JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, A02101, doi:10.1029/2006JA011780, 2007

Click Here for Full Article

# Effects of interplanetary magnetic clouds, interaction regions, and high-speed streams on the transient modulation of galactic cosmic rays

Y. P. Singh[1] and Badruddin[1]

Received 11 April 2006; revised 12 October 2006; accepted 3 November 2006; published 9 February 2007.

[1] Interplanetary manifestations of coronal mass ejections (CMEs) with specific plasma and field properties, called "interplanetary magnetic clouds," have been observed in the heliosphere since the mid-1960s. Depending on their associated features, a set of observed magnetic clouds identified at 1 AU were grouped in four different classes using data over 4 decades: (1) interplanetary magnetic clouds moving with the ambient solar wind (MC structure), (2) magnetic clouds moving faster than the ambient solar wind and forming a shock/sheath structure of compressed plasma and field ahead of it (SMC structure), (3) magnetic clouds "pushed" by the high-speed streams from behind, forming an interaction region between the two (MIH structure), and (4) shock-associated magnetic clouds followed by high-speed streams (SMH structure). This classification into different groups led us to study the role, effect, and the relative importance of (1) closed field magnetic cloud structure with low field variance, (2) interplanetary shock and magnetically turbulent sheath region, (3) interaction region with large field variance, and (4) the high-speed solar wind stream coming from the open field regions, in modulating the galactic cosmic rays (GCRs). MC structures are responsible for transient decrease with fast recovery. SMC structures are responsible for fast decrease and slow recovery, MIH structures produce depression with slow decrease and slow recovery, and SMH structures are responsible for fast decrease with very slow recovery. Simultaneous variations of GCR intensity, solar plasma velocity, interplanetary magnetic field strength, and its variance led us to study the relative effectiveness of different structures as well as interplanetary plasma/field parameters. Possible role of the magnetic field, its topology, field turbulence, and the high-speed streams in influencing the amplitude and time profile of resulting decreases in GCR intensity have also been discussed.

**Citation:** Singh, Y. P., and Badruddin (2007), Effects of interplanetary magnetic clouds, interaction regions, and high-speed streams on the transient modulation of galactic cosmic rays, *J. Geophys. Res.*, *112*, A02101, doi:10.1029/2006JA011780.

## 1. Introduction

[2] Magnetic clouds were first identified by Burlaga and coworkers [*Burlaga et al.*, 1981; *Klein and Burlaga*, 1982] in the interplanetary space near 1 AU. These structures are the interplanetary manifestations of coronal mass ejections [*Burlaga et al.*, 1982; *Wilson and Hildner*, 1984; *Gopalswamy et al.*, 2001; *Manoharan et al.*, 2004; *Gopalswamy*, 2004]. A magnetic cloud is a solar ejection in which (1) the magnetic field strength is enhanced with respect to ambient value, (2) the magnetic field vector undergoes a large rotation, and (3) the proton temperature is lower than average. The magnetic field is usually southward during passage of at least one part of magnetic cloud and northward during the passage of other part. If the leading part is southward, we refer to it as SN cloud. It is also possible that the leading part of the magnetic cloud is northward and the trailing part is southward, such cloud is termed as NS cloud [see also *Zhang at el.*, 2004]. A magnetic cloud may follow a shock/sheath region when moving faster than the ambient solar wind. It may precede an interaction region and high-speed solar wind stream when a slow-moving magnetic cloud is "pushed" by the high-speed stream. It is also possible that a magnetic cloud is moving in the ambient solar wind without any additional (associated) structure, such as shock/sheath/interaction region/high-speed stream. More details about sources, properties, modeling of interplanetary magnetic clouds can be found in the work of *Burlaga* [1991], *Bothmer and Schwenn* [1997], *Lepping and Berdichevsky* [2000], *Hidalgo* [2003], and *Zhang et al.* [2004].

[3] Magnetic clouds and associated structures at 1 AU are found to be associated with the Forbush decrease in cosmic ray intensity [*Badruddin et al.*, 1985, 1986, 1991; *Zhang and Burlaga*, 1988; *Iucci et al.*, 1989; *Sanderson*

[1]Department of Physics, Aligarh Muslim University, Aligarh, India.

Copyright 2007 by the American Geophysical Union.
0148-0227/07/2006JA011780$09.00

*et al.*, 1991; *Lepping et al.*, 1991; *Lockwood et al.*, 1991; *Venkatesan and Badruddin*, 1990; *Ananth and Venkatesan*, 1993; *Cane*, 1993; *Bavassano et al.*, 1994; *Badruddin*, 2002a; *Ifedili*, 2004]. However, conclusions are conflicting as regards the phenomena responsible for the decrease. Some attribute it to the turbulent magnetic fields in the sheath region [e.g., *Badruddin et al.*, 1985, 1986, 1991; *Zhang and Burlaga*, 1988; *Lockwood et al.*, 1991; *Lepping et al.*, 1991; *Bavassano et al.*, 1994; *Badruddin*, 2002b]. On the other hand, *Sanderson et al.* [1990, 1991] observed that the turbulence in the postshock region is not always sufficient to produce a Forbush decrease. *Lockwood et al.* [1991] concluded that the role of the magnetic clouds in producing Forbush decreases are relatively unimportant, while *Cane* [1993] reached at the conclusion that the magnetic clouds do play a role in the depression of cosmic rays. *Cane* [1993] showed that the field strength is directly associated with a decreased amplitude [see also *Duggal et al.*, 1981] irrespective of the magnetic field being magnetically quiet or turbulent, provided the field strength exceeds certain value. On the other hand, *Badruddin et al.* [1986, 1991] concluded that magnetic field strength or the topology alone is not responsible for Forbush decreases but turbulence is the most likely additional effect.

[4] As regards the mechanism mainly responsible for Forbush decreases, earlier studies suggested scattering in turbulent magnetic fields [*Badruddin et al.*, 1986; *Zhang and Burlaga*, 1988; *Lockwood et al.*, 1991], drifts in smooth and high field region [*Barouch and Burlaga*, 1975; *Sanderson et al.*, 1990; *Sarris et al.*, 1989; *Cheng et al.*, 1990], particle scattering by the magnetically turbulent sheath and the high magnetic pressure in magnetic clouds [*Ifedili*, 2004]. Thus the whole area appears to be complex and needs further study.

[5] Magnetic cloud structures are usually very large magnetic flux ropes (~0.25 AU diameter at 1 AU) possessing intense and quiet magnetic fields. Inside the magnetic cloud, plasma $\beta$ and proton temperature is low. Most of the identified magnetic clouds discussed in literature have bipolar Bz (NS and SN); however, unipolar (S and N) magnetic clouds have also been identified [e.g., *Zhang et al.*, 2004]. We could not isolate sufficient number of unipolar Bz clouds; their division in subgroups would further reduce their number in a particular group. Further, as far as CR effectiveness of magnetic cloud is concerned, we were more interested in clouds with turning field during their passage. Owing to these limitations, we did not utilize unipolar magnetic clouds in this work which is based on the superposed epoch analysis.

[6] A shock front, and a sheath region of intense and compressed magnetic field, may form in the interplanetary space ahead of a fast moving magnetic cloud. Thus passage of such structures provide unique opportunity to study the effects of (1) abrupt changes in solar wind plasma and field parameters (at shock front), (2) intense and turbulent magnetic fields (during the passage of sheath), and (3) intense and quiet magnetic fields (during the passage of magnetic clouds), one after the other. Magnetic clouds followed by interaction regions enable us to study the effects of plasma compression and magnetic field fluctuations (in interaction regions) and high-speed solar wind streams (from open field regions of coronal holes), in addition to that of intense and closed field of flux (of magnetic clouds). Magnetic clouds moving approximately with the ambient solar wind, without any additional associated structure, are exclusively suitable for study of the effects of magnetic field strength and its topology on the cosmic ray density. Thus interplanetary magnetic clouds, with a number of distinct features provide a special and unique opportunity to study the role, and relative importance of, various structures with distinct plasma and field properties. Further, such studies are useful for identifying the physical processes, responsible for Forbush decreases and other transient variations in cosmic ray intensity, e.g., particle reflection (at shock front), deflection of particles (by flux rope topology of magnetic clouds), diffusion/scattering of particles (by intense and turbulent fields in sheath and interaction region), convection of particles (by high-speed streams), etc.

[7] A set of 149 well-observed NS and SN magnetic clouds with good data coverage, identified in interplanetary plasma and field data at 1 AU, have been selected on the basis of catalogues found in literature within the period 1967–2003 [e.g., *Klein and Burlaga*, 1982; *Wilson and Hildner*, 1984; *Zhang and Burlaga*, 1988; *Lepping et al.*, 1990; *Gopalswamy et al.*, 2001; *Zhang et al.*, 2004; *Gulisano et al.*, 2005; *Nieves-Chinchilla et al.*, 2005]. These clouds were divided into different groups on the basis of their association with other structures formed in the interplanetary space. Superposed epoch analysis of hourly cosmic ray neutron monitor data, and interplanetary plasma and field data is then performed, separately, with respect to each category of magnetic clouds. In the superposed epoch analyses performed, the reference time (zero epoch) is systematically changed, in order to study (decipher) the effectiveness and relative importance of various structures (shock/sheath, magnetic cloud, interaction region, and high-speed stream) of distinct plasma and field properties.

## 2. Results and Discussion

### 2.1. Magnetic Clouds Associated/Not Associated With Shocks

[8] In order to distinguish between the CR effectiveness of shock-associated magnetic clouds and those without a shock, the set of the interplanetary magnetic clouds (MCs) were divided into two groups depending on their association with a shock or not. Taking start time of the magnetic clouds as epoch (zero hour), superposed analysis of hourly cosmic ray data I (%), solar wind plasma and field data (solar wind velocity V (km/s), IMF strength B (nT), its variance $\sigma_B$ (nT), and north-south component Bz (nT)) has been performed with respect to start time of two groups of magnetic clouds. The superposed variations of cosmic ray intensity and interplanetary plasma and field parameters during, before, and after the passage of (1) shock-associated MCs and (2) MCs not associated with shocks are shown, respectively, in the left and the right panel of Figure 1. From Figure 1, it appears that the shock-associated MCs produce Forbush-type decrease (a fast decrease followed by a slow recovery), as shown at a low cutoff rigidity Oulu neutron monitor (Rc = 0.61 GV) and a higher cutoff rigidity (Rc = 2.97 GV) neutron monitor of Climax. It is also seen from Figure 1 that the decrease in CR intensity starts not at the arrival of the magnetic clouds (zero hour) but a few hours

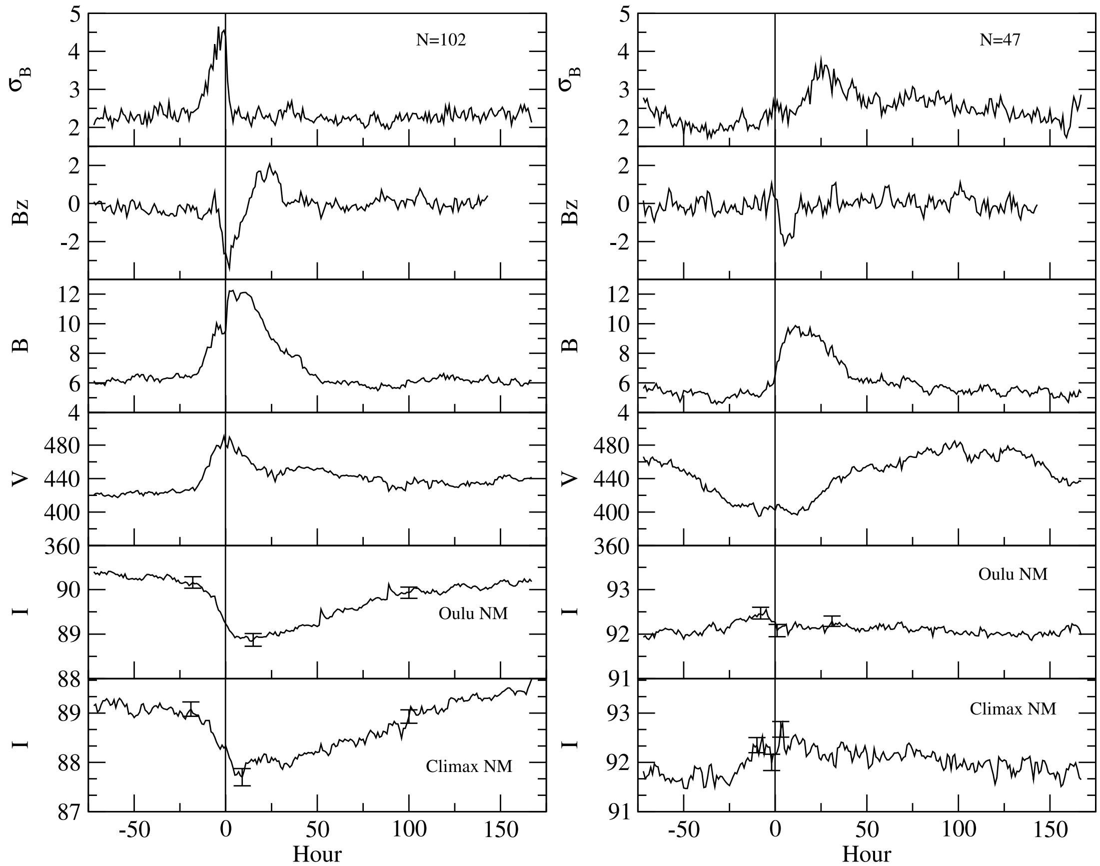


**Figure 1.** Superposed epoch analysis results showing variations in cosmic ray intensity (I) observed at Oulu and Climax neutron monitor, solar wind velocity (V), interplanetary magnetic field (B), north-south component (Bz) and its variance ($\sigma_B$). Epoch (zero hour) corresponds to observed start (arrival) time of (left) the shock-associated interplanetary magnetic clouds and (right) not associated with shock; it includes all MCs, i.e., north-south (NS) as well as south-north turning (SN). The standard error of mean in cosmic ray data is plotted at three points (1) before the start of decrease, (2) during the minimum, and (3) at a time of recovery.

earlier. The onset of intensity decrease appears to coincide with the enhancements in interplanetary plasma and field parameters V, B, and $\sigma_B$. On the other hand, as seen in right panel of Figure 1, decrease due to magnetic clouds not associated with shocks is very small; the effects more clearly seen at lower energies. In this case, V and $\sigma_B$ are low during, and before, the passage of magnetic clouds; however, B is enhanced during the magnetic cloud. Continued depression in intensity seen in this figure, even after the passage of MC is probably due to formation of interaction region (as inferred from the enhanced $\sigma_B$) and presence of high-speed stream (enhanced V) after the passage of magnetic clouds.

### 2.2. Magnetic Clouds With NS/SN Field Orientation

[9] As shown in Figure 1, there is significant difference in CR effectiveness of shock-associated MCs and MCs not associated with shocks. However, in a magnetic cloud the field vector may rotate either from northward-to-southward (NS-MCs) or from southward-to-northward (SN-MCs). To see if the change in field rotation within the magnetic clouds has any effect on the transient modulation of cosmic rays, and to distinguish between the CR-effectiveness of NS and SN-MCs, if any, we have divided all the shock-associated MCs into two groups, namely (1) shock-associated NS-MCs and (2) shock-associated SN-MCs. Hourly cosmic ray and interplanetary plasma/field data were then subjected to superposed epoch analysis with respect to start time (hour) of NS and SN magnetic clouds, and the results are shown in Figure 2. It is seen from Figure 2 that the intensity starts decreasing before the arrival of magnetic clouds. However, there is near-simultaneous increase in the interplanetary parameters V, B, and $\sigma_B$, with the start of the intensity decrease in cosmic rays. In both the cases, there are fast decreases followed by slow recovery. However, the decrease amplitude as well as the recovery time is different in two cases. However, whether this difference in the amplitude of decrease in two cases is due to magnetic field topology (NS/SN) or due to the difference in changes observed in various interplanetary parameters (V, B, Bz and $\sigma_B$) could not be distinguished at this stage of analysis. Also, whether the difference in recovery time (and hence

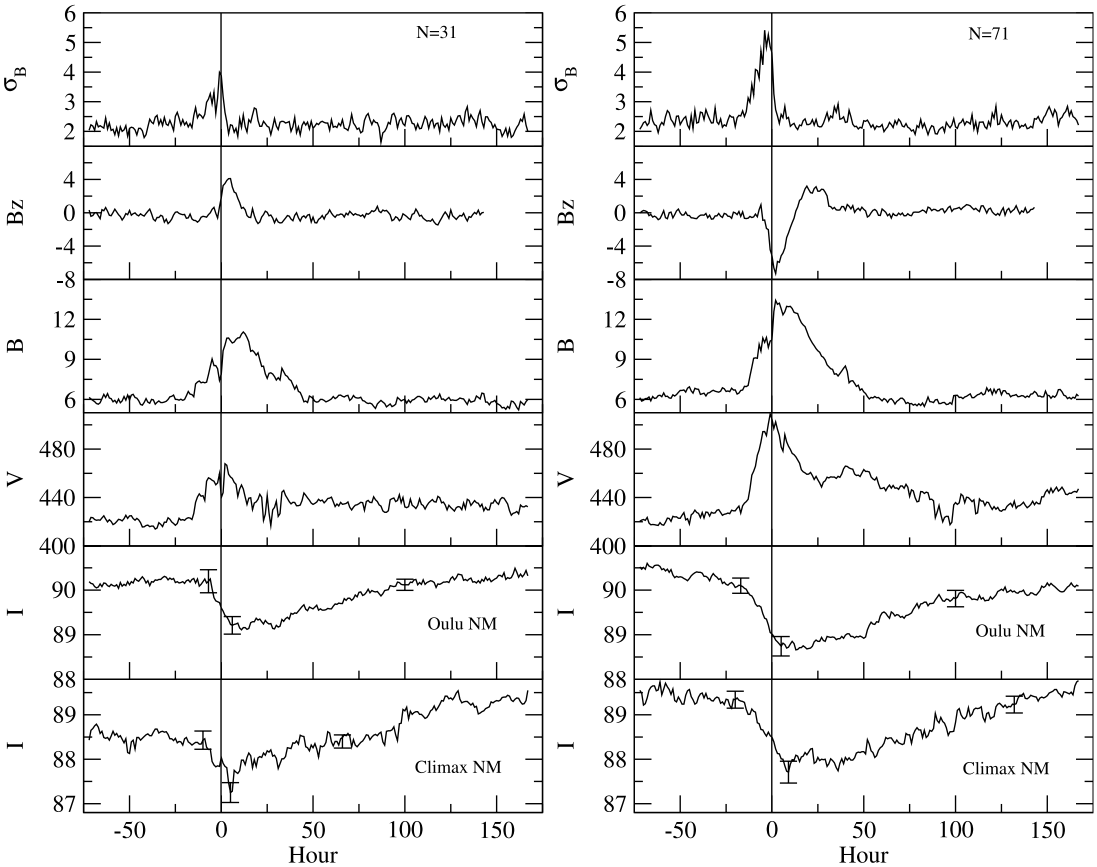


**Figure 2.** Superposed epoch analysis results showing variations in cosmic ray intensity interplanetary plasma/field parameters. Epoch (zero hour) corresponds to observed start (arrival) time of (left) north-south (NS) turning magnetic clouds and (right) south-north (SN) magnetic clouds associated with shock.

recovery rate) is due to difference in high-speed streams following two types of MCs or due to magnetic field topology (NS/SN) within the magnetic clouds is not clear, although the enhancements in interplanetary plasma/field parameters (V, B, Bz, and $\sigma_B$) are larger during shock-associated SN-MCs than shock-associated NS-MCs. Moreover, which one (or more than one) parameter(s) out of V, B, Bz, and $\sigma_B$ is (are) mainly responsible for larger amplitude of decreases due to shock-associated SN-MCs is not known. Further, though it is clear from Figure 2 that the decrease starts before the arrival of magnetic clouds, it is not possible to clearly say, from Figure 2, whether the decrease starts at the arrival of shock front or later during the passage of sheath regions, formed between the shock front and the magnetic cloud.

[10] In Figure 3 we have shown the superposed epoch analysis results of neutron monitor and interplanetary plasma/field data with respect to start time of NS- and SN-MCs not associated with shocks. As seen from this figure, a small depressions in cosmic ray intensity results both due to NS (left panel) and SN (right panel) magnetic clouds. The effect is more clearly seen at lower energies (Oulu NM) than at higher energies (Climax NM). It is also seen from Figure 3 that the intensity remains depressed for several tens of hours even after the passage of MCs, probably due to the formation of interaction regions and presence of high-speed streams following magnetic clouds.

[11] A comparison of Figures 2 and 3 shows that magnetically quiet high field structures of MCs are much less effective in transient modulation of cosmic ray intensity as compared to magnetically turbulent high field region of shock/sheath. These results concur with those of *Badruddin et al.* [1985, 1986, 1991], *Zhang and Burlaga* [1988], *Lockwood et al.* [1991], and *Lepping et al.* [1991] obtained with much smaller data sets. Further, both the interaction region (formed between a magnetic cloud and the following high-speed stream) and the stream itself are likely to keep the CR intensity depressed during their passage.

### 2.3. Magnetic Clouds Followed/Not Followed By High-Speed Streams

[12] From the results of the analyses discussed and presented in Figures 1, 2, and 3, we have seen the effects of shock-associated, NS turning, and SN turning magnetic clouds on the transient modulation of cosmic rays. However, magnetic clouds, whether shock-associated or not, may or may not be followed by the high-speed streams and/or interaction regions and examples of each type have been given [*Klein and Burlaga*, 1982; see also *Badruddin*, 1998]. To study the role of the interaction region and the

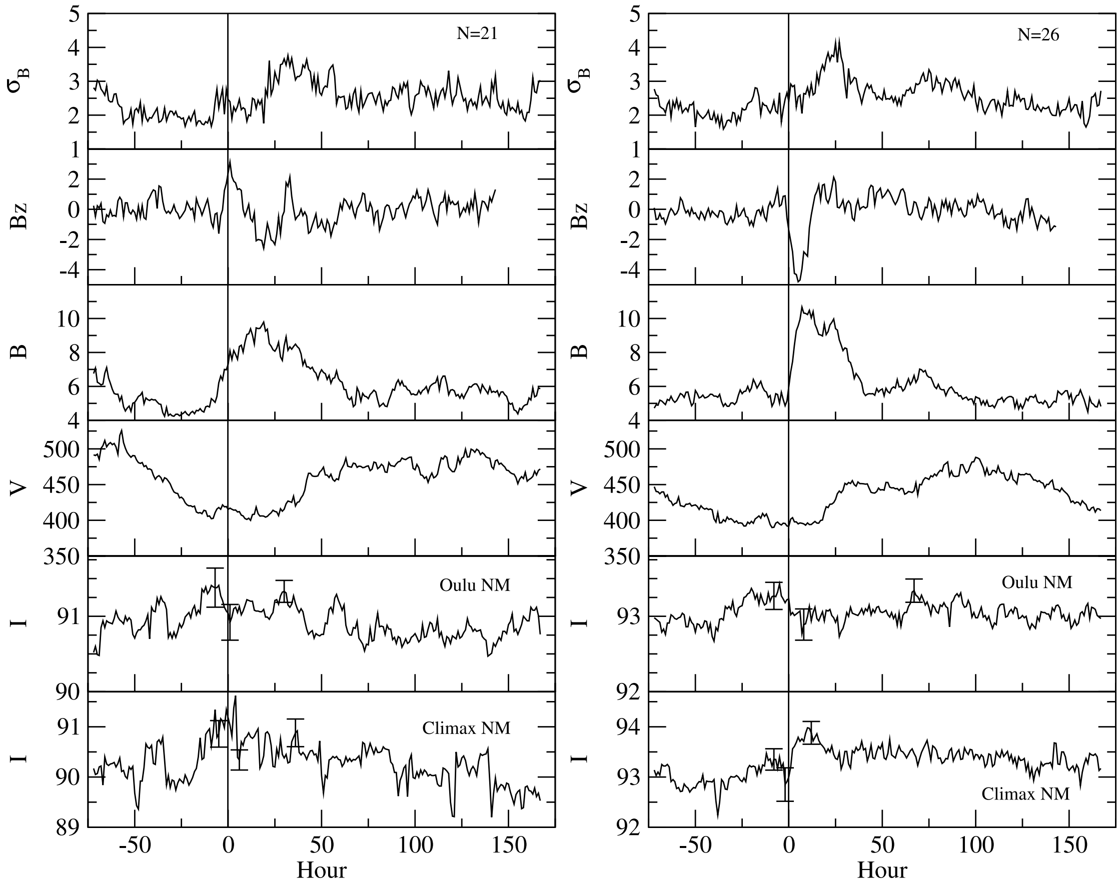


**Figure 3.** Results of the superposed epoch analysis showing variations in cosmic ray intensity, interplanetary plasma/field parameters; epoch in the analysis corresponds to start (arrival) time of (left) NS-MCs and (right) SN-MCs not associated with shock.

high-speed streams (HSS) in influencing the amplitude and the recovery characteristics of resulting decreases in cosmic ray intensity, we have divided the NS/SN magnetic clouds on the basis whether they are followed by HSS or not.

[13] Figure 4 is the superposed epoch plot of cosmic ray intensity, solar wind plasma and field parameters (V, B, Bz, and $\sigma_B$) with respect to shock-associated NS-MC, not followed by HSS (left panel) and those followed by HSS (right panel); zero epoch corresponds to start time of the magnetic cloud. It may be mentioned here that shock-associated MCs followed by HSS have four regions of distinct plasma and field properties, one after the other, namely (1) the shock/sheath region (enhanced and compressed field region of ambient solar wind with large field variance), (2) the magnetic cloud (enhanced, magnetically closed, and quiet field region with low variance), (3) the interaction region (compressed thin region of enhanced field variance), and (4) the HSS (an extended region with high-speed solar wind from open field region of coronal holes). On the other hand, shock-associated MCs without HSS have only two regions of distinct plasma/field properties, i.e., shock/sheath and magnetic cloud. The intensity time profile due to shock associated NS-MCs, whether followed by HSS or not, shows that the Forbush-type decrease proceeds in two steps; the first step decrease of larger amplitude takes place before and second step at the start time of magnetic clouds. Moreover, intensity remains depressed for few hours before recovery starts slowly. However, one major difference that is apparent in two panels of Figure 4 is that the cosmic ray intensity appears to recover at a faster rate in case of MCs not followed by HSS. In other words, HSS might be able to slow down the process of filling the lower-density space created by the passing interplanetary disturbance. As shown in Figure 5, this difference in recovery rate is also observed in case of shock associated SN-MCs, i.e., the cosmic ray density appears to recover at a faster rate if it is not followed by HSS, in comparison to the case when HSS follow the shock associated SN-MCs. It is also interesting to note from Figure 5 that the enhancements in field strength (B), its variance ($\sigma_B$) are nearly same in both the panels.

[14] Next, we divided the combined data set of SN and NS magnetic cloud into two groups (1) those not followed by HSS and (2) those followed by HSS, with the aim of studying (and distinguishing, whenever possible) the effects of magnetic clouds, interaction regions, and HSS on the amplitude and the time profile of cosmic ray intensity changes. Figure 6 shows the average plot obtained by the superposed epoch analysis of neutron monitor data and solar wind plasma/field data with respect to magnetic clouds; zero hour corresponds to the start time of magnetic clouds.

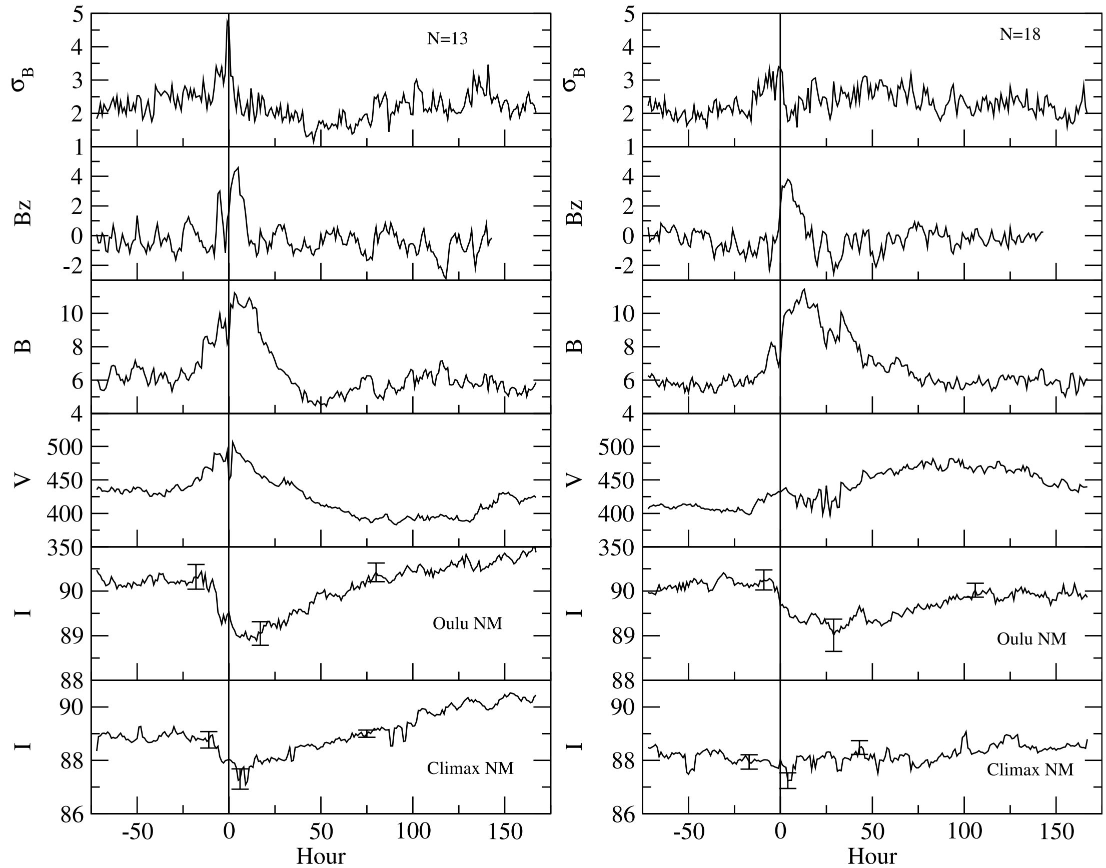


**Figure 4.** Superposed epoch analysis results showing variations in cosmic ray intensity (I) observed at Oulu and Climax neutron monitor, solar wind velocity (V), interplanetary magnetic field (B), north-south component (Bz) and its variance ($\sigma_B$). Epoch (zero hour) corresponds to start (arrival) time of the shock-associated NS-MCs (left) not followed by high-speed plasma stream (HSS) and (right) followed by HSS.

Magnetic clouds, not followed by HSS, are able to produce only a small decrease; intensity recovers quickly after a few hours of depressed cosmic ray density (left panel). This effect of magnetic cloud on cosmic ray intensity modulation is more clearly seen in lower-energy (Oulu NM) particles, ascribed to slow-moving closed structure of magnetic cloud. On the other hand, intensity depression due to magnetic clouds followed by HSS, as seen in right panel of Figure 6, although not large as in case of shock-associated MCs, proceeds in two steps, first step at the arrival of the magnetic cloud and second step at the time of interaction region, followed by a prolonged depression probably due to the influence of high-speed streams. Again, the effects are more clearly seen at lower energies (see the intensity time profile of Oulu and Climax neutron monitors for comparison).

[15] The analyses discussed so far were performed with respect to start time of magnetic clouds. These analyses were particularly useful in studying the role of closed field regions of low variance and enhanced field magnitude in the transient modulation of cosmic rays. In addition, the effects of interplanetary shock/sheath, interaction regions and HSS were also broadly visible to some extent. However, the effects of interaction regions and/or high-speed streams following the magnetic clouds can be better understood if we analyze the data with respect to end time of magnetic clouds.

[16] In Figure 7 we have shown the results of superposed epoch analysis of cosmic ray and solar wind data by taking end time of shock-associated NS-MCs as zero time (hour). Left panel of this figure shows the cosmic ray intensity, interplanetary plasma, and field variations before and after the passage of shock-associated NS-MCs that are not followed by HSS, whereas right panel shows the results of similar analysis performed by taking zero epoch as the end time of shock-associated NS-MCs followed by HSS. As shown in right panel, although the intensity decrease started earlier, an additional step in intensity decrease is evident at zero hour, coincident with the sudden jump in $\sigma_B$ followed by large enhancement in solar wind speed. The intensity remains depressed till, at least, speed reaches its maximum level, magnetic field remains enhanced and fluctuating. Afterward, a slow recovery of intensity follows. On the other hand, left panel shows the intensity time profile due to shock associated NS-MCs not followed by HSS, the recovery in this case starts just after the passage of high field regions of magnetic clouds. Another observable difference in intensity time profiles due to shock-associated NS-MCs (1) not followed and (2) followed by HSS is that intensity

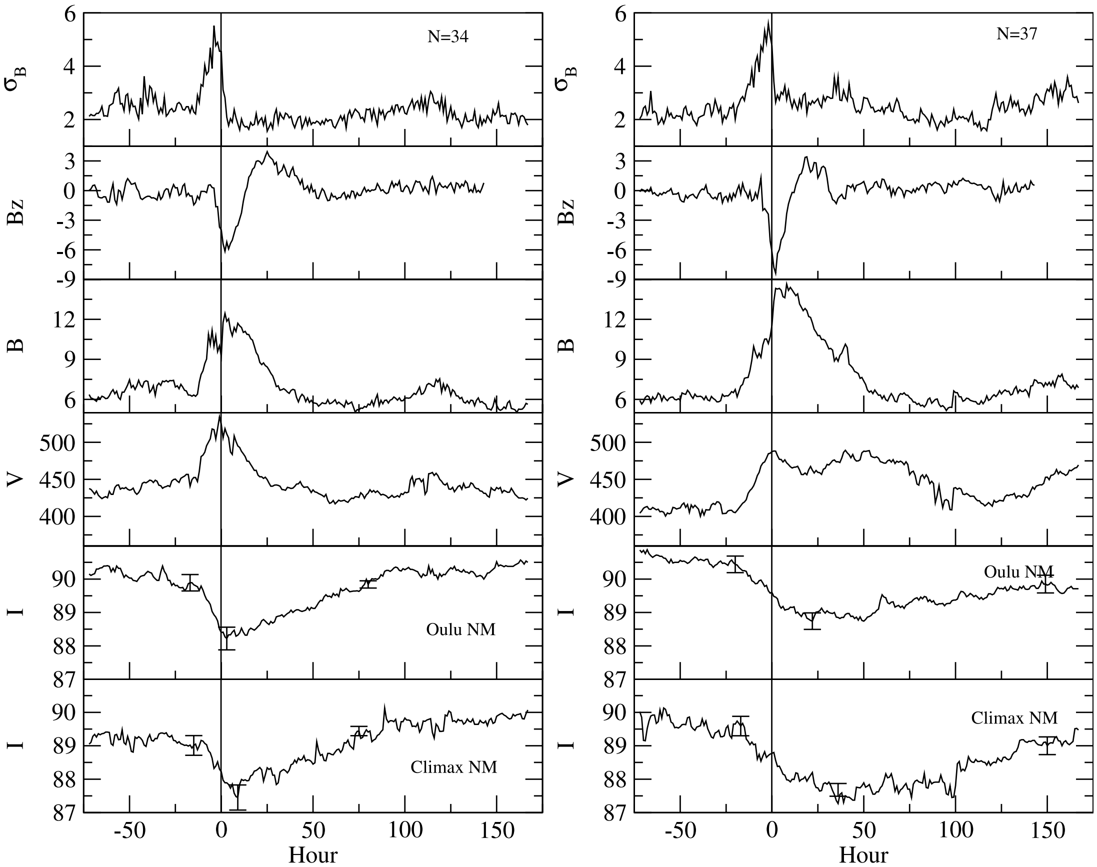


**Figure 5.** Results of superposed epoch analysis showing variations in I, V, B, Bz and $\sigma_B$ with respect to shock-associated SN-MCs (left) not followed by HSS and (right) followed by HSS; epoch (zero hour) corresponds to the arrival time of MCs.

appears to recover at a faster rate in the absence of the high-speed stream.

[17] Plots in Figure 8 due to shock associated SN-MCs without HSS (left panel), and followed by HSS (right panel), show results essentially similar to that in Figure 7. That is, there is an intensity decrease starting before zero hour, an additional step in decrease at zero hour (end time of magnetic cloud), prolonged intensity depression during increasing solar wind speed, and then the recovery takes place slowly. Further, similar to the case of NS clouds, intensity after the passage of shock-associated SN-MCs recovers at a faster rate when the structure is not followed by HSS.

[18] Even though separation of shock-associated NS-MCs, each into two groups on the basis of absence/presence of HSS following MCs, led us to observe certain effects that can be attributed to magnetic clouds and interaction regions/HSS, nevertheless, the observed time profile is substantially influenced by the presence of shock/sheath region ahead of MCs. Therefore it is expected that the effects of the interaction regions, HSS, and/or magnetic clouds will be observable in a better and distinguishable manner if cosmic ray, solar wind plasma, and field data are analyzed with respect to those magnetic clouds which are not preceded by any shock/sheath region. Figure 9 shows the effects of such MCs. In the left panel of this figure, we have shown the superposed epoch analysis results of cosmic ray intensity, interplanetary plasma, and field parameters during, before, and after the passage of the magnetic clouds moving with the ambient solar wind without any additional structure preceding or following them; zero hour corresponds to end time of magnetic clouds. We observe small depression in intensity before zero hour due to magnetically quiet and closed field region of the magnetic cloud followed by fast recovery after zero hour (after passage of MCs), if no HSS follows them (left panel). As shown in the right panel, the intensity depression due to MCs followed by HSS, although small, proceeds in two steps, one due to magnetic clouds and other (at zero hour) due to interaction region and HSS. The time profile of intensity depression in the right panel is different from that shown in left panel; intensity decreases in two steps, followed by slower recovery in case of magnetic clouds followed by HSS.

[19] We have shown that the magnetic clouds preceded by shock/sheath region can produce Forbush-type decreases, that the decrease starts before the arrival of magnetic clouds, and that the recovery time and recovery rate may be influenced by the presence/absence of HSS following magnetic clouds. However, we have yet to see whether the onset of the decrease coincides with the shock

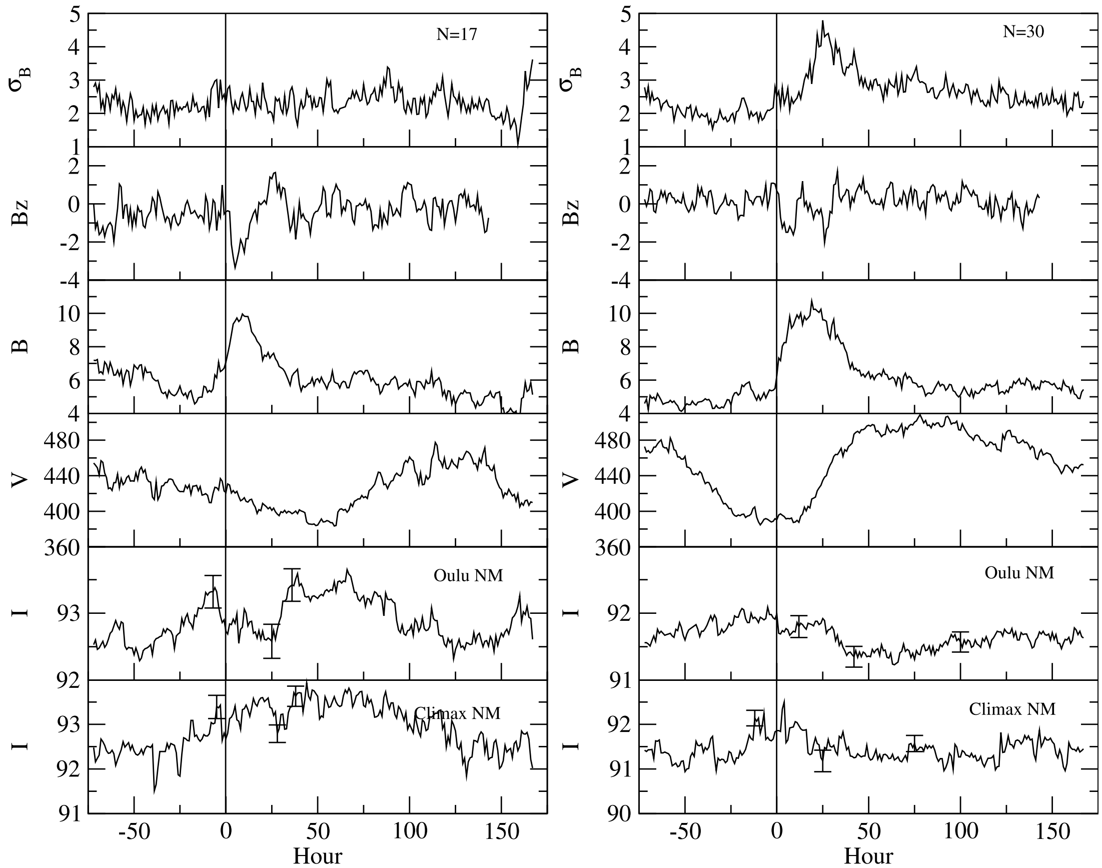


**Figure 6.** Results of variations in cosmic ray and interplanetary parameters with respect to MCs not-associated with shock; epoch corresponds to start (arrival) time of magnetic clouds (left) not followed by HSS and (right) magnetic clouds followed by HSS.

front or the decrease starts sometime later during the passage of magnetically turbulent sheath regions. Moreover, we may obtain more details about the decrease and recovery characteristic of Forbush decreases if the exact cause of onset is known.

[20] Thus in order to gain more insight about the transient modulation of cosmic rays due to shock associated NS/SN-MCs, followed/not followed by HSS, we have analyzed the cosmic ray and solar wind plasma/field data with respect to shock arrival time. Figure 10 shows superposed plots of neutron monitor and solar wind plasma/field data with respect to shock-associated NS-MCs not followed by HSS (left panel) and those followed by HSS (right panel). Intensity-time profiles in this figure show some interesting features. Similar features and differences in superposed epoch plots with respect to shock-associated SN-MCs not followed by HSS (left panel), and those followed by HSS (right panel) are also seen in Figure 11. We can see from the two figures that Forbush-type decrease in all four cases starts at the arrival of shock front, that the intensity decreases at fast rate during the passage of sheath region simultaneous with sudden jump in interplanetary parameters, and that the intensity recovers slowly with time. However, the recovery rate appears to be influenced by the presence of HSS as the recovery is slower in the presence of HSS just after the passage of shock-associated MCs. A combined plot of SN and NS-MCs without any distinction in the field rotation inside the clouds (Figure 12) shows similar results. A comparison of amplitude of intensity plasma/field parameters during the passage of different structures is given in Table 1.

[21] We have calculated the decrease time and rate during the main phase, and the recovery time and rate during the recovery phase of decreases observed in association with different interplanetary structures (see Table 2), namely shock-associated NS-MCs followed by HSS, shock-associated SN-MCs followed by HSS, shock-associated NS-MCs not followed by HSS, shock-associated SN-MCs not followed by HSS, combined shock-associated MCs (SN and NS) followed by HSS, and shock-associated MCs (SN + NS) not followed by HSS. The differences discussed qualitatively can be visualized quantitatively in Tables 1 and 2.

### 2.4. Magnetic Clouds in Positive/Negative Polarity of the Heliosphere

[22] According to drift model of Forbush decreases [*Kadokura and Nishida*, 1986; *Le Roux and Potgeiter*, 1991], the recovery rate should be different during two polarity states of the heliosphere, A > 0 (when the IMF points away from the northern solar pole above the heliospheric current sheet) and A < 0 (when the IMF points

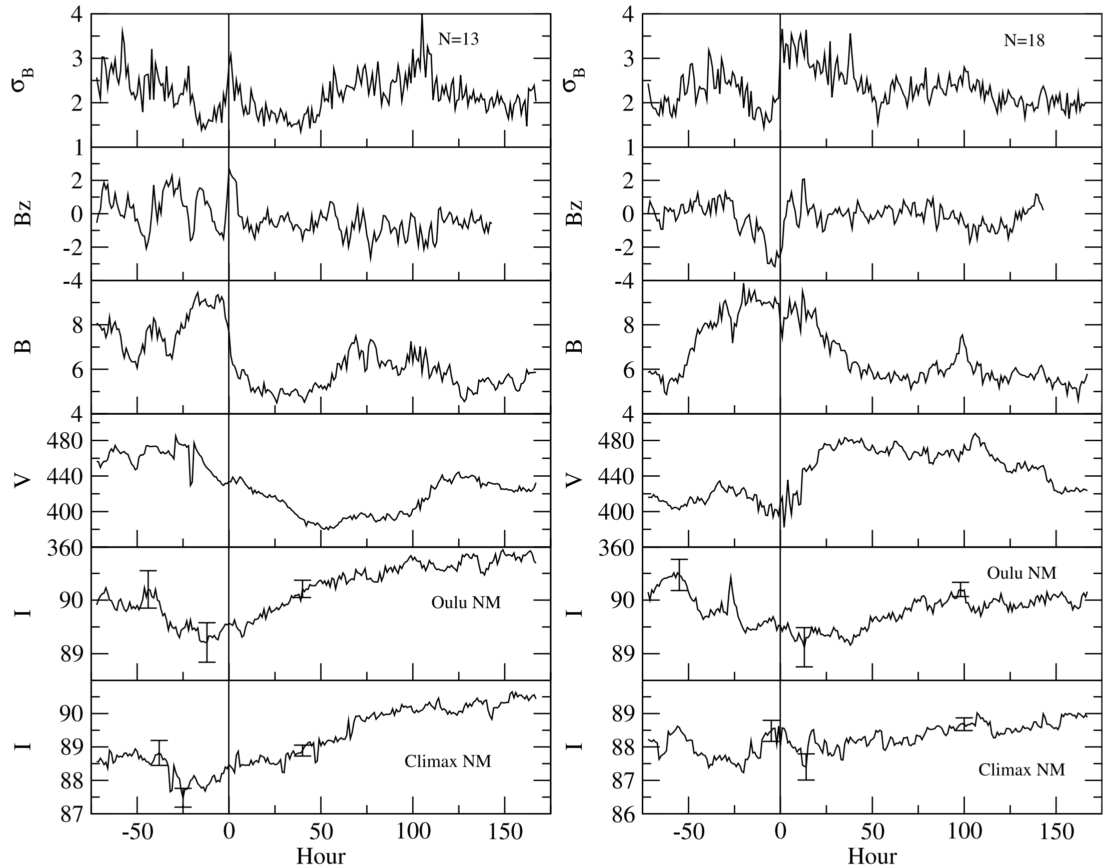


**Figure 7.** Superposed epoch analysis results showing variations in cosmic ray intensity, solar wind velocity, interplanetary magnetic field, north-south component, and its variance; zero hour corresponds to end time (passage of rear part) of shock-associated NS-MCs (left) not followed by HSS and (right) followed by HSS.

toward the northern pole of the Sun above the heliospheric current sheet). In order to see the polarity dependent effect in recovery rate of Forbush-type decreases, we have been somewhat selective; the large duration cosmic ray storms apparently produced by multiple transient disturbances, one after the other, those Forbush-type decreases having superimposed ground level enhancements (GLEs) and those with data gaps have been rejected from the data set. Inclusion of such events might influence the recovery characteristics and, consequently, real effects may not be distinguishable. We have divided the shock-associated magnetic clouds that are not followed by HSS, and producing Forbush-type decreases, into two groups; those observed during the periods when polarity states of the IMF is $A > 0$ (e.g., 1970s, 1990s) and $A < 0$ (e.g., 1960s, 1980s). Superposed epoch analysis of data is then performed with respect to shock arrival time of interplanetary structures in $A < 0$ and $A > 0$ (Figure 13). We observe that in this case, recovery rate is somewhat faster in $A > 0$ than $A < 0$, although recovery continues till about 120 hours in both the periods. A comparison with solar wind parameters show near exponential decay in solar wind velocity in both cases; decay rate appears to be almost equal (or even slightly higher in $A < 0$). We have also divided shock-associated magnetic clouds that follow HSS into two groups according to their happening in $A > 0$ or $A < 0$ periods. A superposed analysis of cosmic ray and solar wind data, with respect to arrival (start) time of shocks in $A < 0$ and $A > 0$ polarity epoch (Figure 14) shows a faster recovery in $A > 0$ epoch, consistent with the expectation of drift models. Characteristic recovery time ($\tau$) obtained from an exponential fit to the data during recovery in the equation

$$I = I_0 - \beta \exp(-t/\tau)$$

concurs with that result [see also *Singh and Badruddin*, 2006]. It may be noted that the solar wind velocity remains enhanced nearly at the same level in both the periods for about 100 hours after initial jump at zero hour. There is also a noticeable difference in the recovery rate of Forbush-type decreases in ($A < 0$ and $A > 0$) epoch, due to shock-associated MCs with and without HSS; recovery rate is higher when shock-associated MCs are not followed by HSS both in $A > 0$ and $A < 0$ (see Table 3). From Figures 13 and 14, we conclude that presence/absence of HSS during recovery phase of Forbush decrease influences the recovery rate. It is therefore suggested that in order to study the polarity dependent effects in cosmic ray intensity recovery

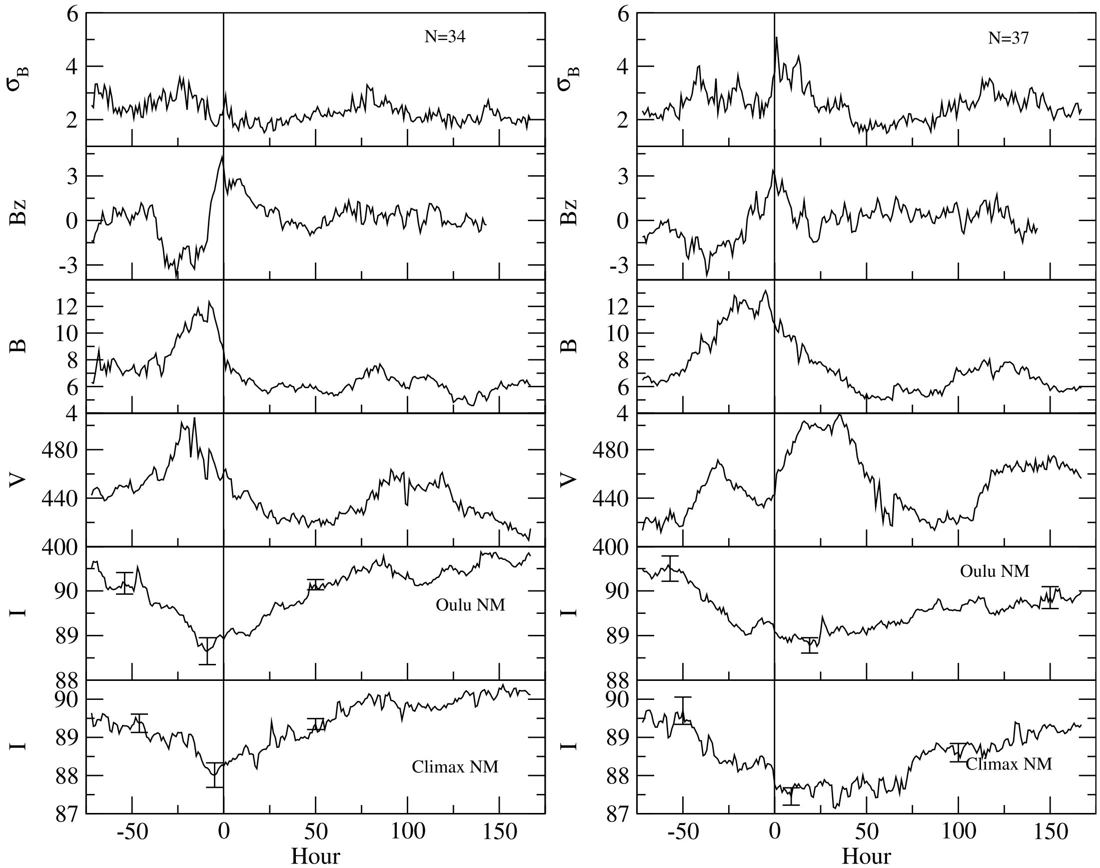


**Figure 8.** Superposed epoch analysis results showing variations in I, V, B, Bz and $\sigma_B$, zero hour corresponds to end time (passage of rear part) of shock-associated SN-MCs (left) not followed by HSS and (right) followed by HSS.

rate during Forbush-type decreases, the plasma and field variations (especially solar wind speed behavior) during recovery should not be much different in two polarity epochs.

## 3. Summary and Conclusions

[23] In this paper we have studied the CR effectiveness and relative importance of various structures of distinct plasma and field properties, namely, shock/sheath, magnetic cloud, interaction region, and high-speed stream. This was done by separating magnetic clouds into different groups on the basis of other features associated with them and performing superposed epoch analysis of cosmic ray data, interplanetary plasma, and field data by suitably selecting and systematically changing reference time (zero epoch) for the data analysis. We have also discussed the role of field strength, its topology, field variance, and high-speed streams in influencing the amplitude and time profile of resulting cosmic ray density depressions.

[24] The results of the analyses show that there are significant differences in amplitude and time profile of depressions in cosmic ray intensity due to isolated magnetic clouds of magnetically quiet regions of high field strength, magnetic clouds with preceding shock/sheath region of compressed plasma and magnetically turbulent field, magnetic clouds with interaction region of fluctuating magnetic field and high-speed streams from open field regions following them, and magnetic clouds with preceding shock/sheath region and high-speed stream following them. The dependence of the recovery rate of cosmic ray density on the polarity state of the heliosphere during Forbush-type decreases due to shock-associated magnetic clouds has also been studied. Some of the significant results as regards the CR effectiveness of magnetic clouds with different associated features and field orientations are highlighted in Tables 1–3.

[25] To summarize, we note the following:

[26] 1. Magnetic clouds with preceding shock/sheath produce Forbuse-like decrease, while isolated magnetic clouds may produce transient decreases of smaller amplitude with fast recovery, as observed by neutron monitors.

[27] 2. Magnetically quiet, high field structure of magnetic clouds are less effective in transient modulation of cosmic rays as compared to magnetically turbulent high field region of sheath. The presence (or absence) of HSS influence the recovery rate; it is faster in the absence of HSS.

[28] 3. Shock-associated magnetic clouds (both NS and SN) may produce two-step Forbush decreases, the first step of larger amplitude starts a few hours before, while second step of smaller amplitude coincides with the arrival time of magnetic clouds.

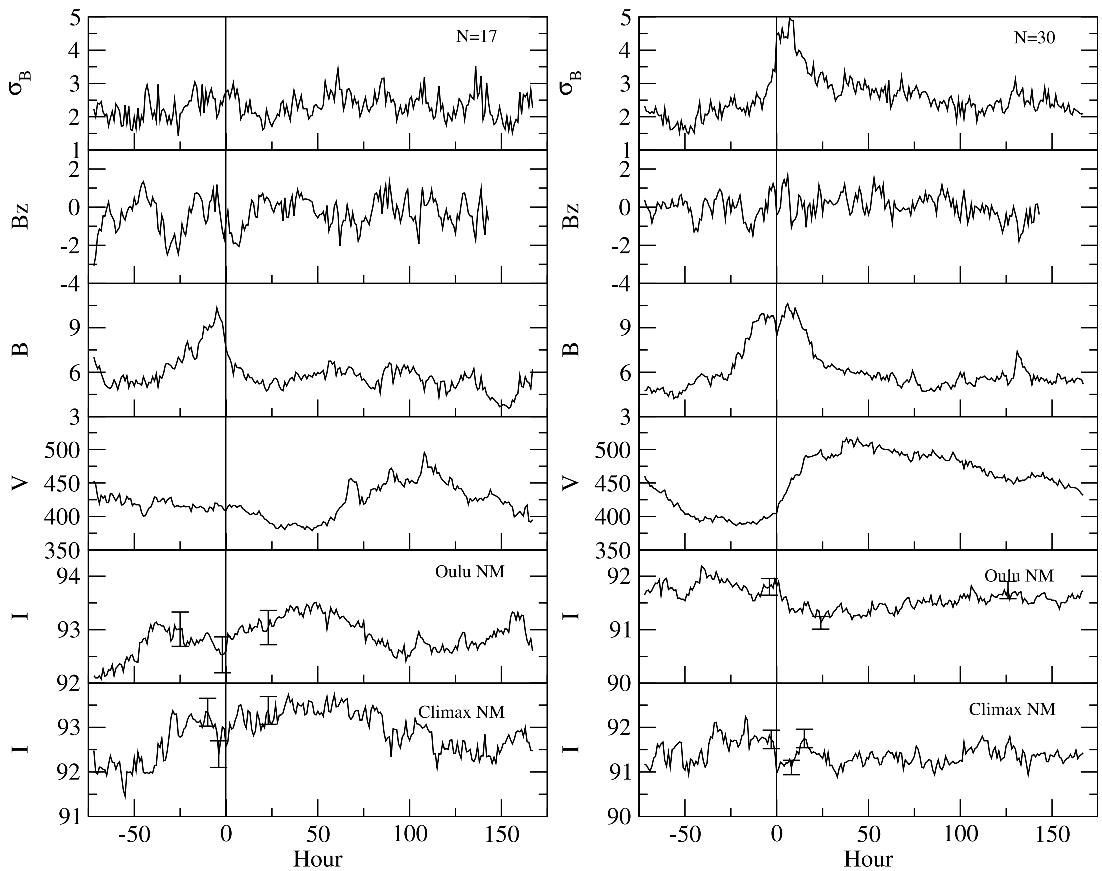


**Figure 9.** Variations in cosmic ray intensity, interplanetary plasma, and field parameters with respect to end time (passage of rear part) of magnetic clouds (NS + SN) not associated with shock (left) without following HSS and (right) with HSS.

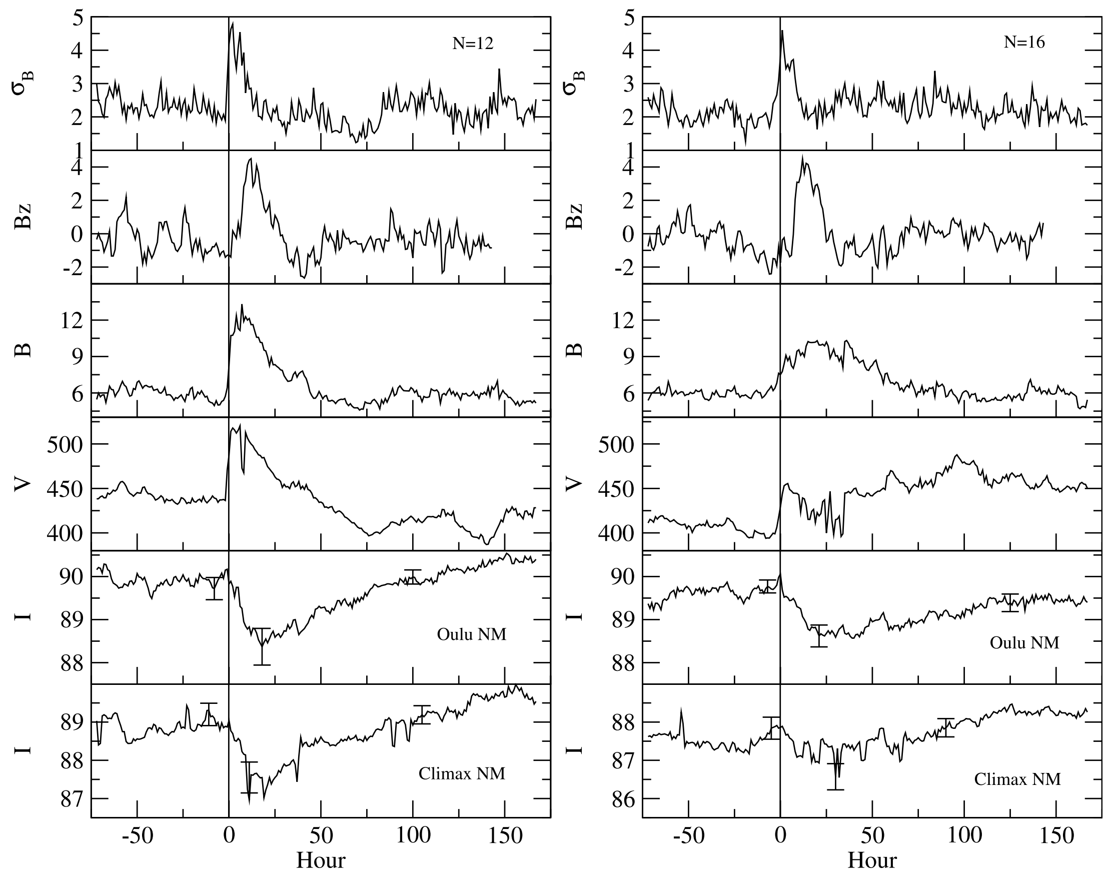


**Figure 10.** Variations in neutron monitor intensity, interplanetary plasma and field parameters with respect to arrival of shock preceding NS-MCs (left) not followed by HSS and (right) followed by HSS.

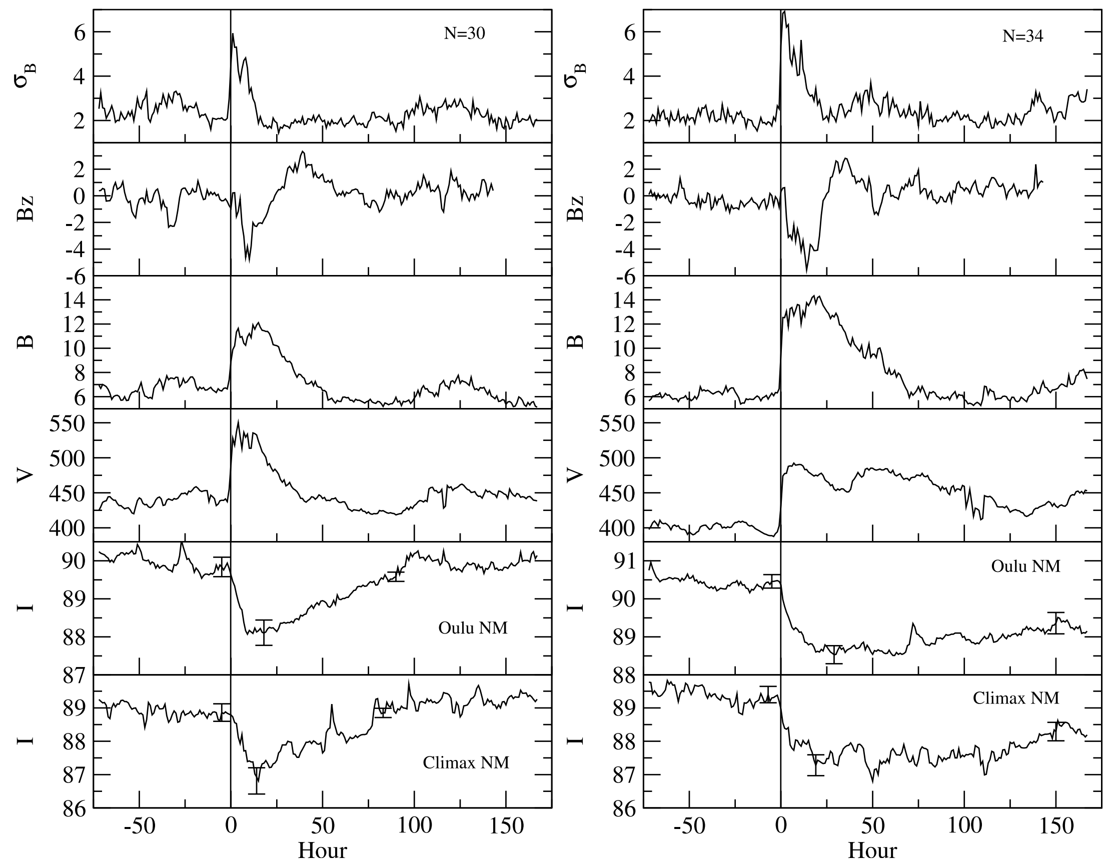


**Figure 11.** Variations in cosmic ray intensity and interplanetary plasma and field parameters with respect to start time (arrival) of shock preceding SN-MCs (left) not followed by HSS and (right) followed by HSS.

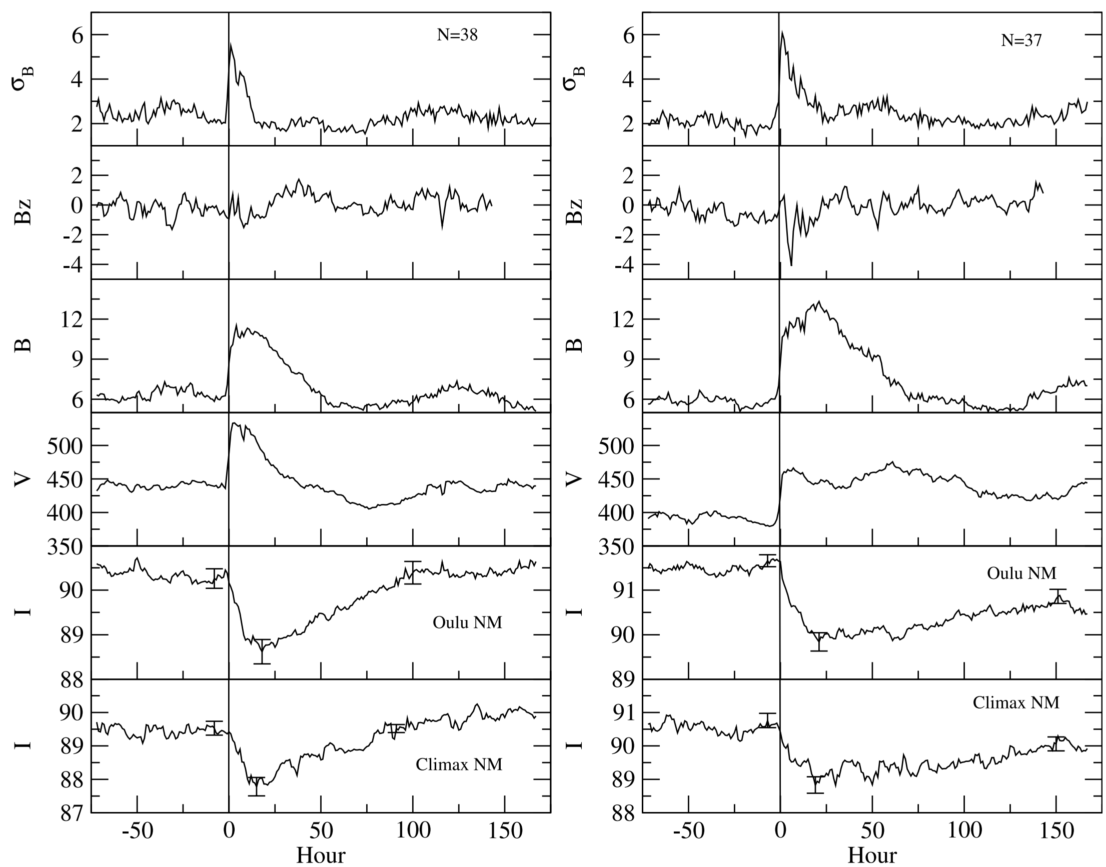


**Figure 12.** Results of superposed epoch analysis showing variations in cosmic ray intensity (I), solar wind velocity (V), interplanetary magnetic field (B), north-south component (Bz), and its variance ($\sigma_B$). Epoch (zero hour) corresponds to start (arrival) time of the shock-preceding both type of magnetic clouds (NS + SN) but (left) not followed by high-speed plasma stream (HSS) and (right) followed by HSS.

**Table 1.** Value of CR Intensity (Oulu NM) and Solar Plasma/Field Parameters Amplitudes During Various Interplanetary Structures

| Magnetic Cloud | Shock | HSS | ΔI, % | $V_{max}$, km/s | $B_{max}$, nT | $\sigma_{Bmax}$, nT |
|---|---|---|---|---|---|---|
| NS | YES | NO | 1.70 | 525 | 13.0 | 4.8 |
| NS | YES | YES | 1.20 | 480 | 10.2 | 4.6 |
| SN | YES | NO | 1.80 | 550 | 12.0 | 6.0 |
| SN | YES | YES | 1.75 | 485 | 14.5 | 6.5 |
| NS + SN | YES | NO | 1.60 | 530 | 11.0 | 5.5 |
| NS + SN | YES | YES | 1.90 | 470 | 13.0 | 6.0 |

**Table 2.** CR Intensity (Oulu NM) Decrease and Recovery Rates During Different Structures in Interplanetary Space

| | | | Decrease Phase | | | Recovery Phase | |
|---|---|---|---|---|---|---|---|
| Magnetic Cloud | Shock | HSS | Time, hour | Rate, %/day | Percent | Time, hour | Rate, %/day |
| NS | YES | NO | 20 | −2.202 | 100 | 100 | 0.322 |
| NS | YES | YES | 25 | −1.248 | 50 | 100 | 0.156 |
| SN | YES | NO | 15 | −3.528 | 100 | 75 | 0.532 |
| SN | YES | YES | 22 | −1.992 | 50 | 130 | 0.120 |
| NS + SN | YES | NO | 24 | −1.872 | 100 | 75 | 0.533 |
| NS + SN | YES | YES | 21 | −2.208 | 25 | 120 | 0.154 |

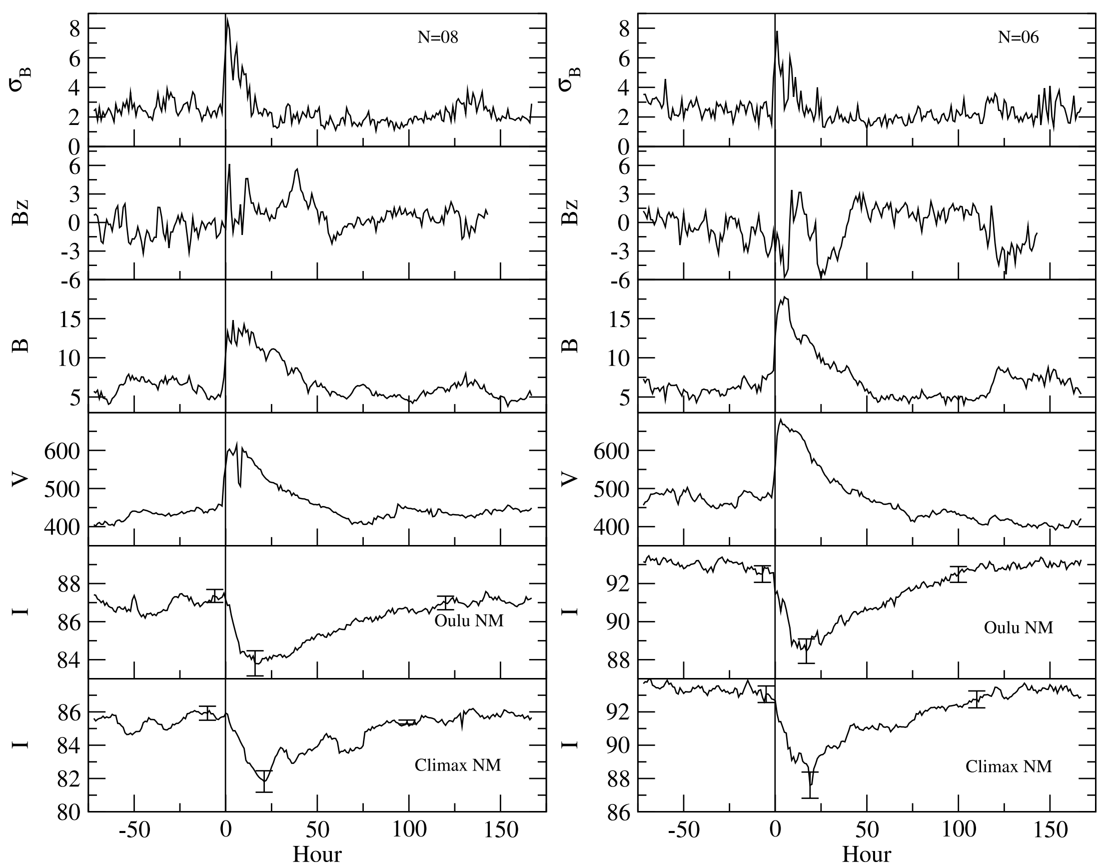


**Figure 13.** Superposed epoch analysis results of cosmic ray and solar wind data during shock-associated magnetic clouds not followed by HSS, observed (left) during $A < 0$ polarity state of the heliosphere and (right) during $A > 0$ epoch.

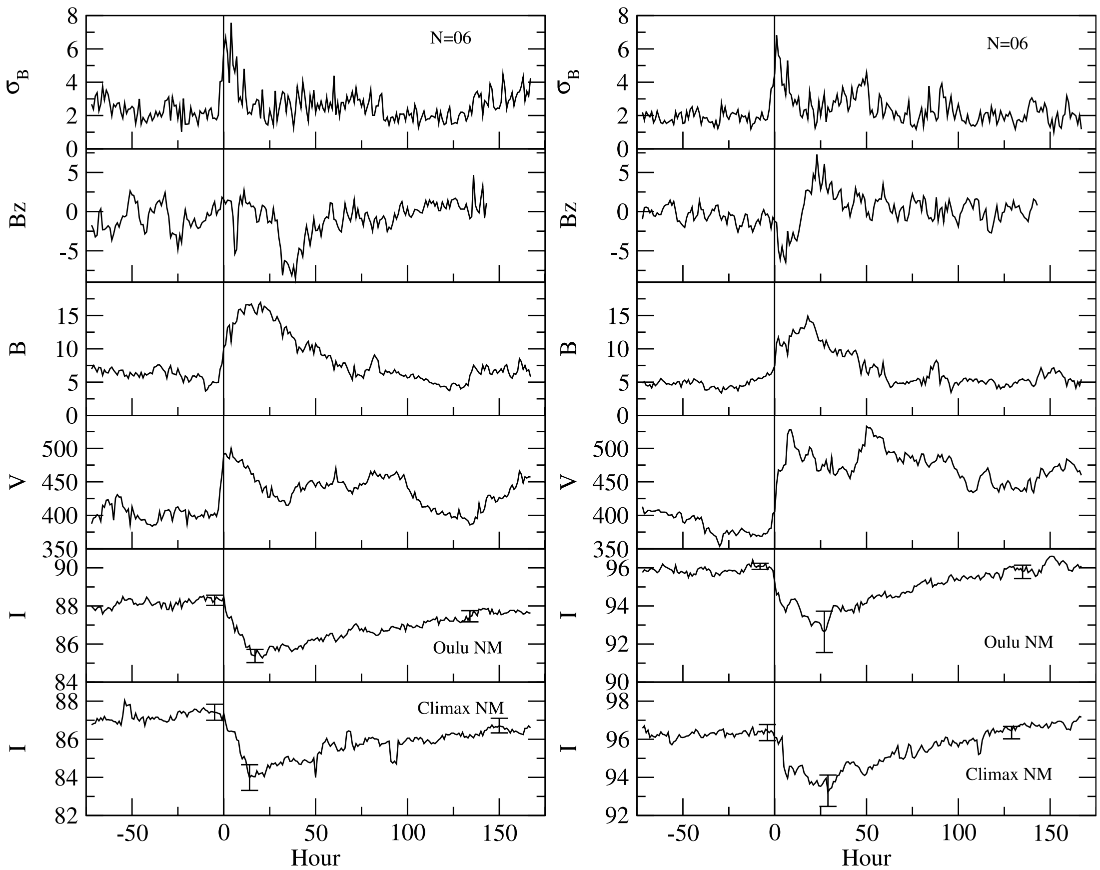


**Figure 14.** Superposed epoch analysis results of cosmic ray and solar wind data during shock-associated magnetic clouds followed by HSS, observed (left) during $A < 0$ polarity state of the heliosphere and (right) during $A > 0$ epoch.

**Table 3.** Characteristic Recovery Time and Recovery Rate (Oulu NM) of Decrease During Different Magnetic States of the Heliosphere

| Magnetic Cloud | Shock | HSS | Polarity | Characteristic Recovery Time, hour | Recovery Rate, %/day |
|---|---|---|---|---|---|
| NS + SN | YES | NO | + | 40 | 0.69 |
| NS + SN | YES | NO | - | 64 | 0.54 |
| NS + SN | YES | YES | + | 48 | 0.47 |
| NS + SN | YES | YES | - | 92 | 0.37 |

[29] 4. Recovery rate of Forbush decreases due to transient interplanetary structure is somewhat different during different polarity states of the heliosphere consistent with the prediction of drift models. However, recovery rate is also influenced considerably by the presence of HSS; recovery is faster in absence of streams. In other words, HSS might be able to slow down the process of filling the lower density region created by passing interplanetary disturbances responsible for initial decrease. Theoretical modeling efforts of Forbush decreases therefore may provide results that are closer to observations, particularly the recovery rate, if the effects of HSS are also incorporated.

[30] **Acknowledgments.** Use of Oulu, Climax neutron monitor data, and solar wind plasma and field data from OMNIWeb is gratefully acknowledged. The principal investigators of various experiments on spacecraft, IMP 8, ISEE-3, ACE, WIND, etc., deserve appreciation for making their data available to various researchers for their use in identification of magnetic clouds. The efforts of R.P. Lepping and his coworkers in WIND MFI team, for making the magnetic cloud data available on the Web, is highly appreciated. We are thankful to the reviewers of the paper for their constructive comments and helpful suggestions.

[31] Zuyin Pu thanks Ronald Lepping and Jichun Zhang for their assistance in evaluating this paper.

## References

Ananth, A. G., and D. Venkatesan (1993), Effect of interplanetary shocks and magnetic clouds on onset of cosmic-ray decreases, *Sol. Phys.*, *143*, 373.

Badruddin (1998), Interplanetary shocks, magnetic clouds, stream interfaces and resulting geomagnetic disturbances, *Planet. Space Sci.*, *46*, 1015.

Badruddin (2002a), Shock orientation, magnetic turbulence and Forbush decreases, *Sol. Phys.*, *209*, 195.

Badruddin (2002b), Transients modulation of cosmic ray intensity: Role of magnetic clouds and turbulent interaction regions, *Astrophys. Space Sci.*, *281*, 651.

Badruddin, R. S. Yadav, N. R. Yadav, and S. P. Agrawal (1985), Influence of magnetic clouds on cosmic ray intensity variation, *Proc. Int. Conf. Cosmic Rays 19th*, *5*, 258.

Badruddin, R. S. Yadav, and N. R. Yadav (1986), Influence of magnetic clouds on transient modulation of cosmic ray intensity, *Sol. Phys.*, *104*, 413.

Badruddin, D. Venkatesan, and B. Y. Zhu (1991), Study and effect of magnetic clouds on transient modulation of cosmic ray intensity, *Sol. Phys.*, *134*, 203.

Barouch, E., and L. F. Burlaga (1975), Causes of Forbush decreases and other cosmic ray variations, *J. Geophys. Res.*, *80*, 449.

Bavassano, B., N. Iucci, R. P. Lepping, C. Signorini, E. J. Smith, and G. Villoresi (1994), Galactic cosmic ray modulation and interplanetary medium perturbations due to a long-living region during October 1989, *J. Geophys. Res.*, *99*, 4227.

Bothmer, V., and R. Schwenn (1997), The structure and origin of magnetic clouds in the solar wind, *Ann. Geophys.*, *16*, 1.

Burlaga, L. F. (1991), Magnetic cloud, in *Physics of the Inner Heliosphere*, chap. 6, p. 1, edited by R. Schwenn and E. Marsch, Springer, New York.

Burlaga, L. F., E. Sittler, F. Mariani, and R. Schwenn (1981), Magnetic loop behind an interplanetary shock: Voyager, Helios and IMP 8 observations, *J. Geophys. Res.*, *86*, 6673.

Burlaga, L. F., L. W. Klien, N. R. Sheeley, D. J. Michels, R. A. Howard, M. J. Koomen, R. Schwenn, and H. Rosenbauer (1982), A magnetic cloud and a coronal mass ejection, *Geophys. Res. Lett.*, *9*, 1317.

Cane, H. V. (1993), Cosmic ray decreases and magnetic clouds, *J. Geophys. Res.*, *98*, 3509.

Cheng, A. F., E. T. Sarris, and C. Dadopoulos (1990), Shock drift mechanism for Forbush decreases, *Astrophys. J.*, *350*, 413.

Duggal, S. P., B. T. Tsurutani, M. A. Pomerantz, C. H. Tsao, and E. J. Smith (1981), Relativistic cosmic rays and corotating interaction regions, *J. Geophys. Res.*, *86*, 7473.

Gopalswamy, N. (2004), A global picture of CMEs in the inner heliosphere, in *The Sun and the Helioshere As an Integrated System*, chap. 8, p. 201, edited by S. Suess and G. Poletto, Springer, New York.

Gopalswamy, N., A. Lara, M. L. Kaiser, and J. L. Bougeret (2001), Near-Sun and near-Earth manifestations of solar eruptions, *J. Geophys. Res.*, *106*, 25,261.

Gulisano, A. M., S. Dasso, C. H. Mandrini, and P. Demoulin (2005), Magnetic clouds: A statistical study of magnetic helicity, *J. Atmos. Sol. Terr. Phys.*, *67*, 1761.

Hidalgo, M. A. (2003), A study of the expansion and distortion of the cross section of magnetic clouds in the interplanetary medium, *J. Geophys. Res.*, *108*(A8), 1320, doi:10.1029/2002JA009818.

Ifedili, S. O. (2004), The two-step Forbush decrease: An empirical model, *J. Geophys. Res.*, *109*, A02117, doi:10.1029/2002JA009814.

Iucci, N., M. Parisi, C. Signorini, M. Storini, and G. Villoresi (1989), Short term cosmic-ray increases and magnetic cloud-like structures during Forbush decreases, *Astron. Astrophys. Suppl. Ser.*, *88*, 367.

Kadokura, A., and A. Nishida (1986), Two-dimensional numerical modeling of the cosmic ray storm, *J. Geophys. Res.*, *91*, 13.

Klein, L., and L. F. Burlaga (1982), Interplanetary Magnetic clouds at 1 AU, *J. Geophys. Res.*, *87*, 613.

Lepping, R. P., and D. Berdichevsky (2000), *Recent Research and Development in Geophysics*, vol. 3, p. 77, Res. Signpost, Trivandrum.

Lepping, R. P., J. A. Jones, and L. F. Burlaga (1990), Magnetic field structure of interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *95*, 11,957.

Lepping, R. P., L. F. Burlaga, B. T. Tsurutani, K. W. Ogilvie, A. J. Lazarus, D. S. Evans, and L. W. Klein (1991), The interaction of a very large interplanetary magnetic cloud with the magnetosphere and with cosmic rays, *J. Geophys. Res.*, *96*, 9425.

Le Roux, J. A., and M. S. Potgieter (1991), The simulation of Forbush decreases with time dependent cosmic ray modulation models of varying complexity, *Astron. Astrophys.*, *243*, 531.

Lockwood, J. A., W. R. Webber, and H. Debrunner (1991), Forbush decreases and interplanetary magnetic disturbances: Association with magnetic clouds, *J. Geophys. Res.*, *96*, 11,587.

Manoharan, P. K., N. Gopalswamy, S. Yashiro, A. Lara, G. Michek, and R. A. Howard (2004), Influence of coronal mass ejection interaction on propagation of interplanetary shocks, *J. Geophys. Res.*, *109*, A06109, doi:10.1029/2003JA010300.

Nieves-Chinchilla, T., M. A. Hidalgo, and J. Sequeiros (2005), Magnetic clouds observed at 1 AU during the period 2000–2003, *Sol. Phys.*, *232*, 105.

Sanderson, T. R., J. Beeck, R. G. Marsden, C. Tranquille, K. P. Wenzel, R. B. McKibben, and E. J. Smith (1990), A study of the relation between magnetic clouds and Forbush decreases, *Proc. Int. Conf. Cosmic Rays 21st*, *6*, 251.

Sanderson, T. R., A. M. Heras, R. G. Marsden, K. P. Wenzel, and D. Winterhalter (1991), An assessment of the post-shock turbulent region in the formation of Forbush decreases, *Proc. Int. Conf. Cosmic Rays 22nd*, *3*, 593.

Sarris, E. T., C. Dodopoulos, and D. Venkatesen (1989), On the E-W asymmetry of Forbush decreases (Ep $\geq$ 35 MeV), *Sol. Phys.*, *120*, 153.

Singh, Y. P., and Badruddin (2006), Effects of the polarity states of the heliospheric magnetic field and particle drifts in cosmic radiation, *Sol. Phys.*, *234*, 339.

Venkatesan, D., and Badruddin (1990), Cosmic ray intensity variations in the 3-dimensional heliosphere, *Space Sci. Rev.*, *52*, 121.

Wilson, R. M., and E. Hildner (1984), Are interplanetary magnetic clouds manifestations of coronal transients at 1 AU, *Sol. Phys.*, *91*, 169.

Zhang, G., and L. F. Burlaga (1988), Magnetic clouds, geomagnetic disturbances, and cosmic ray decreases, *J. Geophys. Res.*, *93*, 2511.

Zhang, J., M. W. Liemohn, J. U. Kozyra, B. J. Lynch, and T. H. Zurbuchen (2004), A statistical study of the geoeffectiveness of magnetic clouds during high solar activity years, *J. Geophys. Res.*, *109*, A09101, doi:10.1029/2004JA010410.

Badruddin and Y. P. Singh, Department of Physics, Aligarh Muslim University, Aligarh 202 002, India. (badr_phys@yahoo.co.in; ypbarkatpur@yahoo.co.in)