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Transient Perturbations and their Effects in the Heliosphere, the Geo-magnetosphere, and the Earth's Atmosphere: Space Weather Perspective

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Abstract. We discuss the effects of certain dynamic features of space environment in the heliosphere, the geo-magnetosphere, and the earth's atmosphere. In particular, transient perturbations in solar wind plasma, interplanetary magnetic field, and energetic charged particle (cosmic ray) fluxes near 1 AU in the heliosphere have been discussed. Transient variations in magnetic activity in geo-magnetosphere and solar modulation effects in the heliosphere have also been studied. Emphasis is on certain features of transient perturbations related to space weather effects. Relationships between geomagnetic storms and transient modulations in cosmic ray intensity (Forbush decreases), especially those caused by shock-associated interplanetary disturbances, have been studied in detail. We have analysed the cosmic ray, geomagnetic and interplanetary plasma/field data to understand the physical mechanisms of two phenomena namely, Forbush decrease and geomagnetic storms, and to search for precursors to Forbush decrease (and geomagnetic storms) that can be used as a signature to forecast space weather. It is shown that the use of cosmic ray records has practical application for space weather predictions. Enhanced diurnal anisotropy and intensity deficit of cosmic rays have been identified as precursors to Forbush decreases in cosmic ray intensity. It is found that precursor to smaller (less than 5%) amplitude Forbush decrease due to weaker interplanetary shock is enhanced diurnal anisotropy. However, larger amplitude (greater than 5%) Forbush decrease due to stronger interplanetary shock shows loss cone type intensity deficit as precursor in ground based intensity record. These precursors can be used as inputs for space weather forecast.

Key words. Space weather—geomagnetic storm—cosmic ray—Forbush decrease—interplanetary shock—coronal mass ejection.

1. Introduction

Space weather refers to conditions on the Sun and in the heliosphere, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-based and ground-based technological systems and can endanger human life or health (e.g., see Kudela *et al.* 2000). Spacecraft systems are vulnerable to space weather through its influence on energetic charged particle and plasma population, while spacecraft electronics and aircrew are vulnerable to cosmic rays and solar particle events (Dyer and Rogers 1998). Space weather effects on the ionosphere affect electromagnetic signal propagation (Marcz 1992). On the ground, the effects of space weather perturbations are due to magnetic field effects (Lanzerotti *et al.* 1998; Pirjola 2005). Space weather predictions and forecasts, therefore, are essential for the protection of both the ground-based and space-based technological systems and other hazardous effects.

The whole space weather chain originating from the Sun, extending in the heliosphere, magnetosphere, ionosphere, lower atmosphere and to the ground is very complicated, and its full understanding, which should be aimed at for being able to forecast, and manage space weather hazards/risks, is a difficult and hard task. However, it is very important that efforts should go on in this direction.

Most of the important space weather effects are related to geomagnetic storms (GS). These geomagnetic storms are related to coronal mass ejections (CMEs) and shocks/sheath associated with them. Cosmic ray intensity, in general, is dramatically affected during the geomagnetic storms. These CMEs are potential causes of intense geomagnetic storms and decreases in cosmic ray intensity (Badruddin *et al.* 1986; Zhang & Burlaga 1988; Venkatesan & Badruddin 1990; Badruddin 1998; Cane 2000; Zhang *et al.* 2004; Kudela & Brenkus 2004; Gopalaswamy 2004).

Previous studies have observed a strong association between interplanetary CMEs and interplanetary shocks (e.g., Manoharan *et al.* 2004); and interplanetary shocks and cosmic ray intensity variations (Badruddin *et al.* 1991; Badruddin 2003); interplanetary shocks and resulting geomagnetic disturbances (Srivastava & Venkatakrishnan 2002). Therefore, to identify the shock properties that correlate better with the intensity of geomagnetic storm and to predict their arrival at Earth are the priority areas of space weather research. Attempts have been made earlier to look for the cosmic ray precursors to Forbush decreases and geomagnetic storms (Bieber and Evenson 1998; Ruffolo 1999; Munakata *et al*. 2000), but the use of cosmic ray data for space weather purposes is still in its infant stage (Kudela *et al.* 2000).

We have performed superposed epoch analysis using hourly neutron monitor data from Deep River, Climax and Calgary as a measure of cosmic ray intensity. In the method of superposed epoch analysis, the time of occurrence of certain events, e.g., CMEs, are defined as key time (zero hour/day). The data under investigation, e.g., cosmic ray intensity, is then listed sometime (hour/day) before and after the key time. In this way the data are listed in the form of a matrix in which rows represent the epochs and the columns represent time before and after the individual key time. The column averages of this matrix, which show some variations, represent the superposed epoch analysis result. As adverse space weather conditions arise due to geomagnetic storms, we have used three indices namely auroral electrojet index AE, planetary magnetic index Kp and equatorial ring current index Dst as measures of geomagnetic activity. Forbush decreases, which are transient changes in galactic cosmic ray intensity, are characterised 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 1950s. For the analysis, based on their decrease amplitude, we have divided the observed Forbush decreases in two groups (greater and less than 5%). This grouping has led us to identify the precursors to Forbush decreases and geomagnetic storms. Precursors to Forbush decreases are of practical interest as possible predictors of space weather effects on earth, several hours or even days before the passage of a major interplanetary shock. Our results show that such efforts could be a useful input in space weather predictions.

2. Results

Figure 1 shows the superposed epoch results of hourly cosmic ray intensity data as observed at three neutron monitors before and after the onset (zero hour) of FDs of amplitudes greater than 5%. In this figure, we see an identifiable cosmic ray precursor, i.e., an intensity deficit some hours prior to the onset of decrease ('loss cone' type precursor) (see Ruffolo 1999; Manakata *et al.* 2000; Kudela *et al.* 2000). Three geomagnetic indices Dst, AE and Kp show sudden enhancement in geomagnetic activity simultaneously with the onset of Forbush decrease. Although the physical processes responsible for the two phenomena (Forbush decrease and geomagnetic storm) are thought to be different, the common cause, i.e., interplanetary shock and/or mass ejection from the Sun are responsible for both (Cane 2000; Kudela & Brenkus 2004).

In order to study the plasma/field properties of transient interplanetary events responsible for FDs of larger amplitude ($> 5\%$) and GS, we have plotted in Fig. 1 the interplanetary magnetic field strength (B), its variance (sigma B) and north–south component (Bz), solar wind velocity (V), their functions V.B and V.Bz.

Figure 2 shows the superposed epoch analysis plots of cosmic ray intensity variation with respect to FDs of smaller amplitude ($< 5\%$) together with the geomagnetic activity represented by indices Dst, AE and Kp. The identified precursor to FDs in this case is 'enhanced diurnal anisotropy' (see Bieber and Evenson 1998). Superposed epoch plots of interplanetary plasma and field parameters B, sigma B, Bz, V, VB and BzV show the simultaneously changing behaviour of these parameters. A comparison in magnitude of parameters plotted in Figs. 1 and 2 is given in Table 1.

Since the superposed epoch analysis shows only average behaviour, in Figs. 3 and 4, we have plotted hourly data of typical events, one from Group I (FD $> 5\%$) and the other from Group II (FD $< 5\%$) showing development of GS, variations in field strength, its variance and north–south component, interplanetary electric field and its dawn-to-dusk component, to show their time behaviour more clearly.

3. Discussion

A critical examination of Figs. 1 and 2 shows that there is a large difference in amplitude of cosmic ray decrease in Figs. 1 and 2. The enhanced field strength at the time of minimum intensity is the same for both sets of events, Group I and Group II (also see Table 1). The average field variance sigma B at the time of minimum intensity is larger for Group II events as compared to Group I events. However, the average speed of the interplanetary disturbances responsible in Group I events is larger compared to that responsible for Group II events. The product VB is almost the same in two cases. These results are consistent with the idea that stronger interplanetary shocks produce more effective modulation in cosmic ray intensity (also see Cane *et al.* 1996). Increased level of magnetic turbulence represented by increased sigma B, is an additional factor in causing Forbush decreases (Badruddin 2003).

Two individual events, one from each group (Figs. 3 and 4), show the variations in cosmic ray intensity, geomagnetic activity, interplanetary plasma and field parameters

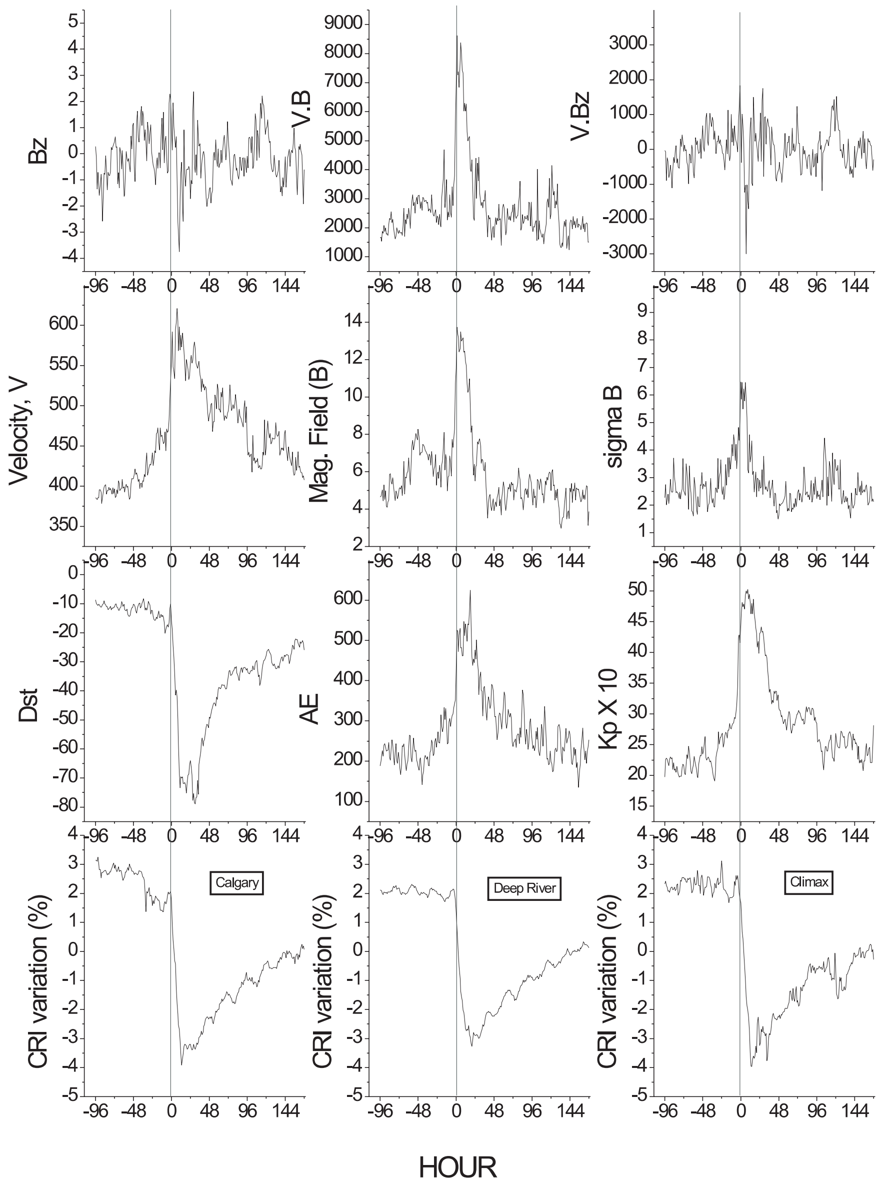

Figure 1. Superposed epoch analysis results of three neutron monitors at Calgary, Deep River and Climax, geomagnetic activity indices Dst, AE, and Kp, interplanetary plasma and field parameters, solar wind velocity (V), magnetic field (B), its variance (sigma B), north–south component (Bz), interplanetary electric field (VB), its component (VBz). Zero hour corresponds to the onset of FDs of amplitude $> 5\%$.

before and after the arrival of disturbance. These figures also show that stronger disturbances moving with higher speed are more effective modulators of cosmic ray intensity. Further, magnetic turbulence in the interplanetary disturbance is also an important factor.

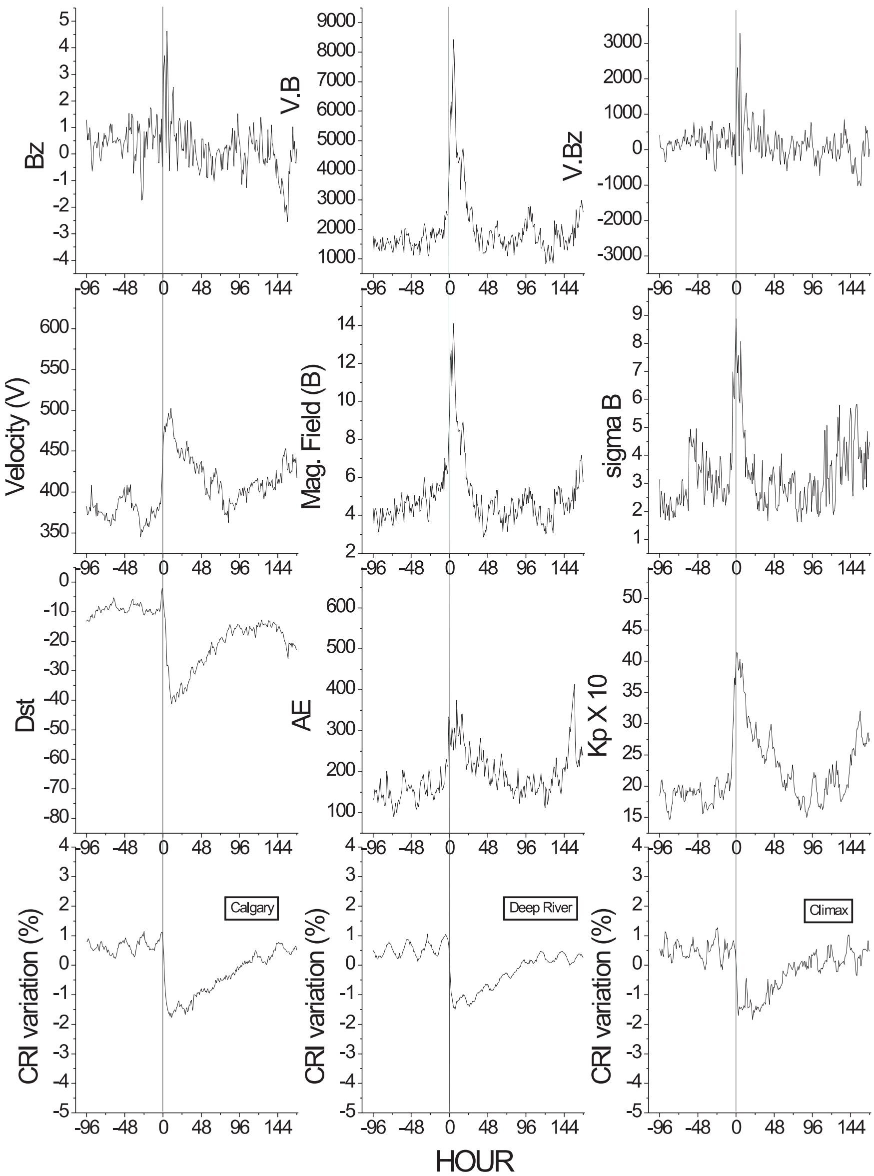

Figure 2. Superposed epoch analysis results of cosmic ray, geomagnetic and interplanetary plasma and field parameters, with respect to FDs of amplitude $< 5\%$.

The superposed epoch plots (Figs. 1 and 2) corresponding to Group I and Group II events show some noticeable features in geomagnetic activity and plasma and field parameters. On an average the magnitudes of B are the same in two cases, Bz and BzV after the passage of disturbance are larger (and negative) for Group I events than for Group II events. Moreover, the large increase in geomagnetic activity coincides with the large negative Bz periods. Similar changes are more clearly seen in individual event plots in Figs. 3 and 4. A correlation analysis between geomagnetic and solar wind

Table 1. A comparison of effects of Group I and Group II events on various parameters.

Sl. no.	Parameter	Group I	Group II
01	CRI decrease (%), Calgary NM	5.93	2.82
02	CRI decrease (%), Deep River NM	5.43	2.55
03	CRI decrease (%), Climax NM	6.58	2.68
04	Dst – Index	−78.58	−41.26
05	AE – Index	624	374
06	Kp – Index	5.04	4.16
07	Solar wind velocity, V (km/s)	623	503
08	Magnetic field, B (nT)	13.72	14.08
09	Sigma B (nT)	6.46	8.29
10	Bz (nT)	−3.74	−0.64
11	V.B	8380	8466
12	V.Bz	−2934	−680

parameters during the disturbance has been done and the best correlation is obtained with dawn-to-dusk electric field (-VBz). These results support the fact that enhanced and efficient energy transfer from solar wind to the magnetosphere is due to magnetic reconnection.

After studying the interplanetary parameters responsible for geomagnetic storms and the mechanism of energy transfer responsible for GS, we have searched for the precursors that can be used for forecasting GS, some times in advance.

We have examined the precursors to Forbush decreases by analysing cosmic ray intensity recorded by three ground-based neutron detectors (see Figs. 1 and 2). The precursors to Forbush decreases are examined in association with the geomagnetic storms. The precursor to FDs of smaller amplitude ($< 5\%$) is the enhanced diurnal anisotropy, and to FDs of larger amplitude ($> 5\%$) is an intensity deficit of cosmic rays ('loss cone' type). Simultaneous analysis of solar wind, cosmic ray and geomagnetic data shows that precursors can be distinguished in terms of weaker and stronger interplanetary shocks responsible for Forbush decreases and geomagnetic storms.

A CME ejected from the Sun moving outward in the heliosphere with a speed larger than the ambient solar wind speed will produce shock/sheath region ahead of it; the shock front will hit the magnetosphere about 12–18 hours before the driving CME. As the shock reaches the ground it may produce Forbush decrease in cosmic ray intensity data and a geomagnetic storm may occur in the magnetic records almost at the same time or a few hours later. But precursors (enhanced diurnal anisotropy and cosmic ray intensity deficit) may be observed by neutron monitors many hours or even a few days before the onset of Forbush decrease and geomagnetic storm.

However, it is important that data from a number of neutron monitors, located at different latitudes and longitudes at Earth should be used to identify the precursors to FDs as all the stations may not show the precursors clearly (see Figs. 1 and 2).

It has been shown that the use of cosmic ray records in space weather research has practical application for its prediction. The observed precursors of Forbush decreases are enhanced diurnal variation and depletion of particles in a narrow loss cone. The enhanced diurnal variation of galactic cosmic ray is presumably due to an excess of

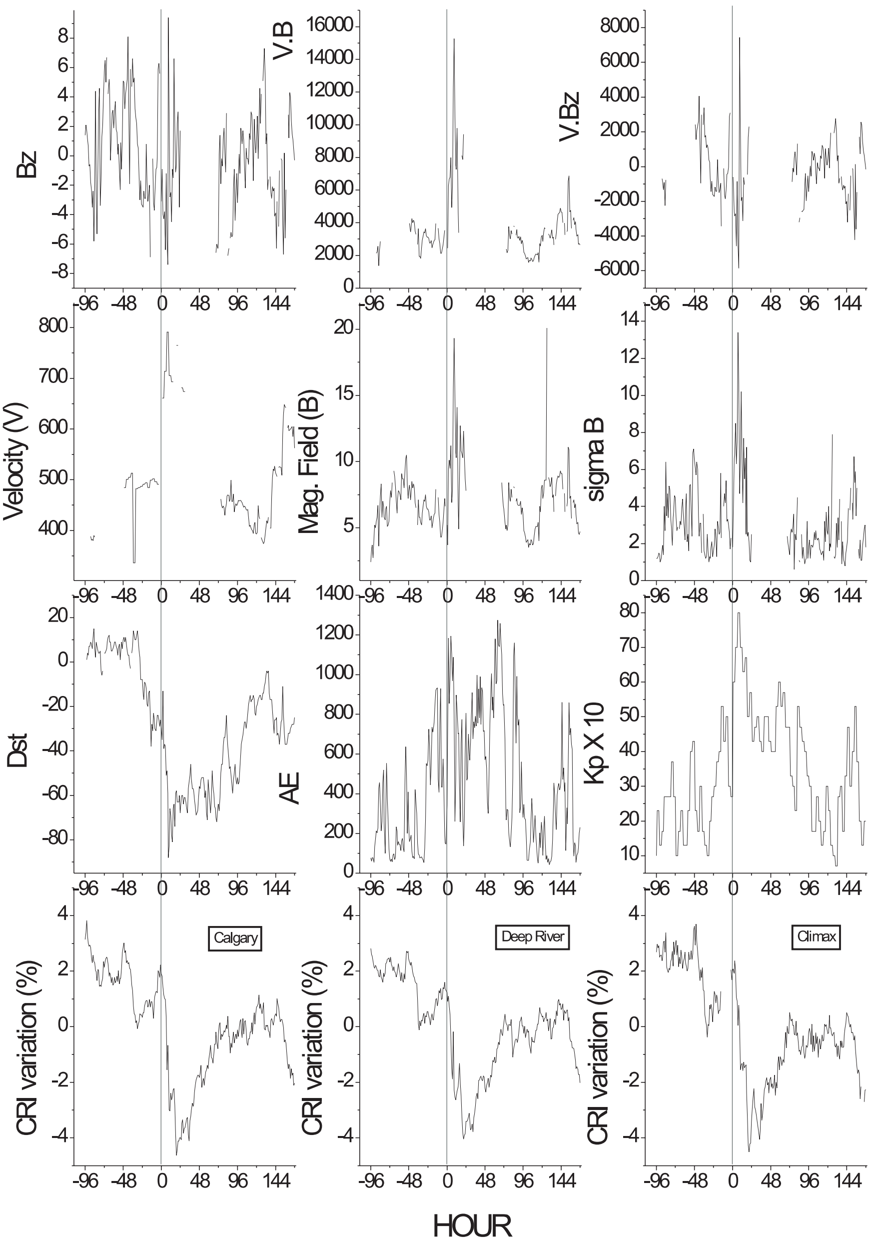

Figure 3. A typical event for Group I events (FD > 5%) showing variations in various parameters before and after the onset (zero hour) of FD. Loss cone type precursory decrease is clearly seen before the onset.

particles traveling towards the Sun along the IMF when interplanetary shocks are weaker. Cosmic rays in the loss cone, i.e., along a narrow range of pitch angles presumably originate in the cosmic ray depletion region, downstream of the approaching shock when the interplanetary events are stronger.

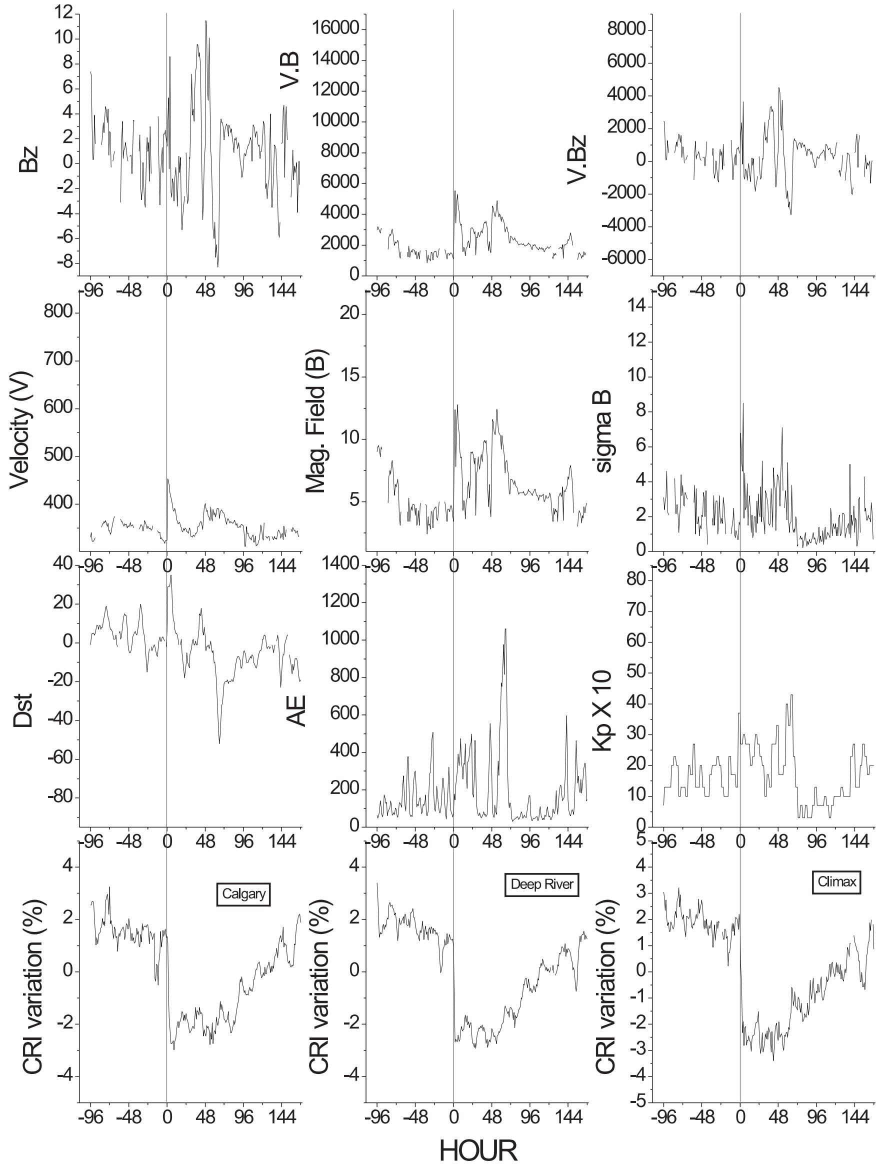

Figure 4. A typical event from Group II (FD < 5%) showing cosmic ray, geomagnetic and interplanetary parameters before and after the onset (zero hour) of FD < 5%, showing enhanced diurnal variation before the onset.

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