STUDY AND EFFECT OF MAGNETIC CLOUDS ON THE TRANSIENT MODULATION OF COSMIC-RAY INTENSITY

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Abstract. Data of cosmic-ray intensity from the Calgary Super Neutron Monitor and interplanetary plasma and field data are divided into three groups corresponding to the magnetic clouds preceded by shocks, followed by interaction region and clouds without any such association, observed during the period 1967–1982. A superposed epoch analysis of these data, in addition to the field variance data, have been performed. The results suggest the hypothesis that the Forbush decreases are caused by the scattering of particles in the region of enhanced turbulence, observed during the passage of shocked plasma (i.e., sheath) between the shock front and the magnetic cloud.

1. Introduction

A fundamental problem of cosmic-ray studies has been the identification of the flow configuration(s) and mechanism(s) producing Forbush decreases (Venkatesan and Badruddin, 1990). In general, it is believed that the days characterized by a high intensity of IMF are associated with cosmic-ray intensity decreases and these IMF variations are presumably related to solar disturbances. But these regions of high field intensity may be the blast waves, driven shocks, corotating high-speed streams or simply the extended structures of intense-ordered magnetic field (such as magnetic clouds). The various proposed mechanisms for the Forbush decreases are the reflection at the front of the blast wave (Parker, 1963), the deflection of particles by extended structures of ordered field (Gold, 1960; Sanderson *et al.*, 1990b), gradient B drift in the environment of shocks of rather ordered structure (Barouch and Burlaga, 1975; Sarris, Dodopoulos, and Venkatesan, 1989; Cheng, Sarris, and Dodopoulos, 1990) and the scattering of particles in the turbulent field region between the shock front and magnetic clouds/loops (Nishida, 1982; Chih and Lee, 1986; Badruddin, Yadav, and Yadav, 1986; Zhang and Burlaga, 1988; Webb and Wright, 1990).

Interplanetary magnetic clouds have meso-scale (i.e., average diameter ~ 0.25 AU at 1 AU) plasma and magnetic field structures. They have a large rotation in the direction of the field, enhanced field strength, low plasma temperature and density (compared to the ambient plasma) and a plasma β significantly lower than 1 (Burlaga *et al.*, 1981). They are probably interplanetary manifestations of coronal mass ejection (Burlaga *et al.*, 1982; Wilson and Hildner, 1984) and disappearing filaments (Wilson and Hildner,

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1986). Magnetic clouds are often associated with interplanetary shock waves (Klein and Burlaga, 1982).

With the identification of magnetic clouds in interplanetary space (Burlaga *et al.*, 1981; Klein and Burlaga, 1982; Zhang and Burlaga, 1988), there have been studies to explore their effects on the propagation of cosmic rays. However, the studies have given conflicting results. Badruddin *et al.* (1985, 1986) using the magnetic clouds have identified during the period 1967–1978 and Zhang and Burlaga (1988), using the magnetic clouds observed during the period 1978–1982, have arrived at a similar conclusion that the turbulent sheath, between the upstream shock and the front boundary of magnetic clouds, is the main cause of cosmic-ray variation rather than the magnetic cloud itself. On the other hand, Sanderson *et al.* (1990a, b) have suggested that the magnetic cloud, in fact, is as effective at causing a decrease as the post-shock turbulent region. They have also indicated that a magnetic cloud driving the shock is responsible for a Forbush decrease; the post-shock turbulent region however has not played any significant role in producing the decrease.

Using the same data base of Badruddin *et al.* (1986) and Zhang and Burlaga (1988) in the present analysis we have tried to confirm their results. We have used the hourly data (as has been done by Zhang and Burlaga, 1988) which is expected to provide detailed information on cosmic-ray intensity variations. We have also calculated the variance of the magnetic field vector in the present study. The advantage of the cloud data used here is that we can study the relative effects of shocks and magnetic clouds on the modulation of cosmic-ray intensity.

2. Analysis

The hourly cosmic-ray intensity data from the Calgary Super Neutron Monitor have been used for the superposed epoch analysis. First, in order to increase the number of epochs, we have combined the magnetic clouds identified during the entire epoch 1967–1982 (Klein and Burlaga, 1982; Zhang and Burlaga, 1988). We have found that the methodology adopted by Klein and Burlaga (1982) and Zhang and Burlaga (1988) in identifying the arrival time of the magnetic cloud is far more appropriate than the methodology which has been adopted by Marsden *et al.* (1987) since in their study they have included Bidirectional Solar Proton Events (BDP's) associated with isolated magnetic structures. This, by definition, does not conform with the accepted definition of magnetic clouds. A total of sixty-four clouds have been selected and divided into two categories, namely those associated with shocks (29 cases) and those not associated with shocks (35 cases). Taking the arrival time (hour) of the cloud as the zero-epoch hour, a superposed epoch analysis of Calgary Super Neutron Monitor data has been performed. The cosmic-ray intensity variations are compared with IMF intensity (F), solar wind velocity (V), and variance in the field (σ_F). Furthermore, we have classified the magnetic clouds into three groups: (i) those associated with a shock, (ii) associated with a stream interface, and (iii) associated with a cold magnetic enhancement. The first group of clouds has been preceded by a shock, the second group has had an interaction region behind the cloud and the third group of clouds have just the regions of high field strength. In addition, high-speed streams of long duration have been observed, after the passage of the interaction region in association with interface-associated clouds. Thus, superposed epoch analyses of hourly cosmic-ray intensity, field magnitude and plasma speed, and variance in the field has been performed separately for all the three categories of the clouds.

3. Results and Discussion

Figure 1 has shown the superposed epoch plots of interplanetary plasma and magnetic field parameters and Calgary neutron intensity for magnetic clouds associated and not associated with shocks. It can easily be seen that a large decrease (Forbush-type) is observed in cosmic-ray intensity for events associated with the clouds preceded by shocks. The decrease started about 14 hours before the arrival of the clouds. This 14-hour lead time of the cosmic-ray intensity decrease coincided with the arrival of the shock front at the Earth.

If this cosmic-ray profile of shock-associated clouds is compared with the corresponding profile of F, V, and σ_F, we observe that there is a simultaneous increase in all these parameters when there is a sudden decrease in cosmic-ray intensity. In the case of shock-associated clouds, F and σ_F are both higher than the corresponding values for the case of clouds not associated with shocks, though not much of a difference in speed is seen.

Since both F and σ_F are higher in the case of clouds preceded by shocks (when the decrease in cosmic-ray intensity is much greater) in comparison to the clouds not associated with shocks (when the decrease in cosmic-ray intensity is hardly noticeable), it is difficult to infer the relative importance of F and σ_F in the modulation of cosmic rays, from this figure. It has been observed that the amplitude of the field fluctuations are greater when the solar wind speed is high (Belcher and Davis, 1971; Behannon and Burlaga, 1981). Since the enhancement in the magnetic field is often correlated with the velocity profiles and the fluctuations in the magnetic field, the relative importance of speed, magnetic field strength, and field fluctuations are difficult to establish. Using the superposed epoch analysis, Wada and Suda (1980) have also reported that the plasma velocity, temperature, density, and the magnitude and the variability of the IMF start increasing at the same time the cosmic-ray intensity begins to decrease. Zhu and Wada (1983) have also analyzed the relation between the magnitude of the Forbush decrease and the degree of enhancement of several interplanetary parameters and reported that the magnitude of the Forbush decrease depends on the enhancement of each parameter.

Fortunately, since the field strength in our Figure 2 is the same in all the three cases (i.e., the clouds associated with shocks, associated with stream interface and associated with cold magnetic enhancement), there is a large difference in the amplitude and time-profile of cosmic-ray intensities associated with these three categories of clouds. In the case of a cloud preceded by a shock there is a sharp decrease in intensity. The enhancement of σ_F coincides with this decrease in intensity. The depression in cosmic-

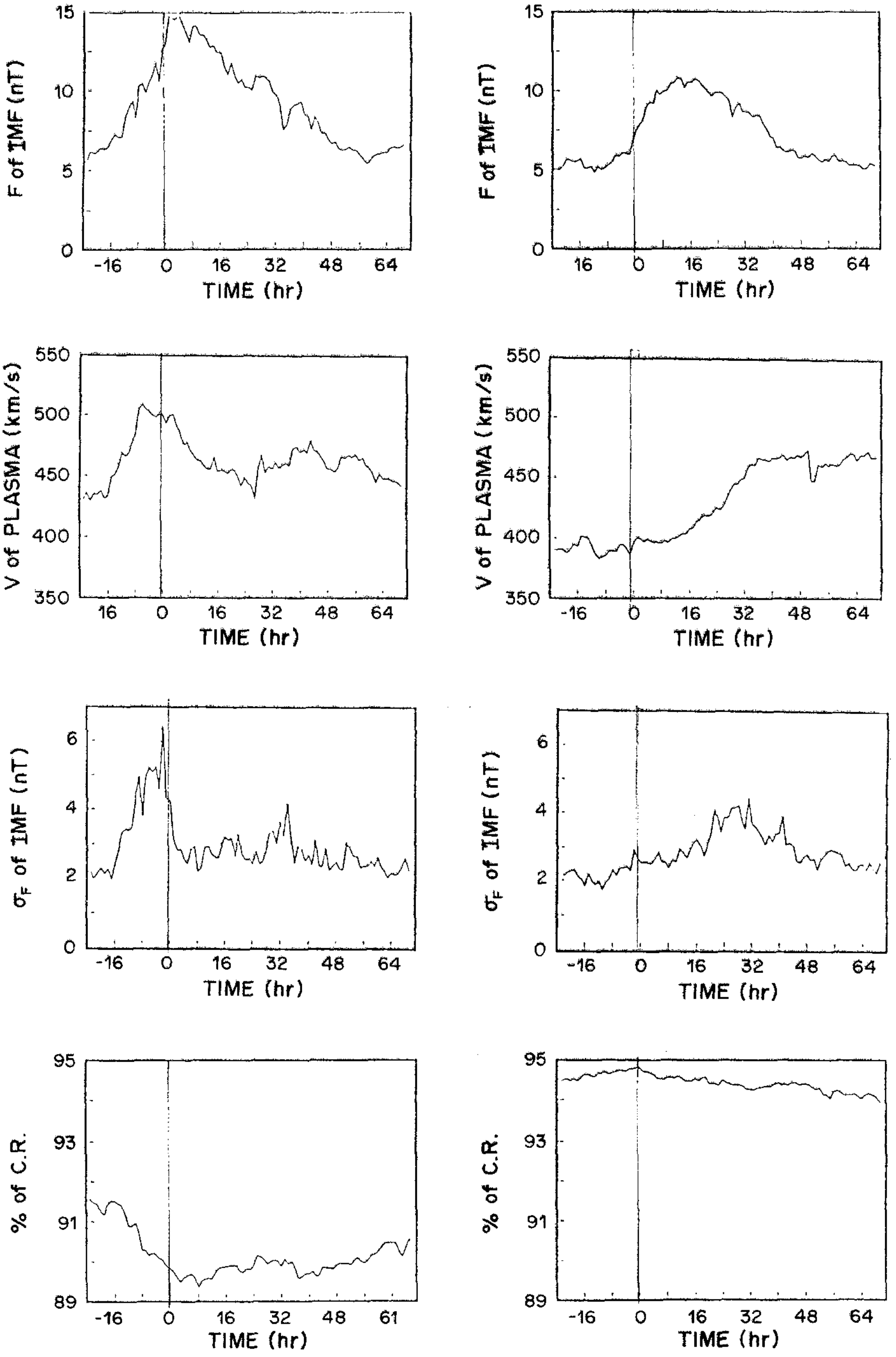

Fig. 1. The superposed epoch plots of the magnetic field strength, F, solar wind plasma speed, V, and the variance in the magnetic field vector, σ_F, together with the Calgary neutron monitor hourly data. The zero-epoch hour is the arrival time of the magnetic cloud. The first column results are for clouds associated with shocks and the second are for clouds not associated with shocks.

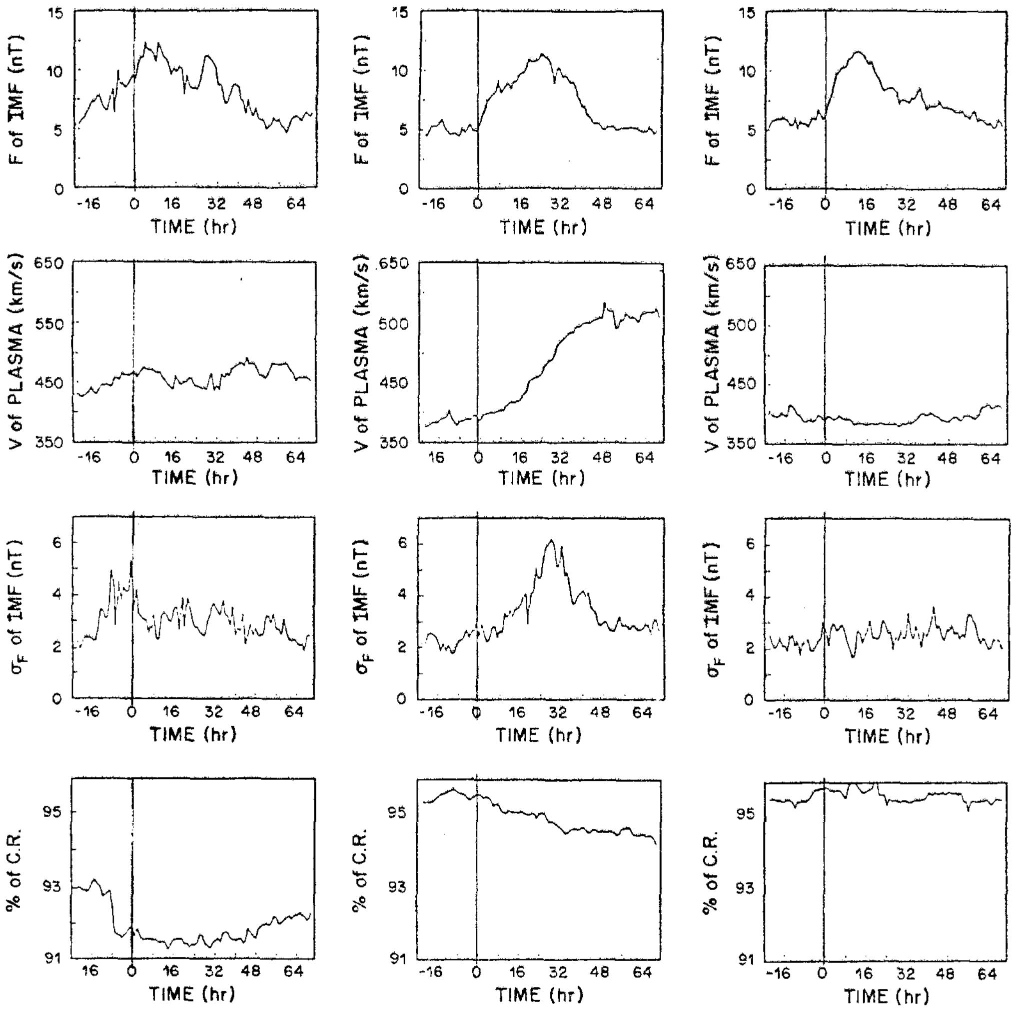

Fig. 2. The superposed epoch plots for clouds associated with shocks (first column), interaction regions (second column), and cold magnetic enhancements (third column).

ray intensity associated with clouds followed by interaction regions is smaller and gradual. The decreases in such cases appear to follow in two steps, one coincides with the arrival of magnetic clouds and the other with the enhancement of σ_F in an interaction region which follows the clouds. This is a result in agreement with those of Morfill, Richter, and Scholar (1979) who reported that the diffusion coefficient is reduced in the corotating interaction regions. Moreover, since the interaction regions are due to the high-speed streams presumably coming from coronal holes, these streams are reported to be less effective in modulating the cosmic rays than the streams associated with transients from the Sun (Iucci *et al.*, 1979; Venkatesan, Shukla, and Agrawal, 1982). In the case of clouds associated with cold magnetic enhancement (of ordered structure) there is no appreciable increase in σ_F and the associated decrease in cosmic-ray intensity, if any, is small.

The observations presented in this paper are consistent with the hypothesis that Forbush decreases are effectively produced by an enhanced magnetic turbulent region between the shock front and the magnetic clouds ejected during a solar flare. These results are in concurrence with the conclusions made by Badruddin *et al.* (1985) Badruddin, Yadav, and Yadav (1986), and Zhang and Burlaga (1988). From a similar analysis, Sanderson *et al.* (1990a, b) have suggested that the magnetic clouds and tangential discontinuity following the shock are also equally effective in producing Forbush decreases. Since the selection criteria adopted by Sanderson *et al.* for determining the arrival time of magnetic clouds are different, the results sometimes lead to different conclusions. However, we would like to emphasize in this paper that our observations clearly demonstrate that the post-shock turbulent region is one of the very effective mechanisms for producing cosmic-ray Forbush decreases. The possibility of other mechanisms such as magnetic clouds and tangential discontinuities causing Forbush decreases cannot be ruled out and needs further investigation.

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