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Magnetospheric effects on cosmic rays during the magnetic storm of March 2015

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magnetic storm; rigidity; magnetospheric effects

Abstract

Cosmic ray variations of magnetospheric origin during the magnetic storm on 17th of March 2015 were studied. Cosmic ray intensity data were obtained from the neutron monitor database (NMDB) and the data of the Dst index were taken from World Data Center for Geomagnetism, Kyoto. The global survey method was employed for the calculation of changes in the cutoff rigidities throughout the storm. A correlation analysis between the Dst index and the calculated cutoff rigidity variations was performed for each cosmic ray station. The most essential decrease in cutoff rigidities occured when the Dst index was around the value of -234nT. A latitudinal distribution of the cutoff rigidities was acquired, showing that the maximum effect took place at mid-latitude stations with rigidities around 8-10GV. During the examined event the maximum change in cutoff rigidity was observed at Athens station where the decrease of the cutoff rigidity reached the value of 1.07GV. Furthermore, corrections of cosmic ray intensity due to the magnetospheric effect were calculated using the derived cutoff rigidities showing a discperancy with the observed values at mid- and low- latitude stations.

1. Introduction

Ground level cosmic ray measurements are affected by disturbances in the Earth's magnetosphere during magnetic storms. The variations in the Earth's magnetic field can alter the charge particle trajectories to such an extent that allowed trajectories become forbidden and vice versa. This has an effect on ground-level observations by changing 1) the effective cutoff rigidities and 2) the asympotic directions of particles. For galactic cosmic rays (GCR) the first effect is the most dominant. The changes in the cutoff rigidities during magnetic storms can alter the behaviour of the observed cosmic ray intensity for a fixed station.

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In this work we studied the magnetospheric effect during the magnetic storm on the 17th March 2015, which was the biggest storm during Solar Cycle 24.
The study of such events is very important for two major reasons:

1. Firstly, from a methodological point of view as these effects hinder the discrimination of primary cosmic rays variations.
2. Secondly, analysis of CR variations due to magnetospheric effects can be used to independently validate current system models during all phases of a magnetic storm. At the initial phase of the storm, which is associated with the magnetopause current system, the cutoff rigidity *R*c increases relative to the quiet level, while during the main phase of the storm *R*c decreases significantly. The latitudinal and longitudinal dependences of these effects reveal themselves in different ways. Cutoff rigidity variations during the main phase of the storm, which are connected to the ring current system, have a negligible dependence on longitude due to the ring symmetry. Conversely, the cutoff rigidity variations during the main phase of the storm depend significantly on latitude.

In this work a detailed study of the magnetospheric effect in cosmic rays during the major magnetic storm on 17 March 2015 has been conducted.

2. Solar activity on March 2015

The period preceding the magnetic storm of 17 March 2015 was particularly disturbed. On the 11th of March there was a X2.1 solar flare that was followed by a series of weaker flares. On the 15/03 a long duration C9 solar flare occured at the sunspot region 2297 with a commencement at 01:15UT. The C9 flare launched a partial halo Coronal Mass Ejection (CME) that arrived at Earth around 04:00UT on the 17th. The result was a major G4 magnetic storm with the Dst index reaching a minimum value of -234nT. Aurora was observed at unusually low latitudes (https://www.spaceweatherlive.com/en/solar-activity.html, last accessed June 27, 2023).

3. Data and method

Hourly data from 21 stations from the Neutron Monitor Database (NMDB) have been employed in the analysis: 8 high-latitude (*R*c < 1.2GV), 13 mid and low-latitude stations. The mid- and low- latitude stations used have a cutoff rigidity range of 2.36GV-9.15GV. The Dst-index for March 2015 was taken from the World Data Centre for Geomagnetism, Kyoto (https://wdc.kugi.kyoto-u.ac.jp/dst_final/index.html, last accessed June 27, 2023).

The Global Survey Method (GSM), which is developed by IZMIRAN, was used for the calculations of the cutoff rigidity variations. The GSM is essentially a version of spherical analysis.

In this method we use the measured ground-level cosmic ray variations to derive a set of parameters connected to the galactic cosmic ray density and anisotropy.

Generally, the measured cosmic ray variations at each neutron monitor can be written as:

$$\frac{\delta I^i}{I^i_o} = \delta^i_{isot} + \delta^i_{anisot} + \delta^i_{err} \quad (1),$$

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where δ^i_{isot} and δ^i_{anisot} are the isotropic and anisotropic components of the CR variations out of the magnetosphere and δ^i_{err} the residual dispersion, which is related to possible variations due to the apparatus and the inadequate utilisation of the model.

The CR intensity out of the magnetosphere (isotropic and anisotropic part) like any function can be expressed by the expansion in spherical harmonics. Assuming only the first order harmonics for the anisotropy :

$$\delta_i = \int_{R_c}^{\infty} \frac{\delta J(R)}{J} \cdot W(R, Rc, hi) \mathrm{d}R + C_x a_x + C_y a_y + C_z a_z \tag{2}$$

where C_i are the coupling coefficients, a_x ,a_y , a_z are the three components of the first harmonic of the CR anisotropy and where $\frac{\delta J}{J} = a_o R^{-\gamma}$ is the rigidity dependence of CR density variations and W(R, Rc, hi) is the response function for a NM, located at an altitude hi with a cutoff rigidity Rc.

The system of equations (1) is solved using the least squares method relative to the unknown parameters ao, γ, a_x ,a_y , a_z. In our approach we employed a two-step method for the calculations. In the first step we solved the set of eq. (1) for the 8 high-latitude stations, where we can disregard the geomagnetic effect since W(R, Rc, hi) is negligible for small Rc, and therefore eqs.(1) practically reduces to eqs.(2). In the next step we employed the derived set of parameters from the first step to correct the mid- and low-latitude stations for the variations due to the magnetospheric effect.

In our analysis, we worked seperately with the residual dispersions δ^i_{err}, which can be expressed as:

$$\delta^i_{err} = \delta^i_{mag} + \delta_{mod} + \delta^i_H + \delta^i_L \tag{3}$$

The CR variation due to the magnetospheric effect can be written as $\delta^{\,i}_{mag} = -\delta R^{\,i}_c \cdot W(R^{\,i}_c, h^{\,i}_O)\left(1 + \frac{\delta J}{J}(R^{\,i}_c)\right)$, δ_{mod} is connected to the inanequacy of the CR variation model (form of rigidity spectrum, contributions from higher order harmonics), δ^i_H is the error due to the statistical accuracy of the data and δ^i_L is the low-frequency component due to the possible apparatus drift. The last two terms of eq. (3) can easily be ignored if we pay particular attention to the good quality of data and δ_{mod} can also be neglected as it does not have a particular longitudinal and latitudinal distribution which is characteristic of the geomagnetic effect. Thus, we can assume that the residual disperancies arise only from the magnetospheric effect ($\delta^i_{err} \cong \delta^i_{mag}$) such that:

$$\mathrm{d}R^i_c = \frac{-\delta^i_{mag}}{W(R^i_c, h^i_0)\left(1 + \frac{\delta J}{J}(R^i_c)\right)} \tag{4}$$

In this way, we calculated the cutoff rigidity variations at different instances during the event and at different stations independently from one another.

4. Results and discussion

Cosmic ray variations due to the magnetic storm on 17 March 2015 were evaluated using data from the worldwide neutron monitor network and the global survey method (GSM) as decribed above. In Fig.1 the uncorrected (upper panel) and corrected (lower panel) variations of the cosmic ray intensity data are presented for two polar stations (Mc-Murdo and Apatity) and two non-polar ones (Athens and Tsu-

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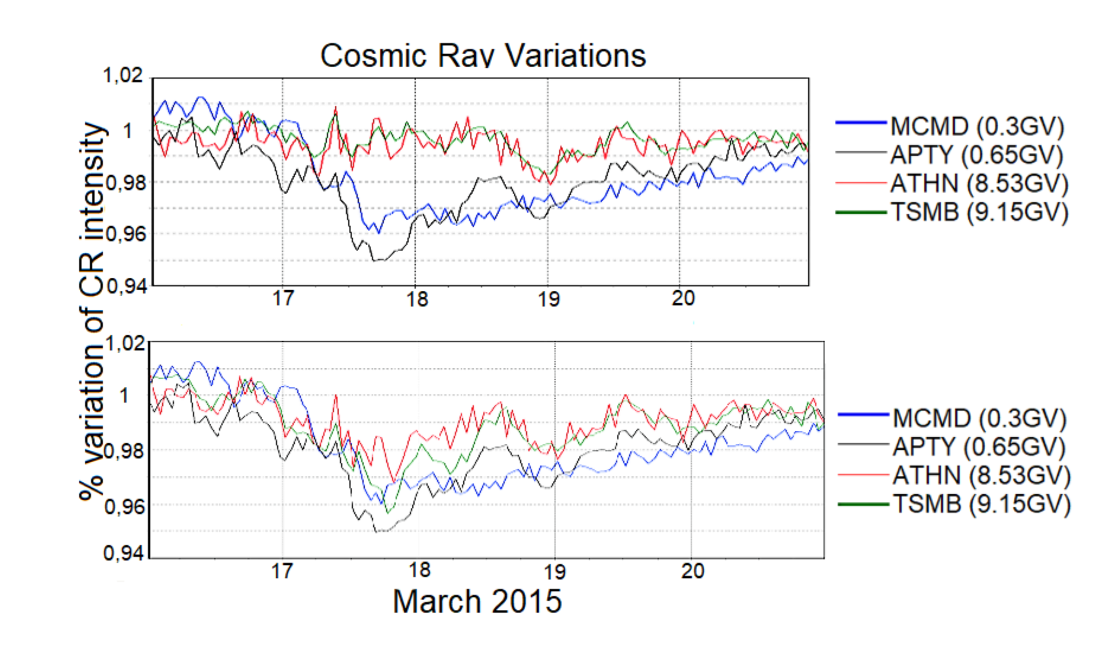

Fig. 1: Uncorrected (upper panel) and corrected (lower panel) CR variations for the magnetospheric effect for two polar station (MCMD and APTY) and non-polar stations (ATHN and TSMB).

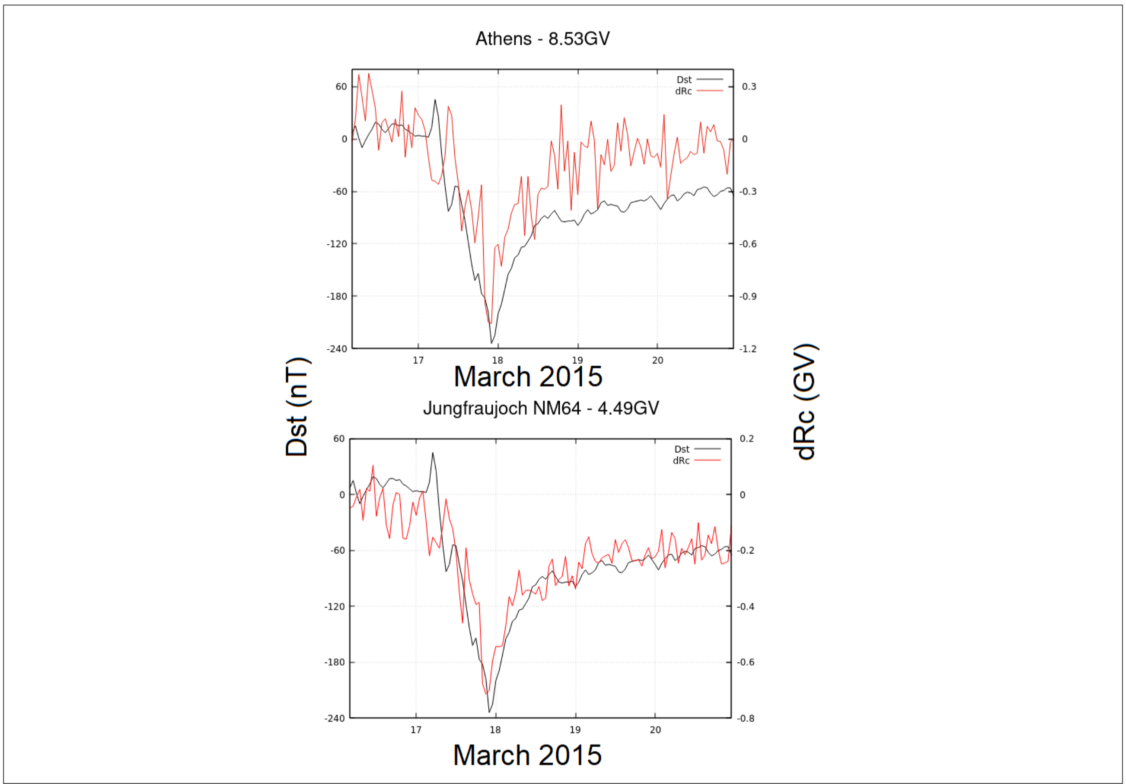

Fig. 2: Derived cutoff rigidity variations dRc and Dst indexes at Athens (ATHN) and Jungfraujoch (JUNG1) stations during the magnetic storm on 16-21 March 2015.

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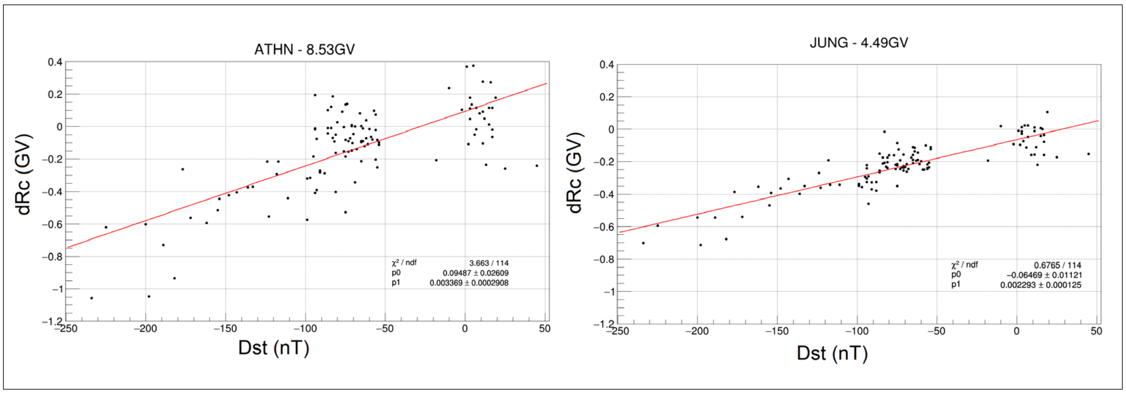

Fig. 3: Examples of regression diagrams for two stations (ATHN and JUNG1) during the magnetic storm on 16-21 March 2015.

meb). The polar and non-polar stations in the uncorrected panel have different time profiles during the magnetic storm. Specifically, for polar stations (*R*c< 1.2GV) we observe a decrease in cosmic ray intensity of a magnitude of 3-4%, whereas this decrease is either diminished or masked completely at mid- and low-latitude stations. After the cosmic ray data are corrected for the magnetospheric effect, mid and low latitude stations (for e.g. Athens) show a similar decrease in intensity. It is evident from the comparison of the corrected and uncorrected cosmic ray graphs that the magnetoshperic effect may hinder the discrimination of the primary cosmic ray intensity.

The cutoff rigidity changes were evaluated for each Neutron Monitor throughout the storm using the above method. A high correlation between the Dst index and the cutoff rigidity changes was observed during the period under consideration, as shown by the diagrams in Fig. 2. The maximum change in *R*c is observed at 22:00 UT and coincides with the *Dst* minimum (*Dst*=-234nT) for the majority of stations. Furthermore, lower latitude stations (eg.Athens and Tsumeb) showed a higher sensitivity to the magnetospheric effect than midlatitude stations. As an example the station at Athens reached a minumum d*R*c value of -1.07GV compared to -0.7GV at Jungfraujoch (JUNG1) station. It has to be noted here, that during the period 15-17 of March 2015 the atmospheric conditions at the Junfraujoch Neutron Monitors were very turbulent which might have had a minor effect on our results. The maximum effect was observed at stations with a cutoff rigidity of 8-10GV.

Regression diagrams between the Dst-index and the d*R*c were plotted, revealing an approximately linear dependence during the storm. The regression coefficient for Athens is 0.0034GV/nT whereas for Jungfraujoch it is 0.0023GV/nT. The latitudinal distribution of cutoff rigidity variations versus the *R*c was evaluated for various instances during the main and recovery phases of the storm as shown in Appendix C. In Fig. 4 four such graphs are depicted for different phases during the event. Diagram (a) represents the results before the storm arrival while the *Dst*=25nT and where we can observe no significant changes in cutoff rigidities. In graph (b), which represents the commencement of the main phase of the storm, we observe a slight decrease in *R*c values, while in graph (c) representing the latitudinal distribution during the maximum of the storm, we observe the maximum variations in cutoff rigidities. Specifically, the maximum effect is observed at lower latitude stations with cutoff rigidities in the range of 8-10GV as previously mentioned. Finally, after the main phase of the storm as shown in diagram (d) the cutoff rigidity values start to recover to their pre-storm values. The latitudinal distribution could have been better observed if a wider range of stations was employed (esp. subeqatorial stations with *R*c>10GV which are absent from our data).

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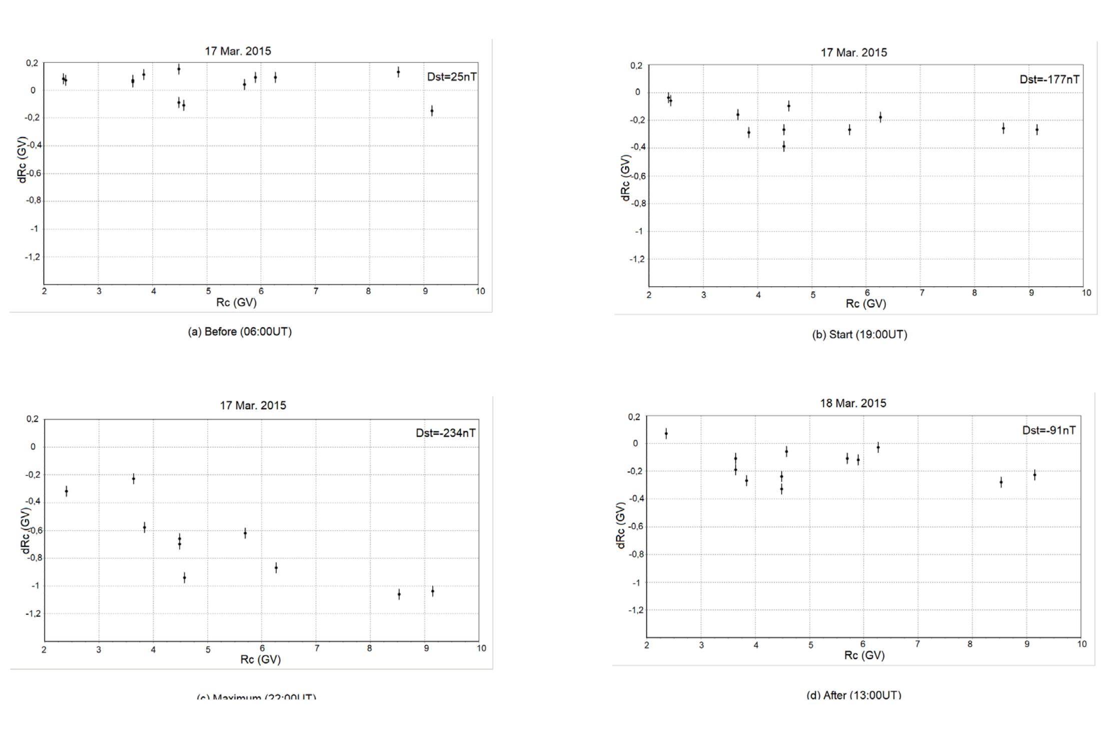

Fig. 4: Cutoff rigidity variations (d*R*c) versus the cutoff rigidities (*R*c) for different instances on 17-18 of March 2015.

5. Conclusions

From the above analysis, we can conclude the following:

1. The maximal magnetospheric effect in CR was recorded at lower latitude stations, but not at mid-latitude stations as is the common case. Due to this anomaly the maximum change of the geomagnetic cutoff rigidity shifted from the usual values of 3-5GV to 8-10GV.
2. Variations in cutoff rigidity reached -1.07GV for Athens and -1.04GV for Tsumeb.
3. The latitudinal dependence of cutoff rigidity variations was obtained for each hour during the main and recovery phases of the geomagnetic storm. This is very useful for analysing the dynamics and evolution of the ring current system.

Acknowledgements

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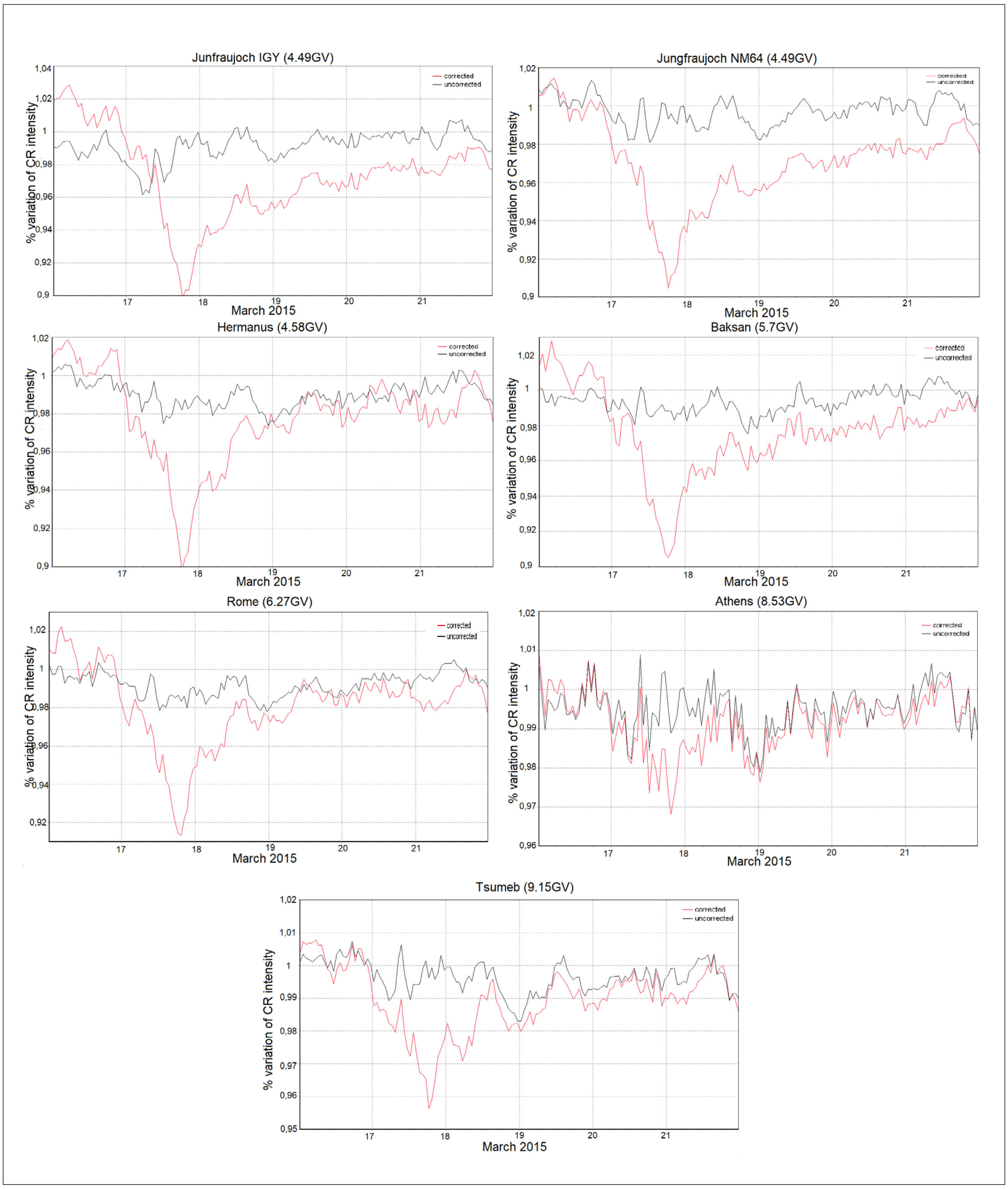

Appendix A: Cosmic ray variations for mid- and low latitude stations: uncorrected (black line) and corrected (red line).

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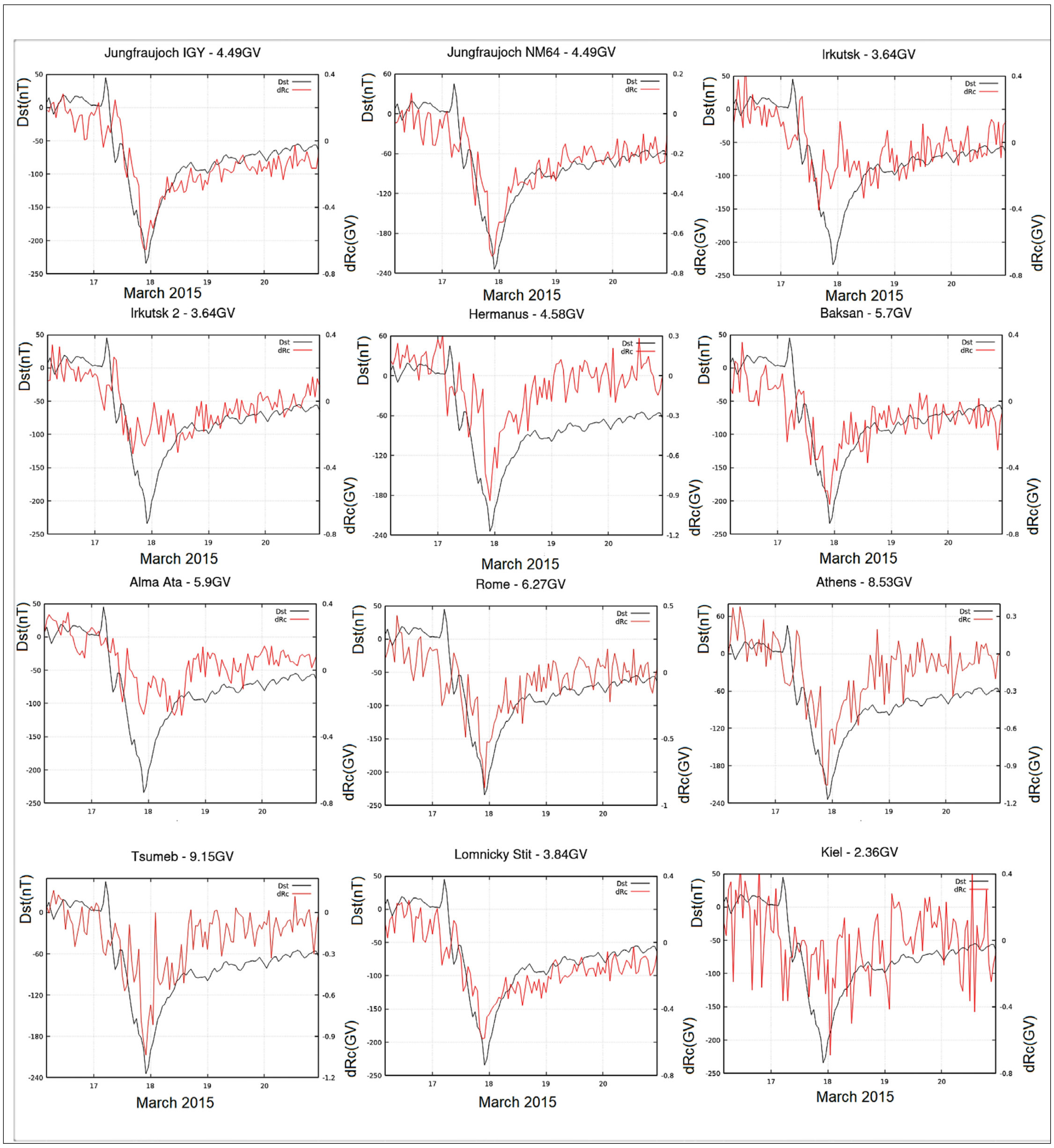

Appendix B: Cutoff rigidity variations and Dst index from 2015/03/16 to 2015/03/21.

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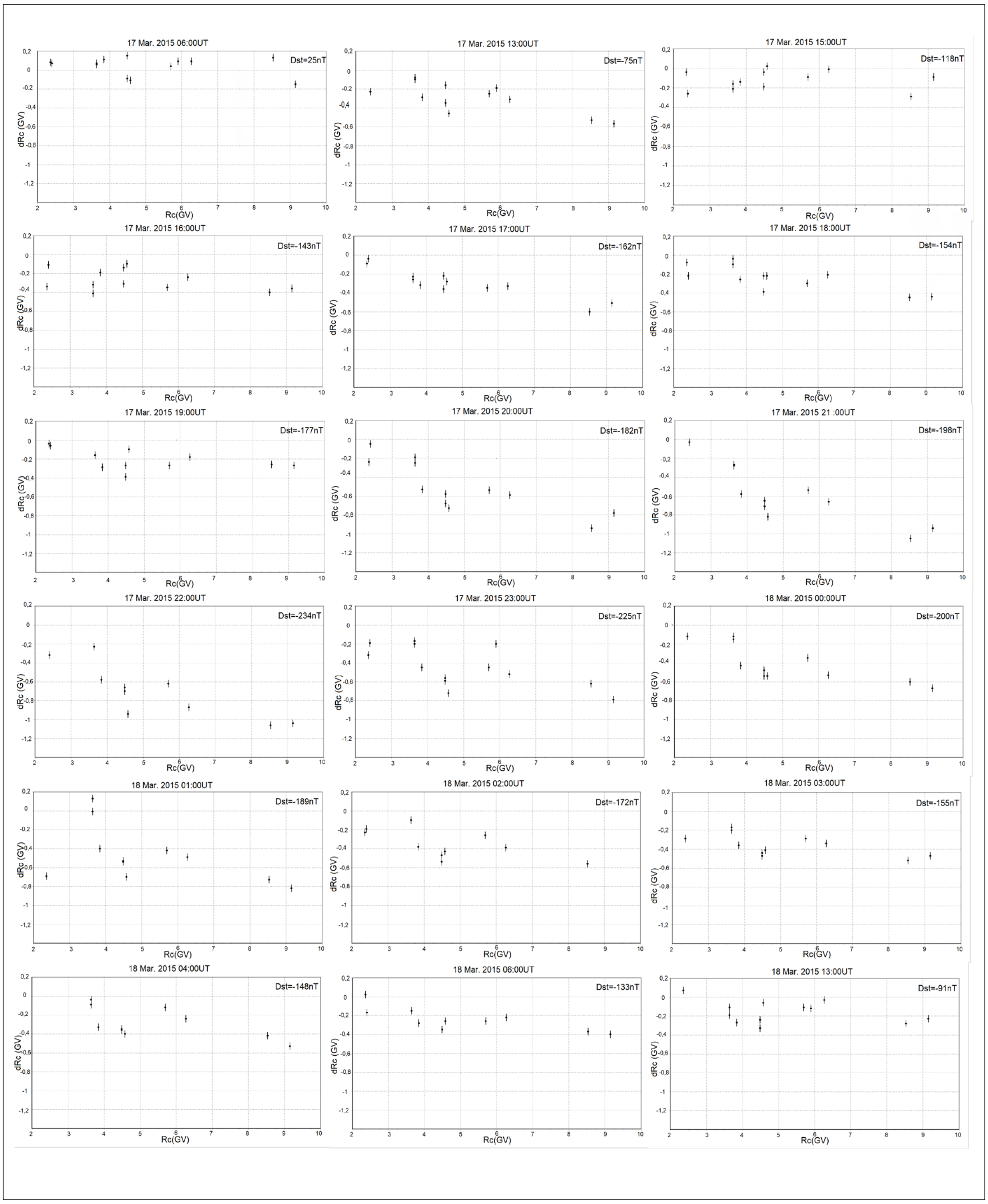

Appendix C: Cutoff rigidity variations versus the cutoff rigidity *R*c at different instances throughout the magnetic storm on 17-18 March 2015.

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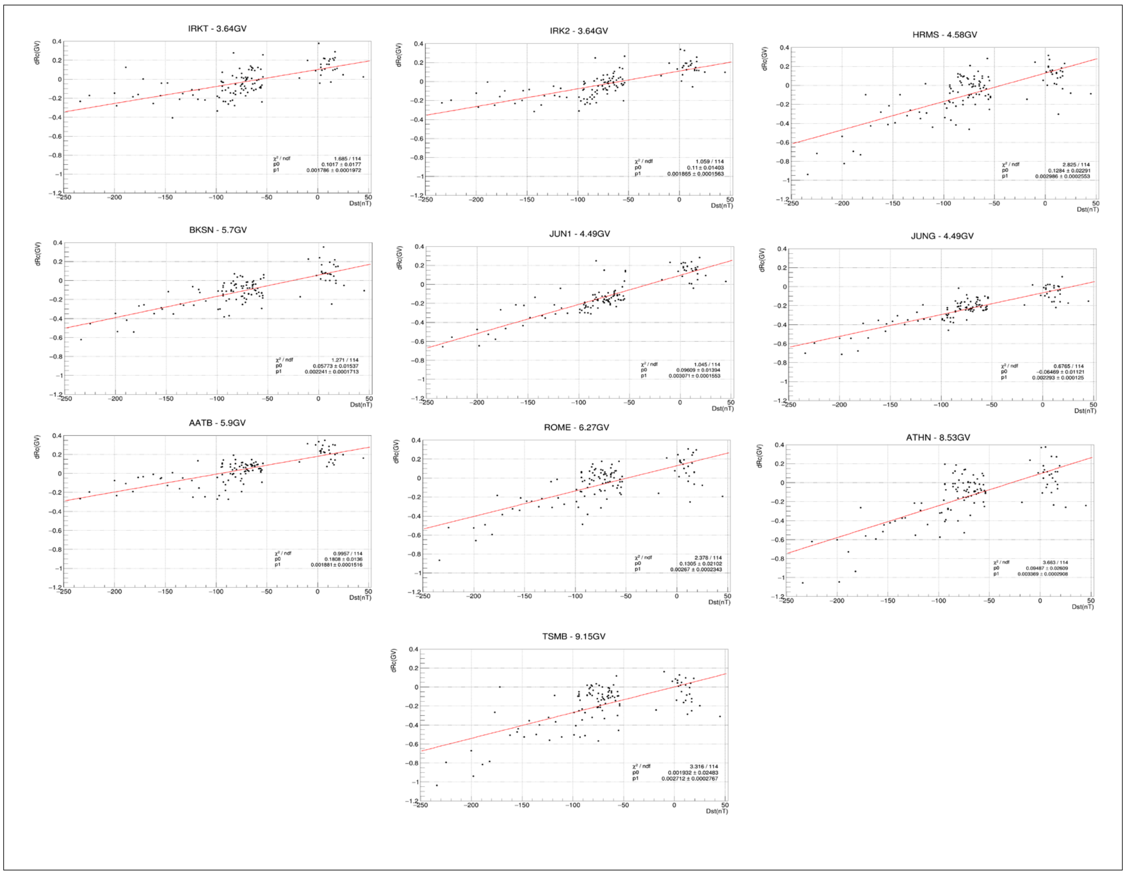

Appendix D: Regression diagrams for cutoff rigidity variations d*R*c and *Dst* index on the magnetic storm on 16-21 March.

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