Study of short-term modulation of galactic cosmic rays: A new approach

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Abstract. Ground-based and space-borne experiments measuring galactic cosmic rays (GCRs) have observed transient depressions in its intensity lasting for several days. Individual depressions vary in their size (amplitude) and shape (time profile). Examination of ground-based neutron monitor cosmic ray intensity data has led us to classify them into symmetric and asymmetric depressions, depending on symmetric/asymmetric decrease and recovery phases of individual depressions. Symmetric depressions were observed to have (i) V-shape and (ii) bowl or U-shape. Asymmetric depressions have been categorized into (i) Forbush-like, (ii) composite, and (iii) wavy depressions. Looking at the solar data, and analyzing the solar wind plasma/field data we have searched for the solar and interplanetary causes of these depressions. Examinations and analysis of simultaneous variations in solar plasma speed, its density and temperature, along with interplanetary magnetic field, its magnitude and fluctuations in it, has led us to identify possible structure(s) such as ICMEs, shock/sheath regions (formed due to compression of ambient magnetic field by high speed CMEs), interaction regions (formed by interaction between slow and high speed solar wind) and compression regions (formed by interaction between slow CMEs and high speed streams from coronal holes). Relationships between GCR intensity and various solar wind parameters, during the passage of these distinct structures, have been examined and possible mechanism (s) producing different type of symmetric and asymmetric depressions have been suggested.

Index Terms. Cosmic ray modulation, heliosphere, solar and interplanetary transients, solar wind.

1. Introduction

Earlier studies of short-term modulation in galactic cosmic ray intensity, lasting several days, were confined with mainly two specific type of depressions, namely corotating and Forbush decrease (see reviews, Lockwood, 1971; Venkatesan and Badruddin, 1990; Cane, 2000; Richardson, 2004). Forbush decreases, characterized by a fast decrease within ~1 day followed by a more gradual nearly exponential recovery over a few days, have been observed continuously with neutron monitors since the 1950's. Recurrent modulations of galactic cosmic rays, characterized by a slow decrease and a gradual recovery within a period of ~27 days, comparatively, are less impressive changes in cosmic ray intensity.

Since their discovery through world-wide distribution of ion-chambers, Forbush decreases have been extensively studied to search for their solar source (e.g. Duggal and Pomerantz, 1977; Badruddin and Singh, 2003), interplanetary structure responsible (Barouch and Burlaga, 1975; Badruddin et al., 1986; Iucci et al., 1989; Nagashima et al., 1990; Lockwood et al., 1991; Cane, 1993; Bavassano et al., 1994; Zhang and Burlaga, 1988; Badruddin, 2000, 2002; Cane, 2000; Ifedili, 2004) and the mechanism(s) playing major role in this phenomenon (Barouch and Burlaga, 1975; Venkatesan and Badruddin, 1990; Cane, 2000). Numerical (modulation) models too have been developed for the study of Forbush decreases (e.g. Kadokura and Nishida, 1986; Chih and Lee, 1986; Le Roux and Potgieter, 1991) in one, two and three-dimensions, in the inner as well as outer heliosphere. In spite of substantial efforts, due to complexity of the phenomenon, none of the above aspects are clearly understood without any ambiguity.

Although less impressive than Forbush decreases, a class of modest cosmic rays intensity variation occurring at intervals ~27 days were inferred, to be closely correlated with recurring unipolar magnetic field regions above the photosphere of the sun and were more prominent during sunspot minimum. These unipolar magnetic field regions were later identified with coronal holes and source of corotating high-speed solar wind streams. Multispacecraft measurements in interplanetary space in conjunction with ground-based observation facilitated in identifying the solar source(s) of recurrent depressions (e.g. coronal holes), interplanetary structure(s) (e.g. corotating interaction regions, high-speed streams, heliospheric current sheet) and possible mechanism(s) (convection, diffusion and/or drifts) (e.g. Badruddin, 1997; Morfill et al., 1979; Richardson et al., 1996, 1999; Kota and Jokipii, 2001; Richardson, 2004; Singh and Badruddin, 2005). Although solar polar coronal holes have been identified as potential solar source of corotating decreases, the relative role of corotating interaction regions, high speed streams and heliospheric current sheet in corotating modulation is yet to be decided. Consequently, the mechanism that plays a dominant role during corotating decreases is not clearly understood.

In most of early studied of short term modulations, most workers focused over one or the other of the two phenomena, i.e. corotating or Forbush decrease. In this paper we have adopted a somewhat different approach for the study of short-term depressions in galactic cosmic ray intensity. After examination of long period of neutron monitor observations, we have categorized all the observed short-term depressions into (i) symmetric and (ii) asymmetric depressions, depending whether the 'decrease' and 'recovery' parts in their time profile are symmetric or asymmetric. 'Symmetric' depressions are observed to have (a) V-shape and (b) bowl or U-shape. Asymmetric depressions are classified into (a) Forbush decreases, (b) composite decreases, and (c) wavy-decreases, based upon the time profile of the depression. After classification of depressions into these categories, one event each from five classes was selected for detailed study. Events were so selected that continuous solar plasma and field data (plasma velocity, magnetic field, density and temperature) were available, at least for the duration of events. Neutron monitor observations together with interplanetary plasma and field parameters were then analyzed to study their solar origin, interplanetary field and flow configurations/structures, and physical mechanisms responsible for these depressions in cosmic ray intensity.

2. Results and Discussion

Symmetric depressions

We have identified two categories of 'symmetric' depressions in cosmic ray intensity recorded at ground-based neutron monitors. We refer depressions as `symmetric' if the time profiles of decrease phase (i.e. onset to minimum intensity level) and recovery phase (i.e. minimum level up to regain of constant level) are similar. Two categories of symmetric depressions are (a) 'V-shape' and (b) 'bowl' or 'U-shape' depressions.

Fig. 1 shows a V-shape depression of about 5% as observed at Climax neutron monitor (Latitude = 39.37°N, Longitude = 106.18° W, Cut-off rigidity = 2.97 GV). The decrease started at 0300 hours on May 21, 2000 with the arrival of slowly increasing high-speed stream. Plasma and field variation during this streams are such that, most likely, it is a corotating stream from coronal hole. Field strength also increases slowly within the stream. Eventually a compression region is formed after about 72 hour of start of the stream. This structure is evident in the interplanetary plasma and field data (V, B, σ_B, T, N and Bz) from the jump in the amplitudes of these parameters. Intensity depression follows the enhancement in solar wind velocity (r = - 0.82). GCR intensity decreases at an average of 1.67(%) per 100 (km/sec) increase in solar wind velocity in this case.

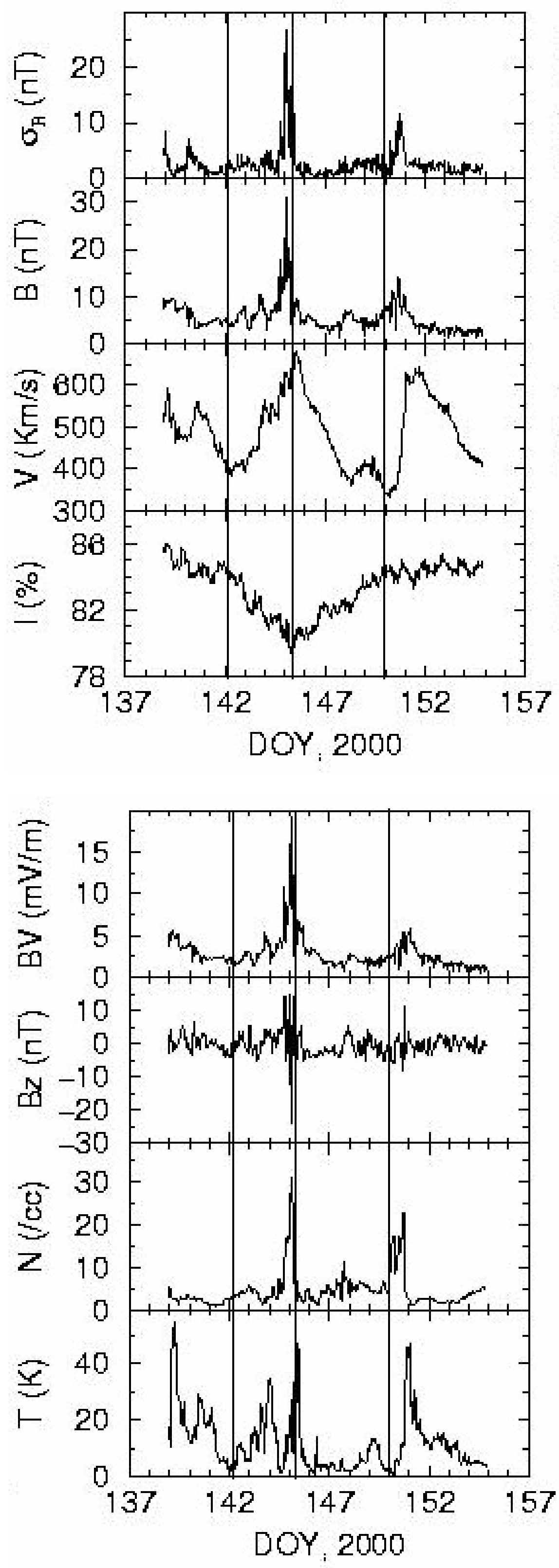

Fig. 1. A symmetric cosmic ray event (V-depression) that started on May 21, 2000 at 0300 hours. Cosmic ray intensity as observed by neutron monitor together with the various interplanetary plasma and field parameters (V, B, σ_B, T, N, Bz and BV) are shown. Vertical lines indicate the start, minimum and end time of event.

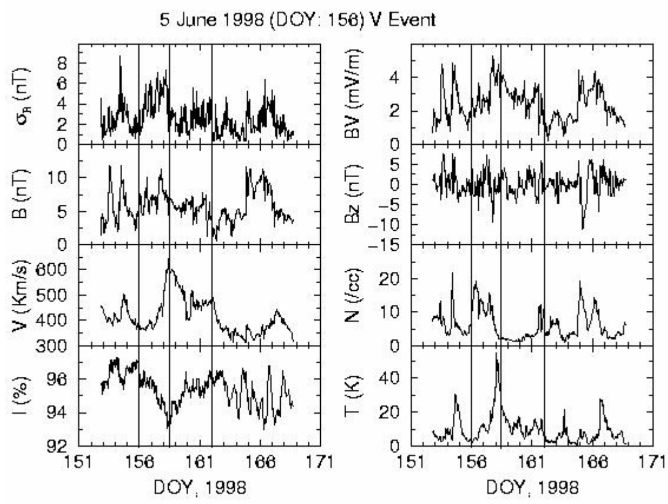

Fig. 2. Intensity time profile of a symmetric type (V-depression) of June 5, 1998 along with the various interplanetary plasma and field parameters are shown in this figure. Vertical lines indicate the start, minimum and end time of event.

Fig. 2 shows a V-depression of about 4% that started at 0100 hour on June 05, 1998 with slowly increasing solar wind speed, minimum intensity reached in about sixty hours at the time of maximum speed of the solar wind stream (r = -0.80). Although the IMF strength (B) and its variance (σ_B) and plasma density (N) remains enhanced during the decreasing phase of this V-depression, the solar wind speed is better correlated (r=-0.80) with time variation in cosmic ray intensity during this phase. This depression appears to be caused by enhanced convection and particle scattering. A GCR intensity decrease with increasing solar wind speed at an average of 1.37(%) per 100 (Km/sec) decrease in solar wind velocity is observed during recovery phase. The intensity recovers at a rate of 0.53% per hour as obtained by a linear fit (r=0.78). The recovery takes place during decreasing solar wind speed and passage of relatively low field and magnetically quiet region. During recovery phase, the correlation analysis between GCR intensity (I) and solar wind parameter (V, B, σ_B and BV) yields better correlation between V and I (r=-0.79) as solar wind speed is continuously decreasing during this phase.

Fig. 3 shows an U-depression of about 5% that lasted ten days; five days decrease time and same number of days it took to recover to pre-decrease level. It started after the passage of magnetically quiet field region with low temperature and density probably a slow moving CME (see Gopalswamy, 2004). As it appears from the plasma and field enhancements (V, B, σ_B, T, N and Bz), this CME was 'pushed' by high-speed stream forming an interaction region behind CME. This March 21, 1998 depression started with the arrival of interaction region and high-speed stream. Even as the depression was continuing, another stream of long duration and comparatively slow speed arrived. This U-depression was a result of a CME, an interaction region, a high-speed stream and a broad stream of low speed. This U-depression appear to be caused by multiple events and could not be ascribed to a single event in interplanetary space.

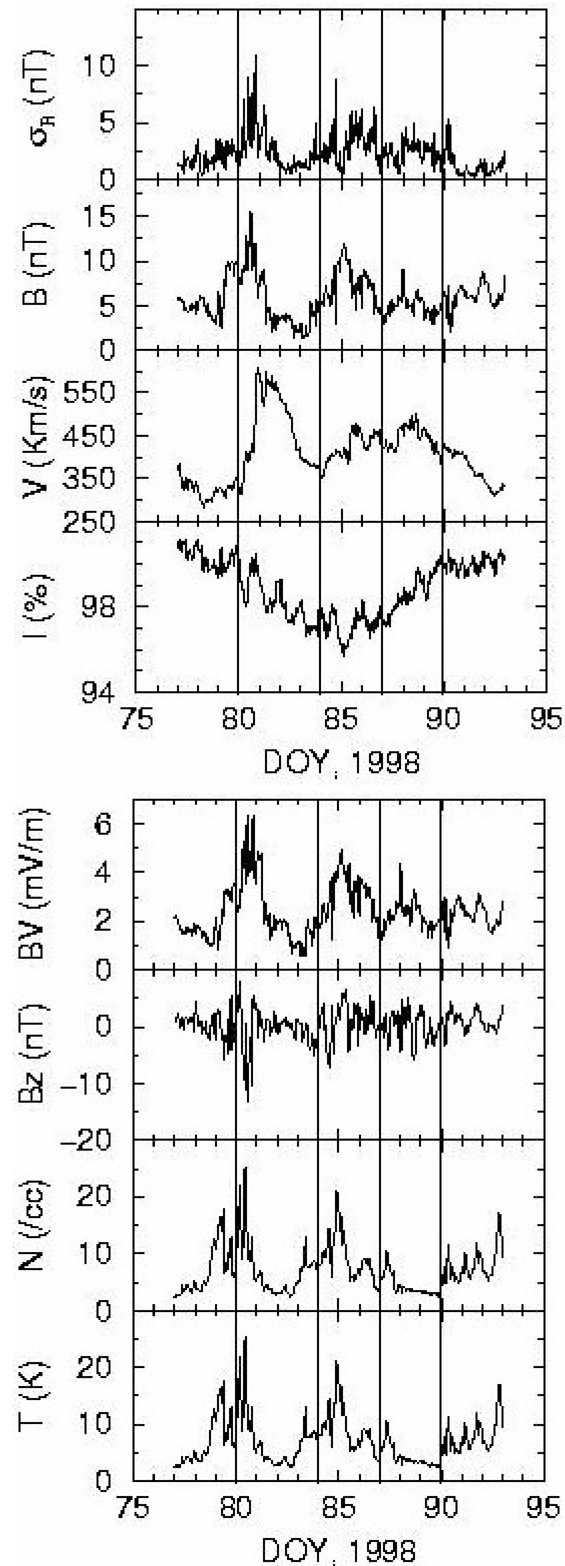

Fig. 3. A transient depression in cosmic ray intensity (U-depression) starting on March 21, 1998 showing cosmic ray intensity time profile and plasma/field variations. Extreme vertical lines indicate the start and end time of cosmic ray event. Two vertical lines in between indicate interplanetary events during the depression.

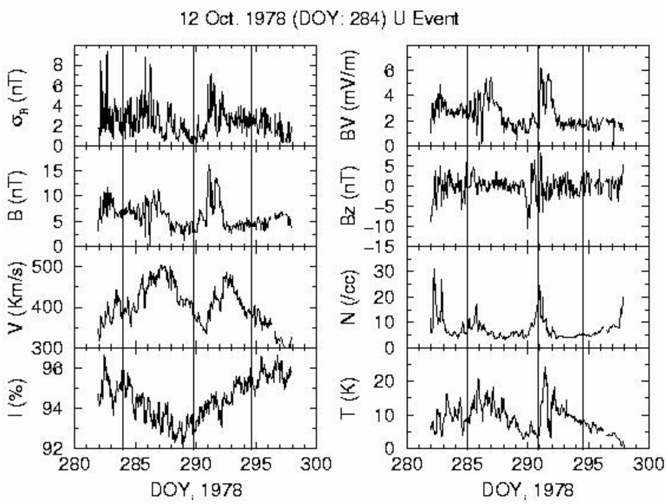

Fig. 4. A symmetric cosmic ray depression (U-type event) starting on October, 12, 1978 showing cosmic ray intensity time profile and plasma/field variations. Vertical lines left and right indicate the start and end time of cosmic ray event.Line in the middle indicates another interplanetary event.

A depression in GCR intensity (Fig. 4) started on October 12, 2000 with the arrival of a solar wind stream with slowly increasing velocity, this stream attained maximum speed after about five days time. The field in the stream is fluctuating during decrease phase. Intensity recovery began when the stream started decaying and field become low and quiet. After about three days of smooth recovery, another structure, an ICME, arrived during the recovery phase and produced a small amplitude decrease of short duration; however, recovery of U-depression continued and it recovered completely to predecrease level in about five days time. This ten-day U-depression of about three percent amplitude shows some correlation (r = -0.43) with plasma speed of the solar wind stream and/or structure that formed in the interplanetary space. These depressions can not be ascribed to a single event in interplanetary space, and both enhanced convection and scattering of cosmic ray particles may be simultaneously important in producing this depression.

Asymmetric depressions

A Forbush-like depression (Fig. 5) of about 7% amplitude started at 1600 hours on September 17, 2000 simultaneous with sudden jump in V, B, σ_B, T and N of solar wind plasma/field parameter. A compressed plasma and turbulent field region (shock/sheath region) is driven by a CME, a high field region with low σ_B, T and N, following the compressed/turbulent field region. A high-speed shock, a high-field, turbulent region excludes the cosmic ray particles resulting in decrease phase data a rate of decreases as 0.37% per hour. The recovery starts slowly and it recovers in a week time. The recovery closely follows the decaying solar wind velocity (r=-0.92) and to same extent the field strength about (r=-0.66). Although, recovery is generally attributed to filling of the void created by propagating interplanetary structures, the speed of the solar wind in influencing the time profile (e.g. recovery rate) is quite possible.

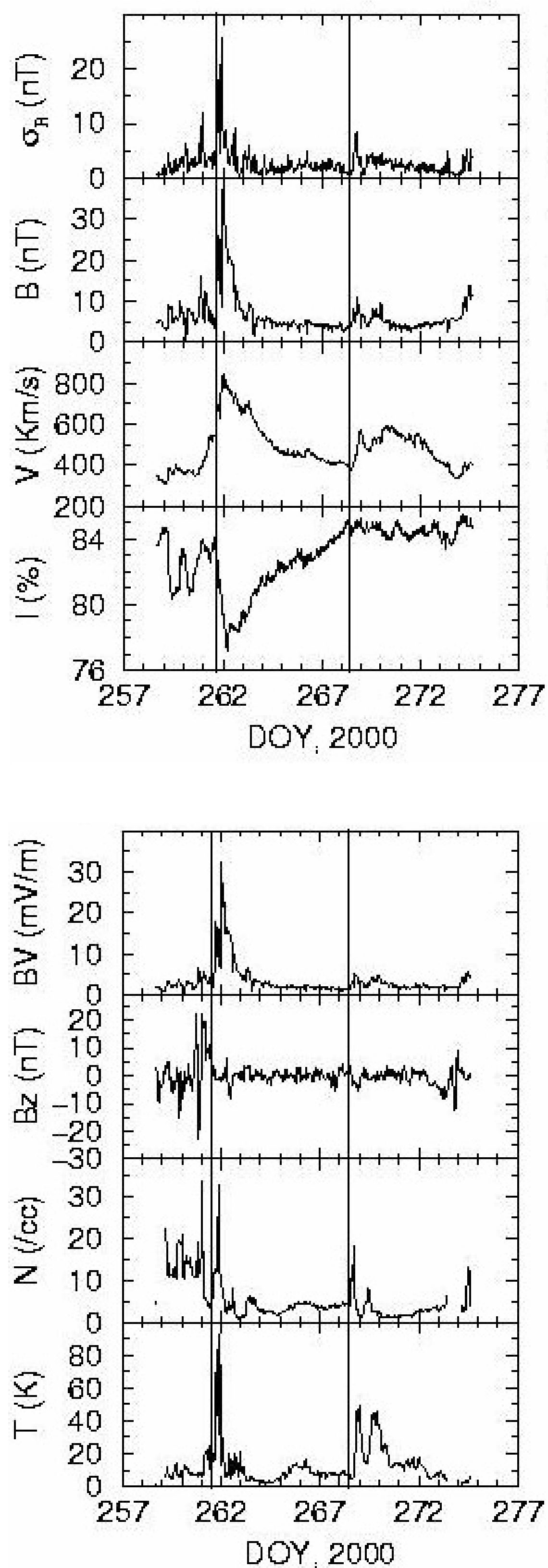

Fig. 5. A Forbush-type cosmic ray depression starting on 1600 hour on September 17, 2000 alongwith plasma/field variations. Vertical lines indicate interplanetary events end of the Forbush-type cosmic depression.

A Forbush depression (fast decrease and slow recovery) started on November 11, 1978 with sudden jump in solar wind parameters V, B, σ_B, T and N indicating that a shock arrived at the time of onset. IMF, its variance, solar plasma temperature and density remained high for a few hours afterwards; indication of a turbulent sheath region. However, intensity at minimum level remains depressed for a few hours during the passage of high field and low σ_B region (a CME). Recovery of the intensity started after the passage of the sheath region followed by CME. Recovery took about a week time when the solar wind speed (and IMF strength) decreased slowly till the intensity recorded to pre-decrease level. During decrease phase the intensity was better correlated with σ_B (r = -0.78) and V (r = -0.68) indicating that speed of the shock and turbulence within the sheath region play an important role in this decrease by scattering cosmic ray particles. The correlation of the intensity with plasma speed (r=-0.58) and IMF strength (r=-0.63) during recovery indicates that these parameters may also influence the recovery characteristics (e.g. recovery rate) of Forbush-type decrease. Thus Forbush-type depression in cosmic ray intensity might be caused by a single ICME (a fast shock/sheath/CME structure); scattering of particles by turbulent sheath playing an important role in producing the decrease.

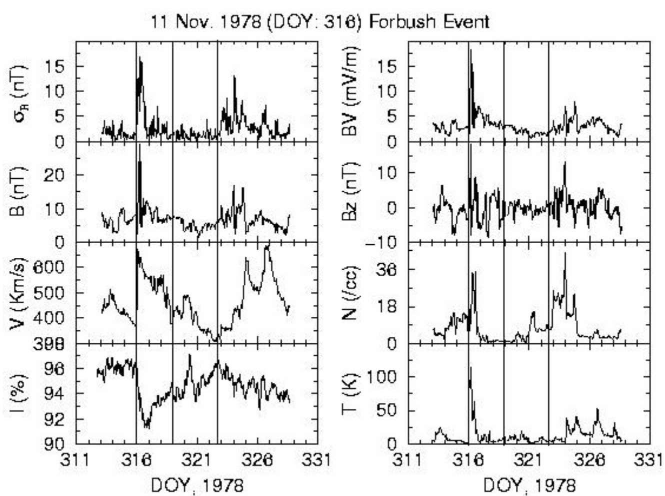

Fig. 6. A Forbush-type cosmic ray depression starting on November 11, 1978 showing cosmic ray intensity time profile and plasma/field variations. Vertical lines indicate interplanetary events end of the cosmic depression.

A 'composite' depression (fast decrease with slow recovery in steps) started at 1000 hours on October 21, 2001. As sudden decrease of about 5% within few hours started with sudden enhancement in solar wind parameters V, B, σ_B, T and N. The duration of enhanced σ_B, T and N lasted only for about 12 hours although field (B) was enhanced for ~36 hours indicating that a compressed/turbulent shock/sheath structure was followed by a CME. Thus the initial decrease in intensity can be ascribed to a fast shock/sheath driven by a CME. The recovery started after the passage of this structure. However, before the intensity could recover completely, three more interplanetary disturbances, respectively on 25 Oct. 2001 (0800 hours), 28 Oct. 2001 (0200 hours) and 31 Oct (1300 hours) of slower speed and lesser field strength kept the intensity depressed till November 01, 2001. In this way it

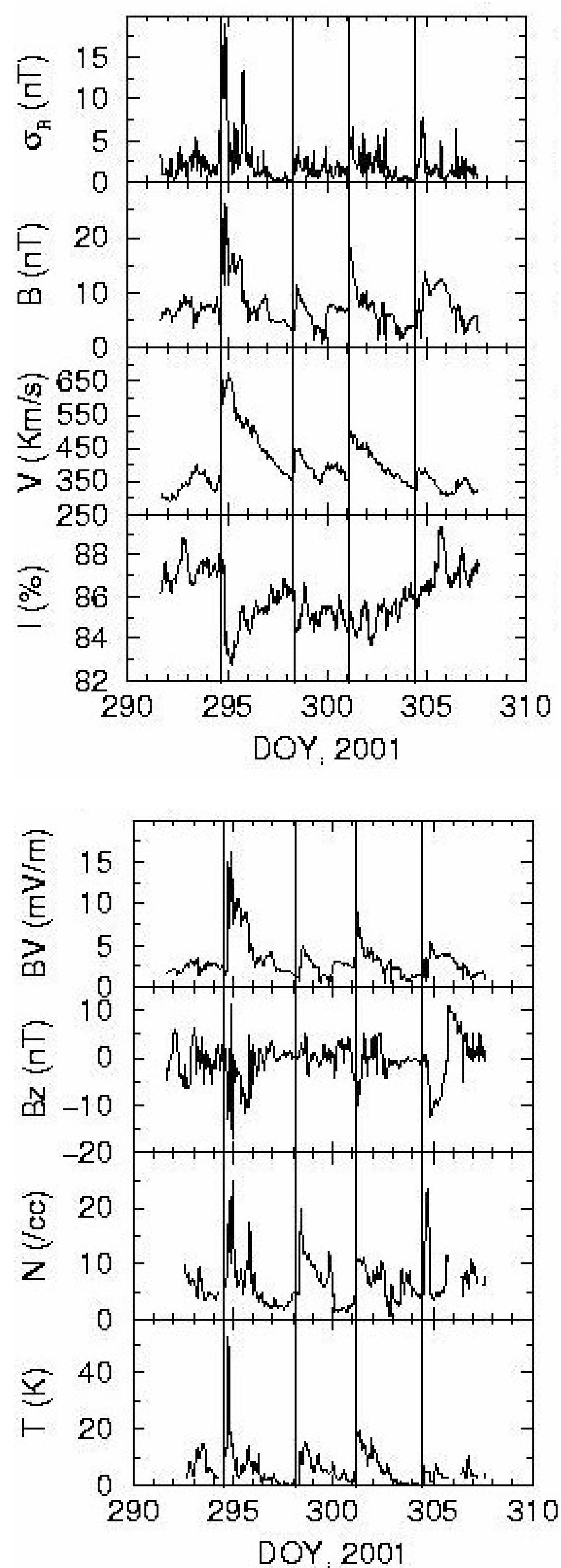

Fig. 7. A composite event showing variation in cosmic ray intensity depression starting on October 21, 2001 alongwith plasma/field variations.

Vertical lines indicate the interplanetary events responsible for the depression.

took eleven days for the intensity to recover completely, that too in steps. The speed of the disturbances which, in turn, may decide the level of compression/turbulence in ambient solar wind, strength of the shock formed etc. is better related with decrease in cosmic ray intensity (r = - 0.60). The decrease of the intensity, during initial phase, fitted with a linear curve provides a rate of intensity decrease 1.42% per hour with r = - 0.92.

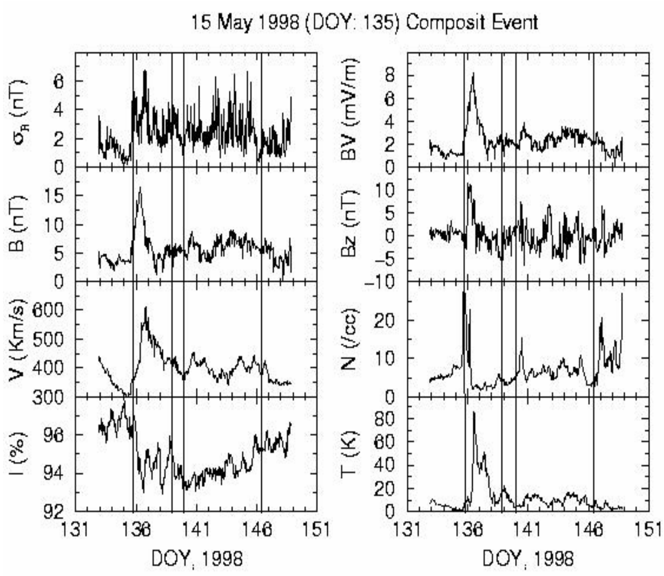

Fig. 8. A composite event showing variation in cosmic ray intensity depression starting on May 15, 1998 alongwith plasma/field variations. Vertical lines indicate the interplanetary events.

A composite decrease of about 4% started on May 15, 1998 at 2100 hours on arrival of a high speed (V), high field (B) compressed (high N) and turbulent (high σ_B) structure formed in the interplanetary space. This decrease, reaching minimum intensity level within 24 hour of its starts, recovered very slowly as another long-duration disturbance of lower speed, enhanced and turbulent field (high B and σ_B) and relatively enhanced density restrained the intensity to almost same level for about a week time, most probably through diffusion process. A linear fit for decrease phase of this composite depression gives the rate of intensity decrease as 7.3% per day with r = -0.93.

A wavy depression started on February 17, 1998 (Fig. 9) with the arrival of CME (Gopalswamy et al., 2001) followed by an interaction region (high B, high σ_B, high T and N) and enhanced solar wind. An other structure, a compressed region of solar plasma and field was responsible a slight depression on February 22, 1998. A third step in depression commenced with slowly increasing field and density in the ambient solar wind.

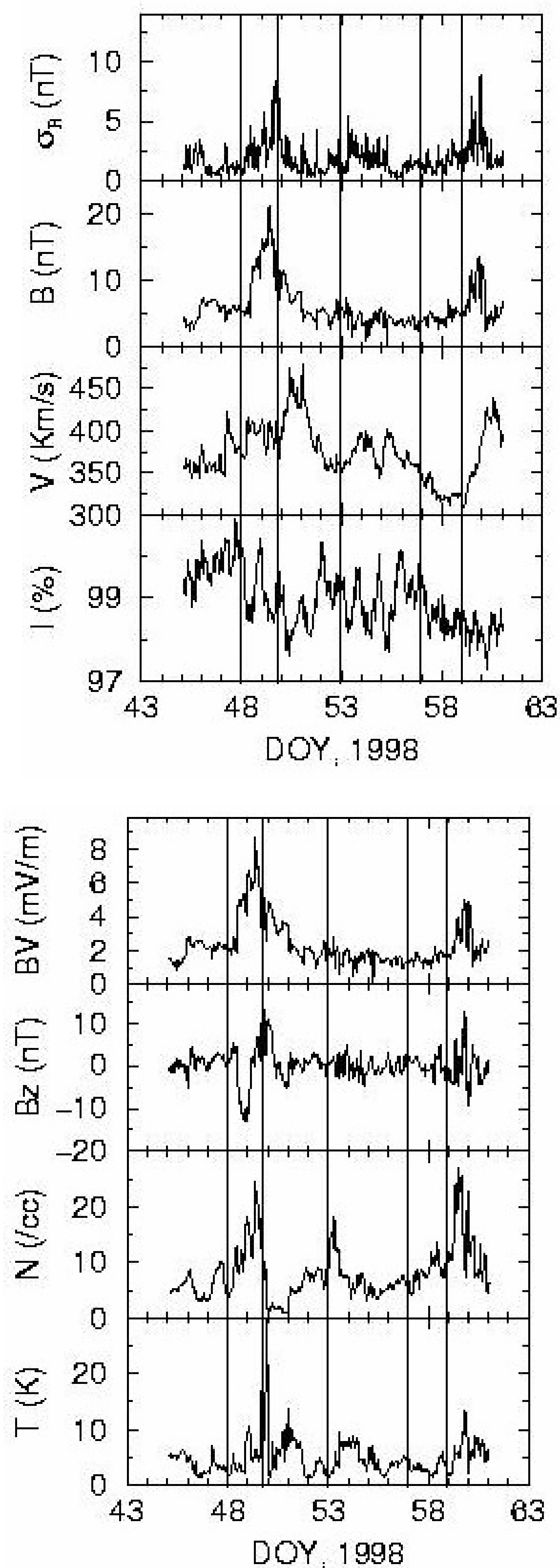

Fig. 9. A wavy depression in cosmic ray intensity on February 17, 1998 alongwith plasma/field variations. Vertical lines indicate the interplanetary events.

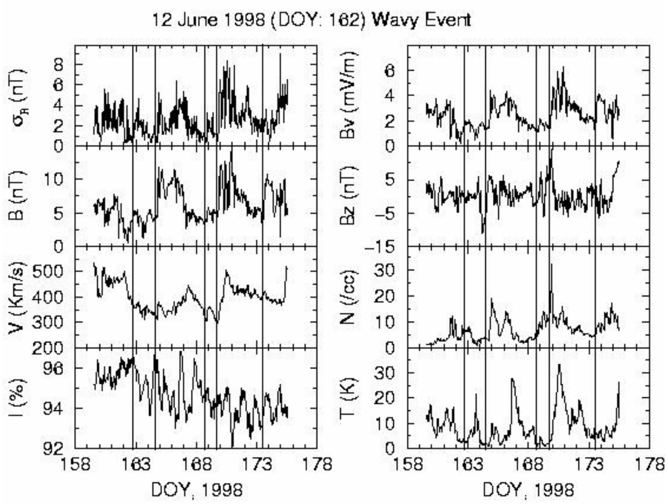

Fig. 10. A wavy depression in cosmic ray intensity at 2100 hr on June 12, 1998 alongwith plasma/field variations. Vertical lines indicate the interplanetary events.

A wavy depression started on February 17, 1998 (Fig. 10) with the arrival of CME like structure (high B, low σ_B, low T) followed by an interaction region (high B, high σ_B, high T and N) and enhanced solar wind. An other structure, a compressed region of solar plasma and field was responsible a slight depression on February 22, 1998. A third step in depression commenced with slowly increasing field and density in the ambient solar wind. A reasonable fit to this wavy depression was obtained by a tenth order equation with r = 0.70.

3. Conclusions

We have classified depression in cosmic ray density into different categories depending on the shape of the depressions. Depressions of each category were selected and plasma and field characteristics were analyzed. We have identified possible interplanetary structures and physical processes playing important role during different type depressions. Although the detailed study of Forbush decreases in cosmic ray intensity is important to understand them fully, it is suggested that study of different types of short-term depressions in intensity together with the solar sources and plasma/field characteristic of various interplanetary structures, responsible for producing them, will help in better understanding the modulation of cosmic rays.

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