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# Forbush decreases: Energy dependence of the recovery

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**Abstract:** We present a statistical study of major Forbush decreases during the last decades, using cosmic ray data from ground based detectors – neutron monitors and ground-level muon telescopes. We show that most of clear Forbush decreases depict the recovery time which strongly depends on the mean response energy of the detector. This is in contrast to some earlier results, based on a poorer statistical study and/or simplified theoretical consideration. Such a behavior is not expected from the 2D standard theory of a Forbush decrease, and it implies a need for a more detailed model.

## Introduction

Forbush decreases (FDs), sudden sharp decreases of the cosmic ray intensity followed by a gradual nearly exponential recovery, are known since long and form an interesting phenomenon. It is qualitatively understood to be caused by a transient interplanetary shock, but a detailed quantitative model is still missing. While the magnitude and general shape of a FD can be realistically modeled by a 1D or 2D models (e.g., [1, 3]), there are much uncertainties regarding the recovery time. E.g., a thorough analysis of some Forbush decreases in 1957-1969 [5, 6] yielded that the recovery rate of FDs is in some cases faster for stations with higher cut-off rigidity. On the other hand, later studies suggest that there is no [2] or little [3] energy dependence of the FD recovery time. A simple 1D or 2D theory predicts that, while the magnitude of a FD strongly depends on the detector's effective energy, the recovery rate should be the same for all detectors [1, 2, 3, 7]. Thus, the question of the recovery rate of FD is still open. Most of earlier studies were based on analyses of a few detectors, either neutron monitors (NMs) or muon telescopes (MT). We note that MT has a higher effective energy than even an equatorial NM, and provides more solid results. Here we present results of a thorough study of FD recovery time for ten major FDs during recent years and from the 1970's, using all the available data from the NM network as well as from ground-level MTs. A full study is under way.

## Data and Analysis Method

We use data from all the NMs available in the WDC-C for a particular event as well as from two ground-level muon telescopes: MUG in Finland and YMT in Yakutsk (Russia). As a characteristic energy of each station we used the median energy $E_{\rm M}$, which halves its response function. The median energy varies between 10 GeV and 30 GeV for NMs and is about 55 GeV for a muon telescope [4]. Here we analyzed only clear FDs, i.e., isolated events with a large enough magnitude (more than 5% in the polar region) and a clear recovery phase. For each such FD we selected all the stations with data covering the recovery phase without apparent errors (gaps, sudden jumps caused, e.g., by snow accumulation/melting, etc.). The number of used station is shown in Table 1 and is above 30 in all studied cases, securing thus good statistics. In order to avoid the influence of diurnal variation, that are usually strong on the recovery phase, we used daily averaged count rates.

Next, we fit the count rate of each individual detector (NM or MT) during the period of the recovery (see Table 1) with an exponential recovery function

$$I = I_0 - A \cdot exp\,(-t/\tau), \qquad (1)$$

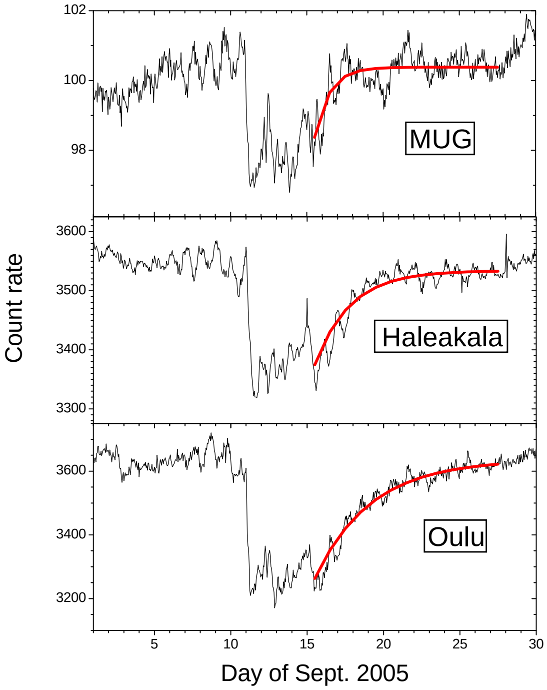


Figure 1: Count rates of MUG, Haleakala NM64 and Oulu NM for September 2005 together with the best-fit exponential recovery (thick lines) after the Forbush decrease.

where the best-fit recovery time $\tau$ is found by the least square method varying free parameters $I_0$ and $A$. In order to evaluate the robustness of the results with respect to the selected time interval and data quality, we performed a boot-strap test. We removed randomly 1 or 2 daily points from the fitted data, and computed the new value of $\tau_j$. We repeated this 100 times to find the distribution of $\tau_j$ which is then fitted by a Gaussian as $\tau^* \pm \delta_\tau$. Note that $\delta_\tau$ evaluates the robustness of the thus obtained recovery time. This procedure is repeated separately for all the selected stations for the given FD, providing us with a set of the recovery time estimates $\tau_i^* \pm \delta_{\tau i}$, where the index $i$ stands for $i^{\text{th}}$ detector. Finally, the dependence of $\tau_i^*$ vs. $E_{\text{M}i}$ for the studied FD is plotted (fig. 2) and approximated, using the weighted least square method, by an exponent

$$\tau^* = B \cdot \exp\left(-\alpha E_{\text{M}}\right). \tag{2}$$

The value of $\alpha$ defines whether (and how strong) does the recovery time depend on the effective energy of a detector: $\alpha > 0$ implies faster recover with energy, $\alpha = 0$ - independence on the energy, and $\alpha < 0$ slower recover with energy. The values of $\alpha$, together with their uncertainties, are shown in Table 1 for two cases: when only data from NMs ($\alpha_{\text{NM}}$), and from both NMs and MT are considered ($\alpha_{\text{NM+MT}}$).

For illustration of the method we present an analysis of the FD of September 2005. The time profile of the FD is shown in Fig 1 for three detectors: MUG ($E_{\text{M}} = 55$ GeV), Haleakala NM ($P_{\text{C}} \approx 13$ GV, $E_{\text{M}} \approx 27$ GeV) and Oulu NM ($P_{\text{C}} = 0.8$ GV, $E_{\text{M}} \approx 10$ GeV). The recovery time is defined for the period of 15–27 Sept 2005 (i.e. 13 days). Thick lines depict the best fit recovery (Eq. 1) with $\tau = 1$, 2.3 and 3.67 days for MUG, Haleakala and Oulu, respectively. This event depicts a strong energy dependence of the recovery time (from 1 day for MUG up to 4–5 days for polar NMs). Moreover, the results with only NMs and NM+MT are totally consistent with each other (see Table 1) and are robust with respect to the interval selection.

## Results

The best-fit recovery times $\tau_i^*$, together with their uncertainties $\delta_{\tau i}$, are shown in Fig. 2 for all 10 analyzed events as a function of $E_{\text{M}i}$ as well as the best-fit exponent of Eq. 2. The results are summarized in Table 1. FDs of Dec 2006, Sep 2005, May 2005 and May 1978 depict a clear energy dependence. Data suggest for an energy dependence of the recovery time for the events of Nov 2004, Nov 2003 and Aug 1972, but at a low level of significance. FD of Jan 2005, Jun 2003 and Mar 1978 are consistent with an idea of the constant energy-independent recovery.

## Conclusions

We have presented the results of a statistical analysis of the recovery time of major Forbush decreases recorded by ground based neutron monitors and muon telescopes. This study is limited to 10 events but a full study is under way. We found a clear energy-dependence of the recovery time for four out of ten events, and a less significant dependence in other three events. In all these seven cases the

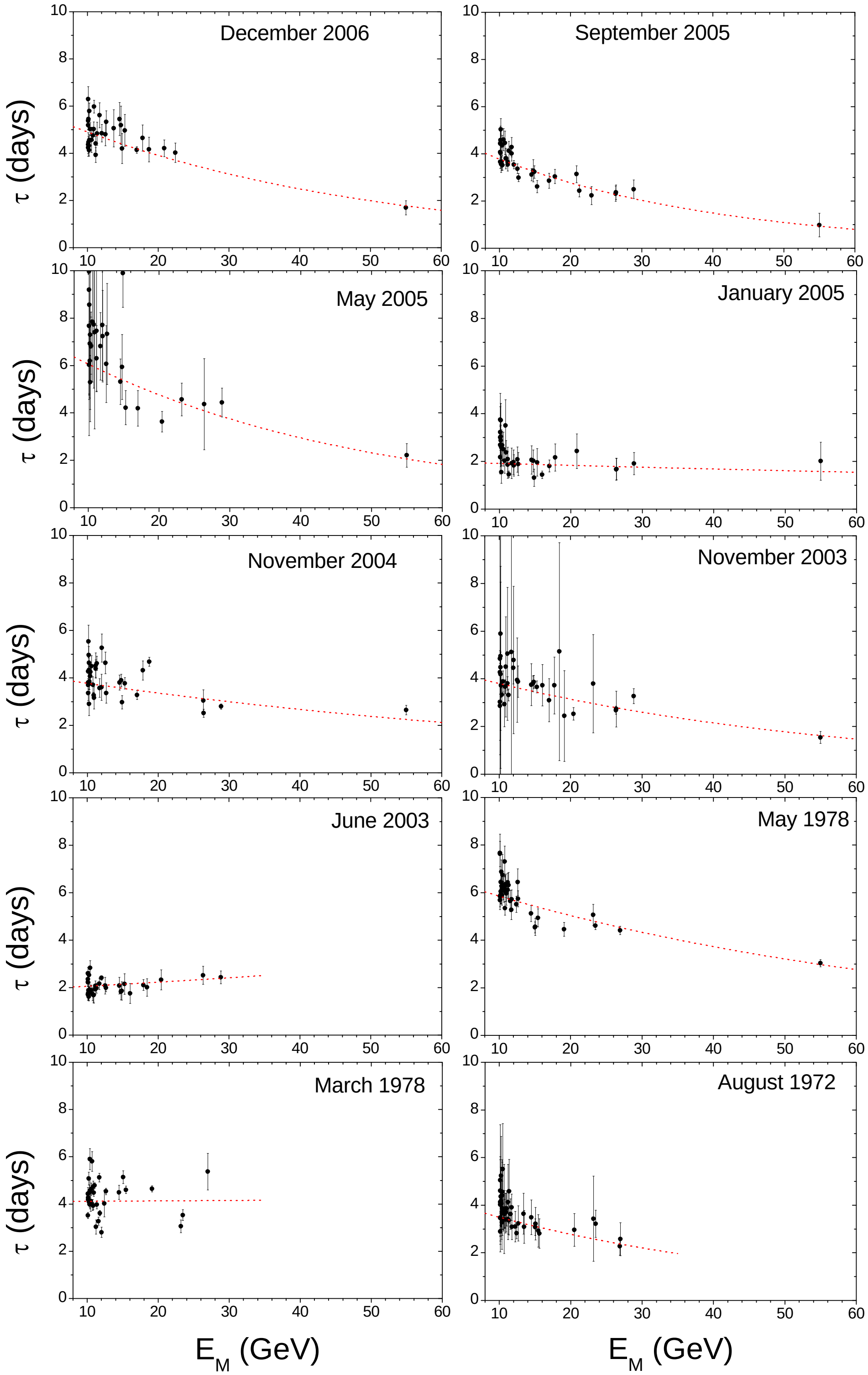


Figure 2: The recovery time $\tau$ as a function of the median energy $E_{\mathrm{M}}$ of individual detectors. The dotted line represents the best fit exponential functions.

Table 1: Parameters of the FD recovery time energy dependence (see text for details).

| Event | period of recovery | $\alpha_{\mathrm{NM}}$ (GeV$^{-1}$) | $\alpha_{\mathrm{NM+MUG}}$ (GeV$^{-1}$) | Used dataset |
|---|---|---|---|---|
| Dec 2006 | 15–26/12[a] | 0.016±0.017 | $0.023 \pm 0.007$ | 33NM+MUG |
| Sep 2005 | 15–27/09 | $0.032 \pm 0.010$ | $0.031 \pm 0.008$ | 35NM+MUG |
| May 2005 | 16–29/05[b] | 0.033±0.03 | 0.024±0.013 | 32NM+MUG |
| Jan 2005 | 21–27/01[c] | 0.009±0.016 | 0.004±0.012 | 36NM+MUG |
| Nov 2004 | 12–23/11 | $0.017 \pm 0.006$ | $0.012 \pm 0.004$ | 35NM+MUG |
| Nov 2003 | 31/10–12/11[d] | 0.018±0.010 | $0.019 \pm 0.006$ | 37NM+MUG |
| Jun 2003 | 31/05–09/06 | $-0.008 \pm 0.015$ | - | 34NM |
| .. | .. | .. | .. | .. |
| May 1978 | 02–15/05[e] | $0.021 \pm 0.010$ | 0.016±0.004 | 39NM+YMT |
| Mar 1978 | 11–22/03 | $0 \pm 0.01$ | – | 34NM |
| Aug. 1972 | 05–19/08 | $0.023 \pm 0.020$ | – | 52NM |

[a] For MUG 15–20/12/2006. [b] For MUG 16–20/01/2005.
[c] The event of 22/01/2005 was removed. [d] For MUG 31/10–06/11/2003.
[e] GLE of 07/05/1978 was removed.

count rate of detectors with higher effective energy recovers faster. In three cases, no energy dependence of the recovery time is found.

Therefore, we conclude that the recovery of cosmic ray intensity after a Forbush decrease does depend on the energy of cosmic rays in most, but not all cases. This is in qualitative agreement with some earlier results (e.g., [5, 6]) but in contrary to some other empirical results and simplified models (e.g., [1, 2, 3, 7]). This verifies a need for a more detailed phenomenological study and a proper modeling of the Forbush decreases.

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## References

[1] Le Roux, J.A., M.S. Potgieter, The simulation of Forbush decreases with time-dependent cosmic-ray modulation models of varying complexity, *Astron. Astrophys.* 243: 531, 1991.

[2] Lockwood, J.A., W.R. Webber, J.R. Jokipii, Characteristic recovery times of Forbush-type decreases in the cosmic radiation. I - Observations at earth at different energies, *J. Geophys. Res.* 91: 2851, 1986

[3] Lockwood, J.A., W.R. Webber, H. Debrunner, The rigidity dependence of Forbush decreases observed at the Earth, *J. Geophys. Res.* 96: 5447-5455, 1991.

[4] Jämsén T., I.G. Usoskin, T. Räihä et al., Case study of Forbush decreases: Energy dependence of the recovery, *Adv. Space Res.* 2007 (in press).

[5] Östman, B., Studies of the recovery part of cosmic ray storms, *Arkiv för Geofysik* 5 (25): 387-399, 1968.

[6] Östman, B., The recovery rate and the energy dependence of decreases of the cosmic-ray intensity during the years 1957-1969, *Arkiv för Geofysik* 6: 549, 1969.

[7] Wibberenz, G., J.A. Le Roux, M.S. Potgieter, J.W. Bieber, Transient effects and disturbed conditions, *Space Sci.Rev.* 83: 309-348, 1998.