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# Forbush decreases in cosmic-ray intensity and large-scale magnetic configuration of interplanetary shocks

BADRUDDIN (*)
*Department of Physics, Aligarh Muslim University, Aligarh - 202 002, India*

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**Summary.** — We present the results of an analysis to study the effects of shock front, sheath region and driver gas (ejecta) on the transient decreases of cosmic-ray intensity. In this work interplanetary plasma and field data along with hourly neutron monitor cosmic-ray intensity records have been subjected to superposed epoch analysis. We have also studied the variations in interplanetary plasma/field parameters (*viz.* solar wind speed, magnetic field strength and its variance) and cosmic-ray intensity during the passage of individual transient interplanetary structures. The sudden decrease in intensity starts after the arrival of certain shocks. The shock front itself is not sufficient for the Forbush decreases but the turbulence generated in sheath region appears to be its main cause. A shock structure is considered which explains the results. The essential feature of this structure is that the extent of the shock front is much more than the ejecta and magnetic turbulence is usually present in the limited region of sheath. Based on this, we explain the reason behind the observation that all the shock-associated disturbances do not produce Forbush decreases on reaching the Earth.

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## 1. – Introduction

One of the two most impressive transient changes in cosmic-ray intensity is known as Forbush decrease. Typically, at earth, this decrease is characterized by rapid reduction in intensity reaching a minimum value in a few hours followed by a slow recovery over a few days. In spite of considerable interest and progress made in the study of this phenomenon several questions remain to be answered (see below) and we still do not have an adequate detailed physical model of Forbush decreases.

It is generally agreed that transient structures (of high field strength) in heliosphere are responsible for Forbush decreases. However, there is considerable disagreement about the characteristics of these structures and the process which plays

(*) E-mail: pht08bdu@amu.up.nic.in

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the dominant role [1, 2]. There are questions regarding the relative importance of shock, the disturbed magnetic field behind the shock, and the driver ejecta following the distrubed field region. There is also question as to whether Forbush decreases are caused by scattering from turbulent magnetic fields or drifting in strong ordered magnetic fields [3]. If turbulence is the main cause, then one should observe a relatively large decrease in cosmic-ray intensity during the passage of the turbulent field region. However, if drifting in strong, smooth magnetic fields is the primary cause of Forbush decreases, then one should expect a decrease during the passage of ejecta as magnetic fluctuations in ejections are relatively very small, if any [4].

Since their discovery [5] Forbush decreases are generally thought to be due to solar-flare–associated interplanetary disturbances [1, 6, 7]. However, only a few questioned the effectiveness of flares in producing such decreases [8]. Webb and Wright [9] found that disappearing filaments, as a distinct class of solar activity, could also be the source of disturbances which significantly depress the cosmic-ray intensity. Recently Gosling [10, 11] emphasized that flares do not generally play a central role in producing major transient (geomagnetic) disturbances in near-Earth space environment. Therefore, a comprehensive study of transient decreases in cosmic-ray intensity in relation to other sources of transient interplanetary disturbances is also needed. The identification of interplanetary magnetic clouds by Burlaga and coworkers [12, 13] has provided a very useful tool for investigating cosmic-ray decreases and the first detailed study of the effects of magnetic clouds and associated disturbances on transient modulation of cosmic rays was done by Badruddin *et al.* [14]. Subsequent studies [4, 15-24] provided more insight about the effects of magnetic clouds on cosmic-ray intensity. Most of these studies, on the effects of magnetic clouds and associated disturbances, are consistent with the hypothesis that Forbush decreases are primarily due to scattering of particles by a region of enhanced magnetic turbulence. However, Sanderson *et al.* [24], Cane [20], Cane *et al.* [23] concluded that a magnetic cloud (region of quiet magnetic field) can also produce significant decreases in cosmic-ray intensity.

Even though the role of interplanetary shocks and associated magnetic structures has received considerable attention in the study of Forbush decreases [23-32], the results are conflicting as regards the phenomenon mainly responsible for the decrease. It has been attributed to a) the sweeping effect of shock itself, b) the gradient drifts in the environment of shock of rather ordered structure, and c) the scattering of particles in the turbulent region between shock front and driver ejecta. Though in most recent models of Forbush decreases it is attributed to the latter phenomenon, it is yet to be established whether the magnetic region that inhibits the cosmic rays spreads all over the extent of the shock wave [33] and what the effect of a shock will be when it moves through an undisturbed magnetic field [3] and whether the shock front itself or the turbulence it generates within the sheath region is of basic importance [18, 34]. If both the shock front and the turbulent sheath are effective in transient cosmic-ray modulation, the relative importance of the post-shock turbulent region and the shock itself needs to be clarified.

Since the interaction between cosmic rays and interplanetary magnetic field is the basic and common cause of cosmic-ray modulation with different time scales [1, 35-37], the investigation of one effect is expected to help in understanding the modulation with other time scales. In particular, long-term (11-year) modulation may be related to the processes that produce transient decreases in cosmic-ray intensity [34]. Global merged interaction regions (GMIRs) are a major element in producing the long-term 11-year cosmic-ray modulation and the GMIR produced modulation results from a decrease in the diffusion coefficient either by increased turbulence and/or an enhanced magnetic field in the region [38-40]. GMIRs are formed by coalescence of shocks, coronal mass ejections (CMEs) and high-speed stream from coronal holes. Since shocks, CMEs and corotating high-speed streams are basic building blocks of GMIRs, the study of their effects on short-term cosmic-ray decreases may help in understanding the modulation due to GMIRs also. Corotating streams are not much effective in producing any net change in cosmic-ray intensity [41-46] but the importance of CMEs for cosmic-ray modulation is becoming increasingly clear [47, 48]. However, more efforts in this direction are required.

## 2. – Analysis

In an attempt to provide more insight into the phenomenon of Forbush decrease and shock structure, nearly one hundred interplanetary shocks observed at 1 AU during the period 1971-79 have been classified into four types based on their observed features and effects, *i.e.* whether they are followed by plasma ejecta or not, and whether they are able to produce Forbush decreases in cosmic-ray intensity or not. The ejecta have been identified by the existence of He-enrichment and/or BDF events. From all these shocks, about half of them are observed to be followed by ejecta. Out of the shocks followed by ejecta, about fifty-five percent are responsible for Forbush decreases and the rest do not produce any appreciable decrease in cosmic-ray intensity. Only about fifteen percent of the total shocks not followed by ejecta are associated with Forbush decrease, while the others are not. After collecting this statistical figure, we tried to find out the reason for this difference in effectiveness of shocks/ejecta in reducing cosmic-ray intensity on their arrival at the Earth. For this purpose we have analysed the variation in interplanetary magnetic field strength, its variance, the solar-wind speed along with hourly cosmic-ray intensity data using the superposed epoch method.

## 3. – Results and discussion

Figures 1(A)-(D) show the results of superposed epoch analysis of cosmic-ray intensity with respect to shocks of four types. From figs. 1(A) and 1(C) one can observe that a Forbush decrease of large amplitude follows the arrival of a shock and sharp decrease continues for $\sim 12$ hours. This duration is comparable to the dimension of shocked plasma (sheath) between shock front and driver ejecta [49, 50]. The intensity variation with respect to other types of shocks (B) and (D) is not appreciable.

In order to understand the reason for the above-mentioned differences in response to the various types of shocks, we have grouped together the shocks that are responsible for Forbush-type decreases in cosmic-ray intensity (type (A) and (C)) and those not showing any appreciable decrease in intensity (type (B) and (D)). This grouping has been done to see the variations in interplanetary plasma and field parameters during the passage of those structures which are responsible for Forbush decreases and during those which are not. In addition the grouping will increase the number in two groups. Then the effects of these two groups of shocks have been studied. Interplanetary parameters such as solar-wind velocity ($V$), IMF strength ($F$)

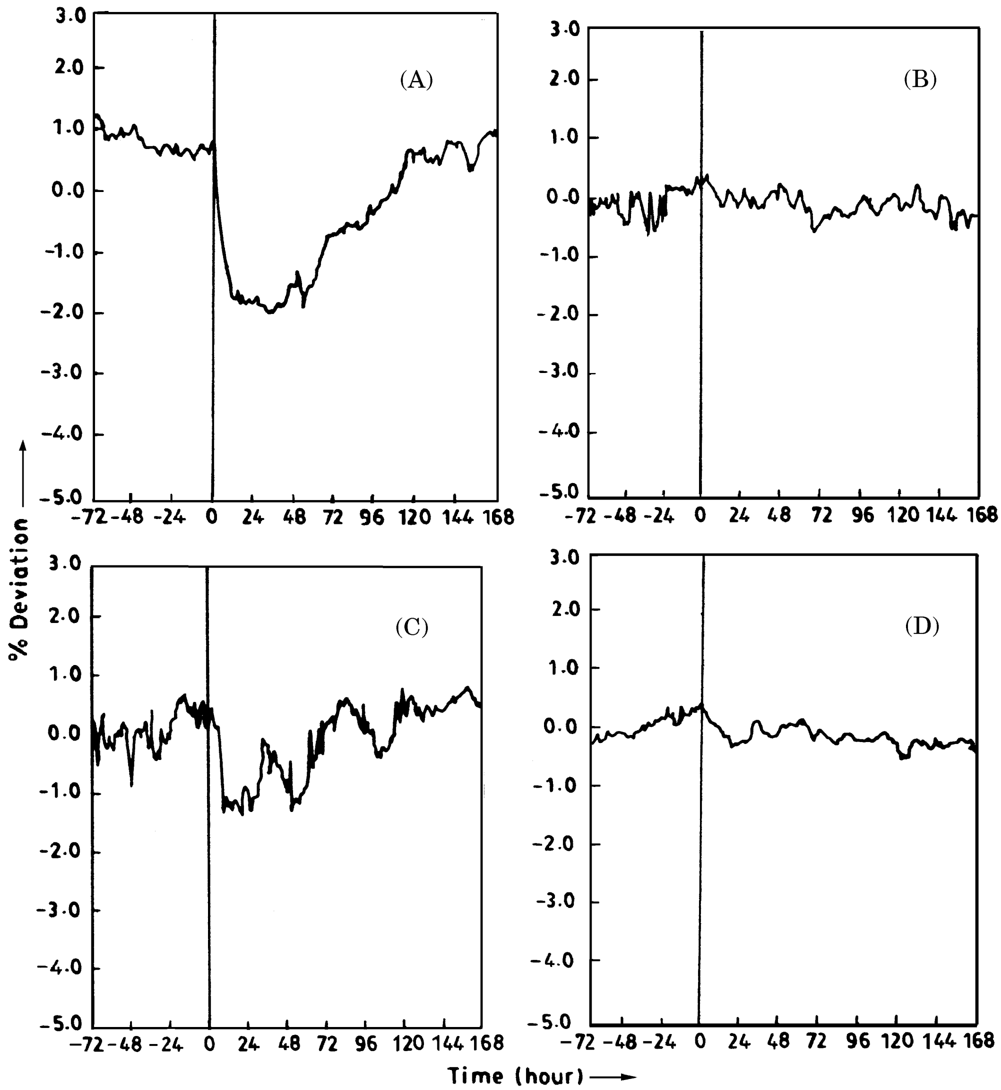


Fig. 1. – Superposed epoch analysis of cosmic-ray intensity recorded at the Calgary neutron monitor with respect to shocks observed to be followed by ejecta and producing Forbush decreases (A); with respect to shocks observed to be followed by ejecta and producing no decrease in intensity (B); with respect to shocks not followed by ejecta, but producing Forbush decrease (C); and with respect to shocks not followed by ejecta and also not producing Forbush decrease (D). The epoch (zero hour) corresponds to the arrival time of shock at 1 AU.

and its variance ($\sigma F$) during the passage of shock have been considered for the analysis as relative effects of these parameters are expected to help in identifying the major factor responsible for short-term cosmic-ray modulation. In these two figures (figs. 2a and b) we have used hourly pressure corrected data of the Calgary neutron monitor and plotted the results of the superposed epoch analysis along with those of $V$, $F$ and

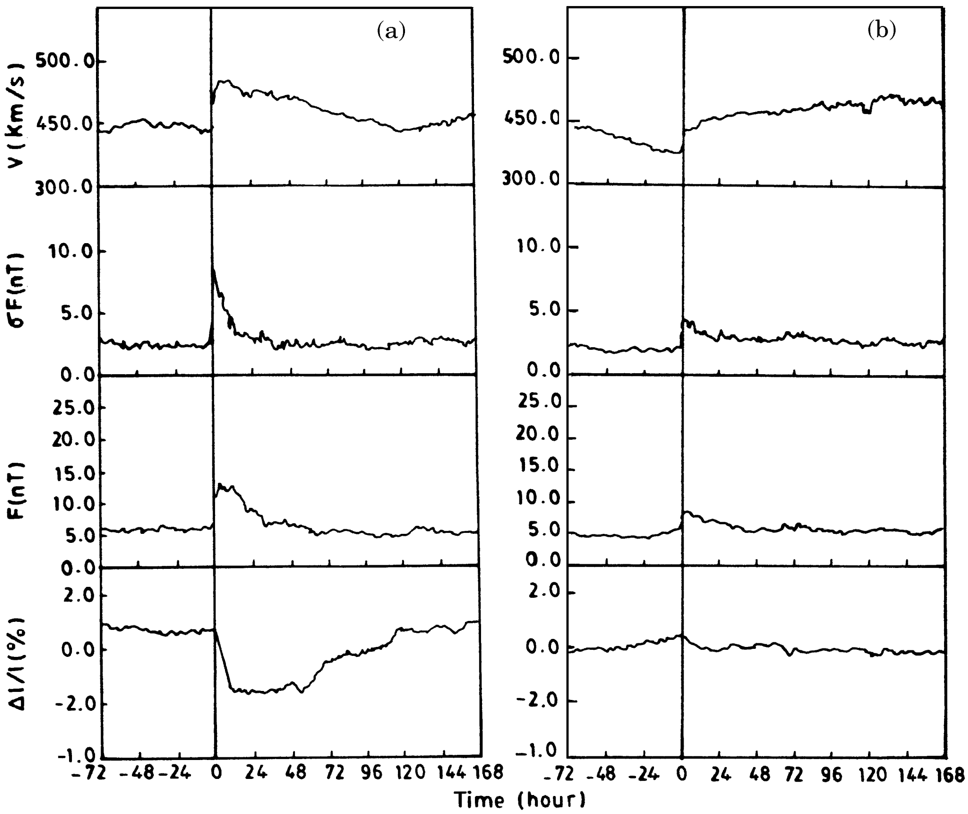


Fig. 2. – Superposed epoch analysis of cosmic-ray intensity recorded at the Calgary neutron monitor ($\Delta I/I$), solar wind speed ($V$), magnetic field strength ($F$) and its variance ($\sigma F$) (a) with respect to shocks producing Forbush decrease, both followed and not followed by ejecta combined togather; and (b) with respect to shocks not producing Forbush decrease, both followed and not followed by ejecta taken together. The shock arrival time is taken as zero-epoch hour.

$\sigma F$. The arrival of the shock is taken as epoch hour. In fig. 2a (for type A+C shocks) it is seen that the Forbush-type decrease in cosmic rays starts at the arrival of shock and the decrease time extends over $\sim 12$ hours. In addition to the enhancement of $V$ and $F$ we also find a large increase in $\sigma F$ at the same time (see also table I). However, on the other hand, the decrease in cosmic-ray intensity shown in fig. 2b (for type B+D shocks) is not appreciable. Moreover, in this case the increase in $\sigma F$ is also very small. In our earlier work, we have demonstrated that the enhancement in solar-wind velocity [44, 46] and magnetic field strength [14] is not sufficient for transient modulation of cosmic rays unless the field is turbulent. During the sheath passage of shock-associated magnetic clouds, a correlation analysis between $F$ and $\sigma F$ has shown very good correlation between these two parameters (Badruddin, in preparation). Thus, when such is the case, it is not surprising if the modulation caused mainly by one of these parameters shows a spurious correlation to the other. It may be mentioned here that in interplanetary transients a region is identified as magnetically quiet

TABLE I. – *Average properties of interplanetary parameters of transient shocks at* 1 AU *and associated cosmic-ray decreases. A: Shocks observed to be followed by ejecta and producing Forbush decrease. B: Shocks observed to be followed by ejecta but not producing Forbush decrease. C: Shocks not followed by ejecta, as observed, but producing Forbush decrease. D: Shocks not followed by ejecta, as observed, and not producing Forbush decrease. $F$: Maximum field strength*; $\Delta F$: *field enhancement from pre-shock value*; $\sigma F$: *maximum variance of magnetic field*; $\Delta(\sigma F)$: *variance increase from pre-shock level*; $V$: *maximum solar-wind speed during shock/ejecta*; $\Delta V$: *enhancement in speed during shock/ejecta from pre-shock level*; $\Delta I/I$: *cosmic-ray intensity decrease with respect to pre-shock level.*

| Shock type | Magnetic field | | Magnetic-field variance | | Solar-wind velocity | | Cosmic-ray decrease |
|---|---|---|---|---|---|---|---|
| | $F$(nT) | $\Delta F$(nT) | $\sigma F$(nT) | $\Delta(\sigma F)$(nT) | $V$ (km/s) | $\Delta V$ (km/s) | $\Delta I/I$(%) |
| A | 14 | 8 | 9 | 7.5 | 550 | 130 | 2.8 |
| B | 10 | 4 | 5 | 3.0 | 450 | 80 | 0.2 |
| C | 14 | 8 | 7 | 4.5 | 480 | 90 | 1.8 |
| D | 8 | 2.5 | 4.5 | 2.0 | 500 | 125 | 0.4 |

(turbulent) where the variance of magnetic field is lower (higher) than the average [4, 15, 17, 32, 33, 51].

In fig. 3 we have selected some typical examples and plotted the hourly records of cosmic-ray intensity, solar-wind velocity ($V$), IMF strength ($F$) and its variance ($\sigma F$) with respect to arrival of shock at earth. In all these plots the cosmic-ray decrease is large when $\sigma F$ is large in addition to $F$ and $V$. The increased variance in the magnetic field vector ($\sigma F$) indicates that the fluctuations in the magnetic field direction are large. In fig. 3 both the examples have almost the same amplitude in cosmic-ray decreases, but a different strength in interplanetary parameters. In spite of very different interplanetary parameters ($V, F$) during two events, the decrease intensity is the same. In the first example, the field intensity is enhanced up to $\sim 30$ nT and the solar-wind velocity reaches up to $\sim 650$ km/s. On the other hand, in the second example the maximum field intensity is $\sim 12$ nT and the speed is not more than 450 km/s, yet the cosmic-ray decrease intensity is the same. These results, together with those presented earlier, are consistent with the suggestion that velocity and field strength may not be the most important parameters in producing Forbush decreases, but the enhanced turbulence appears to be the dominant cause. It is worth mentioning here that the unexpectedly strong residual modulation of cosmic rays over the polar regions observed by Ulysses [52, 53] has been interpreted by Balogh *et al.* [54] as a direct consequence of the increased level of directional fluctuations in the magnetic field [55, 56].

The results discussed above can be explained by considering a shock model as shown in fig. 4. This structure is based on the models proposed earlier [57, 58, 32]. The proposed structure, in our view, seems to be the most appropriate shock model deduced to explain Forbush decreases, although it is not yet known with certainty whether ejecta are completely disconnected from the Sun. In this model (see fig. 4) when the Earth encounters the shock front between b-c and c-d, then we expect a decrease in intensity as in this case the magnetic field behind the shock front will be turbulent for

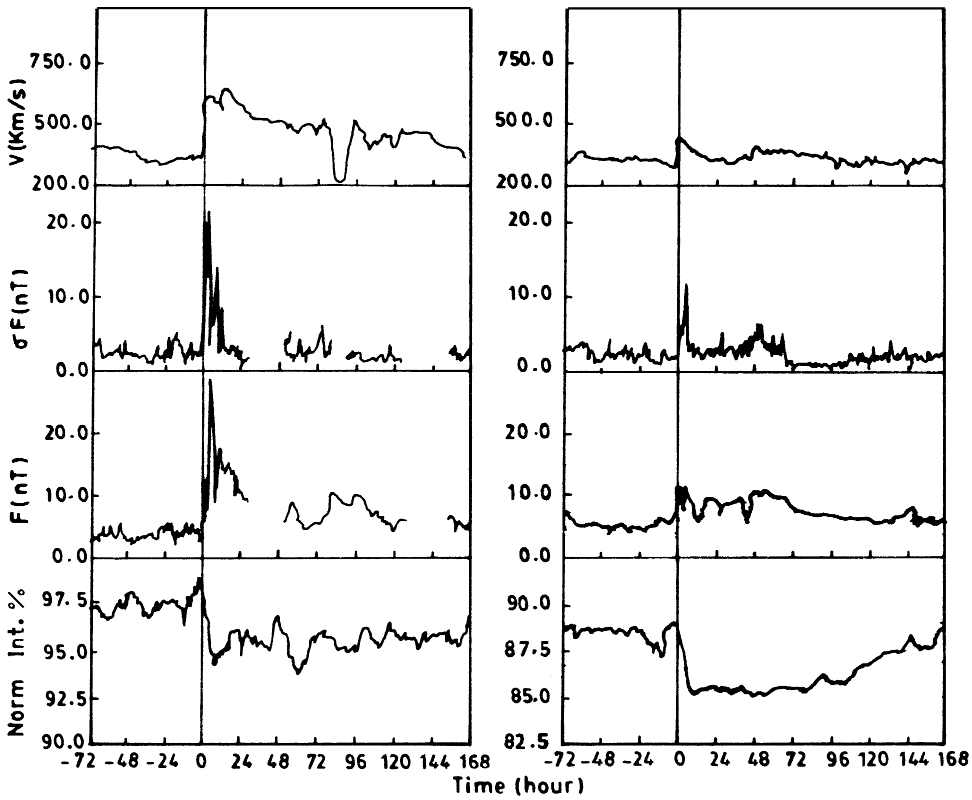


Fig. 3. – Typical examples showing neutron monitor count rate, solar-wind velocity, field strength, and its variance; the zero-epoch hour corresponds to the arrival time of shock at 1 AU.

few hours (typically 10–20 hours). However, if it encounters the shock anywhere between a-b, d-e and e-f, one may not observe any appreciable decrease in intensity as the magnetic field behind the shock front, in this case, may not be turbulent enough to scatter cosmic-ray particles.

In this model it is assumed that almost all the transient shocks observed at 1 AU are driven by ejecta. However, in approximately half of all these transient shock events, the Earth does not encounter the ejecta directly, presumably because the typical shock disturbance is considerably broader than the ejecta which drive it [50, 59, 60].

Forbush decreases were mostly associated with the Earth passage of interplanetary disturbances in which the Earth encountered both shock and ejecta. However, it is noteworthy that many transient shock disturbances did not produce Forbush decreases; even some of the interplanetary disturbances when both shock and ejecta were encountered were relatively ineffective in producing any significant decrease in intensity. We suggest that in such cases the field in shocked plasma might not be turbulent enough to bring about any appreciable decrease. Since compression of ambient field fluctuations in the region behind the shock between b-c and c-d should generally be greater, it is expected that Forbush decrease usually occurs when the

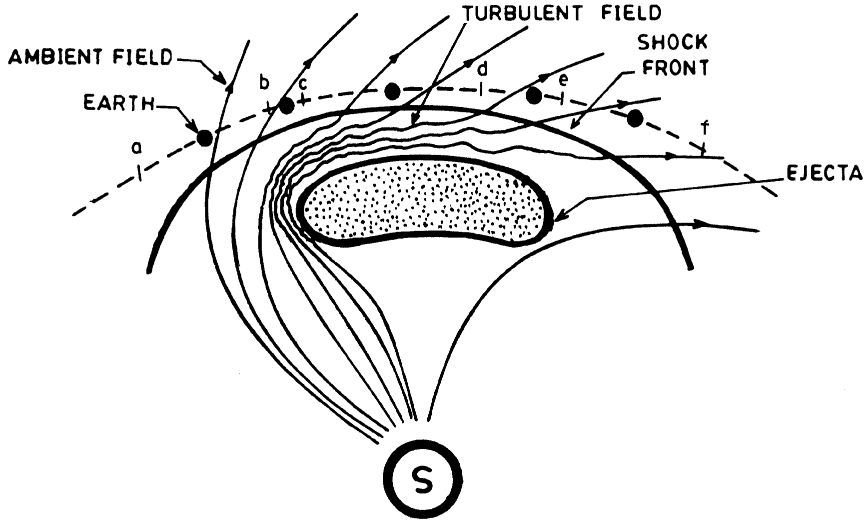


Fig. 4. – A model of shock wave disturbance at 1 AU. In this model, when the Earth's position relative to the shock is anywhere between a-b, d-e, and e-f, there may not be any appreciable decrease in intensity on arrival of the shock at the Earth. However, if the Earth's position is anywhere between b-c and c-d, it is very likely that there will be a decrease in intensity following the arrival of the shock at the Earth.

Earth passes through these regions. This is also the reason behind the observation that most of the decreases are usually associated with disturbances when both shock and ejecta are encountered and only few decreases are observed when ejecta are not encountered hehind the shock.

## 4. – Conclusions

From the results discussed above, we extract the following conclusions:

– The decrease in cosmic-ray intensity starts just after the arrival of certain shocks. Most of the shocks showing such effects on cosmic-ray intensity are observed to be followed by ejecta.

– The intensity decreases abruptly during the passage of the sheath region of turbulent magnetic field, before the arrival of plasma ejecta.

– The shock front itself is not sufficient to produce Forbush decrease but the turbulence that it generates into the sheath region appears to be its dominant cause.

– There is no appreciable effect of shock on cosmic-ray intensity, when it moves through an undisturbed magnetic field.

– The turbulent field region does not extend (behind) all over the extent of the shock wave.

– It appears that the scenario is as follows: The Sun occasionally ejects an energetic burst of plasma called ejecta. The ejection often produces an interplanetary shock wave that moves ourward at high speed. The shock wave is typically followed by a turbulent high-speed stream of plasma. As the shock wave propagates outward, the turbulent magnetic field in high-speed stream inhibits the entry of cosmic rays causing a (Forbush) decrease in cosmic-ray intensity. The essential feature (responsible for Forbush decrease) is an increase in the level of turbulence such as that which is usually caused by the compression of ambient magnetic field fluctuations during the passage of a shock. Intensification of the magnetic turbulence would correspond to the enhancement in the degree of scattring by magnetic irregularities, decrease in diffusion coefficient along field lines and hence intensity reduction of cosmic rays.

– If long-term modulation is related to the processes that produce Forbush decreases, then our results indicate that GMIR-produced long-term modulation of cosmic rays might result from a decrease in the diffusion coefficient as a result of increased turbulence in the region, and may not be because of enhanced magnetic field strength only (unless it is accompanied by enhanced turbulence in the field). It should be interesting then to investigate whether such turbulence extends to the whole shell of GMIR or it is confined to some limited regions (patches) in it.

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