JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, A09S20, doi:10.1029/2005JA011067, 2005

Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003

A. Belov,[1] L. Baisultanova,[1] E. Eroshenko,[1] H. Mavromichalaki,[2] V. Yanke,[1]
V. Pchelkin,[3] C. Plainaki,[2] and G. Mariatos[2]

Received 9 February 2005; revised 16 May 2005; accepted 18 July 2005; published XX Month 2005.

[1] Cosmic ray variations due to changes in the magnetosphere are evaluated for severe magnetic storm on 20 November 2003 using data from the worldwide neutron monitor network and the global survey method. From these results the changes in the planetary distribution of magnetic cutoff rigidities during this disturbed period are obtained in dependence of latitude. A correlation between *Dst* index and cutoff rigidity variations was defined for each cosmic ray station. The maximum changes in cutoff rigidities occurred while *Dst* index was around -472 nT. Geomagnetic effect in cosmic ray intensity reached at some stations 6–8%, and it seems to be the greatest one over the history of neutron monitor observations. The latitudinal distribution shows a maximum changes at geomagnetic cutoff rigidities around 7–8 GV. This corresponds to unusually low latitudes for maximal effect. Cutoff rigidity variations were also calculated utilizing the last model of Tsyganenko for a disturbed magnetosphere (T01S). A comparison between experimental and modeling results revealed a big discrepancy at cutoff rigidities less than 6 GV. The results on the geomagnetic effect in cosmic rays can be used for validating magnetospheric field models during very severe storms.

Citation: Belov, A., L. Baisultanova, E. Eroshenko, H. Mavromichalaki, V. Yanke, V. Pchelkin, C. Plainaki, and G. Mariatos (2005), Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003, *J. Geophys. Res.*, *110*, A09S20, doi:10.1029/2005JA011067.

1. Introduction

[2] Disturbances in the Earth's magnetic field during magnetic storms can cause essential changes in the charged particle trajectories in the magnetosphere, sometimes to such an extent that allowed trajectories become forbidden, and conversely. This has two main consequences for ground-level observations: (1) the effective cutoff thresholds are changing; (2) the effective asymptotic directions of the particles and thus the reception coefficients for different stations are also changing. Both of these consequences are important for solar cosmic rays (CR), whereas for galactic CR the first effect usually dominates. The magnetosphere effect associated with the cutoff rigidity changes may be great enough to distort essentially cosmic ray variations on the fixed station or even to change its behavior completely. An example of such a great magnetosphere effect during the storm on 20 November 2003 is presented in Figure 1.

[3] There are several reasons for the special interest in the CR magnetosphere variations. First, these effects are interesting from a physical viewpoint: creation, evolution, and decay of the magnetosphere current systems, global interaction of cosmic radiation with the geomagnetic field. Analysis of the CR geomagnetic effects makes it possible to carry out independent validation of current system models in all phases of magnetic storms. At the beginning of a magnetic storm, usually associated with the magnetopause current systems, cutoff rigidity *Rc* increases relatively to the quiet level, whereas *Rc* decreases significantly during the main phase of geomagnetic storm. The latitudinal and longitudinal dependences of these effects reveal themselves in different ways [*Flueckiger et al.*, 1981, 1987; *Baisultanova et al.*, 1995] during the magnetic storm. The cutoff rigidity variations caused by the magnetosphere current ring during the main phase of the storm have an insignificant longitudinal dependence because of the ring symmetry. On the contrary, during the initial phase of the magnetic storm they have a significant longitudinal dependence, since current daytime distribution of the magnetosphere differs considerably from the night distribution.

[4] Second, the study of the magnetosphere effect is important from the methodological point of view, since these effects hinder the discrimination of the primary CR variations and should be excluded from the initial data. Large magnetosphere effects are usually observed simultaneously with big modulation effects in cosmic rays since they are both caused by solar and interplanetary activity.

[5] Cosmic ray variations due to cutoff rigidity changes during a big magnetic storm have already been studied in

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[1] Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk, Russia.

[2] Nuclear and Particle Physics Section, Physics Department, Athens University, Athens, Greece.

[3] Polar Geophysical Institute, Murmansk, Russia.

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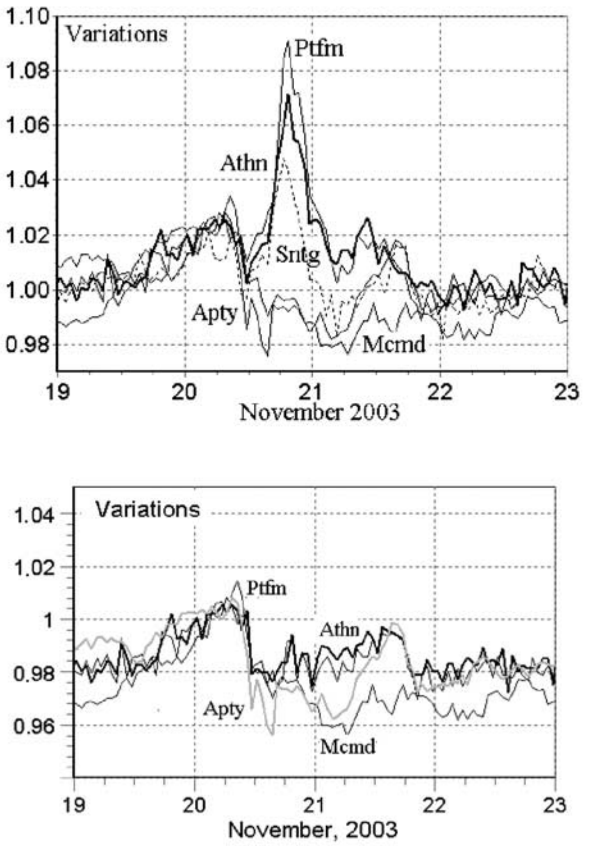

Figure 1. Uncorrected (upper panel) and corrected (lower panel) for the magnetospheric effect cosmic ray variations at the stations Athens(Athn), Potchefstroom (Ptfm), Santjago (Sntg), Apatity (Apty), and Mc Murdo (Mcmd) during the storm on 20 November 2003. Santiago corrected for the magnetospheric effect is not plotted at lower panel to avoid the picture overloading.

many papers [*Debrunner et al.*, 1979; *Baisultanova et al.*, 1987, 1995; *Dvornikov and Sdobnov*, 1988; *Sdobnov et al.*, 2002]. Nevertheless, a several important problems still remain to be solved. They include the following:

[6] 1. To study all large ($Dst < -100$ nT) magnetic storms and thereby develop a method of correction for geomagnetic effect in CR data from the worldwide neutron monitor network. We expect to define a quantitative relation between *Dst* and possible *dRc* for each station after the analysis of a sufficient number of magnetic storms.

[7] 2. To compare the current system models and experimentally derived changes in cutoff rigidities at different stages of the magnetic storm. In this analysis, direct incorporation of cosmic ray data is important in order to study the global effect of the current systems on particle trajectories. This is both during the initial phase of the magnetic storm, associated with currents in the magnetopause, and during the main phase, when cutoff rigidity is significantly reduced.

[8] In this work a detailed study of the magnetosphere effect in cosmic rays during the severe magnetic storm on 20 November 2003 has been performed.

2. Solar and Interplanetary Activity in November 2003

[9] Two sunspot groups were particularly active on 18 November 2003: 501 (484 in previous rotation) and 508 (486). The last big flare in the group 508, accompanied by a powerful coronal mass ejection (CME), was observed on 18 November at the eastern limb (M4, onset at 0923 UT, maximum at 1011 UT). At the same time in the group 501 two long-duration flares occurred in the center of disk (M3.2/2N N00E18, onset at 0716 UT, maximum at 0754 UT; M3.9, onset at 0812 UT, maximum at 0831 UT), which were also followed by powerful and extremely effective CMEs. The severe magnetic storm associated with the flares on 18 November (at least with the two central flares and possibly with all three) started on 20 November. After a shock arrival at 0728 UT (SOHO) and corresponding SSC at 0804 UT, when the Earth ran into a long magnetic cloud, the IMF intensity reached 60 nT, and its negative *Bz* component had almost the same value. Consequently geomagnetic activity at the end of 20 November increased up to the level of a severe magnetic storm and the *Dst* index fell to −472 nT, it was lower only on one occasion on 13–14 March 1989. Red aurora was observed even in southern Europe (Athens, http://www.perseus.gr/Astro-Aurorae-20031120-001.htm).

3. Data and Method

[10] Hourly data from 46 neutron monitors (NMs) of the worldwide network have been employed in a detailed analysis: 19 high-latitude ($Rc < 1.2$ GV), 22 middle and low-latitude, and 5 subequatorial ($Rc > 10$ GV) stations. A list of the stations and the neutron monitors used is presented in the acknowledgments. *Dst* index for November 2003 was taken from http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/ (WDC-C2).

[11] The global survey method (GSM) which is conceptually a version of spherical analysis [*Krymsky et al.*, 1966; *Belov et al.*, 1999] has been utilized for calculations. This

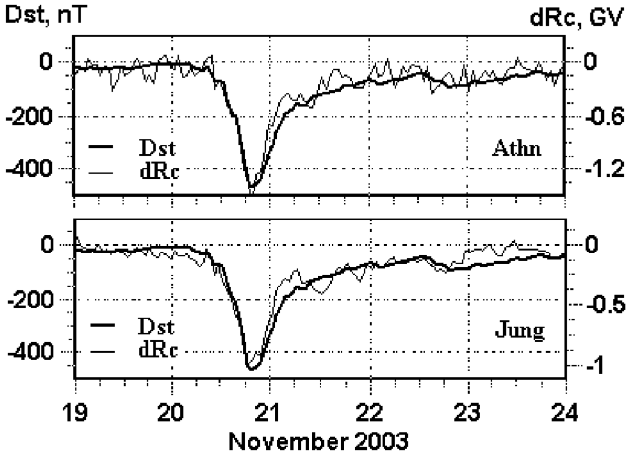

Figure 2. Derived variations of the cut off rigidity *dRc* and *Dst* indexes at the stations Athens (ATHN) and Jungfraujoch (JUNG) during the severe magnetic storm on November 2003.

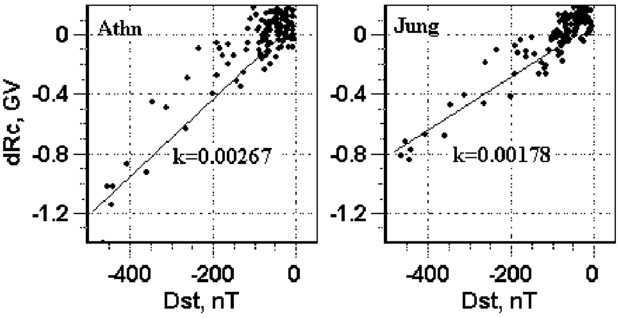

Figure 3. Example of regression diagrams as an evidence of the high correlation between the cutoff rigidity variations *dRc* and *Dst* index (*dRc* = *K*(*Dst* + 50)) for the two stations (Athens and Junfraujoch) during the magnetic storm in November 2003.

method allows a set of parameters defining the galactic cosmic ray density and anisotropy to be derived from the ground-level neutron monitor network. The method takes into account the cosmic ray transformation in the magnetosphere and atmosphere and uses trajectory calculations in the Earth's magnetic field and the neutron monitor response functions [*Dorman*, 1963]. Different versions of this method have been evolved and improved at different stages of data processing. We used as a basis the version described by *Baisultanova et al.* [1987, 1995].

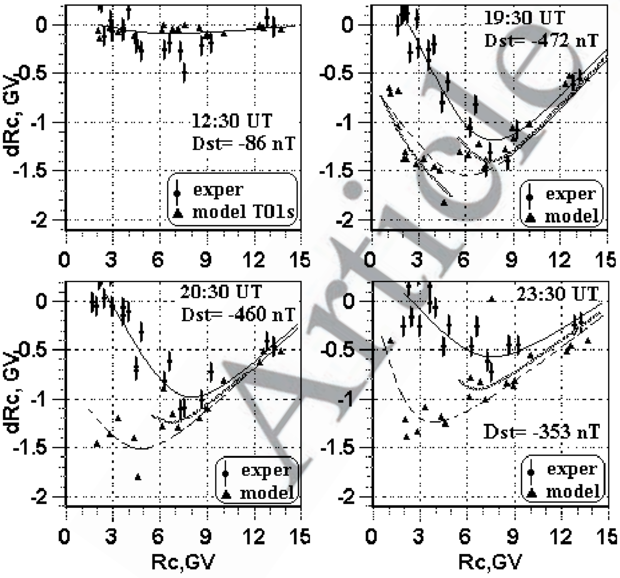

Figure 4. Cutoff rigidity variations (*dRc*) versus the cutoff rigidities (*Rc*) (which proves latitudinal distribution) for different instants of the 20 November 2003 geomagnetic storm: (a) before the main phase of the storm, (b) during the peak phase, and (c) 4 hours later peak phase of the storm. Dots mark the points derived from experimental data by the global survey method with their errors, triangles correspond to *dRc* calculated by the "storm" model (T01S) of Tsyganenko. Cutoff rigidities *Rc* (along the abscissa) are determined by the main magnetic field model IGRF-1995 [*Smart and Shea*, 2003]. Solid and dashed lines illustrate an interpolation throughout the experimental and model points correspondingly, light lines interpolate the model points for rigidities more than 6 GV.

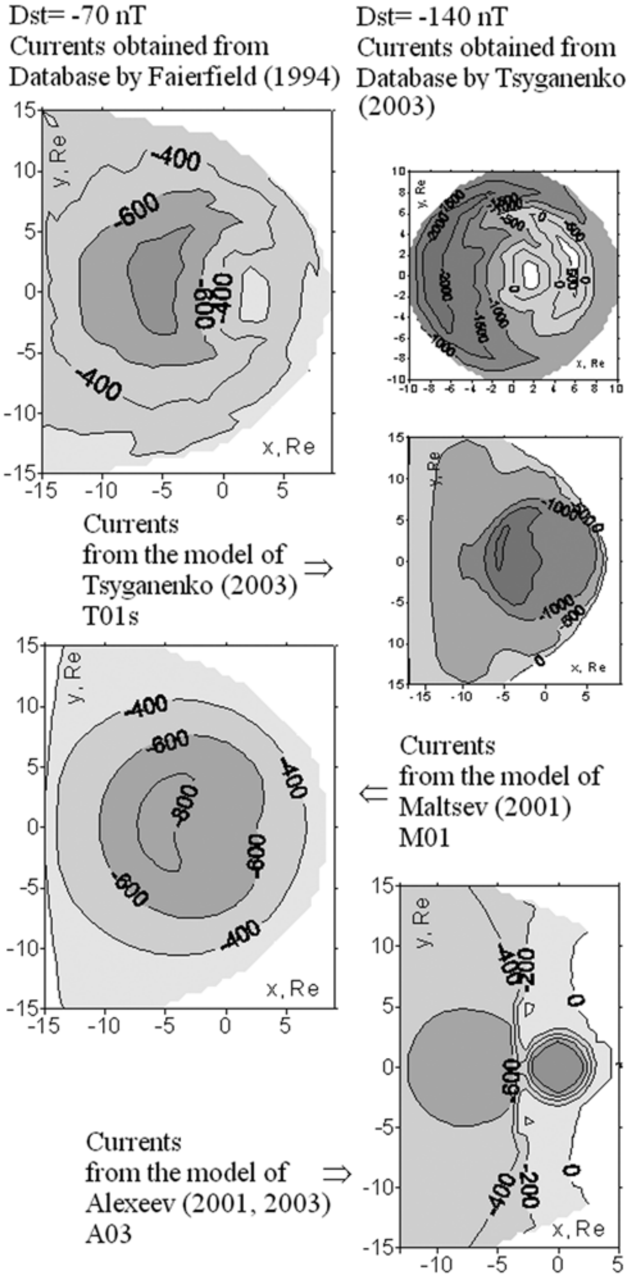

Figure 5. Azimuthally currents in the magnetosphere extracted from the magnetic databases statistically [*Maltsev and Ostapenko*, 2004] (left column) in comparing with model currents calculated from various models (other pictures) for two levels of the magnetospheric storm: *Dst* = −70 nT and *Dst* = −140 nT.

[12] In general the observed cosmic ray variations at each neutron monitor consist of the following components:

$$\frac{\delta I^i}{I_0^i} = \delta^i_{izot} + \delta^i_{anizot} + \delta^i_{err}, \qquad (1)$$

where δ^i_{izot} and δ^i_{anizot} mean isotropic and anisotropic CR variations out of the magnetosphere and δ^i_{err} is residual

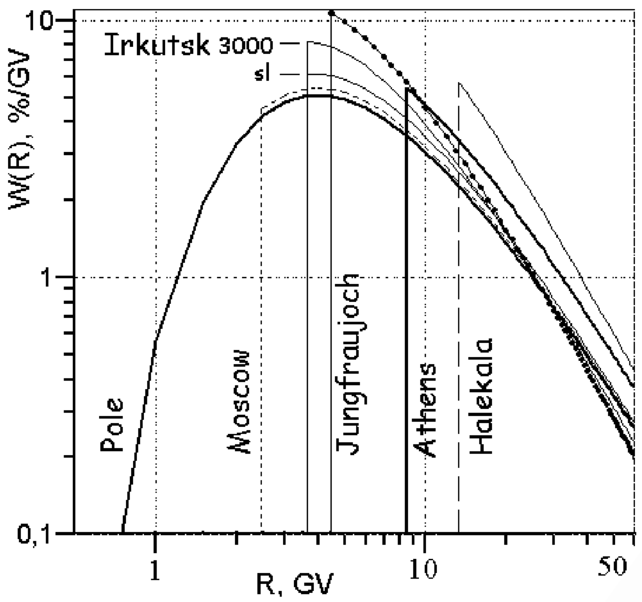

Figure 6. Response functions of the cosmic ray neutron component for several cosmic ray stations.

dispersion related to possible apparatus variations and inadequate utilization of a model. On the assumption of only the first spherical harmonic of CR anisotropy (which is true in the majority of events), the variation in the counting rate of NM at a point *i* with rigidity *Rc* located at level h^i may be described by the equation:

$$\frac{\delta I^i}{I_0^i} = \int_{R_c}^{\infty} \frac{\delta J}{J}(R) \cdot W^i\left(R, R_c^i, h^i\right) \cdot dR + \left(C_x^i \cdot ax + C_y^i \cdot ay + C_z^i \cdot az\right) + \delta_{err}^i, \qquad (2)$$

where $\frac{\delta J}{J} = a_o R^{-\gamma}$ is a rigidity dependence of the galactic CR density variations, a_0 is the magnitude of CR density variation (zero harmonic of CR variations), *ax*, *ay*, *az* are three components of the first harmonic of CR anisotropy; C_x^i, C_y^i, C_z^i are the coupling coefficients for each component respectively taken from *Yasue et al.* [1982]; W^i (R, R_c^i, h^i) is response function for detector, located at the level h^i in the point with geomagnetic cutoff rigidity R_c^i; δ_{err}^i is residual discrepancy. In this equation the first add (integral) describes isotropic part and the second one describes anisotropic components of the CR variations.

[13] The system from *n* equations (*n* is a number of neutron monitors) is solved by the least squares method relative to the unknown parameters: a_0, γ and *ax*, *ay*, *az* components of anisotropy. This model has been verified on a large number of cases and usually gives a proper fit to the experimental data. It would be reasonable to include in model (2) a detailed description of the magnetosphere part of CR variations. This approach is utilized by *Dvornikov and Sdobnov* [2002] where they specify the model dependence δR_c^i on the rigidity R_c^i as $\delta R_c^i = (b_1 R_c + b_2 R_c^2) \cdot \exp(-R_c^{1/2})$. In this case the system solves the set parameter b_1, b_2, and a_0, γ, and *x*, *y*, *z*. This method has some advantages, but unfortunately, the assignment of a dependence δR_c^i on R_c^i in this approach limits in advance the form of derived latitudinal δR_c^i distribution. Also, introducing the additional unknown parameters makes the solution more unstable.

[14] In our approach we work separately with the residual discrepancies. Utilizing our model (2) during strong magnetosphere disturbances, we used a two-step method for the calculations. The CR variation due to magnetospheric effect may be written as $\delta_{mag}^i = -\delta R_c^i \cdot W^i\,(R_c^i, h_0^i) \cdot (1 + \frac{\delta J}{J}(R_c^i))$. Since the W^i (R, R_c^i, h^i) value is small for low *Rc*, the magnetosphere CR density variation could be disregarded for high-latitude stations. The first step is to solve the set (2) of equations for 19 high-latitude neutron monitors. The next step is to use the found parameters and correct the middle and low-latitude monitor data (27 stations in our case) for the extraterrestrial variations. The discrepancies are assumed to arise from the geomagnetic effect. Our approach is based directly on this difference between the model and experi-

Table 1. List of the Most Sensitive Stations to the Geomagnetic Effects[a]

Station Name	Short	Lat	Long	Alt., m	*H*0, mb	*Rc*, GV	*W*(*Rc*), %/GV
Jungfraujoch	JUNG	46.55	7.98	3550	643	4.48	10.62
Irkutsk3	IRK3	52.28	104.02	3000	715	3.66	9.49
Climax	CLMX	39.37	−106.18	3400	685	3.03	9.36
Alma-B	AATB	43.14	76.60	3340	675	6.69	9.10
Erevan3	ERV3	40.50	44.17	3200	700	7.60	8.33
Irkutsk2	IRK2	52.28	104.02	2000	800	3.66	8.29
Erevan	ERVN	40.50	44.17	2000	800	7.60	7.36
Potchefstroom	PTFM	−26.68	27.92	1351	869	7.30	6.82
Mexico	MXCO	19.33	−99.18	2274	794	9.53	6.59
ESOI	ESOI	33.30	35.78	2025	800	10.00	6.37
Alma-A	AATA	43.25	76.92	806	938	6.66	6.36
Irkutsk	IRKT	52.10	104.00	433	965	3.66	6.18
Tibet	TIBT	30.11	90.53	4300	606	14.10	6.12
Tsumeb	TSMB	−19.20	17.60	1240	880	9.29	6.00
Hermanus	HRMS	−34.42	19.22	26	1013	4.90	5.89
Huancayo	HUAN	−12.03	−75.33	3400	704	13.45	5.79
Rome	ROME	41.90	12.50	60	1009	6.32	5.75
Haleakala	HLEA	20.72	−156.27	3052	724	12.91	5.72
Athens	ATHN	37.93	3.72	40	980	8.53	5.22
Beijing	BJNG	40.04	116.19	48	1000	9.56	5.01
Santjago	SNTG	−33.48	−70.71	560	960	11.00	4.71

[a] Lat means latitude, Long means longitude, and Alt means altitude of the station. *H*0 is a standard atmospheric pressure at the station, *Rc* is cut-off rigidity. *W*(*Rc*) is a sensitivity of the station to the geomagnetic effect.

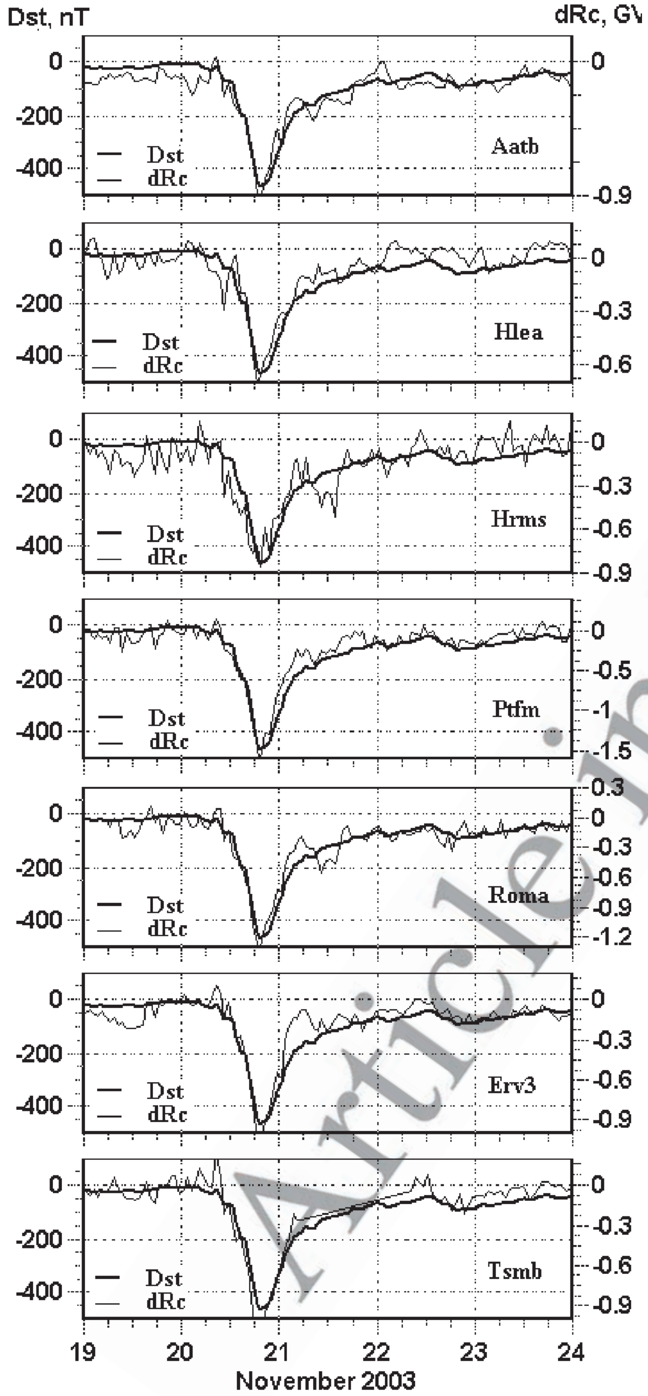

Figure A1. Correlation of the cut-off rigidity variations *dRc* at different stations and D_{st} index during the period 19–24 November 2003.

mental data during periods of a distorted magnetosphere, and we can write:

$$\delta^i_{err} = -\delta R^i_c \cdot W^i\left(R^i_c, h^i_0\right) \cdot \left(1 + \frac{\delta J}{J}\left(R^i_c\right)\right) + \delta_{\mathrm{mod}} + \delta^i_H + \delta^i_L, \qquad (3)$$

where δ_{mod} is a contribution to dispersion of nonadequacy of the CR variation model (form of rigidity spectrum, effect of higher-order harmonics), δ^i_H is the error due to statistical accuracy of the data, and δ^i_L is the low-frequency component due to the possible apparatus drift. We can minimize the contribution from the last two terms, paying particular attention to the quality of the employed data (correction for the drifts and meteorological effect, selection of stations with good data). We cannot completely avoid a contribution from δ_{mod} due to possible second harmonic or more complicated spectrum. However, this part of the dispersion would not have a certain longitudinal or latitudinal distribution which is characteristic for geomagnetic effects. So, we can consider the three last adds to be negligible compared with magnetosphere variations, and then $\delta^i_{err} = \delta^i_{mag}$, i.e., all residual errors may be attributed to the magnetosphere effect. In this case we can write:

$$dR^i_c = -\frac{\delta^i_{mag}}{W^i_c\left(R^i_c, h^i\right) \cdot \left(1 + {}^{\delta J}/_{J}\left(R^i_c\right)\right)}. \qquad (4)$$

In such a way the planetary distribution of the geomagnetic cutoff rigidity variations can be found, and *dRc* values at different points are determined independently of each other. This determination is absolutely irrelevant to the model concepts concerning the latitude and longitude distribution of the magnetic storm effects.

4. Results and Discussion

[15] The uncorrected (upper panel) and corrected (lower panel) for the magnetosphere effect cosmic ray variations at the Athens, Potchefstroom, and Santjago stations are presented in Figure 1. They are compared with the same variations at high-latitude stations Apatity and McMurdo. Data from different neutron monitors indicate that Forbush decrease was moderate despite extremely severe magnetic storm (*Dst* ~ -472 nT) in this period. Magnetosphere effect in cosmic rays was maximal at the relatively low latitude, but not at the midlatitude stations, as it is often observed. It was so significant by the amplitude (6–8%) that Forbush decrease at the Athens, Potchefstroom, and other low-latitude stations was masked completely.

[16] Cutoff rigidity variations *dRc* were calculated for each station throughout the storm by the method above mentioned. This result is plotted for Athens and Jungfraujoch stations in Figure 2. For all other stations it is presented in Figure A1 in Appendix A. Comparison of the obtained *dRc* with *Dst* index reveals a very high correlation over the whole period under consideration. Although the Jungfraujoch station is usually two times more sensitive to geomagnetic effects than the station in Athens (see below), in this case Athens recorded a geomagnetic effect twice bigger than Jungfraujoch. As shown below, such an effect is caused by the peculiarity of the storm on 20 November 2003, namely, by the specific space distribution of the current system. A regression dependence between *dRc* and *Dst* for the same stations is plotted in Figure 3 (for all other stations these dependences are collected in Figure A2 in Appendix A). Two regions are clearly pronounced in this figure: one with a small (>-50 nT) and another with a large (<-50 nT) *Dst* index. Within the first region an accuracy of *dRc* can be estimated as $\sim$0.1 GV for each station. Within the region of large *Dst* index an approximately linear dependence *dRc* on *Dst* is

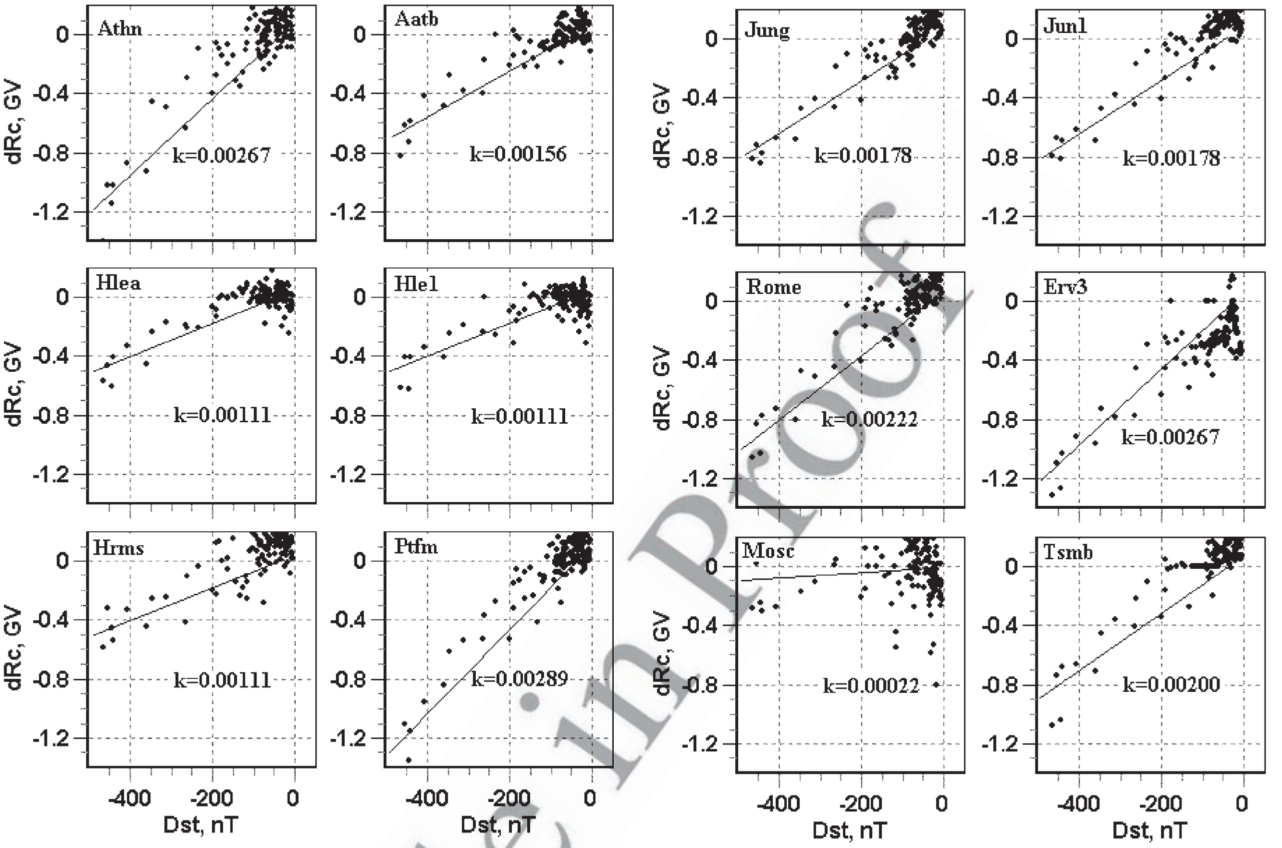

Figure A2. Regression diagrams for the cutoff rigidity variations *dRc* and D_{st} index ($dRc = K(Dst + 50)$) at different stations throughout the severe magnetic storm on 19–23 November 2003.

observed. For the Athens station the regression coefficient is equal to 0.0027 GV/nT, whereas for Jungfraujoch it is 0.0018 GV/nT. The latitudinal dependences of cutoff rigidity variations were defined as *dRc* distribution by the *Rc* for each hour starting from the shock arrival and up to final recovery of the magnetosphere. These results are presented in Figure A3 in Appendix A.

[17] For certain points of this magnetic storm an attempt was made to compare the "experimental" results derived by the above-mentioned method with the calculations by the model for a distorted magnetosphere. The "experimental" cutoff rigidity variations *dRc* (dots) and *dRc* calculated from the storm magnetosphere model (triangles) of *Tsyganenko* [2002] versus cutoff rigidity *Rc* (for a quiescent magnetosphere in the epoch 1995) are illustrated in Figure 4 for the hours before, at the peak, and after the storm peak. Calculations were performed utilizing the latest Tsyganenko model T01S for a stormed magnetosphere by the *Pchelkin and Vashenyuk* [2001] method. The particle trajectories were calculated from the main cone to the Stormer cone adding all allowed intervals (i.e., for the flat spectrum of CR). The step of calculations was 0.002 GV. The time for the trajectory calculations for quasi-trapped particles was chosen so as to reach the vicinity of the asymptotic value. The model was tested for the rather quiet period at 0630 UT on 20 November. For this point the classical package T89 and the new T01S give very close values. Cutoff rigidity variations *dRc* were determined relative to this moment of the quiescent magnetosphere. Since experimental points have been derived for the *Rc* determined by the main magnetic field model IGRF-1995 [*Shea and Smart*, 2001] they may be shifted along the abscissa by 0.1–0.2 GV relative to those calculated from the Tsyganenko model. One can see that there is a good agreement between experimental and calculated values for rigidities >6 GV, moreover, without any normalization. However, we see a sharp discrepancy at rigidities less than 6 GV. Possibly, the model T01S still is not adequate for the greatest magnetosphere disturbances and this causes a discrepancy at lower rigidities. Using our "experimental" method, the same analysis was performed in other magnetic storms of less magnitude, and the classical latitudinal dependence of *Rc* changes with maximum at 3–4 GV was obtained [*Baisultanova et al.*, 1987, 1995].

[18] The consistency of the existing "storm" models with the experimentally derived current distribution based on large sets of spacecraft data was analyzed by *Maltsev and Ostapenko* [2004]. In Figure 5, adopted from this paper, the azimuthally diagrams of the electric currents flowing in the magnetosphere are presented as plotted by experimental data and as calculated statistically from different models. The currents were extracted from the magnetic databases of *Fairfield et al.* [1994] for $Dst = -70$ nT and from *Tsyganenko* [2002], for $Dst = -140$ nT (this procedure is described in

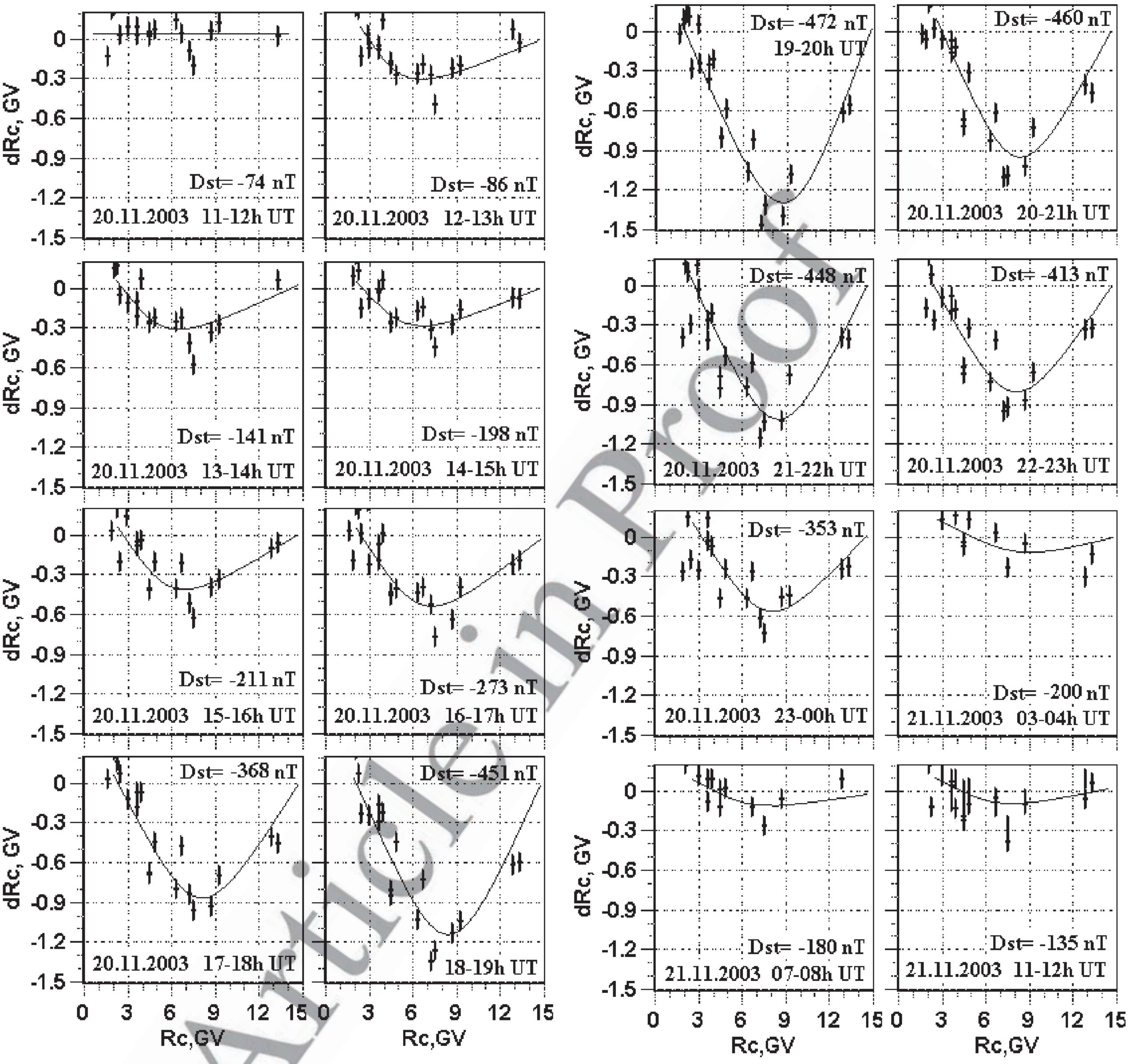

Figure A3. Cutoff rigidity variations *dRc* versus *Rc* at different instants throughout the magnetic storm on 20–21 November 2003. *Rc* are taken for a quiescent magnetosphere and determined by the main magnetic field model IGRF-1995 [*Smart and Shea*, 2003].

detail by *Maltsev and Ostapenko* [2004] and *Maltsev et al.* [2005]). Several models of the magnetic field in the magnetosphere have been used to calculate current flows for the same *Dst* [*Tsyganenko*, 2002; *Tsyganenko et al.*, 2003; *Alexeev et al.*, 2001, 2003; *Maltsev and Ostapenko*, 2001, 2004; *Maltsev et al.*, 2005]. A comparison of the model and experimental measurements shows a fairly good agreement for a moderately disturbed magnetosphere while *Dst* = −70 nT (Maltsev and Ostapenko model), but no model reflects adequately the real distribution of the current flows in a very disturbed magnetosphere, even under *Dst* = −140 nT, not to mention a lower *Dst*. In particular these models are not adequate for calculations of *dRc* during giant magnetic storms with *Dst* amplitude of several hundreds nT as occurred on 20 November 2003.

[19] As we have already mentioned, a specific feature of this event is that maximal magnetosphere effect in CR was recorded at low-latitude stations, instead of at midlatitude as is usually the case. On this occasion the maximum in the latitudinal distribution of the cutoff rigidity variations is shifted significantly to the bigger rigidity and is around 8–9 GV (instead of the usual 3–5 GV). This means that the ring current, which, according to the simplest model [*Treiman*, 1953] is distributed by latitude proportionally to cosines of this latitude, flows maximally close to the Earth in this case and is located at 3 R_E from the Earth center. In

magnetic storms when the maximum in latitudinal distribution of the cutoff rigidity variations is nearly 3–5 GV, the current system is placed at a geocentric distance ~5 R_E.

[20] The errors in Figure 4 are given as those derived from the system equation solution for the quiet period and caused by a statistical accuracy of observation at each point. In fact the errors may be caused by some other sources which are more difficult to estimate. In particular, we do not know the exact response function around the geomagnetic cutoff rigidity for each station. The response functions from *Clem and Dorman* [2000, and references therein] are presented for several stations in Figure 6. Penumbra region, as well as inclined incident particles, lead to a blur and uncertainty in the response function near the R_c; hence some effective values have to be used to account properly for this blur. The observed dispersion of dR_c in Figure 4 seems to be related partly to this uncertainty and sometimes to the difference between the dayside and nightside magnetosphere at the points of observation (longitudinal effect). Since the magnetosphere variation in CR is defined as the product $\delta R_c^i \cdot W^i\,(R_c^i, h_0^i)$, the value of the response function near the cutoff rigidity R_c indicates station sensitivity to the magnetosphere effect. A list of the stations most sensitive to the geomagnetic effect, together with their characteristics (geographic coordinates, altitude, standard atmospheric pressure, cutoff rigidity for the epoch 1995) is presented in Table 1. In the last column the sensitivities as the values of $W^i\,(R_c^i, h_0^i)$ are given for the quiet magnetosphere in %/GV units. It means that if *dRc* at all stations are the same and not too big, the magnetosphere CR density variations will be proportional to this value. One can see from this table that the Jungfraujoch station is approximately twice as sensitive to magnetosphere effect as Athens. At the same time, high-latitude stations with low cutoff rigidity possess very low sensitivity. They practically never respond to geomagnetic disturbance and do not show any effect in CR at this time. A different effect in CR variations at different stations during magnetic storms characterizes *Rc* changes and the peculiarity of the *dRc* planetary distribution during this storm. Thus in the event of 20 November 2003, Athens showed a magnetosphere effect double the size of that shown by the Jungfraujoch. This is related to the particular latitudinal distribution of the cutoff rigidity variations during this event.

5. Conclusions

[21] From the above analysis, we can conclude the following:

[22] 1. At the beginning of the extreme magnetic storm on 20 November 2003 a small magnetosphere effect in cosmic rays was recorded, whereas an exclusively large effect was observed during the main phase of this storm.

[23] 2. The global survey method applied to the cosmic ray data from the worldwide neutron monitor network allowed the latitudinal distribution of the cutoff rigidity variations to be obtained for each hour during the main and recovery phases of this magnetosphere storm. These results may be employed in analyzing the dynamics of the evolution and damping out of the ring current systems.

[24] 3. During the magnetic storm on 20 November 2003, the ring current system was located at a closer geocentric distance (~3 R_E) than is usually observed. As a consequence, the maximal magnetosphere effect in CR was recorded at lower latitudes but not at the usual midlatitude stations. Owing to this anomaly the maximum changes of the geomagnetic cutoff rigidity were shifted from the usual value of 3–5 GV to 7–8 GV.

[25] 4. The calculations of the cutoff rigidity changes performed utilizing the last "storm" model T01S of the magnetosphere magnetic field show a good agreement between experimental and modeling values for rigidities >6 GV and great discrepancy for the lower rigidities. One reason for this may be that the "storm" model is not yet an adequate description of the real magnetosphere during the greatest disturbances.

Appendix A

[26] Figure A1 shows the cutoff rigidity variations *dRc* calculated for each station throughout the storm by the method mentioned in text for all stations but Athens and Jungfraujoch (shown in Figure 2). Figure A2 shows a regression dependence between *dRc* and *Dst* for the same stations. Figure A3 shows the latitudinal dependences of cutoff rigidity variations defined as *dRc* distribution by the *Rc* for each hour starting from the shock arrival and up to final recovery of the magnetosphere.

[27] **Acknowledgments.** This work in operating of the Russian CR stations is partly supported by Russian FBR grants 04-02-16763 and 03-07-90389 and for USA stations by NSF grant ATM-0000315. The authors thank the collaborators from all CR stations which data were taken for analysis: Alma-Ata, Apatity, Barentzburg, Beijing, Calgary, Cape Shmidt, Climax, Erevan, Erevan3, ESOI, Fort Smith, Haleakala, Hermanus, Irkutsk, Irkutsk2, Irkutsk3, Inuvik, Jungfraujoch, Kergelen, Kiel, Kingston, Larc, Lomnicky Stit, Magadan, Mawson, McMurdo, Mexico, Moscow, Nain, Newark, Norilsk, Novosibirsk, Oulu, Peawanuck, Potchefstrom, Rome, Sanae, Santiago, South Pole, Tbilisi, Terre Adelie, Thule, Tixie Bay, Tsumeb, and Yakutsk. This work is partly supported by HRAKLITOS project of the Greek Ministry of Education (grant 70/3/7218) and PENED2004 project of the Greek Secretariat of Research and Technology (grant 70/3/6830).

[28] Arthur Richmond thanks Galina Bazilevskaya and D. F. Smart for their assistance in evaluating this paper.

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L. Baisultanova, A. Belov, E. Eroshenko, and V. Yanke, Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 142092, Troitsk, Moscow Region, Russia. (erosh@izmiran.rssi.ru)

G. Mariatos, H. Mavromichalaki, and C. Plainaki, Nuclear and Particle Physics Section, Physics Department, Athens University, Pan/polis-Zografos 15771, Athens, Greece. (emavromi@cc.uoa.gr; cplainak@phys.uoa.gr)

V. Pchelkin, Polar Geophysical Institute, 183010 Murmansk, Russia. (pchelkin@pgi.kolasc.net.ru)