SIGNIFICANCE OF THE TURBULENT SHEATH FOLLOWING THE INTERPLANETARY SHOCKS IN PRODUCING FORBUSH DECREASES

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Abstract. The physical processes responsible for transient cosmic-ray decreases have been investigated for two types of interplanetary shock events associated with helium enhancement (He-shocks) and those not associated with helium enhancement (non-He-shocks). The Calgary cosmic-ray neutron monitor data and the interplanetary field data have been subjected to a superposed-epoch Chree analysis. The difference in the profiles of the cosmic-ray intensity have been compared with the interplanetary field data and its variance. It is suggested that the turbulence sheath following the shock front is very effective and of major importance for producing cosmic-ray decreases. A simple model has been proposed to explain the observations which show that a Forbush decrease modulating region consists of a shock front associated with a plasma sheath in which the magnetic field is turbulent and the sheath, in turn, is followed by an ejected plasma cloud having ordered structure and high magnetic field strength.

1. Introduction

There is considerable interest in identifying the configurations and physical processes responsible for producing Forbush decreases (Venkatesan and Badruddin, 1990). The field configurations such as magnetic loops/clouds of ordered field topology, turbulent clouds, magnetic bubbles, blast waves, interplanetary shock waves (having comparatively ordered field structure), and the turbulent field in the environment of shocks or tangential discontinuities and several physical processes such as deflection of the particles by smooth field lines (Gold, 1962; Sanderson *et al.*, 1990), grad-B drift in the environment of magnetic blobs/shocks of rather ordered field structure (Barouch and Burlaga, 1975; Sarris, Dodopoulos, and Venkatesan, 1989; Cheng, Sarris, and Dodopoulos, 1990), scattering due to a turbulent field in the environment of shocks (Badruddin, Zhu, and Venkatesan, 1991; Zhang and Burlaga, 1988) and extra cooling between the shock and the Sun (Thomas and, Gall, 1984) have been considered for explaining Forbush decreases. It has been found (Badruddin, Yadav, and Yadav, 1986; Zhang and Burlaga, 1988) that a magnetic cloud itself is not sufficient for explaining a Forbush decrease unless it is associated with a shock. On the other hand, Sanderson *et al.* (1990) have found some evidence that magnetic clouds themselves can produce

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large Forbush-type decreases. Though, in general, solar flares have been the primary cause of Forbush decreases, Webb and Wright (1990) have concluded that disappearing filaments, as a distinct class of solar activity, could also be the source of disturbances which significantly depress the galactic cosmic-ray intensity and produce Forbush decreases when they are associated with interplanetary shocks. Thus the whole area is somewhat complex and needs to be looked into critically.

Badruddin, Yadav, and Yadav (1986) have utilized three categories of magnetic clouds observed at 1 AU and performed the superposed epoch analysis of cosmic-ray intensity. Their analysis includes the category of clouds associated with shocks, stream interface and cold magnetic enhancements. In spite of the fact that for all the three categories of clouds maximum field strength was the same, the average field profiles were similar. The three types of clouds might be simply different manifestations of a single phenomenon (e.g., coronal mass ejections). They still found a large difference in the amplitude and time profile of cosmic ray depressions associated with the three categories of clouds. The observations have also indicated (Zhang and Burlaga, 1988) that the field strength may not play any significant role in modulating cosmic rays. Furthermore, Badruddin and Yadav (1987), by an examination of a number of helium and non-helium shocks, came to the conclusion that there is a significant difference in the amplitudes and profiles of Forbush decreases observed in the two cases and suggested that the magnetic turbulence behind the shock front may cause a Forbush decrease. Since the interplanetary shocks are sometimes associated with field enhancements or field fluctuations, either of them could be effective in causing a cosmic-ray decrease.

In the present analysis we have examined the cosmic-ray intensity, interplanetary magnetic field and plasma parameters using the arrival times at 1 AU for the He-shocks followed by driver gas showing helium enhancement (He-shocks) and those not followed by the same (non-He-shocks). Based on the results, we have suggested a simple model of shock configuration to explain the observations related to Forbush decreases.

2. Analysis

Badruddin, Venkatesan, and Ananth (1991) have performed analysis with two types of shocks: those associated with helium enhancement (helium enhancement is a signature of mass ejecta) and those that are not associated with helium enhancement as identified by Borrini *et al.* (1982). They have found that among these two types of shocks, the ones which are associated with helium enhancements are able to produce large Forbush decreases. Their study has been useful in identifying some features of the modulating regions responsible for Forbush decreases.

Following similar procedures in the present analysis, we have classified the shock wave disturbances into two groups, i.e., those that are followed by helium enhancement (He-shocks) and those not followed by helium enhancements (non-He-shocks). We have used a total of 91 shock wave disturbances observed during the epoch 1971–1978 detected at 1 AU (Borrini *et al.*, 1982). The hourly intervals of passage at the Earth of 44 He-shocks and the 47 non-He-shocks have been considered for superposed epoch analysis using hourly pressure-corrected count rates of Calgary neutron monitor (Venkatesan *et al.*, 1989) and interplanetary field vectors, its variance and solar wind speed.

3. Results

We have shown in Figure 1 the results of the superposed epoch analysis using the arrival times of He-shock as the zero-epoch hour. In this figure, it is seen that a decrease (Forbush type) in cosmic rays starts at the time of arrival of the shock and extends over nearly ~15 hours. In addition to the enhancement of V and F, associated with the

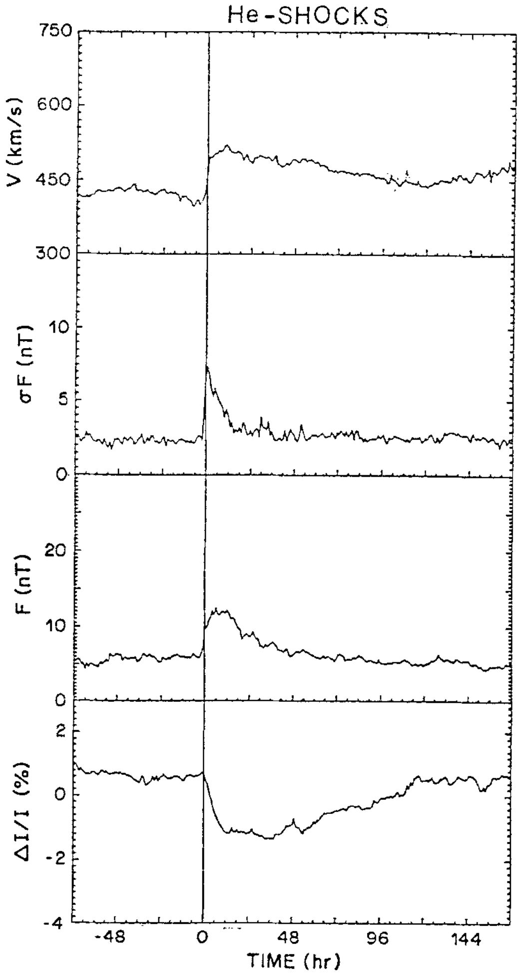

Fig. 1. The results of superposed epoch analysis of Calgary neutron monitor data together with magnetic field strength (F), the variance in magnetic field σB and solar wind speed (V) plotted for shocks associated with He-enhancement observed during 1971–1978. The arrival time of the shock is taken as zero-epoch hour.

cosmic-ray decrease we also find a large increase in *σF* observed at the same time. The enhancement in *σF* indicates enhanced turbulence following the shock wave. Similarly Figure 2 shows the cosmic-ray intensity variations observed for non-He-shocks which are not followed by the driver gas. The observed cosmic-ray decrease in this case is very small when compared to that of He-shocks. Moreover, the increase in *σF* associated with the time of arrival of the shock is also not very significant. We see in both cases that a decrease (small or large) is observed to start immediately following the passage of a shock.

However, it may be noted here that not all the He-shocks are associated with typical Forbush decreases (Badruddin, Venkatesan, and Ananth, 1991). Thus, in order to understand the process of cosmic-ray modulation, we have again divided these He-

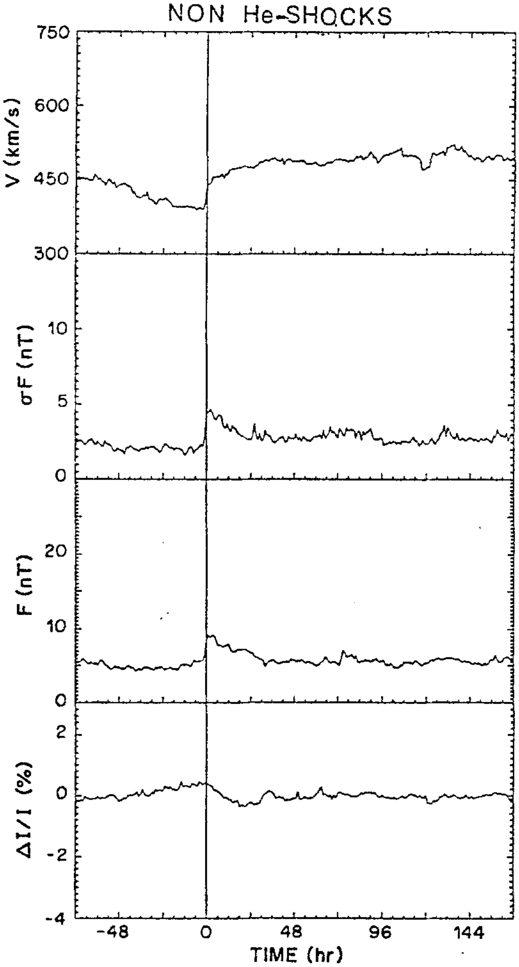

Fig. 2. The results of superposed epoch analysis of Calgary neutron monitor data together with magnetic field strength (*F*), the variance in magnetic field *σB* and solar wind speed (*V*) plotted for non-He-shocks which are not associated with helium enhancement.

shocks into two different categories, i.e., those which produce Forbush decreases and those which do not produce Forbush decreases. Figure 3 shows that the He-shocks responsible for Forbush decreases indicate further enhancement in σF and suggest the presence of a turbulent sheath following the shock wave. Figure 4 deals with He-shocks which are not associated with any Forbush decreases. The figure does not show any increase in σF for He-shock events. These observations clearly show that the He-shocks which produce cosmic-ray Forbush decreases are always associated with enhancement in magnetic field fluctuations σF and clearly indicate the presence of a turbulent sheath behind the shock wave.

Table I summarizes the number of He-shocks and non-He-shocks associated with Forbush decreases. It is clearly evident from Table I that a good majority of the

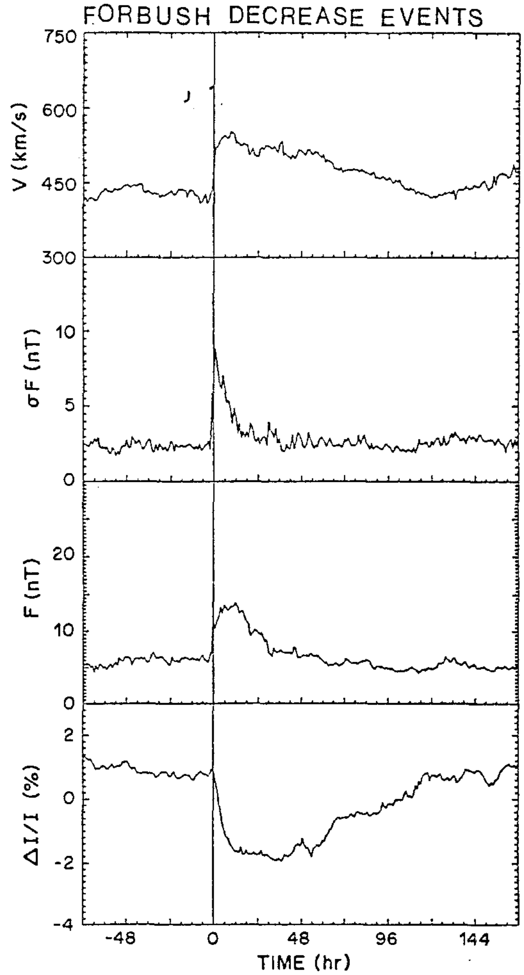

Fig. 3. The results of superposed epoch analysis of Calgary neutron monitor data together with magnetic field strength (F), the variance in magnetic field σB and solar wind speed (V) plotted for He-shocks which produce Forbush decreases.

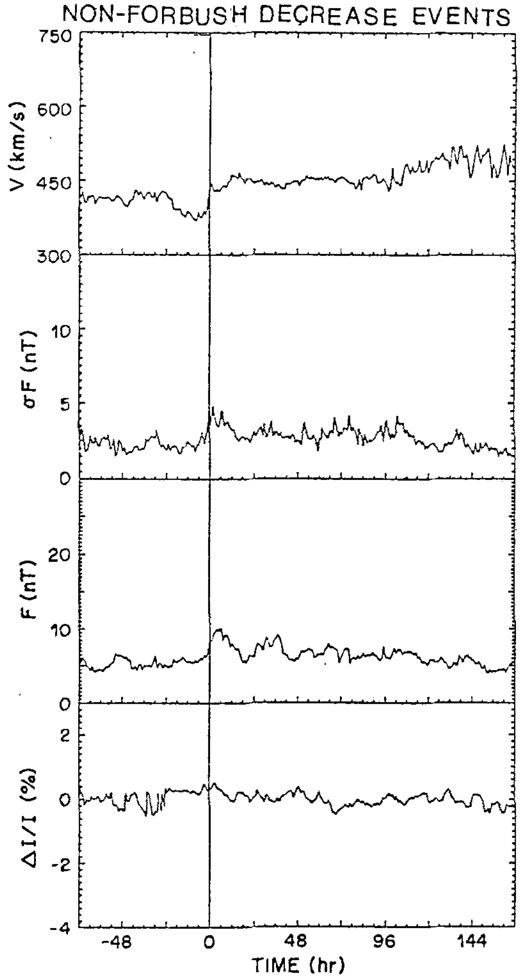

Fig. 4. The results of superposed epoch analysis of Calgary neutron monitor data together with magnetic field strength (F), the variance in magnetic field σB and solar wind speed (V) plotted for He-shocks not associated with Forbush decreases.

TABLE I

Interplanetary shocks associated with Forbush decreases (amplitude > 2%)

Sl. no.	Shocks	He-shocks	Non-He-shock
1	Total number of shocks	44	47
2	Number of shocks associated with Forbush decreases	28	8
3	Number of shocks which are not associated with Forbush decreases	16	39

He-shocks produce a Forbush decrease, and the number of He-shocks which do not produce Forbush decrease are comparatively small. It is further noted from the table that a large number of non-He-shocks are not associated with Forbush decrease and the number of Forbush decreases associated with non-He-shocks are significantly small. These observations presented in the figures and table clearly indicate that Forbush decreases are mostly caused during the passage of He-shocks when they are associated with a turbulent region, following the shock wave.

4. Discussion

It is to be noted from earlier studies (Badruddin, Yadav, and Yadav, 1986; Zhang and Burlaga, 1988) that magnetic clouds with ordered field structure may not be sufficient to produce Forbush decreases, and the magnetic field strength itself may not play any major role in initiating Forbush-type decreases. Subsequently, Venkatesan and Badruddin (1990) have proposed that the possible scattering of particles in the turbulent environments of shocks or the grad-B drift in the ordered field structure in a shock environment may account for cosmic-ray decreases. However, our present observations indicate that σF is high during the passage of He-shocks and specifically for those producing Forbush decreases. The increased turbulence and presence of a turbulent sheath in the environment of a shock is seen to be the major cause of Forbush decreases.

Furthermore, the results from various spacecraft have clearly demonstrated the existence of hydromagnetic shocks and a sheath behind the shock-front in which there are large fluctuations in both the strength and the direction of the magnetic field (Burlaga *et al.*, 1981; Sanderson *et al.*, 1983). There has also been evidence that this turbulent sheath is followed by a plasma cloud of more limited angular extent in which the magnetic field is ordered and higher than average. It has also been suggested that many (or even all) the interplanetary shocks are driven by such plasma clouds (Borrini *et al.*, 1982).

We have tried to explain the observations by considering a simple shock model configuration similar to the one proposed by Cane (1988) for flare-associated interplanetary shocks and by including the effects of magnetic turbulence. Figure 5 shows the proposed model for two different positions of the Earth. In position A the Earth passes through the region of maximum turbulence during the passage of the shock and results in a large Forbush decrease in cosmic-ray intensity. When the turbulence is minimum we find that the cosmic ray decrease is small. In position B, due to the limited driver size, the Earth passes through the region of minimum turbulence and produces only a small cosmic-ray decrease. Further it is found that the shock orientation with respect to the foreshock IMF direction is one of the important parameters for producing turbulence (Smith, 1983; Kennel *et al.*, 1982). This essentially explains the observations when a He-shock does not produce a major Forbush decrease in position B, since the Earth passes through a lesser turbulent region during the passage of the shock front. In case of non-He-shocks it is indicated that the individual shocks may have distorted surfaces during their propagation in the inhomogenous interplanetary medium. The

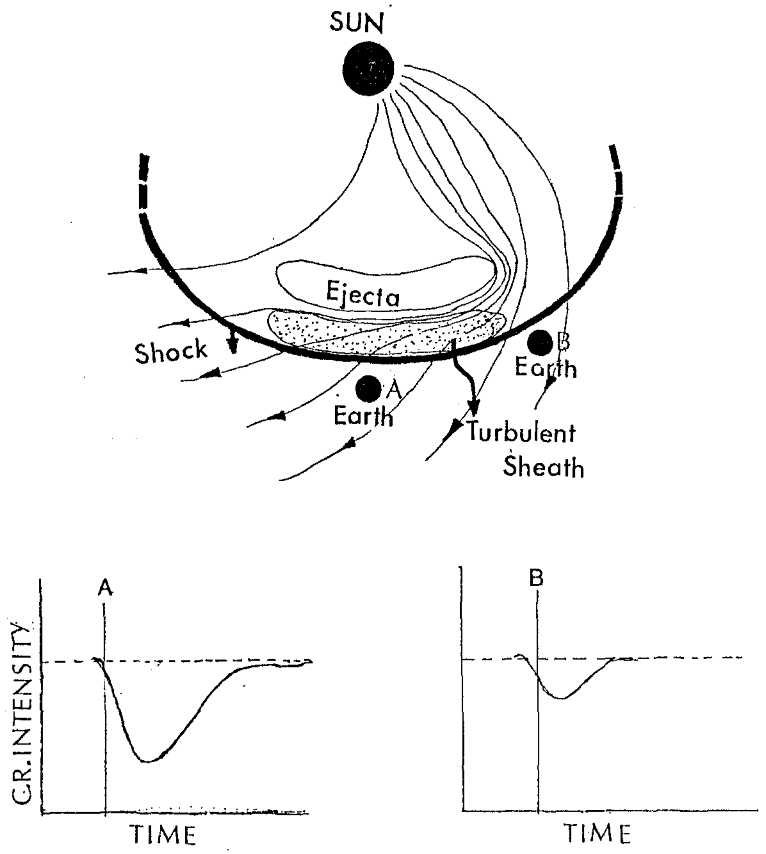

Fig. 5. The proposed model of the shock wave disturbance at 1 AU. In the same figure below are shown two hypothetical expected time profiles of cosmic-ray intensity when the shock crosses Earth at position 'A' (He-shocks) and 'B' (non-He-shocks). The IMF lines outside the shock front are also shown (Cane, 1988).

limitations of this simple model is to be remembered, though the proposed shock model is expected to account for the observations presented in this paper. It is also to be realized that field lines outside the shock front may not always be similar to that shown in Figure 5. However, the same model could be used to explain the cosmic-ray decreases based on the fore shock IMF orientation relative to the shock front during the passage of He-shocks.

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