Chapter 2

Short-term modulation of cosmic ray intensity associated with transient eruptions from the Sun

2.1 Introduction

Magnetic clouds were first identified by Burlaga and coworkers [Burlaga et al., 1981; Klein & Burlaga, 1982] in the interplanetary space near 1 AU. These structures are the interplanetary manifestations of coronal mass ejections [Burlaga et al., 1982; Wilson & Hildner, 1984; Gopalswamy et al., 2001; Manoharan et al., 2004; Gopalswamy, 2004]. A magnetic cloud is a solar ejection in which (i) the magnetic field strength is enhanced with respect to ambient value, (ii) the magnetic field vector undergoes a large rotation, and (iii) 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 it 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 et al., 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
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 & Burlaga, 1988; Iucci et al., 1989; Sanderson et al., 1991; Lepping et al., 1991; Lockwood et al., 1991; Venkatesan & Badruddin, 1990; Ananth & 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 & 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 post shock 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.

As regards the mechanism mainly responsible for Forbush decreases, earlier studies suggested scattering in turbulent magnetic fields [Badruddin et al., 1986; Zhang & Burlaga, 1988; Lockwood et al., 1991], drifts in smooth and high field region [Barouch & 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 [Iledili, 2004]. Thus the whole area appears to be complex and needs further study.

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, and discussed in literature, have bipolar Bz (NS and SN); however a few unipolar (S and N) magnetic clouds have also been identified [e.g. Zhang et al., 2004].

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 (a) abrupt changes in solar wind plasma and field parameters (at shock front), (b) intense and turbulent magnetic fields (during the passage of sheath), and (c) 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 nearly 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.

A set of 149 well observed NS and SN magnetic clouds with good data cov-
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... 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 & Burlaga, 1982; Wilson & Hildner, 1984; Zhang & Burlaga, 1988; Lepping et al., 1990; Gopalswamy et al., 1991; 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.

2.2 Results

2.2.1 Magnetic clouds associated/not-associated with shocks

In order to distinguish between the CR-effectiveness of shock-associated magnetic clouds and those without a shock, a 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) and its variance \( \sigma_B \) (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 (a) shock-associated MCs and (b) MCs not associated with shocks are shown, respectively, in the Figures 2.1 and 2.2 respectively. From these figures, it appears that the shock-associated MCs produce Forbush-type decrease (a fast decrease followed by a slow recovery), as shown at a low cut-off rigidity Oulu neutron monitor (\( Rc = 0.61 \) GV) and a higher cut-off rigidity (\( Rc = 2.97 \) GV) neutron monitor...
of Climax. It is also seen from these figures that the decrease in CR intensity starts not at the arrival of the magnetic clouds (zero hour) but a few hours 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 from Figure 2.2, 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.

2.2.2 Magnetic clouds with NS/SN field orientation

As shown in Figures 2.1 and 2.2, there is large 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, the shock-associated MCs were divided into two groups, namely (a) shock-associated NS-MCs and (b) 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; the results are shown in Figures 2.3 and 2.4. It is seen from these figures, 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. But, 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
Figure 2.1: 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) and its variance ($\sigma_B$). Epoch (zero hour) corresponds to observed start (arrival) time of the shock-associated interplanetary magnetic clouds; it includes all MCs i.e. north-south (NS) as well as south-north turning (SN).
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Figure 2.2: Same as Fig. 2.1, but epoch (zero hour) is the observed start (arrival) time of magnetic clouds not associated with shock.

interplanetary parameters (V, B and \(\sigma_B\)), could not be distinguished at this stage of analysis. Also, whether the difference in recovery time (and hence 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 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 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 Figures 2.3 and 2.4 that the decrease starts before the arrival of magnetic clouds, it is not possible to clearly say, from these figures, 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.

In Figures 2.5 and 2.6, 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 are plotted. As seen from these figures, a small depressions in cosmic ray intensity results both due to NS and SN
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Figure 2.3: Superposed epoch analysis results showing variations in cosmic ray intensity and various interplanetary plasma/field parameters. Epoch (zero hour) corresponds to observed start (arrival) time of north-south (NS) turning magnetic cloud.

Figure 2.4: Same as Fig. 2.3, but zero hour corresponds to the observed start time of south-north (SN) magnetic clouds associated with shock.
Figure 2.5: 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 NS-MCs, not associated with shock.

magnetic clouds. The effect is more clearly seen at lower energies (Oulu NM) than at higher energies (Climax NM). It is also seen from these figures 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.

A comparison of Figures 2.3, 2.4 and 2.5, 2.6 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 & Burlaga [1988], Lockwood et al. [1991], 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.
Figure 2.6: Same as Fig. 2.5, but zero hour corresponds to the observed start time of south-north (SN) magnetic clouds.

2.2.3 Magnetic clouds followed/not-followed by high-speed streams

From the results of the analyses presented in Figures 2.1, 2.2, 2.3, 2.4, 2.5, and 2.6, the effects of shock-associated, NS turning and SN turning magnetic clouds on the transient modulation of cosmic rays have been discussed. 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 & Burlaga, 1982; see also, Badruddin, 1998]. To study the role of the interaction region and the high speed streams (HSS) in influencing the amplitude and the recovery characteristics of resulting decreases in cosmic ray intensity, the NS/SN magnetic clouds have been divided on the basis whether they are followed by HSS or not.

Figures 2.7 and 2.8 are the superposed epoch plot of cosmic ray intensity, solar wind plasma and field parameters (V, B and $\sigma_B$) with respect to shock-associated NS-MC, not followed by HSS and those followed by HSS respectively; zero epoch corresponds to start time of the magnetic cloud in these figures. It
Figure 2.7: 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) and its variance ($\sigma_B$). Epoch (zero hour) corresponds to start (arrival) time of the shock-associated NS-MCs, not followed by high speed plasma stream (HSS).

Figure 2.8: Same as Fig. 2.7, but zero hour corresponds to the start time (arrival) of shock-associated NS-MCs followed by HSS.
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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 (i) the shock/sheath region (enhanced and compressed field region of ambient solar wind with large field variance), (ii) the magnetic cloud (enhanced, magnetically closed and quiet field region with low variance), (iii) the interaction region (compressed thin region of enhanced field variance), and (iv) the HSS (an extended region with high speed solar wind presumably 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 Figures 2.7 and 2.8 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 Figures 2.9 and 2.10, 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 Figures 2.9 and 2.10 that the enhancements in field strength (B), its variance ($\sigma_B$) are nearly same in both the figures.

Next, the combined data set of SN and NS magnetic cloud has been divided into two groups (i) those not-followed by HSS and (ii) 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. Figures 2.11 and 2.12 show 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
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Figure 2.9: Results of superposed epoch analysis showing variations in I, V, B and \( \sigma_B \) with respect to shock-associated SN-MCs not followed by HSS; epoch (zero hour) corresponds to the arrival time of MCs.

Figure 2.10: Same as Fig. 2.9, with respect to shock-associated SN-MCs followed HSS but zero hour corresponds to the start time (arrival) of shock-associated MCs followed by HSS.
Figure 2.11: 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 not followed by HSS.

Figure 2.12: Same as Fig. 2.11, but followed by HSS, zero hour corresponds to the start time of magnetic cloud.
hour corresponds to the start time of magnetic clouds. 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 (Figure 2.11). 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 Figure 2.12 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).

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 one analyzes the data with respect to end time of magnetic clouds.

Figures 2.13 and 2.14 are 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). Figure 2.13 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 Figure 2.14 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 Figure 2.14, 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 fluc-
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Figure 2.13: Superposed epoch analysis results showing variations in cosmic ray intensity, solar wind velocity, interplanetary magnetic field and its variance; zero hour corresponds to end time (passage of rear part) of shock-associated NS-MCs not followed by HSS.

Figure 2.14: Same as Fig. 2.13, but zero hour corresponds to the end time of shock-associated NS-MCs followed by HSS.
Figure 2.15: Superposed epoch analysis results showing variations in I, V, B and $\sigma_B$, zero hour corresponds to end time (passage of rear part) of shock-associated SN-MCs not followed by HSS.

Figure 2.13 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 (a) not followed and (b) followed by HSS is that intensity appears to recover at a faster rate in the absence of the high speed stream.

Plots in Figures 2.15 and 2.16 due to shock associated SN-MCs without HSS and followed by HSS respectively, show results essentially similar to that in Figures 2.13 and 2.14. That is, 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.

Even though by separating shock-associated NS-MCs, each into two groups
Figure 2.16: Same as Fig. 2.15, but zero hour corresponds to the end time (passage of rear part) of shock-associated SN-MCs followed by HSS.

Figure 2.17: 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, not followed by HSS.
on the basis of absence/presence of HSS following MCs, certain effects that can be attributed to magnetic clouds and interaction regions/HSS have been observed, 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. Figures 2.17 and 2.18 show the effects of such MCs. In Figure 2.17, we have shown the superposed epoch analysis results of cosmic ray intensity, interplanetary plasma and field parameters have been shown 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. A small depression in intensity is seen 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 (Figure 2.17). As shown in the Fig-
Figure 2.19: Variations in cosmic ray intensity and interplanetary plasma and field parameters with respect to start-time (arrival) of shock preceding NS-MCs not followed by HSS.

Figure 2.18, 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 possible interaction region and HSS. The time profile of intensity depression in the Figure 2.18 differ from that shown in Figure 2.17; intensity decreases in two steps, followed by slower recovery in case of magnetic clouds followed by HSS.

It has been 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, it is yet to be seen in this analysis whether the onset of the decrease coincides with the shock front or the decrease starts sometime later during the passage of magnetically turbulent sheath regions. Moreover, it is expected that more details about the decrease and recovery characteristic of Forbush decreases can be obtained if the exact cause of onset is known.

Thus, in order to gain more insight about the transient modulation of cos-
Figure 2.20: Same as Fig. 2.20, with respect to shock preceding NS-MCs followed by HSS.

mic rays due to shock associated NS/SN-MCs, followed/not-followed by HSS, the cosmic ray and solar wind plasma/field data has been analyzed with respect to shock arrival time. Figures 2.19 and 4.20 show superposed plots of neutron monitor and solar wind plasma/field data with respect to shock-associated NS-MCs not followed by HSS (Figure 2.19) and those followed by HSS (Figure 2.20). Intensity-time profiles in these figures show some interesting features. Similar features and differences in superposed epoch plots with respect to shock-associated SN-MCs not-followed by HSS (Figure 2.19), and those followed by HSS (Figure 2.20) are also seen in Figures 2.21 and 2.22. We can see from these 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 plots of SN and NS-MCs without any distinction in the field rotation inside the clouds (Figures 2.23 and 2.24) show similar results. A comparison of amplitude of cos-
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Figure 2.21: Variations in cosmic ray intensity and interplanetary plasma and field parameters with respect to start-time (arrival) of shock preceding SN-MCs not followed by HSS.

In Table 2.2 are given the calculated 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, 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 2.1 and 2.2.
Figure 2.22: Same as Fig. 2.21, with respect to shock preceding SN-MCs followed by HSS.

Figure 2.23: Results of superposed epoch analysis showing variations in cosmic ray intensity (I), solar wind velocity (V), interplanetary magnetic field (B) 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 not followed by HSS.
Figure 2.24: Same as Fig. 2.23, but zero hour corresponds to the arrival time of shock-preceding both types of magnetic clouds (NS+SN) followed by HSS.

Table 2.1: Value of cosmic ray intensity (Oulu NM) and solar plasma/field parameters amplitudes during various interplanetary structure.

<table>
<thead>
<tr>
<th>Magnetic Cloud</th>
<th>Shock</th>
<th>HSS</th>
<th>ΔI (%)</th>
<th>( V_{max} ) (km/s)</th>
<th>( B_{max} ) (nT)</th>
<th>( \sigma_{B_{max}} ) (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>YES</td>
<td>NO</td>
<td>1.70</td>
<td>525</td>
<td>13.0</td>
<td>4.8</td>
</tr>
<tr>
<td>NS</td>
<td>YES</td>
<td>YES</td>
<td>1.20</td>
<td>480</td>
<td>10.2</td>
<td>4.6</td>
</tr>
<tr>
<td>SN</td>
<td>YES</td>
<td>NO</td>
<td>1.80</td>
<td>550</td>
<td>12.0</td>
<td>6.0</td>
</tr>
<tr>
<td>SN</td>
<td>YES</td>
<td>YES</td>
<td>1.75</td>
<td>485</td>
<td>14.5</td>
<td>6.5</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>NO</td>
<td>1.60</td>
<td>530</td>
<td>11.0</td>
<td>5.5</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>YES</td>
<td>1.90</td>
<td>470</td>
<td>13.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Table 2.2: Cosmic ray intensity (Oulu NM) decrease and recovery rates during different structures in interplanetary space.

<table>
<thead>
<tr>
<th>Magnetic cloud</th>
<th>Shock</th>
<th>HSS</th>
<th>Time (hr)</th>
<th>Rate (%/day)</th>
<th>Percent</th>
<th>Time (hr)</th>
<th>Rate (%/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>YES</td>
<td>NO</td>
<td>20</td>
<td>-2.202</td>
<td>100</td>
<td>100</td>
<td>0.322</td>
</tr>
<tr>
<td>NS</td>
<td>YES</td>
<td>YES</td>
<td>25</td>
<td>-1.248</td>
<td>50</td>
<td>100</td>
<td>0.156</td>
</tr>
<tr>
<td>SN</td>
<td>YES</td>
<td>NO</td>
<td>15</td>
<td>-3.528</td>
<td>100</td>
<td>75</td>
<td>0.532</td>
</tr>
<tr>
<td>SN</td>
<td>YES</td>
<td>YES</td>
<td>22</td>
<td>-1.992</td>
<td>50</td>
<td>130</td>
<td>0.120</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>NO</td>
<td>24</td>
<td>-1.872</td>
<td>100</td>
<td>75</td>
<td>0.533</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>YES</td>
<td>21</td>
<td>-2.208</td>
<td>25</td>
<td>120</td>
<td>0.154</td>
</tr>
</tbody>
</table>

Table 2.3: Characteristic recovery time and recovery rate (Oulu NM) of decrease during different magnetic states of the heliosphere.

<table>
<thead>
<tr>
<th>Magnetic cloud</th>
<th>Shock</th>
<th>HSS</th>
<th>Polarity</th>
<th>Characteristic Recovery time (hr)</th>
<th>Recovery rate (%/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>NO</td>
<td>+</td>
<td>40</td>
<td>0.69</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>NO</td>
<td>-</td>
<td>64</td>
<td>0.54</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>YES</td>
<td>+</td>
<td>48</td>
<td>0.47</td>
</tr>
<tr>
<td>NS+SN</td>
<td>YES</td>
<td>YES</td>
<td>-</td>
<td>92</td>
<td>0.37</td>
</tr>
</tbody>
</table>
2.2.4 Magnetic clouds in positive/negative polarity states of the heliosphere

According to drift model of Forbush decreases [Kadokura & Nishida, 1986; Le Roux & 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 towards 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, the analysis presented here includes somewhat selective; the large duration cosmic ray storms apparently produced by multiple transient disturbances, one after the other; 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. Shock-associated magnetic clouds that are not followed by HSS, and producing Forbush-type decreases, have been divided 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 (Figures 2.25 and 2.26). It is observed 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 A < 0). The shock-associated magnetic clouds that follow HSS were divided 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 (Figures 2.27 and 2.28) show 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

$$I = I_0 - \beta exp(-t/\tau)$$
Figure 2.25: Superposed epoch analysis results of cosmic ray and solar wind data during shock-associated magnetic clouds not followed by HSS, observed during $A < 0$ polarity state of the heliosphere.

...concurs with that result [also see, Singh & 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 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 2.3). From Figures 2.25, 2.26, 2.27 and 2.28, 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 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.
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Figure 2.26: Same as Fig. 2.25, during $A > 0$ epoch.

Figure 2.27: Superposed epoch analysis results of cosmic ray and solar wind data during shock-associated magnetic clouds followed by HSS, observed during $A < 0$ polarity state of the heliosphere.
2.3 Conclusions

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 have been studied. 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. 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 have also been discussed here.

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,
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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 2.1-2.3.

From the results of the analysis presented here, we conclude the following:

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

- 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.

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

- 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.
Bibliography


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