correct for altitude differences. The negative values of intensity deviations in the figure are measured inward from the circumference of the circle, the circumference representing the 100% pre-decrease intensity level and the centre of the circle denoting 50% decrease. A close examination of the sequence of hatched patterns, which reveal the presence of significant decrease in different directions in the interplanetary space, brings out the existence of anisotropic pattern during this event. The figure clearly shows that the earliest onset of the decrease was observed along 45° west of the Sun–Earth line at around 0100 UT, gradually spreading to all other directions and becoming isotropic only at about 0900 UT. The latest onset was observed by Japanese stations at 0800–0900 UT the anti-Sun direction.

In addition to the strong east–west anisotropies, appreciable north–south anisotropies were also present during this event. Figure 12 shows the detailed time profile

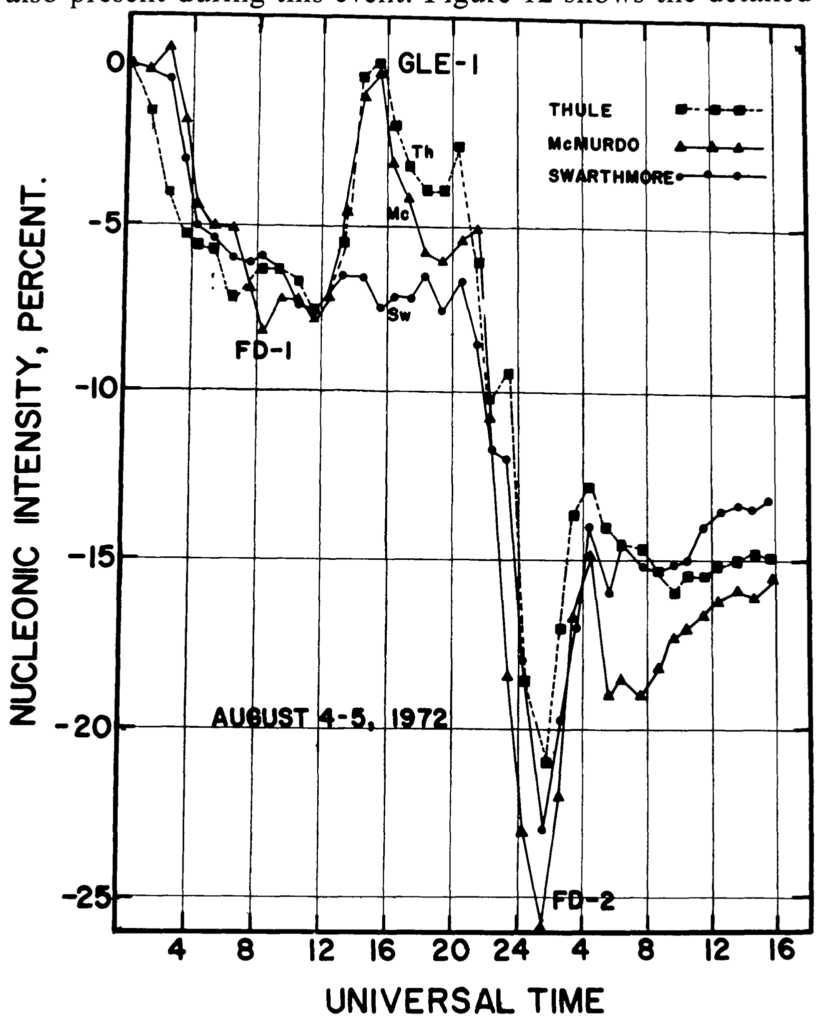

Fig. 13. Detailed comparison of the Forbush decrease FD-1 and FD-2 at three sea level stations (after Pomerantz and Duggal, 1973).

observed at three pairs of neutron monitor stations namely (a) Polar stations, Thule and McMurdo, (b) high latitude stations Tixie Bay and Mawson, and (c) equatorial stations Yakutsk and Swarthmore. Each pair of stations having almost the same cut off rigidity, is so chosen as to have complementary asymptotic latitudes of viewing, one viewing north and the other viewing south of the ecliptic, to highlight the existence of north–south asymmetries. The time intensity profiles at Thule, McMurdo and Swarthmore are separately shown in Figure 13. The difference between the observed neutron intensity at Thule and McMurdo is shown in Figure 14.

Comparing the decreases observed at different stations with different cut off rigidities, the spectral characteristics of the Forbush decrease event FD-1 have been estimated by a number of workers. Referring to Table IV, we observe that the spectral characteristics of this event can be adequately represented by a power law with an index of about -0.8 ± 0.2.

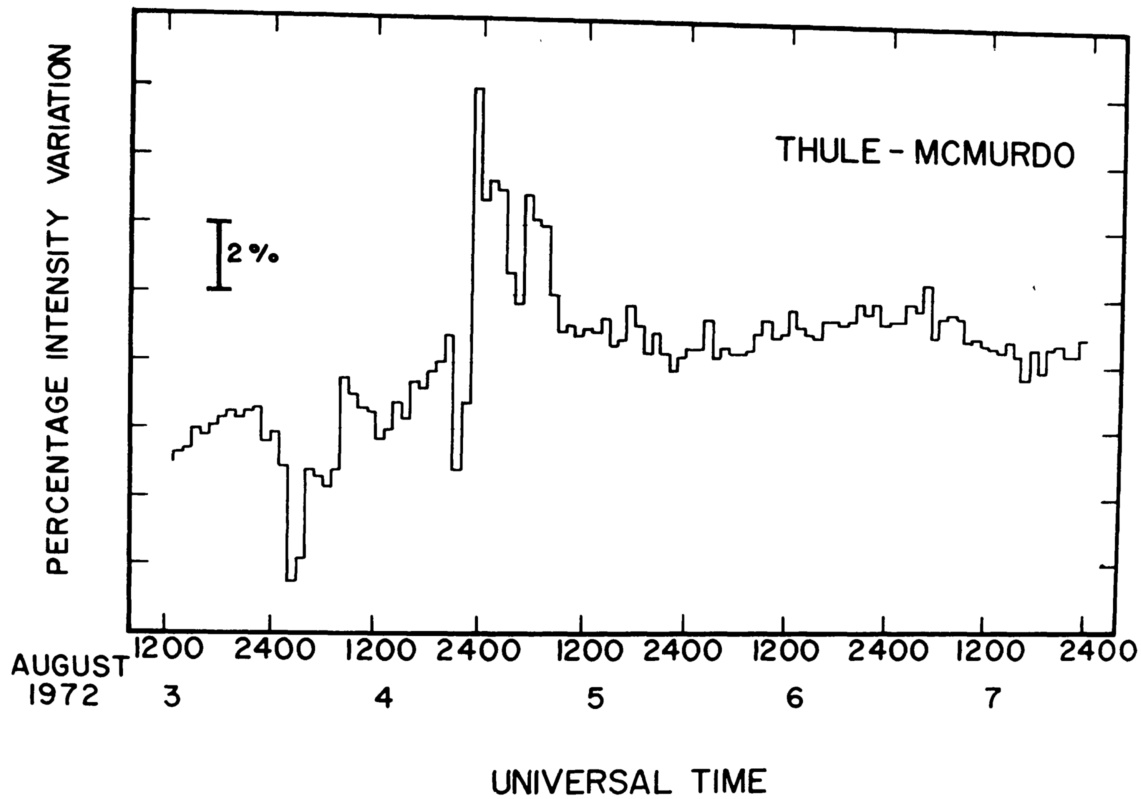

Fig. 14. The difference between the observed neutron intensity at Thule and McMurdo is plotted as a function of time. The existence of large north–south asymmetry is clearly noticeable in the figure (after Pomerantz and Duggal, 1972).

5.2.2. *FD-3 on 9 August*

The third Forbush decrease event FD-3 which commenced at about 0100 UT on 9 August was initiated by the last proton flare event of the series, which had its onset at 1500 UT on 7 August and which was also responsible for the GLE-2 event. The time coincidence between the onset of FD-3 event and the Sudden Commencement geomagnetic storm which occurred at 0037 UT on 9 August confirms the association between the proton flare event P-4 and the Forbush event FD-3. One of the interesting features of this Forbush decrease event is its short duration, the total time from the onset to the recovery being less than 24 h.

The satellite observations of low energy particles indicate that the intensity of cosmic ray flux at these energies remain quite high after the proton flare event on 7 August. Based on transit time calculations, the average velocity of the shock wave (Table I) between the Sun and the Earth works out to be about 1200 km s^{-1}, whereas the drift velocity derived from Type II radio bursts indicates velocity of the order 1500 km s^{-1} at 0.3 AU, thus again substantiating the deceleration of shock waves in the interplanetary space as they move away from the Sun. Based on these data, Dryer *et al.* (1975) have concluded that during this event, the shock wave velocity varied with the distance from the Sun as $V \propto R^{-0.62}$ ($R > 0.4$ AU) during this event.

Ground-based neutron monitors at most of the midlatitude stations registered a decrease of $\sim 5\%$ during this event. Large east–west ($\sim 3\%$) and north–south ($\sim 2\%$) anisotropies were observed during the event, the minimum intensity being observed along the 1800 h direction. The time of onset of the decrease varied widely by as much as 4 h between different stations due to the persistence of east–west anisotropy. This event, unlike the preceding two Forbush events, showed an unusually hard spectrum of the type $E^{-0.5 \pm 0.1}$.

5.2.3. *Forbush Event FD-2 and Other Associated Variations during 4–5 August 1972*

The major Forbush event FD-2 which had its onset at 2100-2200 UT on 14 August is undoubtedly one of the most spectacular events observed to date in the history of cosmic rays. The proton flare event which had its onset at 0621 UT on 4 August was responsible not only for the GLE-1 event but also for the FD-2 event and the associated Sudden Commencement geomagnetic storm at 2054 UT. The velocity of the associated shock wave derived from transit time calculations is one of the highest estimated so far – it is of the order to 2700 km s^{-1} which compares quite well with the observed peak solar wind velocities of ~ 2000 km s^{-1} measured at the orbit of the Earth.

The unusual Forbush event FD-2 is associated with three major distinctive features. Just prior to the actual onset of this event, a highly anisotropic intensity increase was recorded by both meson and neutron monitors on the ground. This increase, in fact, occurred even before the completion of the decay phase of the GLE-1 event. The main Forbush event itself is the largest recorded so far, being $\sim 20\%$ at high latitude stations. Finally, during the recovery of intensity, a rapid square wave increase PI-2 of about 10–15% at high latitudes took place. The general characteristics of each of these features are listed in Table V. Figure 15 defines the method of computing the various intensity variation observed during this event. We will first describe the salient features of these three events and their associated interplanetary characteristics. In the following section, we present a tentative physical model to explain the entire Forbush decrease event.

TABLE V

Summary of observed intensity changes during FD-2 (after Lockwood *et al.*, 1975)

Station	P_c (GV)	PI-1		FD-2		PI-2	
		Approx. Time of max.	Amplitude %	Onset time approx.	Amplitude %	Approx. Time of max.	Amplitude %
Ahmedabad	15.9	2100	1.5	21–22	4.0	0500	3.4
Huancayo	13.5			21–22	9.1	0600	6.9
Gulmarg	11.9	2100	1.7	21–22	7.3	0400	6.6
Mt. Norikura	11.4	2200	2.6	22–23	8.0	0400	5.8
Rome	6.3			21–22	12.4	0600	11.0
Pic du Midi	5.36			21–22	17.6	0500	14.5
Hermanus	4.9	2100	1.0	22–23	16.8	0500	13.7
Lindau	3.0	2100	$\leqslant$0.5	22–23	18.2	0500	14.3
Leeds	2.2	2100	$\leqslant$0.5	21–22	19.0	0500	14.1
Kiel	2.29	2100	1 ± 0.3	21–22	19.7	0500	17.3
Swarthmore	1.91			21–22	17.8	0500	10.0
Mt. Wellington	1.89	2100	2.3	22–23	14.3	0500	10.6
Yakutsk	1.85	2200	$\sim$1	22–23	11.0	0500	7.7
Mt. Washington	1.24			21–22	21.6	0500	11.5
Kerguelen	1.19			22–23	20.8	0500	14.4
Sulphur Mountain	1.14			21–22	26.5	0500	12.0
Calgary	1.09			21–22	23.0	0500	10.5
Deep River	1.02	2200	$\lesssim$1	21–22	16.9	0500	8.2
Oulu	0.81			21–22	21.3	0500	14.0
Goose Bay	0.52			21–22	16.9	0500	9.9
Mawson	0.22			22–23	29.0	0500	16.0
Inuvik	0.18	2100	2.4	22–23	16.2	0400	9.8
DuMont	0.01			22–23	18.7	0400	10.2
McMurdo	$\sim$0	2100	$\sim$1	22–23	22.9	0500	14.1
Thule	$\sim$0	2100	$\sim$1	21–22	16.4	0500	8.1
Alert	$\sim$0	2100	$\lesssim$1	21–22	17.2	0600	9.0

(a) *Pre-increase PI-1*

An examination of Figures 2 and 10 shows that the main Forbush event FD-2 was preceded by a pre-increase which was as high as $\sim 2\%$ at many stations such as Ahmedabad, Mt. Norikura and Inuvik. The maximum intensity occurred around 2100–2200 UT on 4 August, which coincides with the passage of the shock front at the Earth at 2054 UT, prior to the onset of second Forbush decrease event FD-2. The increase at stations with $P_c < 1.4$ GV is not clearly identifiable due to the superposition of the solar proton event GLE-1, whose decay phase persists even beyond 2100 UT.

The cosmic ray intensity at stations with $P_c > 1.4$ GV being practically constant for about 6–8 h prior to the onset of pre-increase of PI-1, the intensity level for this period provides the requisite base level for computing the magnitude of this increase. The

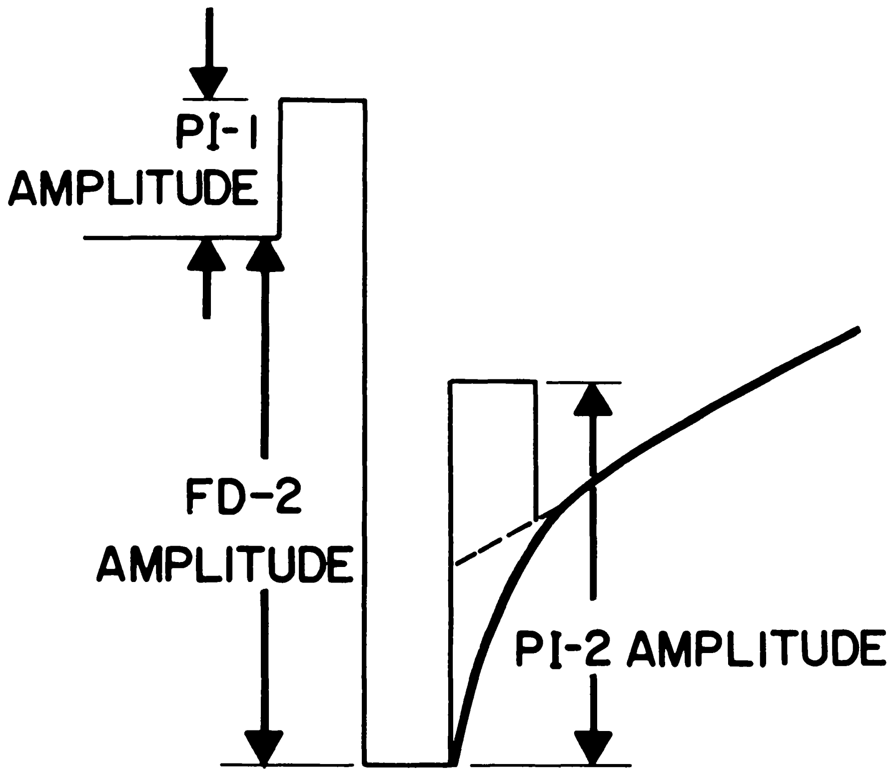

Fig. 15. Figure defining the amplitude of FD-2 decrease, the precursory increase PI-1 and the square wave spike PI-2.

percent increase as observed at a number of stations is plotted in Figure 16 (Agrawal *et al.*, 1974) against their mean asymptotic longitude of viewing at 2100 UT. It may be noted both from Figure 15 and from Table V that in each given asymptotic direction, the percent increase observed at low latitude stations ($P_c > 8$ GV) is comparable in magnitude to the percent increase observed at high latitude stations, indicating a flat spectrum for the increase. In view of this, a smooth curve has been drawn through all the observational points shown in Figure 16. The presence of a predominant anisotropy of $\sim 2.2\%$ ($\sim 4\%$ in free space) with the maximum increase being registered by stations viewing along the sunward direction is clearly evident from the figure. The absence of the pre-increase at Huancayo, Rome, Pic du Midi and the relatively small increases observed at Leeds, Lindau and Yakutsk, all of which have their look angles away from the Earth–Sun line ($>90°$), establish that the anisotropy was essentially along the sunward direction. From a detailed analysis, Lockwood *et al.* (1975) have concluded that the pre-increase had a narrow width of ~ 2 h and a flat energy spectrum with a power law index of 0.2 ± 0.1, consistent with the conclusions drawn by Agrawal *et al.* (1974).

Referring to Figure 10, it is seen that the anisotropic pre-increase continues to be significant up to 2200 UT in the Asian longitude belt (Sunward direction) even one hour after the onset of SSC, by which time the decrease in intensity has already commenced in the other two longitude belts. In other words, the pre-increase observed about 2 h

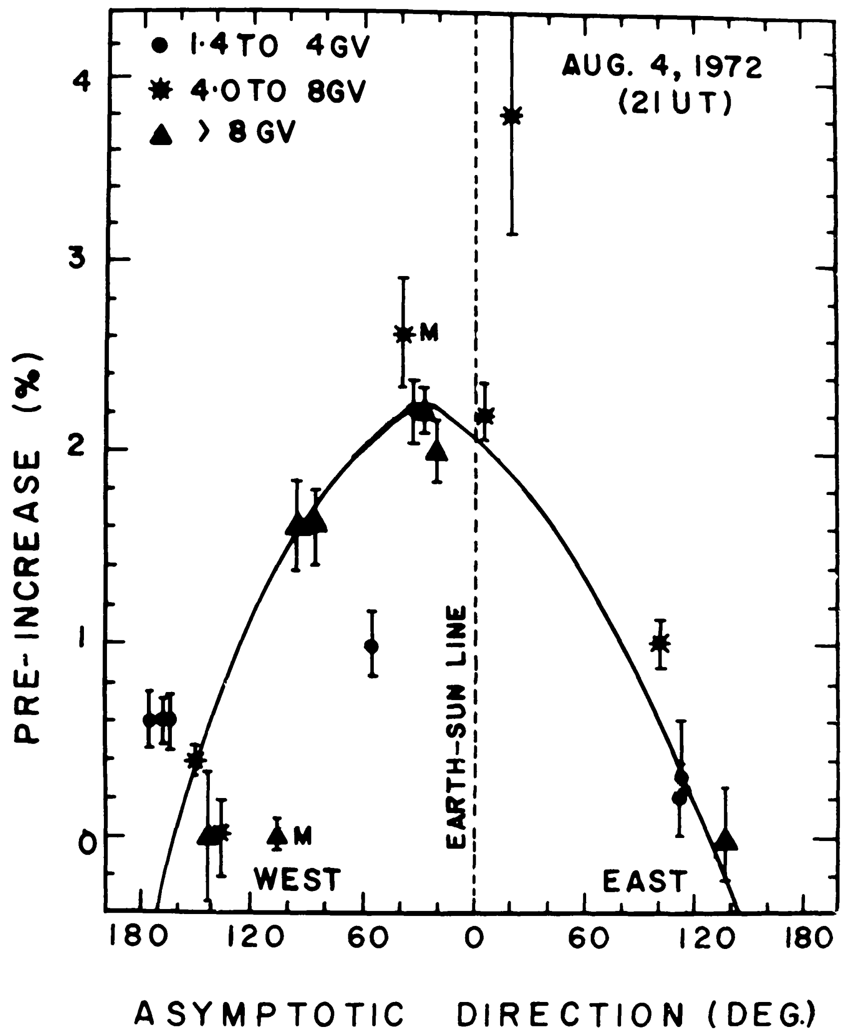

Fig. 16. Percent increase PI-1 in the cosmic ray intensity recorded by different stations plotted against their mean asymptotic longitude at 21 UT, on 4 August, 1972. 'M' denotes the observed increase for the meson monitor in this figure (after Agrawal *et al.*, 1974).

earlier to the onset of main Forbush event occurred when the cosmic ray depression was about 0.08 AU from the Earth under the assumption that it was advancing at $\sim$1800–2000 km s^{-1}. Since the geomagnetic field was almost constant at least up to 2100 UT, the increase PI-1 cannot be attributed to the lowering of the cut off rigidity. However, a small contribution due to the geomagnetic perturbations at and beyond 2200 UT cannot be completely ruled out.

Several anisotropic precursory increases of the type of PI-1, observed on earlier occasions, have been described by Dorman (1963), Dorman *et al.* (1970), Lockwood (1971) and Kusmicheva *et al.* (1972). These have been generally explained as due to the reflection of particles (albedo mechanism) from the sweeping action of the outward moving shock fronts from the Sun (Dorman, 1963; Rao *et al.*, 1967; Dorman *et al.*, 1970) containing large magnetic fields. Behind such a moving magnetic barrier, the cosmic ray flux density is assumed to be low. The albedo mechanism predicts an anisotropic increase from the sunward direction, the increase generally preceding SSC by a few hours. Assuming reasonable values for different parameters, Dorman (1963) had calculated the pre-increase for a number of earlier events, and found them in qualitative agreement with the observations.

Following Quenby (1971), the magnitude of the precursory increase at relativistic energies derived using the well known Fokker-Planck equation and assuming a spherical symmetry can be written as

$$\frac{\partial n}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} r^2 \left[Vn\left(1 + \frac{\gamma - 1}{3}\right) - K_{\parallel} \frac{\partial n}{\partial r} \right] = \frac{1}{r^2} \frac{\partial r^2}{\partial r} S \tag{1}$$

where n is the cosmic ray density, r is the radial distance, V is the solar wind velocity, $K_{\parallel}$ is the diffusion coefficient parallel to the magnetic field and γ is the spectral exponent of the cosmic ray primary energy spectrum. Under the condition that the velocity V of the radially moving shock wave is much greater than the normal average solar wind velocity V_0 (in the present case $V/V_0 \approx 7$), and neglecting the term containing $K_{\parallel}$, the current density S due to the particles swept out by the shock can be represented by

$$S = S_0(V/V_0) \tag{2}$$

where S_0 is the current which gives rise to the average corotational anisotropy of galactic cosmic radiation which is $\sim$0.6% (Rao, 1971). In other words, from theoretical considerations, the expected magnitude of the precursory increase in free space for this event should be $\sim$4% which is in good agreement with the observations. From the previous discussion, it is obvious that significant precursory increases must usually occur in association with moving shock fronts with very large velocities.

(b) *Sharp Forbush Decrease FD-2*

Immediately after the SSC at 2054 UT on 4 August, a sudden decrease in cosmic ray intensity was observed, reaching a magnitude of $\sim$20% within 5 h at most of the high latitude sea level neutron monitor stations. The neutron monitor at Mawson registered a $\sim$29% decrease (Dutt *et al.*, 1973), which is partly due to its very narrow cone of acceptance and partly to its being in a favourable position. The hourly rate of decrease exceeded 6% per hour which is the highest recorded so far. Even the underground telescopes (Swinson, 1973) at Bolivia ($\sim$3%), Socorro ($\sim$1%) and Embudo cave ($\sim$2%) registered significant decreases indicating that the upper cut off rigidity up to which particle flux modulation took place extended well beyond 60 GV.

The onset of this decrease was highly anisotropic exhibiting both north–south anisotropy and longitudinal anisotropies in the equatorial plane (see Figure 14). The onset at stations looking North of the ecliptic was found to be earlier compared to that at stations such as McMurdo, South Pole and Dumont D'Urville looking South of the ecliptic (Pomerantz and Duggal, 1972). Likewise, stations viewing along 06–08 h direction registered larger decreases relative to those observed at other stations.

Agrawal *et al.* (1974) have made a careful study of the characteristics of the rapidly evolving anisotropies by constructing the space–time diagram of cosmic ray intensity using neutron monitor data from a number of high latitude sea level stations ($P_c < 2$ GV), with narrow asymptotic cones of acceptance (Fenton *et al.*, 1959; Ables *et al.*, 1967; Mercer and Wilson, 1968). Figure 17 depicts such a space–time diagram which provides the snapshots of the cosmic ray intensities at various longitudes in the equatorial plane as a function of time during FD-2 and PI-2. An examination of the figure reveals that the decrease commenced at least an hour earlier at stations viewing within a cone of 120° centred around the anti-Sun direction. The anisotropy amplitude during this period (2200 UT) was about 3–4%. The early onset along the anti-Sun direction is also reflected in the intensity profile observed by low latitude monitors. This picture is contrary to what has been usually observed, namely the early onset of the Forbush decrease from the garden hose direction (Fenton *et al.*, 1959; McCracken,

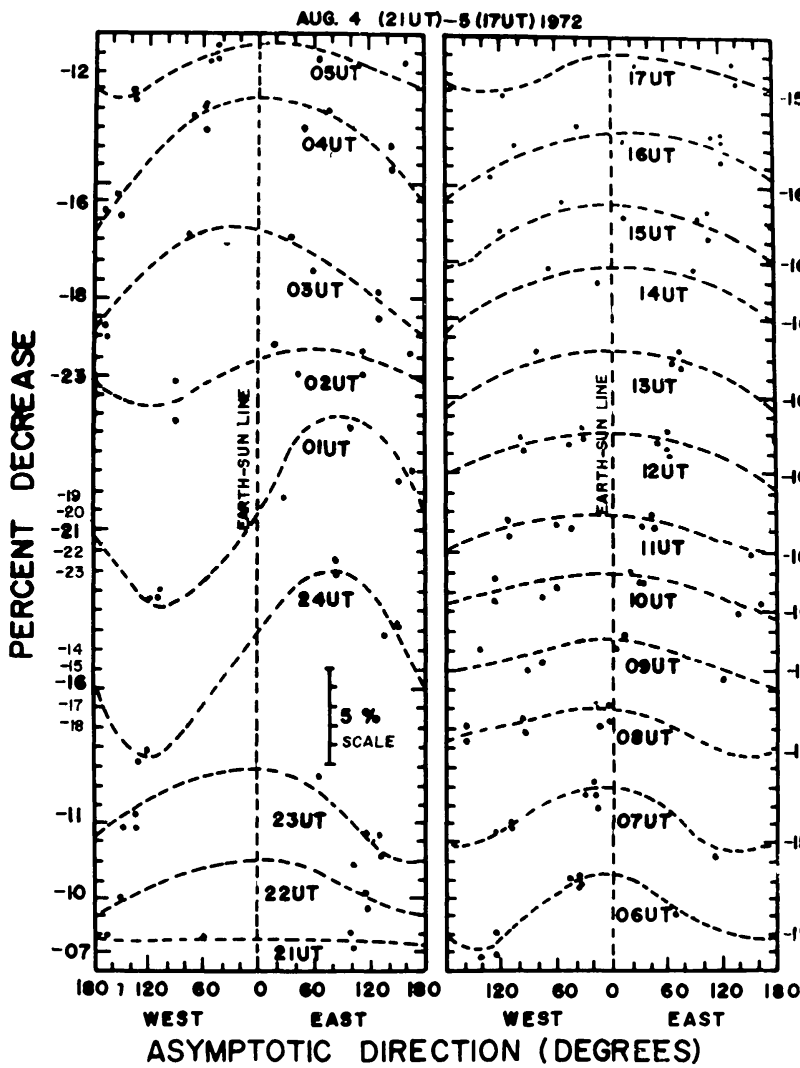

Fig. 17. Snapshots showing percent decrease in cosmic ray intensity times derived from the data of a number of high latitude neutron monitors ($P_c < 2$ GV) viewing the equatorial plane. The intensities are plotted as a function of mean asymptotic longitude from 21 UT on 4 August to 17 UT on 5 August, 1972, covering the entire period of FD-2 and PI-2 (after Agrawal *et al.*, 1974).

1962; Lockwood and Razdan, 1963), which is understood in terms of sampling of the depressed cosmic ray intensity behind an approaching shock wave from the garden hose direction.

During the main phase of FD-2, following the anisotropic depression along the anti-Sun direction, a large anisotropic depression with a maximum along 100°–120° West of the Earth–Sun line was developed between 2400 UT on 4 August, and 0200 UT on 5 August. The maximum amplitude of the anisotropy was about 7–8% at 2400 UT which reduced to 3–4% at 0200 UT, the cosmic ray intensity profile thereafter showing an abrupt increase (PI-2) at all the stations. Yoshida and Ogita (1973), by plotting 3 dimensional contour maps of cosmic ray intensity at various stations also concluded that about 4–5% east–west and approximately same amount of north–south anisotropies existed during this event.

Referring to Figure 2, it is seen that the onset of the Forbush event coincides with the sharp decrease in the intensity of low energy particles measured on Explorers 34 and 41. The low energy particle flux at Explorer-41 decreased by as much as a factor of 50 at about 2200 UT. The early onset of the FD-2 event at stations viewing in the anti-Sun direction compared to the onset time at stations viewing along the sunward direction is most probably due to the anisotropic precursory increase predominantly being recorded at the latter stations. Coincident with the onset time of FD-2, the interplanetary field showed a sharp increase in magnitude and change in direction. Figure 18, which shows the *in situ* field observations made on HEOS-2 (Cattaneo *et al.*, 1973), clearly indicates the increase in the magnitude of the interplanetary field from

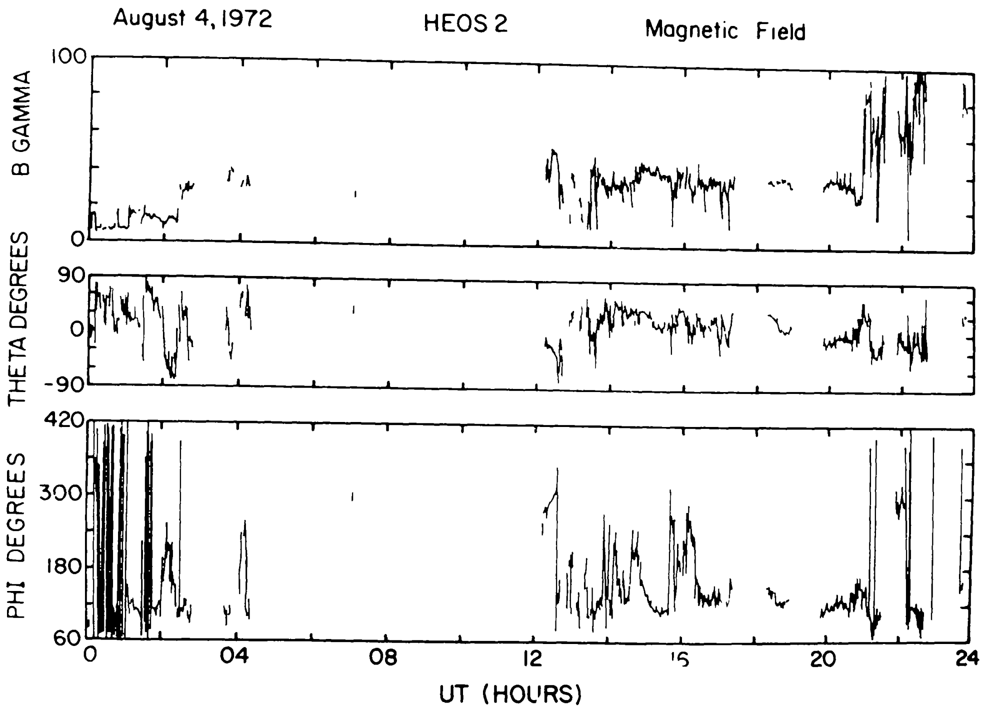

Fig. 18. The interplanetary magnetic field observations made on HEOS-2 on 4 August, 1972. Positive values of θ ($\theta > 0°$) indicate field directions above the plane of ecliptic. Field azimuth is measured clockwise from the Earth–Sun line (after Cattaneo *et al.*, 1973).

around 20 γ to almost 100 γ at the shock front, with corresponding changes both in field azimuth and inclination signifying the arrival of the shock front at the Earth.

The sharp decrease observed during the FD-2 event is most probably due to the magnetic tangential discontinuity behind the shock wave. Considering the magnitude of the large increase in the magnetic field behind the shock front, Lockwood *et al.*, (1975) have qualitatively estimated the particle flux density behind the shock front and have shown that it is consistent with the $\sim$20% decrease observed during this event.

(c) *PI-2 Square Wave Increase*

One of the most noticeable features of the August Forbush decrease events is the sharp spike-like recovery of solar proton flux and cosmic ray intensity observed on 5 August. The observed rate of increase PI-2 in the cosmic ray intensity, just after the maximum decrease in FD-2, is comparable or even faster (10% per hour for some stations) than the rate of decrease. Such a fast increase of non-solar origin has been observed for the first time. Since the observations from various monitors suggest that the recovery in cosmic ray intensity continues over a long period of time ($\sim$7 days), the abrupt increase observed on 5 August (03–06 UT) can be considered as a short lived enhancement superimposed on the otherwise smooth recovery of the Forbush decrease event FD-2.

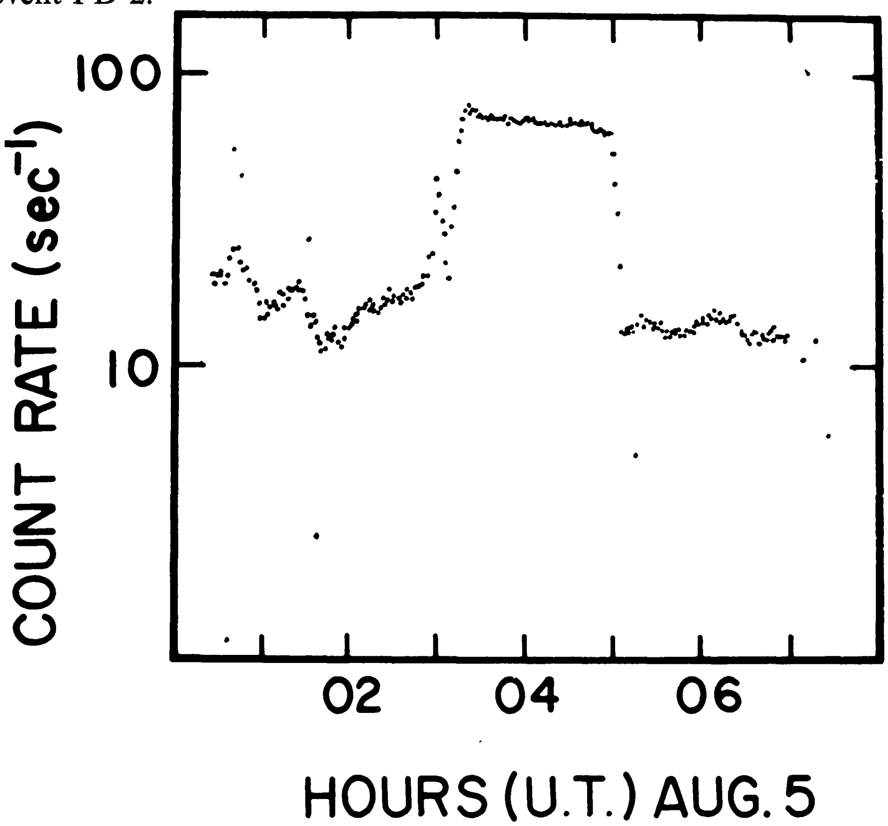

Fig. 19. Square wave enhancement as seen by the total ion detector deployed on Apollo 14. The counting rate represents the approximate omnidirectional flux of protons > 50 MeV in particles cm^{-2} s^{-1} (after Medrano *et al.*, 1975).

A survey of the past Forbush decrease since IGY shows a number of superimposed abrupt universal time increases during their recovery periods. Examples are the Forbush decreases of 11 February, 1958; 17 August, 1958; 18 September, 1959; 27 April, 1960; 29 October, 1963 and 13 January, 1967. A few of these increases have been discussed in the literature (Lockwood, 1960; Lockwood and Razdan, 1963; Block *et al.*, 1964; and Yoshida *et al.*, 1968) and have been mainly attributed to a reduction in the cut off rigidity at the monitoring station, following a geomagnetic storm (Kondo, 1961; Dorman, 1963; Yoshida *et al.*, 1968). However, the decrease in geomagnetic cut off rigidity (P_c) cannot produce any increase in the cosmic ray intensity observed by the sea level neutron monitors with $P_c < 1.4$ GV (since atmospheric cut off rigidity ~ 1.4 GV) and the meson monitors with $P_c < 4$ GV (atmospheric cut off ~ 4 GV). We note that the abrupt universal time increase PI-2 on 5 August is observed at all stations including the neutron monitors with $P_c < 1.4$ GV (see Figures 2 and 5), which excludes the reduction in P_c as the cause for the observed abrupt increase PI-2. The square wave spike observed on ground was also detected well beyond the magnetosphere thus conclusively establishing an interplanetary origin for this feature.

Figure 19 shows the observed increase as seen by the Total Ion Detector (TID) which was deployed on the lunar surface by Apollo-14 astronauts (Medrano *et al.*, 1975). In Figure 20, the observed cosmic ray intensity variations both on Explorer-41 satellite and at a few selected ground stations along with the interplanetary field data for the period 0200–0700 UT on 5 August are plotted (Venkatesan *et al.*, 1975) on an expanded scale. On the left-hand side,the electron enhancement (>0.35 MeV) on Explorer-41 is compared with the observed neutron monitor intensity increases at Calgary, Sulphur Mountain and Alert. On the right hand side, the low energy proton and alpha particle increases on Explorer-41 are shown along with the changes in the azimuth and magnitude of interplanetary field, again observed onboard Explorer-41. The close association of the rapid increase of cosmic ray flux over a wide range of energies accompanied by a sharp decrease in the interplanetary field from around 40 γ to 10 γ is clearly brought out in the figure. The field direction abruptly changes its direction from an outward direction at an angle of $\sim 60°$ to the ecliptic, to a radially inward direction in the ecliptic plane. At the end of the square wave event at ~ 0500 UT, the interplanetary field recovers back to its original value of 35–40 γ. The field azimuth also becomes steady at the end of the spike changing back to the direction away from the Sun and at an angle of 60° to the ecliptic almost the same as the pre-spike value. The time coincidence between the particle flux enhancement and the interplanetary field variation is characteristic of the enhanced flux being confined between tangential magnetic discontinuities. The above supposition is further strengthened by the observed near simultaneity in the variations of particles over a wide range of energies ranging from low energy electrons and protons in space to relativistic particle flux variations at ground which extends to both the onset of the increase at ~ 0240 UT and its duration up to ~ 05 UT.

Agrawal *et al.* (1974) have studied the characteristics of this increase PI-2 by esti-

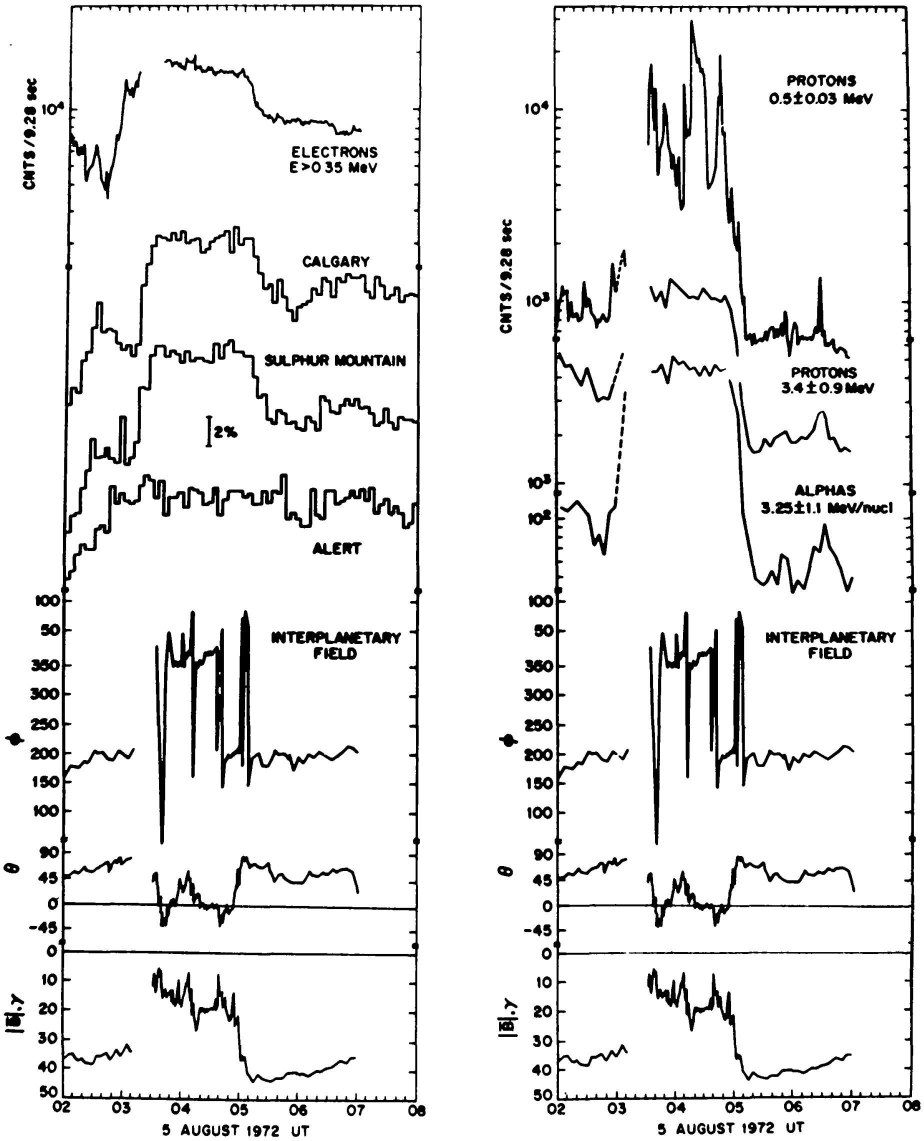

Fig. 20. The 5 min interval cosmic ray intensity variations and the interplanetary field data during 02–07 UT on 5 August, 1972. The low energy electron ($E > 0.35$ MeV) and the low energy proton (0.5 and 3.4 MeV) and alpha-particle (3.25 MeV) data are from Explorer-41 observations. The interplanetary field data shown in the figure are also from the same spacecraft (after Venkatesan *et al.* 1975).

mating the magnitude of the increase for various stations by two independent methods: (a) by considering the amplitude of the increase from the minimum of FD-2 to the maximum at about 05 UT, and (b) by estimating the magnitude of the increase above a smooth recovery curve drawn through the intensity profile from the minimum of FD-2. Both the methods yield a power law rigidity spectrum with an exponent -1.2 ± 0.2 and an upper limiting rigidity of 50–60 GV for the increase PI-2, the same as that for the main Forbush decrease event FD-2. The observed spectral behaviour is significant evidence to show that PI-2 was not of solar flare origin, but essentially consisted of the same population as galactic cosmic ray particles.

Even though the onset was simultaneous, the existence of spatial anisotropies during the increase PI-2 are evident from Figure 17. The existence of a pronounced north–south asymmetry is clearly evident from Figure 21 where the observed variations at the southern stations South Pole and McMurdo are compared with the observations recorded at the northern pairs of stations Alert and Thule and Deep River and Goose Bay. In order to correct for altitude differences, the data from the South Pole station have been divided by a factor of 1.64 (Pomarentz and Duggal, 1973). The relatively sharper intensity increase and its larger magnitude at southern stations compared to the selected northern pair of stations is clearly evident from the figure.

The anisotropy maximum during the entire event was practically along the sunward direction. The anisotropy amplitude, however, shows a gradual decrease from about 5% during the onset at ~0240 UT to ~2% at around 0500 UT. It again increases to ~4% at 0600 UT, beyond which it gradually decreases resulting in an almost isotropic behaviour at about 1700 UT.

Two possible sources of origin for these particles have been discussed in the literature (Medrano *et al.*, 1975). The region connected to the Sun but bounded by tangential discontinuities can act as a 'free corridor' for the propagation of energetic charged

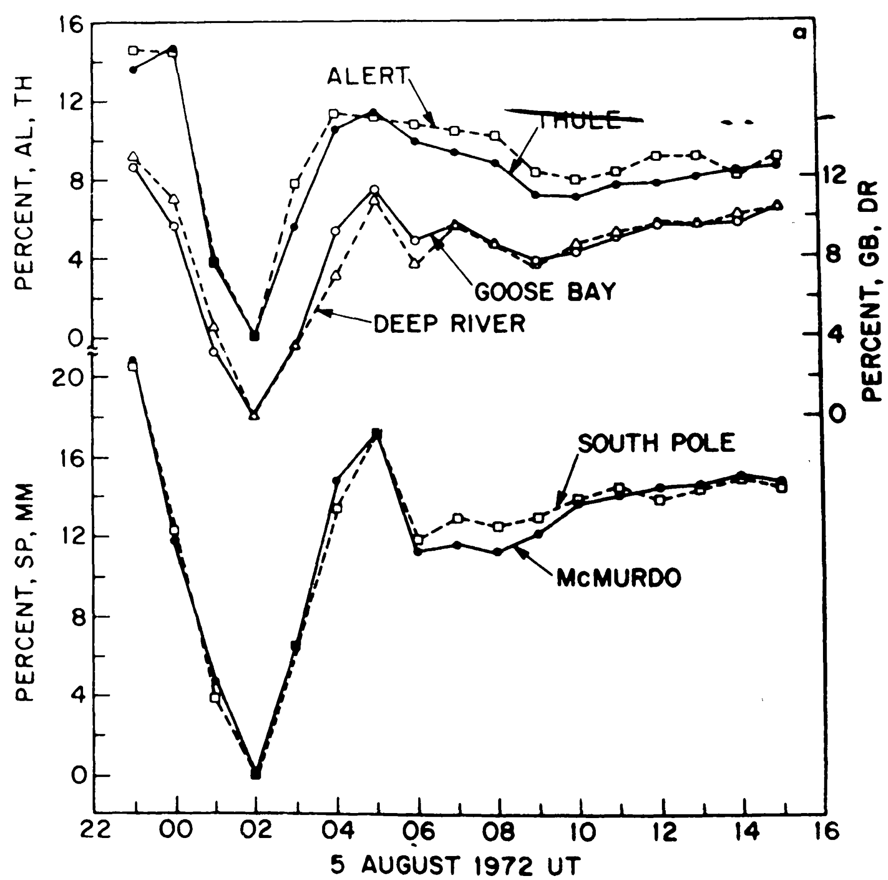

Fig. 21. Figure showing the comparison between the observed variations at the southern stations South Pole and McMurdo with the observed variations at pairs of northern stations (i) Alert and Thule, and (ii) Goose Bay and Deep River on 5 August, 1972. South Pole data are normalized by dividing by a factor of 1.65 to correct for altitude differences (after Venkatesan *et al.*, 1975).

particles, if the flare site is still active. The sharp rise time and fall time are consistent with there being little transverse diffusion. If this mechanism is true, it is difficult to explain the observed relativistic particle enhancement by ground-based monitors since such an interpretation would require the continued acceleration of particles up to relativistic energies over a long period of time.

We, therefore, strongly propose that the square wave enhancement is a result of the modulation of galactic cosmic ray intensity. We propose that the observed enhancement is a result of the passage of the Earth through a region containing enhanced flux density. The enhancement of particulate flux in this region is through diffusion of galactic cosmic radiation into the magnetic cavity bounded by tangential discontinuities. The observed energy spectral characteristics are consistent with this flux being of galactic origin rather than of solar origin.

The unusual features exhibited both at the time of the onset of FD-2 and during its main phase, in our opinion, provide a very important clue for an understanding of the Forbush decrease mechanism. A simple unified model explaining all these features is proposed and discussed in the next section.

6. Unified Model to Explain the Forbush Event of 4–5 August, 1972

The prominent features in the series of cosmic ray intensity variations during August 1972 which require an adequate explanation are (1) the establishment and evolution of the pre-increase PI-1, (2) the unusual anisotropy from anti-Sun direction during the onset time of the main Forbush decrease FD-2 coinciding with the decay phase of the pre-increase PI-1, (3) the unusually large magnitude of the decrease during FD-2 which takes place in a short duration of about 5 h, and (4) an even sharper increase in intensity PI-2 with a prominent anisotropy from the sunward direction.

With the availability of interplanetary field and plasma information through various *in situ* measurements, it is now possible to propose a comprehensive model to explain the observed features of this complex event. The model presented here takes into account the various models proposed for this event (Agrawal *et al.*, 1974; Venkatesan *et al.*, 1975; Lockwood *et al.*, 1975; Medrano *et al.*, 1975), and also the available low and high energy particle as well as field and plasma observations. The model is essentially based on the Gold (1959) type narrow-tongue model. The absence of intensity changes corresponding to this Forbush event at Pioneer-9 indicates that the total extent of the plasma tongue was less than 50° in azimuth. The unusually high solar wind observations recorded during this period are also consistent with such a narrow tongue model.

The essential features of the model we propose are summarized in Figure 22. The onset of FD-2 event as well as the sharp decrease in low energy particle flux on Explorer-34 and -41 satellites coincide with the arrival of the shock front at the Earth ($\sim$2000 km s^{-1}). The highly tangled magnetic fields ($\sim$100 γ) behind the shock front are responsible for the fast decrease in the cosmic ray flux observed on the ground.

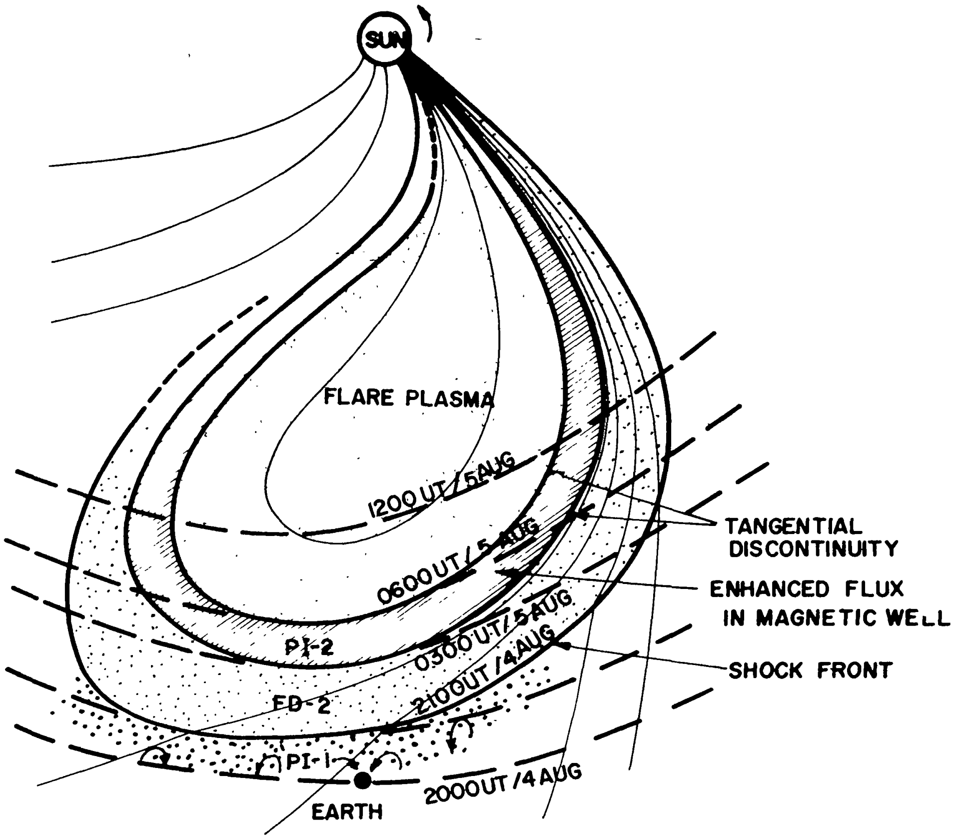

Fig. 22. Sketch of the propagation of a flare-induced shock wave several days after the onset of the flare. The model presented here explains the complex intensity profile observed during the major Forbush event FD-2 which occurred on 4-5 August, 1972.

Immediately behind this is a region of enhanced particle density constrained in a 'magnetic well', a region of low magnetic intensity ($\sim 10\ \gamma$). This is followed by the normal Gold/Parker type cavity containing fairly well ordered magnetic fields and depressed cosmic ray intensity. The cosmic ray intensity within this cavity recovers exponentially with time. The Earth-bound monitors experience different cosmic ray intensity 'states' as the entire beam convects past the Earth.

At about 2000–2100 UT, just prior to the arrival of the shock front at the Earth, the Earth bound cosmic ray monitors viewing along the sunward direction were able to sample, well in advance of the arrival of the shock front, enhanced cosmic ray flux resulting from the reflection of cosmic ray particles at the shock boundary. As noted earlier, the magnitude of PI-1 which is 2–3%, as well as the spectral characteristics are in gross agreement with the predictions of the albedo mechanism. The monitors looking along the anti-Sun direction, however, sample only the galactic flux and consequently do not show any pre-increase. Note that particles which reach monitors viewing along the anti-Sun direction come from a large number of asymptotic directions. Consequently, as the leading edge of the shock front approaches the Earth, whereas the albedo particles are still being received along the sunward direction from the inner region of the shock front, contributing to the enhanced intensity above normal level from these directions, the number of allowed directions for the particles which reach the anti-Sun direction is reduced considerably, resulting in the early onset of the decrease along the anti-Sun direction. In other words. even though the monitors viewing along the anti-Sun direction have started sampling a reduced intensity in the interval 2100–200 UT, the sunward pointing monitors are still seeing the enhanced flux due to the reflection of particles from the inner region which is approaching the Earth.

At about 2200 UT, the inner region containing large tangled magnetic fields has engulfed the Earth resulting in a fast decrease in all directions. Barnden (1973) has shown that such a magnetic barrier or tangential discontinuity extending over large region in space can produce intense Forbush decreases. The unusually high solar wind velocity and the large field magnitude in the shock region observed during this event make this hypothesis very attractive.

The most unusual feature of this event is the abrupt universal time increase of cosmic ray intensity PI-2 following the main phase of FD-2. The interplanetary field observations clearly show that the square wave like particle enhancement was essentially confined in a magnetic well, the onset of this increase coinciding with the presence of a tangential discontinuity at 0300 UT on 5 August, 1972, when the field magnitude decreased from about $50\,\gamma$ to $10\,\gamma$ and its direction also changed. The evidence presented in the earlier sections very clearly shows that the observed increase in the cosmic ray intensity at the ground belonged to the same population as galactic particles and was not of solar origin. On the other hand, the evidence from low energy particles indicates that they were of solar origin.

We propose that the magnetic well region bounded by magnetic discontinuities had direct access to the interplanetary region thus facilitating the leakage of cosmic ray particle flux into this region. The transient increase observed at the ground is due to the replenishment of this magnetic well region with galactic cosmic ray particles through transverse diffusion. The observed direction of anistropy, which is from the sunward direction during the entire duration of PI-2 event, is explained as due to the particle diffusion along the lines of force, which were radially inward and along the plane of ecliptic. The width of the magnetic well region, from the time duration of this increase, is estimated at $\sim 10^7$ km in the ecliptic plane.

The low energy square wave observed during the same period is undoubtedly of solar origin. Energetic storm particle events, where enhancements of solar proton fluxes occur in association with sudden commencement storms, have been reported in the literature (Bryant *et al.*, 1962; Rao *et al.*, 1967; McCracken and Rao, 1970). Since such events are associated with sudden commencement storms, we believe that the mechanism proposed for energetic storm particle events, namely, acceleration of particles in shock fronts, is not applicable here. Medrano *et al.* (1975) have proposed that the low energy particle enhancement is caused by the solar particles injected into the field lines within the magnetic well, which are connected with the flare site. Continuous injection of energetic particles over a long period of time have been reported earlier (Bryant *et al.*, 1965; Roelof and Krimigis, 1973). However, in our opinion, this mechanism does not satisfactorily answer the absence of these particles immediately following this region in spite of the good connection existing between the magnetic lines of force in the cavity containing flare plasma (driver gas) and the sun. Whereas the negligible perpendicular diffusion across the field lines will certainly confine the particles injected into the well within this region, if continuous injection were to exist, one would still observe enhancement of particles beyond 0500 UT with the intensity time profile, however, showing abrupt changes due to variable intensity content of different magnetic flux tubes. Further, any fresh injection into a well defined bottle model should necessarily produce bidirectional anisotropy over time scales consistent with bounce time of these particles within the bottle, unless large scale scattering of particles occur. The sharp onset and cut off in intensity at widely varying energies completely rules out such a scattering. Since the half bounce time for 60 MeV particles for a maximum trapping dimension of ~ 1 AU is of the order of 25 min and for 10 MeV particles is of the order of ~ 1 h, the crucial test which can decide in favour or against the hypothesis of continuous low energy injection would be the detection or otherwise of the presence of bidirectional anisotropy towards the later half of the PI-2 event. Whereas one would expect similar behaviour if the low energy enhancement of particles is due to trapping, the possibility of trapping producing such an enhancement, due to the considerable time involved, is not an attractive explanation.

In the absence of definitive evidence on anisotropies of low energies, it is difficult to totally reject the hypothesis of continuous acceleration. However, we believe that the same mechanism, which provides explanation for the enhancement of high energy particles, can also explain the enhancement at low energies. The good magnetic connection between the 'well' region and interplanetary space, which provides for the leakage of relativistic particles from interplanetary space into this region, can also explain the low energy enhancement through leakage of low energy particles of solar origin which were already present in the interplanetary space, and which had their origin in the main flare event. The presence of a large flux of low energy particles in the interplanetary space is confirmed from the time profile of low energy particle intensity observed at Pioneer-9, which was not affected by the shock wave. The smooth magnetic connection of this region with the interplanetary space thus provides for easy access to both galactic high energy particles and low energy particles of solar origin not affected by the shock waves.

The level of intensity following PI-2 and its gradual recovery to normal represents the classical picture observed in any Forbush decrease, the depressed intensity being representative of the flux within the cavity, and the recovery with time being affected due to the slow diffusion of particles into the cavity from outside (Lockwood, 1971).

7. Conclusion

As a result of the study of cosmic ray disturbances observed during August 1972, we present the following conclusions:

(1) Four major proton flares which originated in the McMath plage region 11976 were responsible for the sudden commencement geomagnetic storms at the Earth and the major cosmic ray disturbances observed during this period. These were accompanied by large Type II, Type III and Type IV radio bursts and X-ray bursts. Estimated velocities of interplanetary shock waves from Type II drift are 1000 km s^{-1}, 3950 km s^{-1} and 1500 km s^{-1} for the three proton flares occurring at 1958 UT on 2 August, at 0621 UT on 4 August, and $\sim$1500 UT on 7 August respectively.

(2) The spectacular cosmic ray disturbances observed during this period included two relativistic particle enhancements at ground and three major Forbush decrease events.

(3) The first relativistic particle enhancement which had its onset at $\sim$13 UT on 4 August had an amplitude of $\sim$6% at high latitude stations. The flare enhancement was almost isotropic. The rigidity spectrum of particles was very steep (power law index $= 8.0 \pm 0.5$). An interesting feature of the event was the abnormal time delay ($\sim$6 h) between the onset of particle increase and the flash maximum of the parent 2B solar flare which occurred at 0635 UT on 2 August. The most plausible explanation for this delayed event seems to be longitudinal coronal spreading of particles onto flux tubes which produce the enhancement when they convect past the Earth.

(4) The second relativistic particle enhancement which had its earlier onset at $\sim$1530 UT on 7 August occurred within 30 min of the optical flare event of importance 3B indicating that particles accelerated in the flare region suffered very little scatter along their propagation path to the Earth. Large east–west and north–south anisotropies were present during this event. The rigidity spectrum of accelerated particles was comparatively softer, having a power law index of -4.7 ± 0.5, and the particle enhancement was restricted to energies below $\sim$3 GeV.

(5) The first of the three Forbush events occurred at 0200 UT on 4 August. The earliest onset was observed at stations viewing along the garden hose direction and the latest onset at stations viewing along the anti-Sun direction. The decrease, which was about 7% at high latitude stations, extended to almost 60 GeV. Large east–west and north–south ($\sim$3%) anisotropies were registered during this event.

(6) The third Forbush decrease event FD-3 which had its onset at 01 UT on 9 August, again showed large east–west ($\sim$3%) and north–south ($\sim$2%) anisotropies, the maximum intensity decrease ($\sim$5%) being registered by stations viewing along the 18-hour direction.

(7) A precursory increase of galactic cosmic rays having a flat spectrum and a maximum amplitude of $\sim$2–3% along the sunward direction was recorded by all ground-based monitors at 2100 UT, less than 2 h prior to the onset of the major Forbush event FD-2. The observed enhancement preceding the main event is consistent with its being caused by the reflection and sweeping of particles by the approaching shock front.

(8) The onset of the main Forbush event FD-2 occurred at around 2100–2200 UT, in time association with the sudden commencement geomagnetic storm at 2054 UT on 4 August, 1972. The large rapid decrease is attributed to the magnetic barrier containing large fields ($\sim 100\,\gamma$) behind the shock front overtaking the Earth. The apparent early onset of FD-2 from the anti-Sun direction is explainable in terms of the occultation of particle trajectories reaching the detectors viewing along this direction as the shock front engulfs the Earth, while the detectors looking along the sunward direction are still sampling enhanced albedo flux reflected from the shock front. The low energy particle observations in space also show an abrupt decrease in flux due to the effect of the moving shock front.

(9) During the main phase of FD-2, a square wave like enhancement is observed both at high and at low energies. The interplanetary observations indicate that the enhanced flux was essentially confined to a region of low magnetic density ($10\,\gamma$) behind the main shock front. The tangential discontinuity separating the main shock front and the 'magnetic well' prevents diffusion of enhanced flux into the shock region. The enhancement of the high energy flux is explained as due to the leakage of galactic particles into this region along the lines of force connecting this region with interplanetary space. The low energy particle enhancement is also attributed to the same phenomenon since the interplanetary space outside the narrow shock wave tongue is heavily populated by low energy particles of solar origin. An alternate explanation is to invoke a different mechanism for low energy particles above, namely the presence of continuous acceleration of low energy particles at the flare site with easy access to the 'magnetic well'.

(10) The depressed cosmic ray intensity inside the cavity behind the tangled magnetic field region where the driver gas is present, shows typical exponential recovery with time, consistent with its being due to slow diffusion of particles from the interplanetary space.

8. Acknowledgements

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