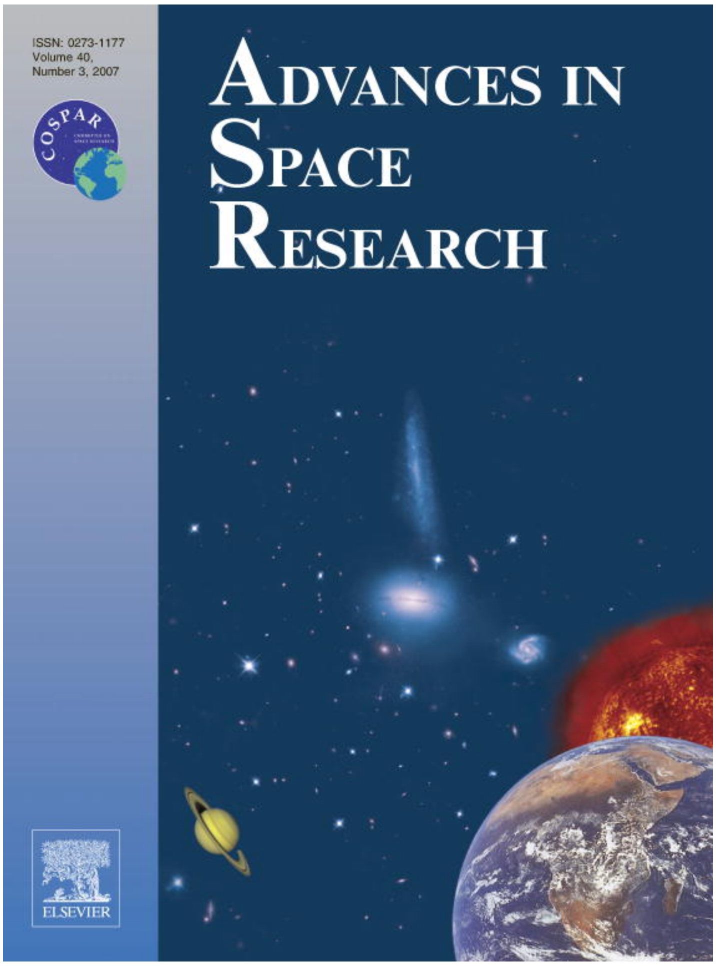
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Case study of Forbush decreases: Energy dependence of the recovery

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Abstract

Case study is presented for three Forbush decreases in 2004–2005, using cosmic ray data from ground-based detectors – neutron monitors and a muon detector. One of them was a typical event (September 2005), while two other were quite unusual (November 2004 and January 2005). Two unusual features, not expected from the standard theory, are revealed: (1) the recovery time of a Forbush decrease can strongly depend on the energy; (2) an over-recovery is observed in the most energetic cosmic ray data (muon detector). A simple scenario is suggested for the observed phenomenon.

Keywords: Forbush decrease; Cosmic ray; Neutron monitor

1. Introduction

Forbush decrease (FD) is a transient depression in the galactic cosmic ray (CR) intensity which is typically characterized by a sudden onset, reaching a minimum within about a day, followed by a more gradual recovery phase typically lasting for several days. The magnitude of FD varies from a few percent up to 25% in the neutron monitor energy range. FDs are usually caused by transient interplanetary events, which are related to coronal mass ejections. Main properties of FD are described, e.g., in recently review by Cane (2000). Here, we study isolated FDs produced by transient perturbation locally in the inner heliosphere, in contrast to step-like decreases caused by diffusive barriers (GMIRs) propagating in the outer heliosphere (see, e.g., Wibberenz et al., 1998).

Here, we are interested in the gradual recovery of FD. Its shape is close to an exponent in time and is characterized by the recovery time, τ (Lockwood et al., 1986). The time profile of the CR intensity I, may be approximated by the following function

$$\delta I \equiv \frac{I_0 - I}{I_0} = A \cdot \exp\left(\frac{t_0 - t}{\tau}\right), \quad (1)$$

where I_0 is the pre-event level and t_0 is the time when the recovery starts. This is illustrated in Fig. 1. The recovery time is about 5 days on average but may vary for individual events from 3 to 10 days. While the magnitude A of FD depends on the local geomagnetic rigidity cutoff of a detector (it is smaller for equatorial stations), the recovery time is expected to be similar for all detectors observing the same event, implying that it does not depend on CR energy. This fact has been reported by Lockwood et al. (1986) who analyzed a number of FDs observed by the world network of neutron monitors (NMs) during 1958–1984. Similar conclusion follows from the results by Mulder and Moraal (1986) (see Fig. 3 therein) based on a superposed epoch analysis of FDs. We are not aware of more recent experimental investigations of the energy (in)dependence of the FD recovery time. A recent empirical study of the dependence of the FD recovery time on the parameters of interplanetary disturbances (Penna and

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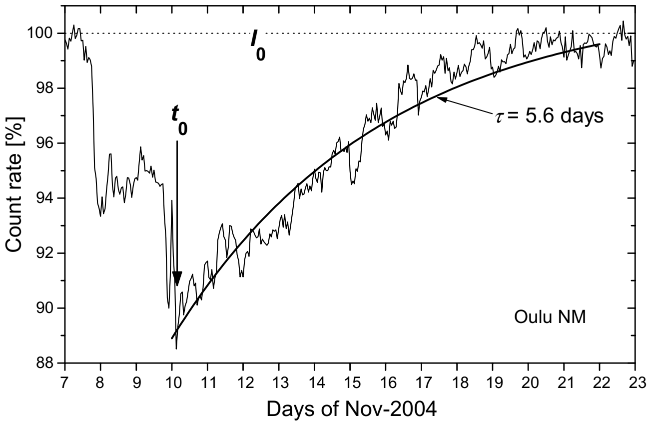

Fig. 1. Forbush decrease of November 2004 according to the Oulu NM data. The dotted line depicts the pre-event level I_0, and the thick line – the best fit exponential recovery with $\tau = 5.6$ days (see Eq. (1)).

Quillen, 2005) is based on data from a single NM and thus gives no information on the energy dependence. One expects the recovery time being independent on the energy of CR particles because it mainly depends on the decay of interplanetary disturbance and only secondly on the transport parameters of particles (Lockwood et al., 1986). This idea is consistent with the model computations (e.g., le Roux and Potgieter, 1991). On the other hand, Mulder and Moraal (1986) have shown, using the superposed epoch analysis, that the FD recovery time is related to the heliospheric magnetic field polarity. This result has been later confirmed by Rana et al. (1996) and Singh and Badruddin (2006). The dependence of τ on the polarity is explained by the effect of CR particles drift in the heliosphere, that implicitly depends on the energy of CR. This gives a hint at a possible relation between CR energy and the FD recovery time τ.

Here, we present a thorough analysis of the recovery time for three Forbush decreases during 2004–2005, which were recorded by a plastic scintillator muon detector (called MUG, see Section 2) as well as by the world network of NM (see Table 1).

2. Response of ground-based detectors

A neutron monitor is a standard ground-based cosmic ray detector with low pressure proportional counters filled

Table 1
Detectors and values of their geomagnetic rigidity cutoff P_c and median energy E_M

Detector	P_c (GV)	E_M (GeV)
MUG	1	55
Haleakala NM	13	27
ESO NM	8	17
Alma-Ata NM	6.6	15
Rome NM	6.2	14
Lomnicky Stit NM	3	12
Oulu NM	0.8	10

with BF_3 enriched with the ^{10}B isotope. There are two basic types of NM: NM-64 and IGY detectors, both are standardized. NM responds to the nucleonic (mostly superthermal neutrons and partly protons) component of the atmospheric cosmic-ray induced cascade. A specific yield function (detector's response per unit flux of primary cosmic rays with fixed energy E) of a sea-level NM-64 is shown in Fig. 2. This yield function $Y(E)$ was computed by Clem and Dorman (2000) using simulations of the full development of the atmospheric nucleonic cascade as well as the detector's own response function. On the other hand, muon detectors are not standardized and have different designs. Here, we analyze data from a plastic scintillator muon detector (called MUG), designed at the University of Oulu and located in Pyhäsalmi (63°39′N 26°02′E, Central Finland) on the ground level (Jämsén et al., 2001; Enqvist et al., 2005). The MUG experiment consists of two detectors: one at the ground level, whose data we use here, and another at 90 m underground (about 250 mwe). We do not consider here the latter one since FD cannot be separated over the statistical fluctuations of count rate at this depth. In order to calculate the yield function of the MUG we performed a full Monte-Carlo simulation of the cosmic-ray induced cascade in the atmosphere, with particular emphasis on the muon component. The simulation was done using the CORSIKA tool (Heck et al., 1998), specially developed for cosmic ray cascades in the atmosphere. Here we assume that the MUG detector detects (with equal efficiency) all muons which hit the detector. The resultant yield function is shown in Fig. 2a. One can see that the muon detector is sensitive to much higher energies of CR than a neutron monitor. However, in order to evaluate the actual sensitivity of a detector to CR one needs to account also for the rapidly decreasing energy spectrum of CR. Therefore, we computed also the differential response function F of the two detectors, which is a product of the yield function Y and the differential energy spectrum of CR J:

$$F(E,x,\phi) = J(E,\phi) \cdot Y(E,x), \quad (2)$$

where E is the CR kinetic energy, x is the atmospheric depth in the instrument location, and ϕ is the parameter defining the solar modulation of the CR spectrum (e.g., Caballero-Lopez and Moraal, 2004; Usoskin et al., 2005). The differential response function is shown, for both detectors, in Fig. 2b for the medium solar activity ($\phi = 500$ MV). The count rate of a detector is defined by an integral of the differential response function over kinetic energy E:

$$Q(x,\phi) = \int_{E_c}^{\infty} F(E,x,\phi) \cdot \mathrm{d}E, \quad (3)$$

where E_c is the kinetic energy corresponding to the local geomagnetic rigidity cutoff P_c.

We note that using E_c or the energy corresponding to the peak of F as a characteristic energy of the detector is not appropriate. Instead, it is common to use the so-called effective energy E_{eff} (Alanko et al., 2003) or the median

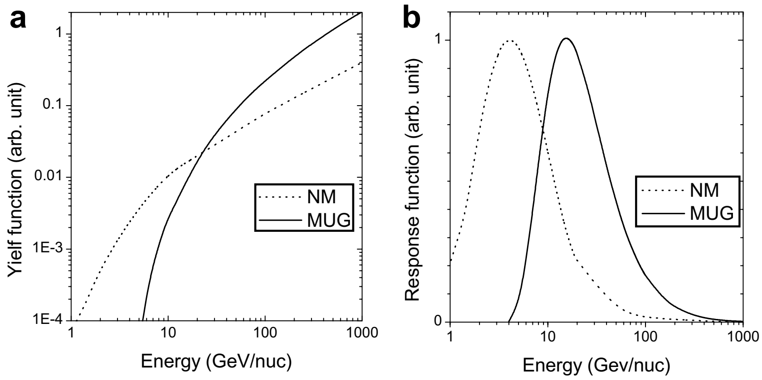

Fig. 2. (a) Yield function of the two ground-level detectors: MUG and a sea-level NM. (b) Differential response function of the two detectors for the medium solar activity.

energy E_M (e.g., Lockwood and Webber, 1996; Ahluwalia and Dorman, 1997). In this paper, we use the latter concept which is defined as the energy that halves the count rate Q in Eq. (3). Approximate values of E_M for the detectors used in this study are listed in Table 1.

3. Forbush decrease case studies

Here, we study three isolated strong FDs during 2004–2005. These events have been selected using the following criteria:

- The event was recorded by MUG in a stable mode;
- The level of cosmic rays was not largely disturbed at least several days before the onset of FD, so that the pre-event level can be clearly defined;
- The level of cosmic rays was not largely disturbed after the event so that the level to which the intensity has recovered can be estimated.

For each event studied here we found the recovery time as follows. First, we have defined the pre-event level using a quiet period before the disturbance onset. The pre-event base interval, whose exact duration is given in subsequent subsections, was taken the same for all the analyzed detectors. Next, a clear recovery period has been identified (removing, e.g., GLE or local "ejecta" effects – see Wibberenz et al. (1998)), and finally the recovery time has been defined by fitting the actually observed time profile of intensity with the exponential model (Eq. (1)), individually for each detector but for the same time interval (see subsequent subsections).

The recovery time is plotted, together with 1σuncertainties, in Fig. 3 versus the median energy of detectors (Table 1) for the three events studied here and will be discussed in the forthcoming Section.

3.1. November 2004

This event (Fig. 4) is interesting to study since the CR intensity was undisturbed during the entire October 2004 so that the pre-event level can be identified. The two-step FD started 08 Nov with the second step occurring on 10 Nov. The decrease was caused by a double transient interplanetary perturbation, initiated by two strong increases of IMF on 08 and 10 Nov, the solar wind speed did not exceed 800 km/s (see low panel). It took about a week to recover to the pre-event level.

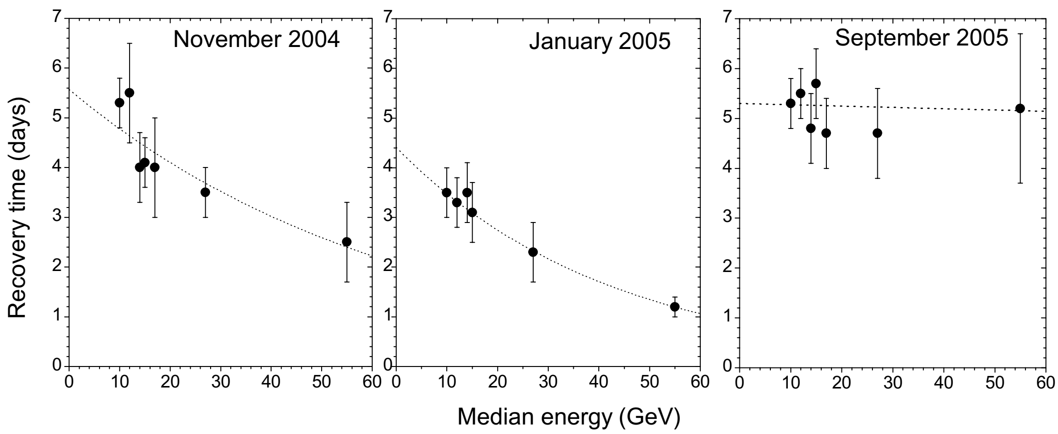

Fig. 3. Energy dependence of the recovery time for the three Forbush decreases studied here. Dots depict the recovery time, together with 1σ error bars, for different cosmic ray instruments with different median energy (see text), while the dotted line corresponds to the best-fit exponential law.

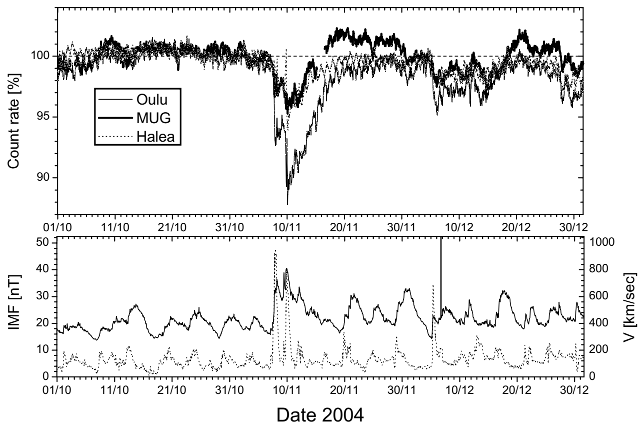

Fig. 4. Forbush decrease of November 2004. The upper panel depicts count rates of the ground-based detectors: MUG, Oulu NM and Haleakala NM. The lower panel shows variations of the IMF strength (dotted line, left axis) and solar wind speed (solid line, right axis).

The pre-increase basis interval was chosen as 07 Oct–07 Nov 2004. The recovery time was calculated for all detectors listed in Table 1 for the period 11–19 Nov 2004, as shown in the left-hand panel of Fig. 3. Two facts make this event of particular interest. First, the recovery time had strong dependence on the median energy, varying from 5.6 days for the Oulu NM (see Fig. 1) to 1.5 days for MUG. This is contrary to the expectations discussed above. Second, while the count rates of all NMs, including the tropical Haleakala station, recovered to the pre-event level, the MUG detector recorded the CR level exceeding the pre-event level by 1–2% during a fortnight, indicating an "over-recovering" of the CR flux after this FD. There was a gap in the MUG data during 15–16 Nov. caused by failure of the measuring computer, but we may securely say (using log-files and inter-calibration) that no off-set occurred during the gap. Variations of MUG data were nearly identical to the Haleakala count rate from 30 Nov until about 18 Dec. A recurrent suppression of CR level occurred with a 27-day delay with respect to the main event, and an over-recovering was again observed in MUG data, but for a shorter period – 3 days. A possible scenario for such an unusual behavior is discussed in Section 4.

3.2. January 2005

Another case study is related to the famous event of January 2005. The time profile of CR intensities is shown in Fig. 5 for different ground-based detectors. Although the CR level was varying in December 2004, and a minor CR suppression occurred in the beginning of January 2005, the period from 11 Jan till 17 Jan was quiet enough to establish the pre-event level. A major FD, caused by an transient interplanetary perturbation initiated by an interplanetary shock, started on 18 Jan. It was followed by a Ground Level Enhancement (GLE) on 20 Jan 2005, that was one of the strongest GLEs ever observed.

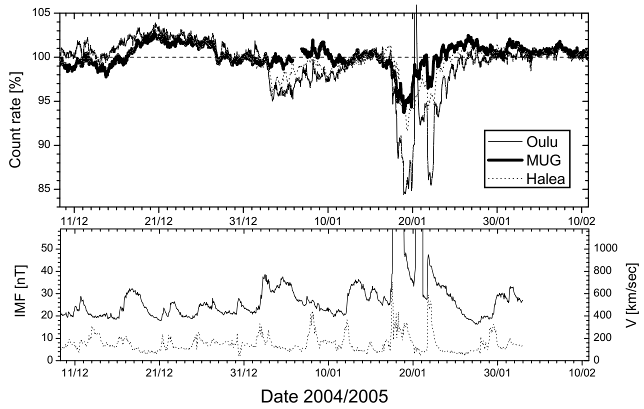

Fig. 5. Forbush decrease of January 2005. Notations are the same as in Fig. 4.

The pre-increase basis interval was chosen as 11 Jan–17 Jan 2005. The recovery time was calculated for all the detectors listed in Table 1, except for ESO NM (snow on the roof), for the period 19–23 Jan 2005, as shown in the middle panel of Fig. 3. The period with GLE (20 Jan 2005) has been removed from the fitting procedure. The recovery after this event was faster than for Nov 2004, but also shows a strong energy-dependence: τ took values from 1.2-day for MUG to about 3 days for mid- and high-latitude NMs. A small over-recovery (about 1%) of the MUG count rate was observed for a few days, but it was comparable to the magnitude of diurnal variations. There is also a hint at a small over-recovery in the Haleakala data, but it is not significant.

3.3. September 2005

The Forbush decrease of September 2005 (Fig. 6) was caused by an transient interplanetary perturbation initiated

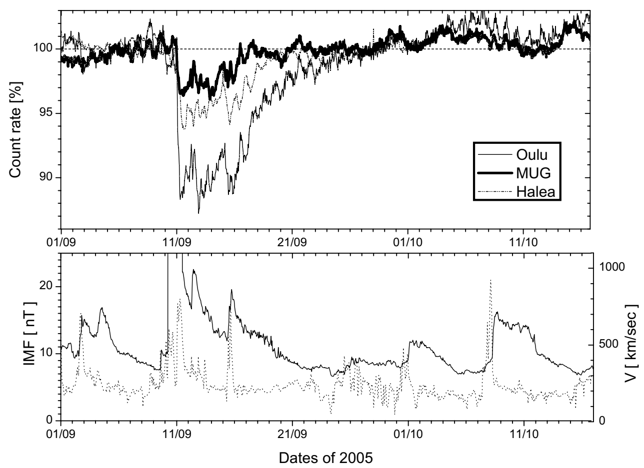

Fig. 6. Forbush decrease of September 2005. Notations are the same as in Fig. 4.

by an interplanetary shock passing the Earth on 10–11 September 2005. The depth of FD was different for different detectors – from 4% for MUG to 13% for the Oulu NM. The pre-increase basis interval was chosen as 02–10 Sep 2005. The recovery time was calculated for all detectors listed in Table 1 for the period 13–25 Sep 2005, as shown in the right-hand panel of Fig. 3. The recovery time for this events was almost constant for all the detectors, being about 5 days, in agreement with the theoretical expectations and earlier analyzes (e.g., Lockwood et al., 1986). Thus, this event is considered as a typical FD, whose recovery time does not depend on the characteristics energy of a detector.

4. Discussion and speculations

We have studied three FDs and found that one of them was a typical event (September 2005), while two other were quite unusual (November 2004 and January 2005). In particular, the recovery time of the latter two events appeared dependent on the median energy of CR detector, contrary to the expectations (Lockwood et al., 1986; Mulder and Moraal, 1986). Another interesting feature of the unusual events was an over-recovery of most energetic cosmic rays after the event. Here, we suggest a qualitative speculative scenario to understand such a non-trivial behavior.

A typical temporal scale of FD is about a week. This corresponds not only to the radial propagation of the disturbed region (interplanetary shock) to the distance of about 2 AU but also to the azimuthal displacement of Earth, due to the Sun's rotation, by about 90° with respect to the shock. This displacement may be comparable with the angular extend of the shock. Accordingly, the time profile of the FD recovery phase may be defined preferably not by the radial extension of the shock but rather by the azimuthal gradients of CR particles around the disturbed region. A schematic cartoon of the relative sun–earth-shock geometry is shown in Fig. 7 for the event of November 2004. The period before the FD was quiet since there were no disturbances in CR flux during the entire October 2004. Moreover, since the CR intensity remained at the high level after the FD recovery (period between marks 2 and 3 in Fig. 7), one can conclude that the large-scale disturbance, which caused this FD, was sole during the period under investigation. In about 27 days after the main FD, Earth again entered the same azimuthal region and a

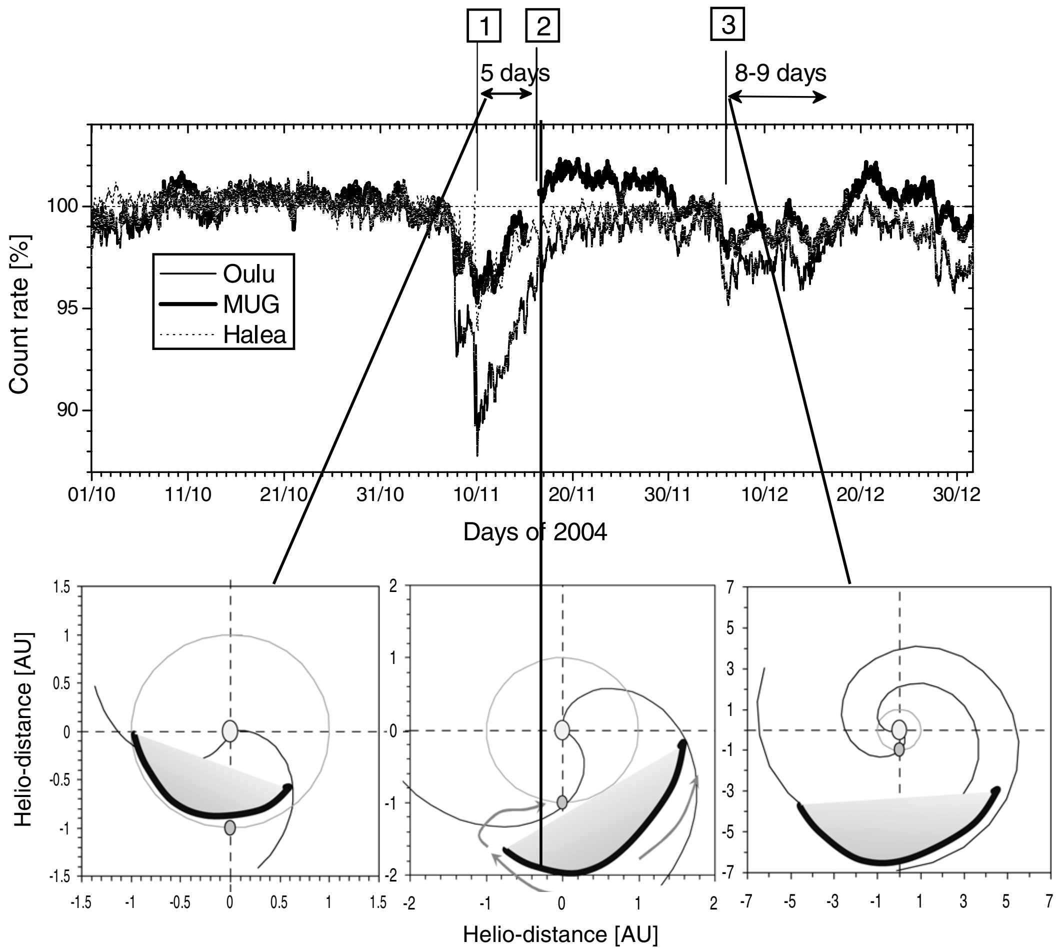

Fig. 7. Cartoon of a possible scenario for the event of November 2004. Upper panel is identical to Fig. 4 while the three incuts illustrate the relative geometry of the Sun (central dot), Earth (small dot at the grey circle denoting the Earth's orbit) and the shock (shaded object) during different phases of the event (see text). Arrows denote possible access of cosmic ray particles to the Earth. Note different scales in the incuts.

typical "recurrent decrease", usually associated with corotating high speed solar wind streams (Lockwood, 1971), was observed (mark 3 in Fig. 7). This suggests that this region was characterized by rarefaction of CR particles for at least one solar rotation period.

Enhanced intensity of high-energy CR (observed as over-recovery of the muon detector count rate) can be understood under the following assumption (see incut 2 in Fig. 7). High energy CR particles can experience an azimuthal drift in the foreshock region so that they can reach less disturbed (or undisturbed) magnetic lines and propagate along them. This results in a "focusing" or concentration of energetic CR from large area into a relatively small area next to the disturbed region. A hint for the over-recovery in muon data can be observed also after the recurrent decrease. We note that this azimuthal drift can be less effective for lower energy CR with smaller Larmor radius.

The above scenario does not pretend to offer a physical explanation of the observed phenomenon but rather a systematic empirical description. In order to understand the process in its full extend one needs to reconstruct the parameters of the disturbed region (shock, magnetic cloud, etc.) and perform a detailed modeling of particles' transport in its vicinity in a realistic 3D geometry. This is left to forthcoming studies.

5. Conclusions

We have studied three Forbush decreases in 2004–2005 by means of analyzing cosmic ray data from ground-based detectors – neutron monitors with different cutoff rigidities as well as a muon detector. Our analysis reveals two unusual features with the recovery of cosmic ray intensity, which were not expected from the standard theory and earlier studies.

(1) The recovery time in some events was found to be strongly dependent on the median energy of the detector – more energetic cosmic rays recover faster.
(2) An over-recovery (recovery of the cosmic-ray intensity to the level exceeding the pre-event level) is observed in the most energetic cosmic ray data (muon detector).

We suggest a simple scenario which might be responsible for the observed phenomenon. A more detailed study, including detailed reconstruction of the relative 3D geometry and full modeling of the particle transport, is needed for these events.

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