
# Cosmic ray transmissivity in variable magnetosphere on various time scales

K. Kudela

Department of Space Physics,
Institute of Experimental Physics, SAS,
Watsonova 47, 04001 Košice, Slovakia
*kkudela@kosice.upjs.sk*

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## Outline:

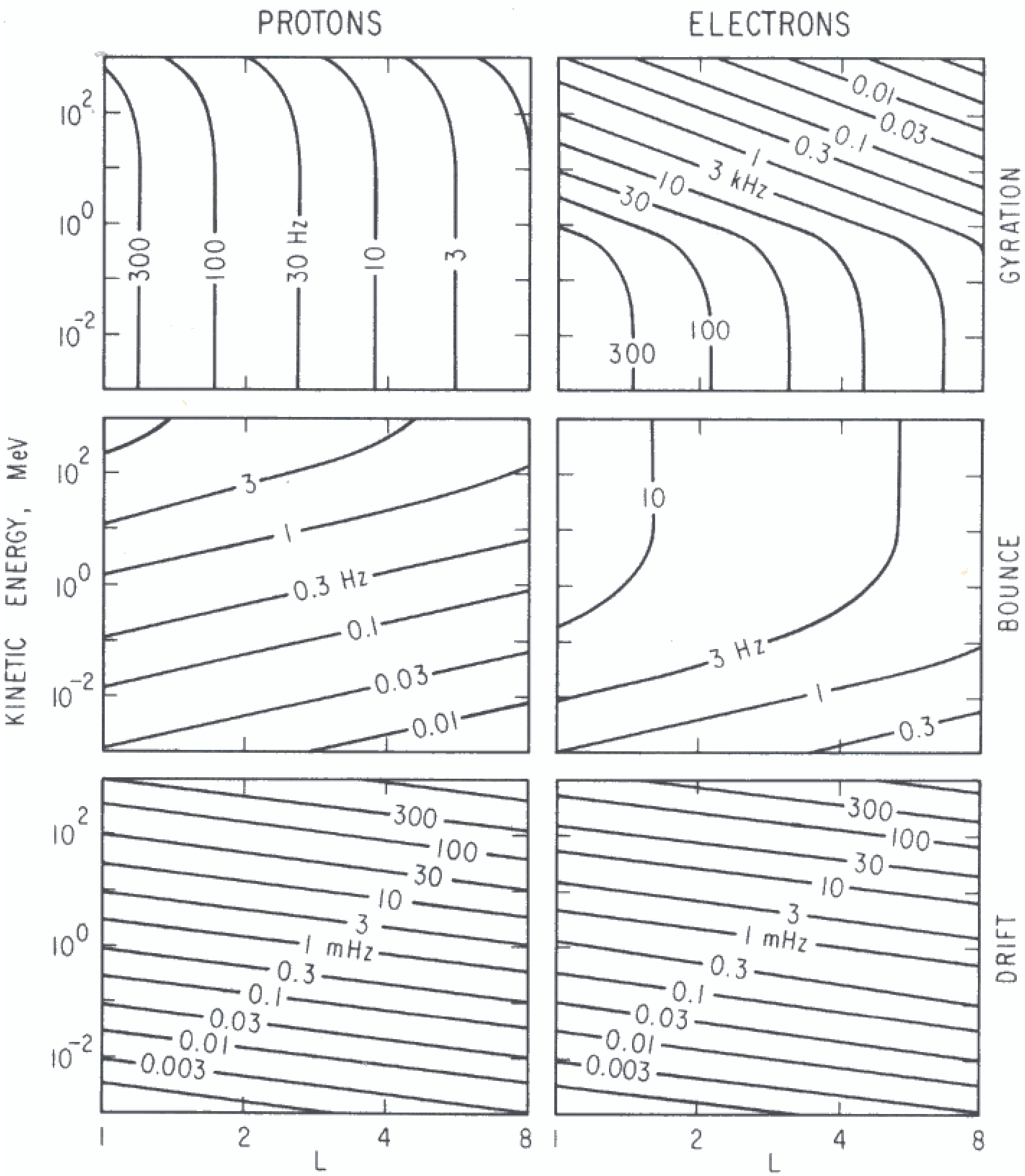
1. Introduction, basic concepts, trajectory tracing.
2. Geomagnetic field models used for CR tracing.
3. Long term variations of cutoff.
4. External current sources, examples during geomagnetic disturbances
    - a. October 28-November 1, 2003
    - b. November 20-23, 2003
    - c. November 7-8, 2004
    - d. April 6, 2000
5. Discussion and concluding remark.

# *1. Introduction. Basic concepts. Trajectory tracing.*

Classification of charged particles according to characteristic dimensions of their trajectories (d – curvature radius, Larmor radius) with respect to dimension of magnetosphere ($d_m$) or to Stormer length ($l_s$),

$l_s = (\mu_o.M.|q|/(4\pi.m.v))^{1/2}$, $M_E$=8.1. 10 $^{22}$A.m$^2$

| A | B |
|---|---|
| $d << d_m$ | $d\ {}^{3}\ d_m$ |
| $l_s >> d_m$ | $l_s\ {}^{2}\ d_m$ |
| RB, magnetospheric plasma p. etc. | CR |
| drift approx., adiabatic invariants | |




Frequencies of cyclic motions for equatorially trapped charged particles.

Copied from *M. Schulz, L.J. Lanzerotti, Particle diffusion in the radiation belts, Springer, 1974*

Adiabatic approximation fails for $E_p \sim 1$ GeV at high L (upper right corner), when periodicities of 3 cyclic motions are comparable (protons)

CR - **Trajectory tracing**.

# ***Estimates of cut-off rigidities:***

*Simplest approach by Stormer cut-off in dipolar field*

***the direct access for particles of all rigidity values lower than Stormer cut-off rigidity is forbidden from outside the field.***

$$R_s = (M.\cos^4(\lambda))/\{r^2.[1 + (1 - \cos^3(\lambda).\cos(\varepsilon).\sin(\xi))^{1/2}]^2\}$$

M - the dipole moment and has a normalized value of 59.6 when r is expressed in units of earth radii and $R_s$ in GV

$\lambda$ - magnetic latitude

r - distance from the dipole in earth radii

$\varepsilon$ - azimuth angle measured clockwise from geomagnetic east direction (for positive particles)

$\xi$ - angle from the local magnetic zenith direction

*Cooke, D.J. et al., Il Nuovo Cimento, 14 C, N 3, 213-233, 1991*

***Trajectory tracing.***

The differential equation describing trajectory of a particle (charge q, mass m) in the static magnetic field **B**(**r**) is given by

$d^2\mathbf{r}/dt^2 = (q/m).\ d\mathbf{r}/dt \times \mathbf{B}$ (1)

This equation leads to system of 6 linear differential equations with unknown values (x, y, **z**, dx/dt, dy/dt, d**z**/dt) which is usually solved numerically (earlier e.g. *Shea M.A. et al.,ERP 141, AFCRL-65-705, 1965; Flückiger, E.O., AFGL-TR-82-0320,1982* among others).

We use the scheme of Runge-Kutta of 6th order or 4th order

(*Kaššovicová, J. and Kudela,K., preprint IEP SAS 1995;*

*Bobík, P., PhD thesis, 2001*).

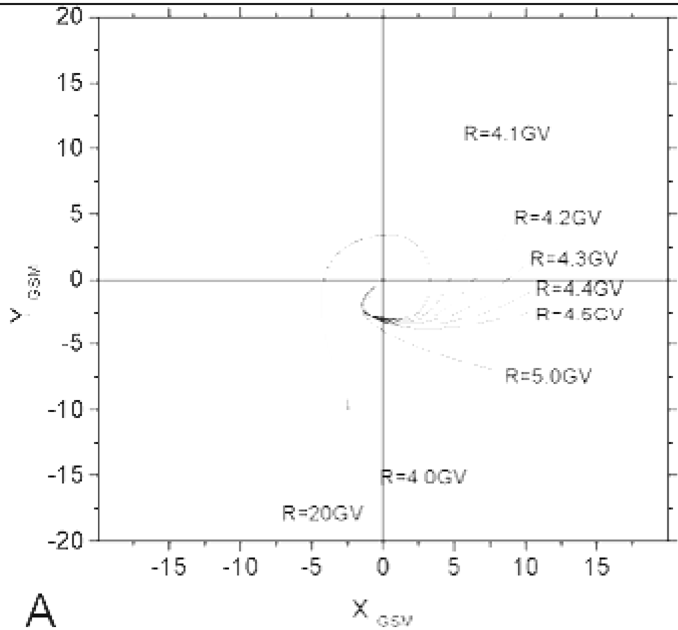
Initial conditions: rigidity (velocity), charge, direction of access (zenith, azimuth angle) $\Rightarrow$ $(x,y,\mathbf{z},v_x,v_y,v_z)$, back tracing numerical integration of (1) in given **B** (x,y,z) from the point of observation in given direction with charge sign reversed.

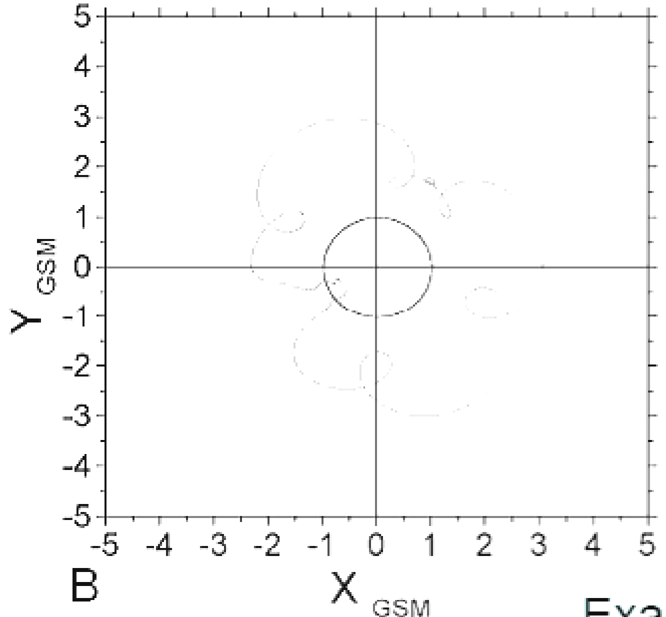
Time step (elementary straight line) is based on gyroperiod (according to local |**B**|; $\Delta t=T/n$; T is gyroperiod, n=100 usually).

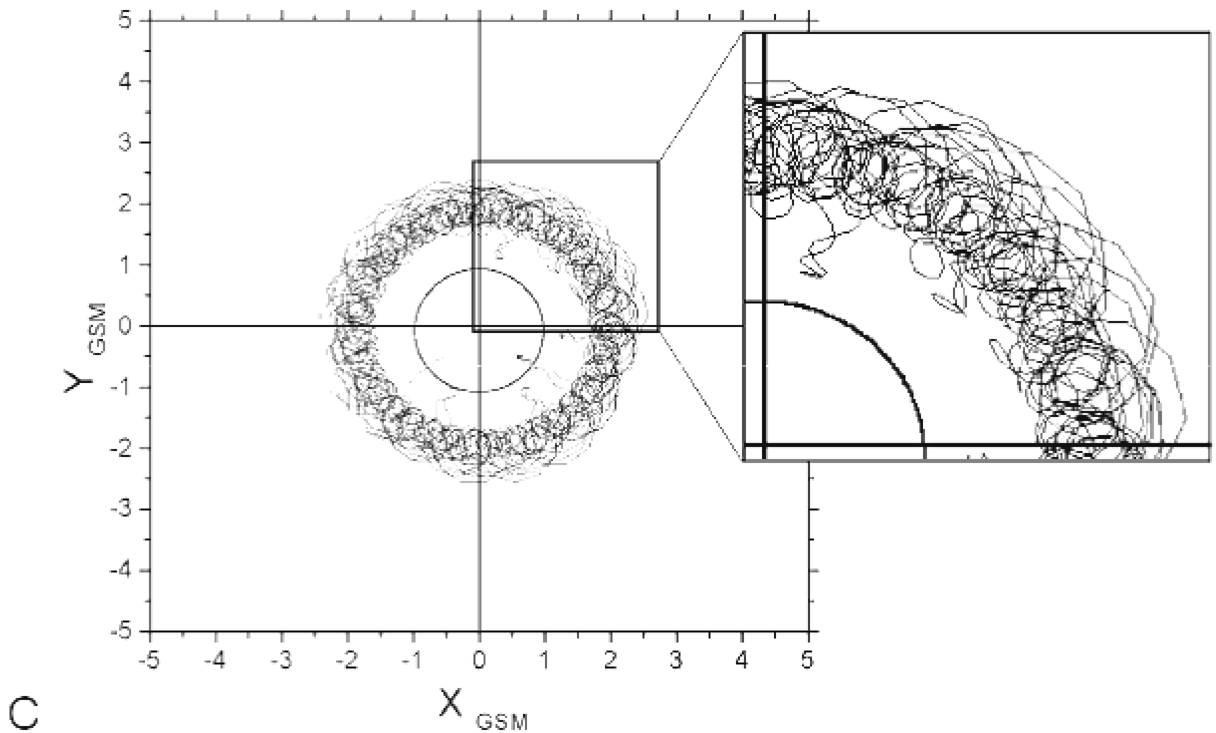
Conditions for smoothness of trajectory (angle between two subsequent elementary straight lines on trajectory < $\alpha$, usually $\alpha$ = 0.001 rad)

Conservation of initial module v ($|\mathbf{v}-\mathbf{v}_{\mathbf{initial}}|/|\mathbf{v}_{\mathbf{initial}}| < \varepsilon$, $\varepsilon = 10^{-4}$ usually)

Conditions for finishing the trajectory tracing (N=max. number of steps, crossing earth, crossing magnetopause, N=50000 usually)



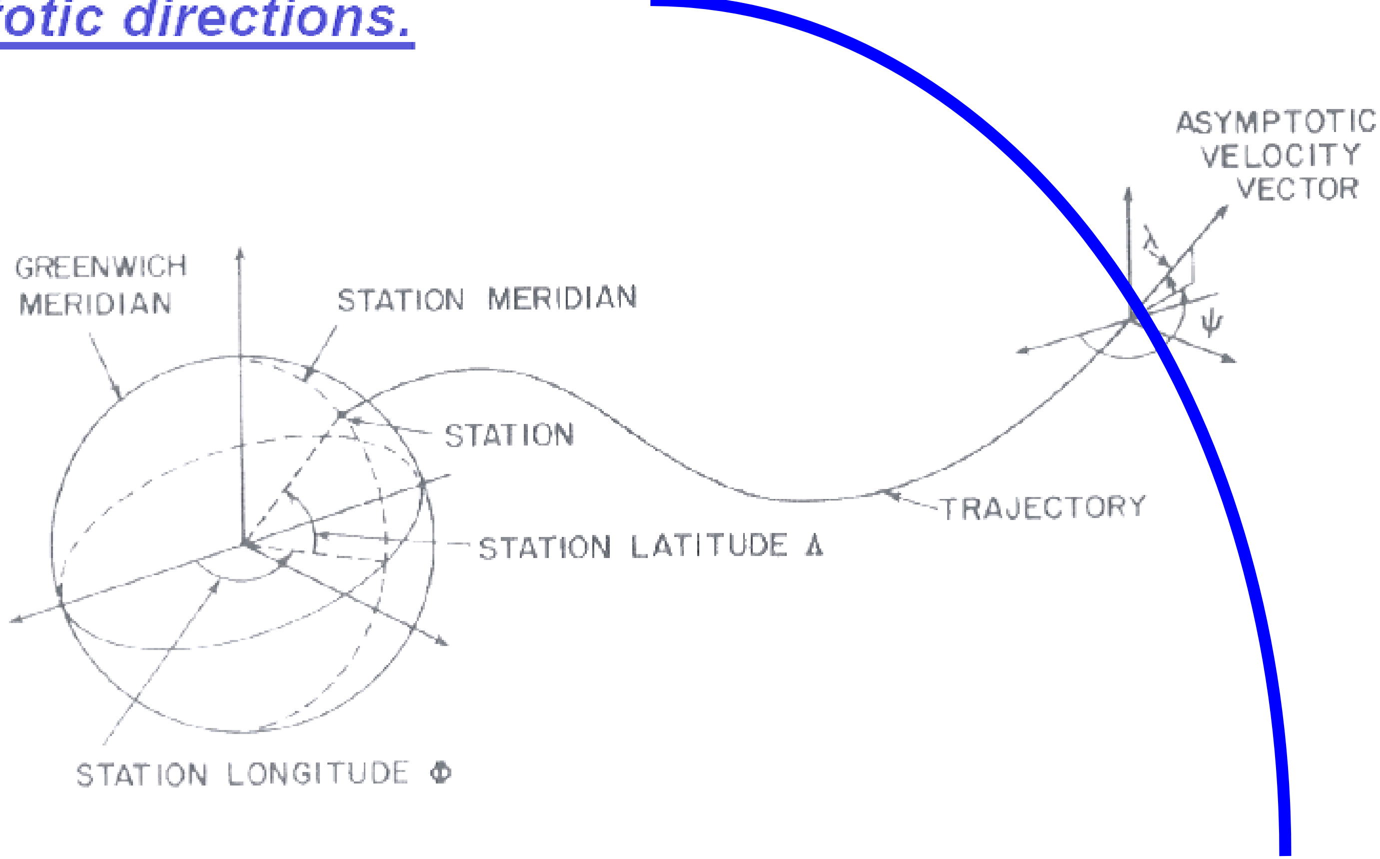

Examples of trajectory computations (projections to $XY_{GSM}$ plane). Position of Lomnický Štít, vertical access.

A: allowed traj.

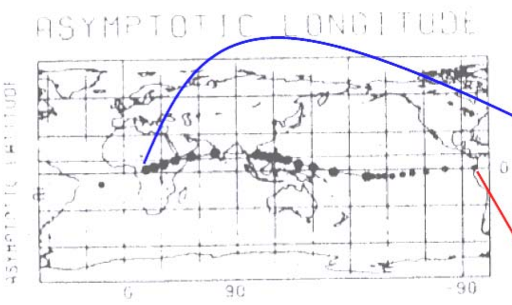
B: R=3.25 GV forbidden

C: R=2.25 GV quasitrapped

## Asymptotic directions.




Allowed trajectory. Charged particle of cosmic rays arriving above the site of particular station from a given direction (local) arrived formerly to magnetospheric boundary at another direction (asymptotic direction). Figure (*from Shea,M.A. and Smart, D.F., ERP No 524, AFCRL-TR-75-0381, 1975*) illustrates the definition of ***asymptotic latitude and longitude***.




CHACALTAYA, BOLIVIA

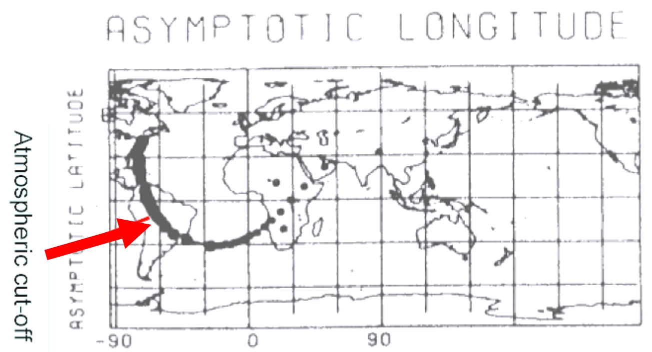
GEOGRAPHIC LATITUDE = -16.31
GEOGRAPHIC LONGITUDE = 291.85

EFFECTIVE VERTICAL CUTOFF RIGIDITY = 13.10 GV

| RIGIDITY (GV) | ASYMPTOTIC LAT. | LONG. |
|---|---|---|
| 20.00 | 2 | 19 |
| 19.00 | 4 | 25 |
| 18.00 | 7 | 32 |
| 17.00 | 10 | 42 |
| 16.00 | 13 | 55 |
| 15.00 | 15 | 73 |
| 14.00 | 14 | 106 |
| 13.90 | 13 | 111 |
| 13.80 | 12 | 117 |
| 13.70 | 10 | 123 |
| 13.60 | 8 | 131 |
| 13.50 | 6 | 140 |
| 13.40 | 2 | 151 |
| 13.30 | -2 | 167 |
| 13.20 | -6 | 195 |
| 13.19 | -7 | 199 |
| 13.18 | -7 | 204 |
| 13.17 | -7 | 209 |
| 13.16 | -6 | 215 |
| 13.15 | -6 | 222 |
| 13.14 | -5 | 231 |
| 13.13 | -4 | 242 |
| 13.12 | -2 | 256 |
| 13.11 | -1 | 280 |
| 13.10 | -11 | 343 |
| 13.09 | R | R |

Figure A11. Station Orientated World Map Illustrating the Asymptotic Directions for Chacaltaya, Bolivia

Asymptotic directions are usually plotted as (long, lat) projection on the map. The computed asymptotic longitudes and latitudes for a high cut-off rigidity station and vertical access. Wide range of asymptotic longitudes for 13-20 GV. Example for ***high cut-off rigidity*** station (*from Shea, M.A. and D.F. Smart, 1975*)




CHURCHILL, CANADA

GEOGRAPHIC LATITUDE = 58.75
GEOGRAPHIC LONGITUDE = 265.91

EFFECTIVE VERTICAL CUTOFF RIGIDITY = .21 GV

| RIGIDITY (GV) | ASYMPTOTIC LAT. | LONG. |
|---|---|---|
| 20.00 | 42 | -72 |
| 19.00 | 41 | -72 |
| 18.00 | 40 | -72 |
| 17.00 | 39 | -73 |
| 16.00 | 38 | -73 |
| 15.00 | 37 | -74 |
| 14.00 | 36 | -74 |
| 13.00 | 35 | -75 |
| 12.00 | 34 | -75 |
| 11.00 | 34 | -76 |
| 10.00 | 33 | -76 |
| 9.00 | 33 | -76 |
| 8.00 | 32 | -75 |
| 7.00 | 30 | -74 |
| 6.00 | 26 | -74 |
| 5.00 | 23 | -75 |
| 4.00 | 21 | -73 |
| 3.00 | 16 | -73 |
| 2.00 | 7 | -71 |
| 1.90 | 6 | -71 |
| 1.80 | 5 | -71 |
| 1.70 | 4 | -70 |
| 1.60 | 2 | -69 |
| 1.50 | 1 | -69 |
| 1.40 | -1 | -68 |
| 1.30 | -2 | -68 |
| 1.20 | -4 | -66 |
| 1.10 | -6 | -65 |
| 1.00 | -9 | -64 |
| .90 | -12 | -62 |
| .80 | -15 | -60 |
| .70 | -19 | -56 |
| .60 | -23 | -51 |
| .50 | -28 | -43 |
| .40 | -31 | -26 |
| .39 | -31 | -24 |
| .38 | -31 | -21 |
| .37 | -31 | -19 |
| .36 | -31 | -16 |
| .35 | -30 | -13 |
| .34 | -29 | -9 |
| .33 | -28 | -6 |
| .32 | -27 | -2 |
| .31 | -25 | 2 |
| .30 | -22 | 6 |
| .29 | -19 | 11 |
| .28 | -14 | 16 |
| .27 | -9 | 22 |
| .26 | -1 | 29 |
| .25 | 9 | 38 |
| .24 | 23 | 53 |
| .23 | 32 | 90 |
| .22 | -28 | 384 |
| .21 | 13 | 379 |
| .20 | F | F |

Figure A12. Station Orientated World Map Illustrating the Asymptotic Directions for Churchill, Canada

Asymptotic directions computed for a ***low cut-off rigidity station***. The interval of asymptotic longitudes is narrower. (*from Shea, M.A. and D.F. Smart, 1975*)

Vertical incidence of CR.

*a. Vertical incidence of particles*

starting (probably) from

*IQSY Instruction Manual No 10 (Cosmic Ray Tables, Asymptotic Directions, Variational coefficients and Cut-off Rigidities) by K.G. McCracken, U.R. Rao, B.C. Fowler, M.A. Shea, D.F. Smart, pp. 183, May 1965, Issued by IQSY Committee, London*

(more references in appendix)

Most commonly: use of IGRF/DGRF model (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html), V (magnetic potential) as a series expansion of orthogonal spherical functions  with Gauss coefficients, 5 year step, 1945-2000

*Vertical cut-off rigidities for many cosmic ray stations* were computed for epochs 1955 – 1995 with 5 year step given by the IGRF models are in paper *(M.A. Shea and D.F. Smart, Proc. ICRC, Hamburg, p. 4063-4066, 2001*).

*Approach by L* (McIlwain parameter) :

*M.A. Shea, D.F. Smart, L.C. Gentile, Phys. of Earth and Planet. Inter. 48, 200-205, 1987* ( $R_C \sim L^{-\gamma}$, $\gamma \sim 2$)

*Extrapolation to low altitude orbits*:

*e.g. W. Heinrich, A. Spill, J. Geophys. Res., 84, A8, 1979*: geomagnetic shielding at Apollo-Soyuz orbit, approximation of vertical cut-off using $R_c(1)/R_c(2) = L^2(2)/L^2(1)$ for points 1 and 2 on the same radius vector from the center of Earth.

*b. Cut-offs for non-vertical directions.*

Obliquely incident particles have to be taken into account too. One approach is e.g. in paper (*J.M. Clem et al, J. Geophys. Res. 102, No A12, 26,919-26,926, 1997*) – apparent cutoff (*rigidity which, if uniform over the whole sky, would yield the same NM counting rate as the real, angular dependent cutoff distribution).* Cut-off sky-maps are computed.

Simplification: effective cutoffs are computed for 9 directions (vertical and ring $30^{o}$ off vertical with 8 directions by azimuth) and apparent cut-off is computed with corresponding statistical weights (*J.W. Bieber et al, Proc. ICRC, Durban, 2, 389-392, 1997*) .

*Transmissivity function (TF) for defined direction:*

Trajectory computations with dR step (dR < DR). TF(R,DR) is probability that particle of rigidity (R,R+DR) can access the given point in the model field. Introduced for description of fine structure of penumbra (e.g. *Bobík, P. et al., ICRC 2001; Kudela and Usoskin, Czech. J. Phys., 2004*)

Earlier:

Cutoff probability (*Heinrich and Spill, J. Geophys. Res., 1979*),

Geomagnetic transmission in disturbed magnetosphere (*Boberg et al, Geophys. Res. Lett., 1995*)

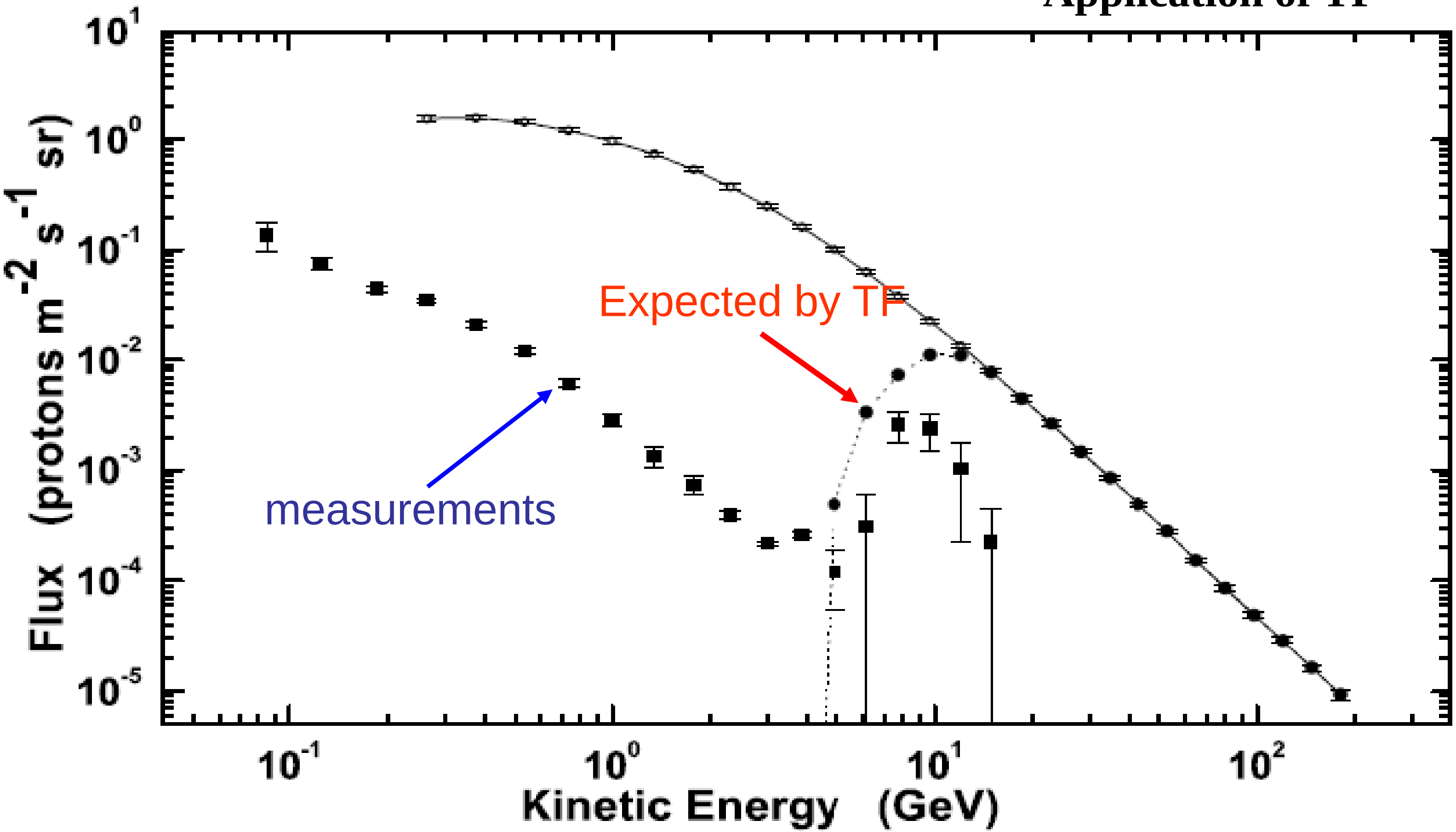



Figure 5. Fluxes per units of solid angle as a function of the proton kinetic energy for the 4th geomagne
(○) $\Phi^{1AU}(R_b)$, (●) $\Phi_4(R_b)$ and (■) $\Phi_4^s(R_b)$. The lines are to guide the eye.

In penumbra the observed energy spectra (AMS) showed the excess above those expected by primary cosmic ray (CREME96 model) and TF ⇨ estimate of contribution of secondary CR (mainly re-entrant albedo protons), *Bobík, P. et al., J. Geophys. Res. 2006.*

# 2. Geomagnetic field models used for CR tracing.

## *Internal field: IGRF model*

The IAGA released the 10th Generation International Geomagnetic Reference Field — the latest version of a standard mathematical description of the Earth's main magnetic field. The coefficients for this degree and order 13 main field model were finalized by a task force of IAGA in Dec. 2004.

(http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html )

The IGRF is a series of mathematical models of the Earth's main field and its annual rate of change (secular variation). In source-free regions at the Earth's surface and above, *the main field, with sources internal to the Earth, is - grad (V), V - potential which can be represented by a truncated series expansion:*

$$V(r,\theta,\lambda,t) = R\sum_{n=1}^{n_{max}}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left(g_n^m(t)\cos m\lambda + h_n^m(t)\sin m\lambda\right)P_n^m(\theta)$$

We use the GEOPACK library: it consists of subsidiary FORTRAN subroutines for magnetospheric modeling studies, including the current (IGRF) and past (DGRF) internal field models, a group of routines for transformations between various coordinate systems, and a field line tracer.

(http://modelweb.gsfc.nasa.gov/magnetos/data-based/geopack.html )
(http://modelweb.gsfc.nasa.gov/magnetos/data-based/Geopack_2005.html )

## External field (contributions of external current systems).

A. Tsyganenko’89 model (*Tsyganenko, N.A., PSS,37,1, pp. 1-20, 1989*)
Code at http://modelweb.gsfc.nasa.gov/magnetos/data-based/T89c.html
Input parameters:
IOPT – specifies the ground disturbance level:
IOPT= 1, 2, 3, 4, 5, 6, 7 correspond to Kp= (0,0+), (1-,1,1+), (2-,2,2+), (3-,3,3+), (4-,4,4+), (5-,5,5+), (> =6-).
Dipole tilt angle; x, y, z position in GSM.

B. *Tsyganenko’89 model with extension of Dst.*
Putting one parameter of model (A) depending on Dst, an approach to geomagnetic transmission during the disturbances in October 1989 was proposed (*Boberg, P.R. et al., GRL, 22, No 9, 1133-1136, 1995*).

*C. Tsyganenko 96 model*

Ts96 input values: solar wind pressure, Dst, By- and Bz-components of the interplanetary magnetic field, the geodipole tilt angle, and GSM position of the observation point (X,Y,Z). *Tsyganenko, N.A.* (*JGR, v.100(A4), pp.5599-5612, 1995*).

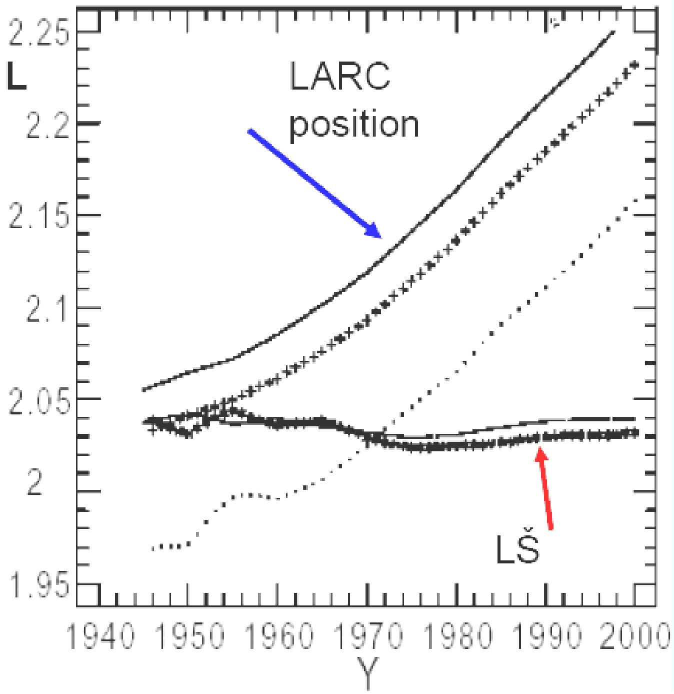
*D.Tsyganenko 2004 model*

Model of external (i.e. without Earth's contribution) part of the magnetospheric field. Input: solar wind pressure; Dst; $B_y$ ; $B_z$ of IMF and indices *W1 – W6 calculated as time integrals from beginning of a storm* ($B_z$, n, v; described by *Tsyganenko,N.A. and M. I. Sitnov, Modelling the dynamics of the inner magnetosphere during strong geomagnetic storms, JGR v. 110, 2005, JGR, 110, A03208, doi:10.129/2004JA010798, 2005*); dipole tilt angle; x,y,z GSM position

# *3. Long term variations of cutoffs.*

Vertical cut-off rigidities for many cosmic ray stations were computed for epochs 1955 – 1995 with 5 year step given by the IGRF models are in paper *(M.A. Shea and D.F. Smart, Proc. ICRC, Hamburg, p. 4063-4066, 2001)*.

There are positions on the earth where the geomagnetic cut-offs are changing over past century more dramatically than in another positions.

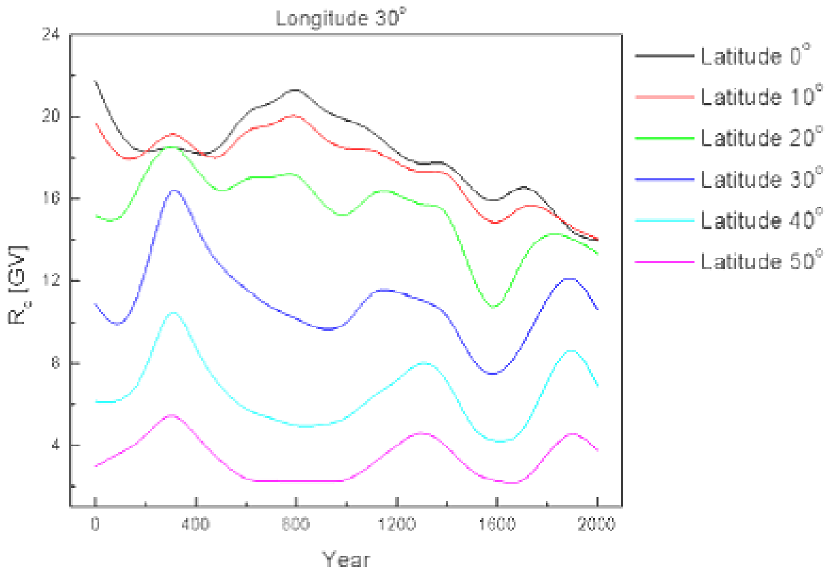


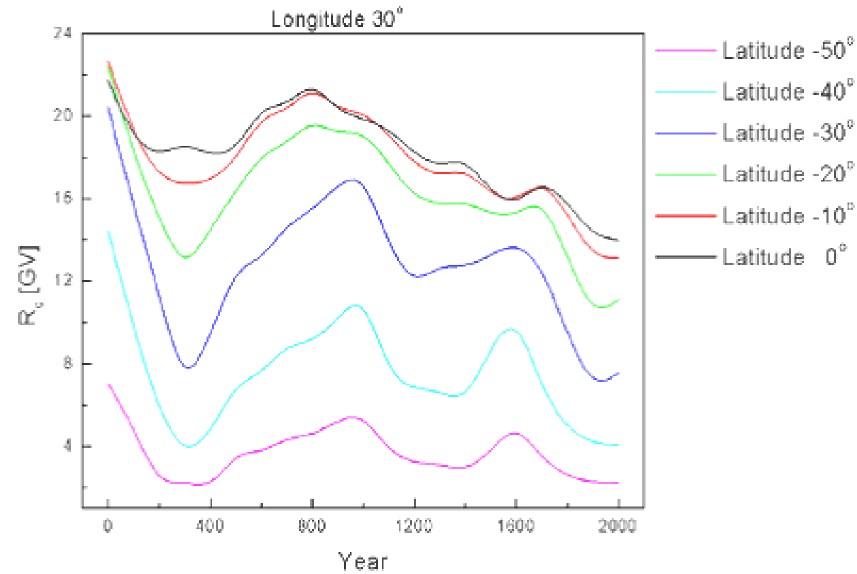

The vertical cut-off can be approximated as a function of L, McIlwain's parameter (e.g. *Shea, M. A. et al, Phys. Earth and Planet. Interiors, 48, 200-205,1987*).

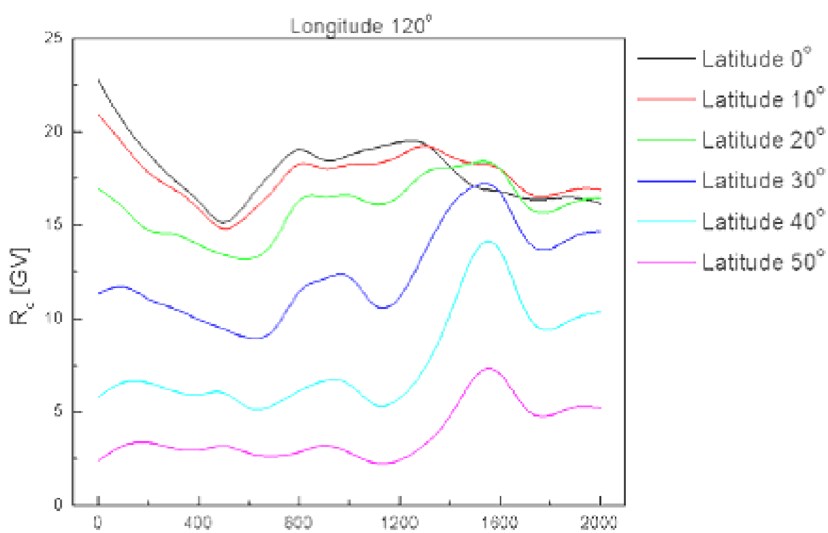
While around 1950 positions of LŠ and LARC (in opposite hemispheres) had almost the same value L, by the end of last century L at LARC was significantly higher (lower cut-off) than at LŠ (*Kudela,K. and M. Storini, Proc. ICRC, Hamburg, 9,4106-4109, 2001*)

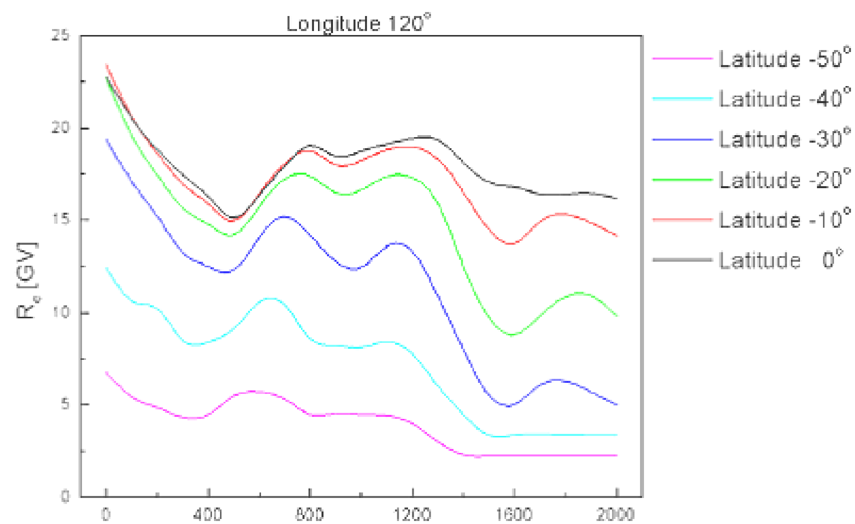
Updated algorithm of using L for vertical cutoff estimate was recently published by *Storini et al (JASR, 2007*)

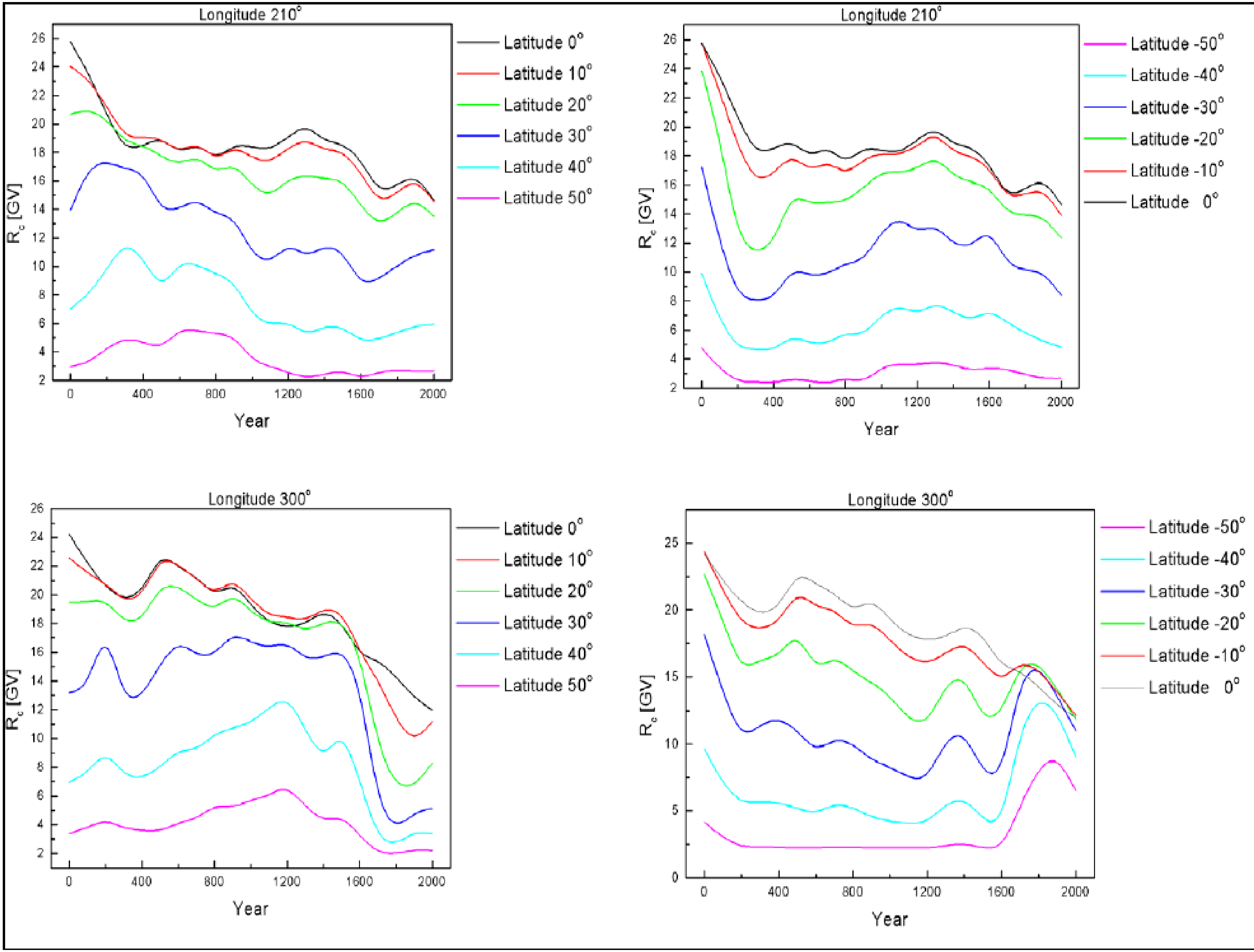
Changes of geomagnetic cut-offs in the past: available models of geomagnetic field are used (e.g. *Kudela, K., Bobík, P., Solar Phys., 224, N 1-2, 423 – 431, 2004*). Different positions on earth had different cut-off rigidity time changes.




Longitude 210°
Latitude 0°
Latitude 10°
Latitude 20°
Latitude 30°
Latitude 40°
Latitude 50°
R_c [GV]
Year
Longitude 210°
Latitude -50°
Latitude -40°
Latitude -30°
Latitude -20°
Latitude -10°
Latitude 0°
R_c [GV]
Year
Longitude 300°
Latitude 0°
Latitude 10°
Latitude 20°
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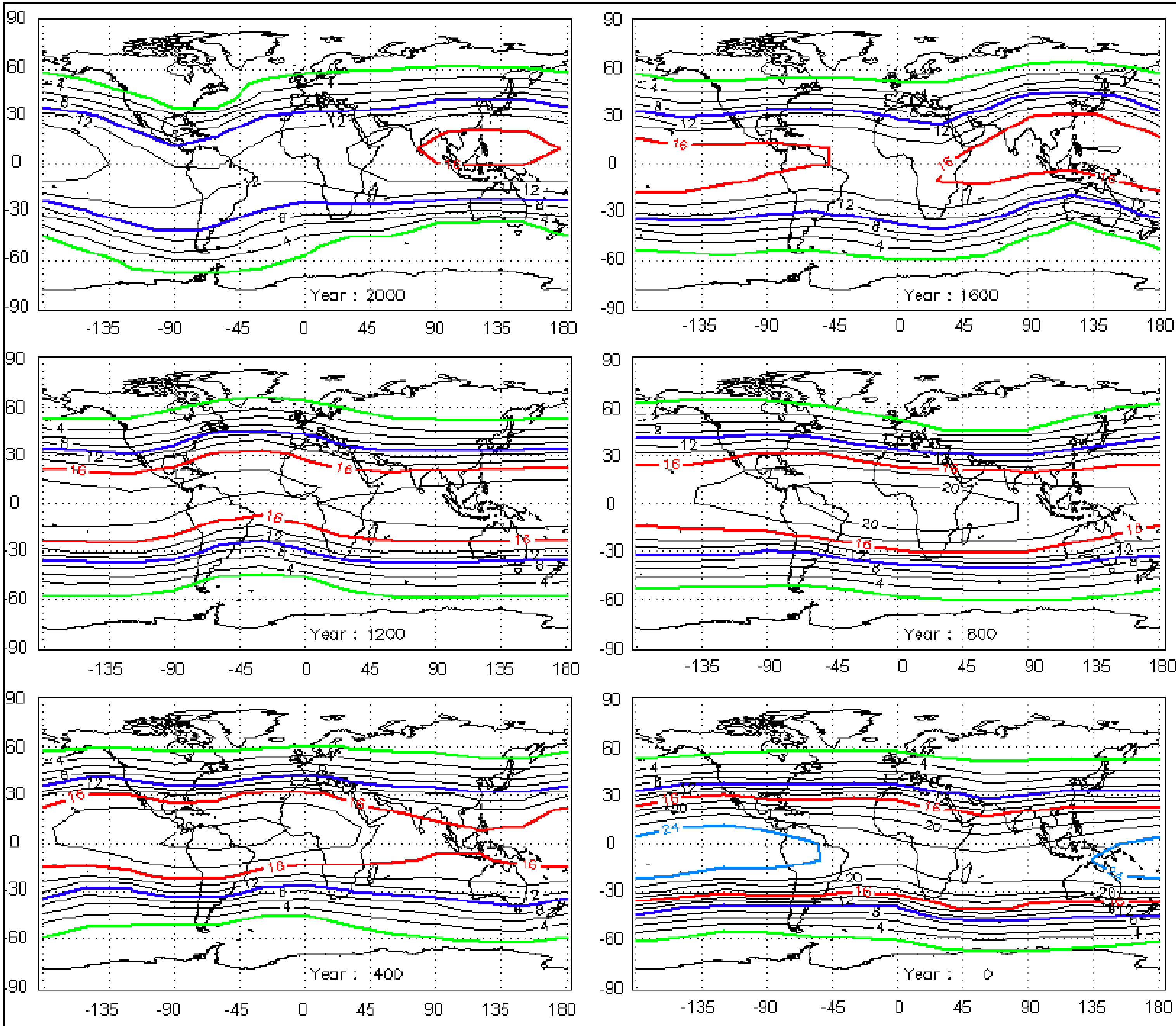
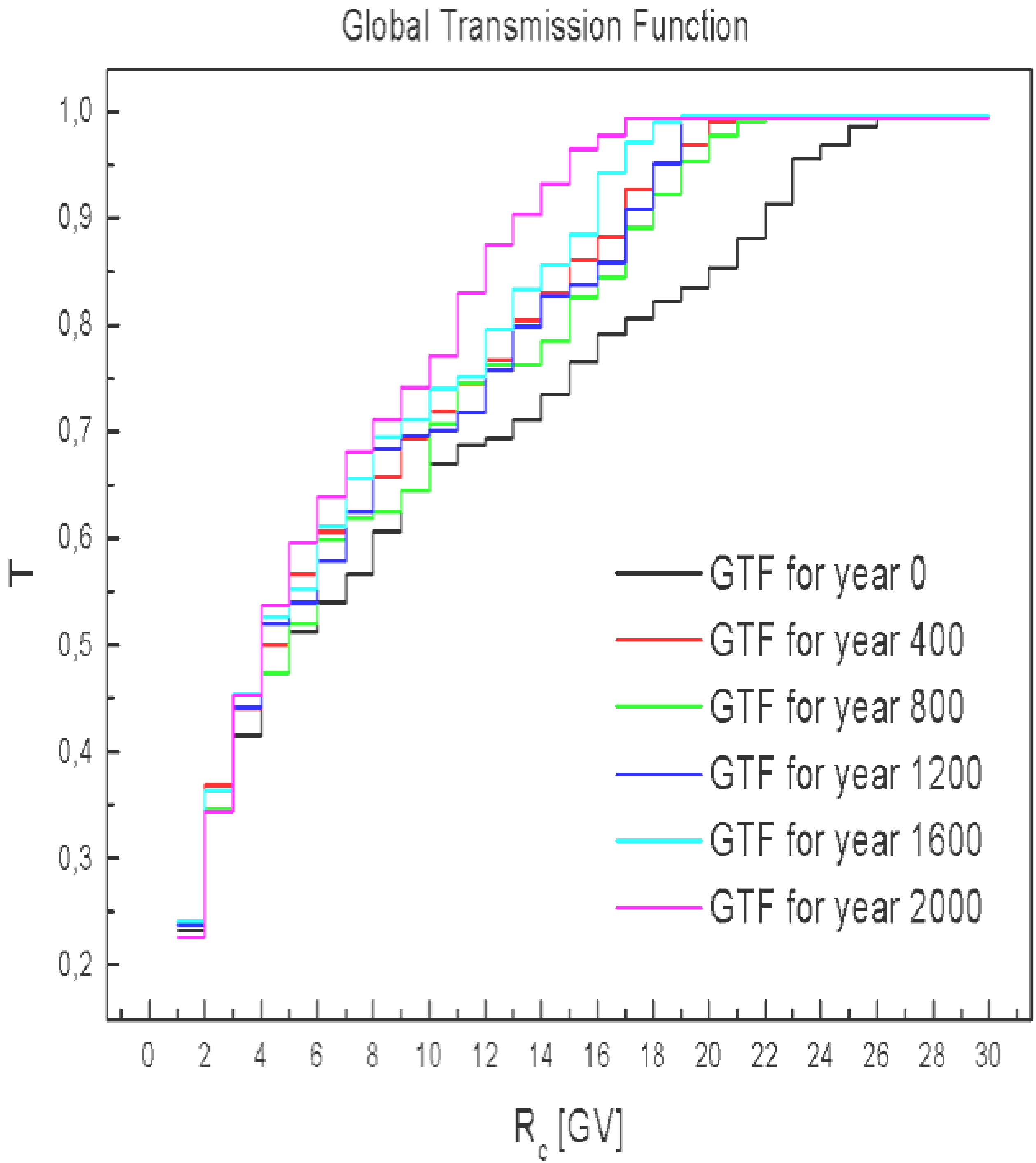



Lines of constant vertical cut–offs during the interval of years 0 to 2000.

Computations done from available magnetic field models.



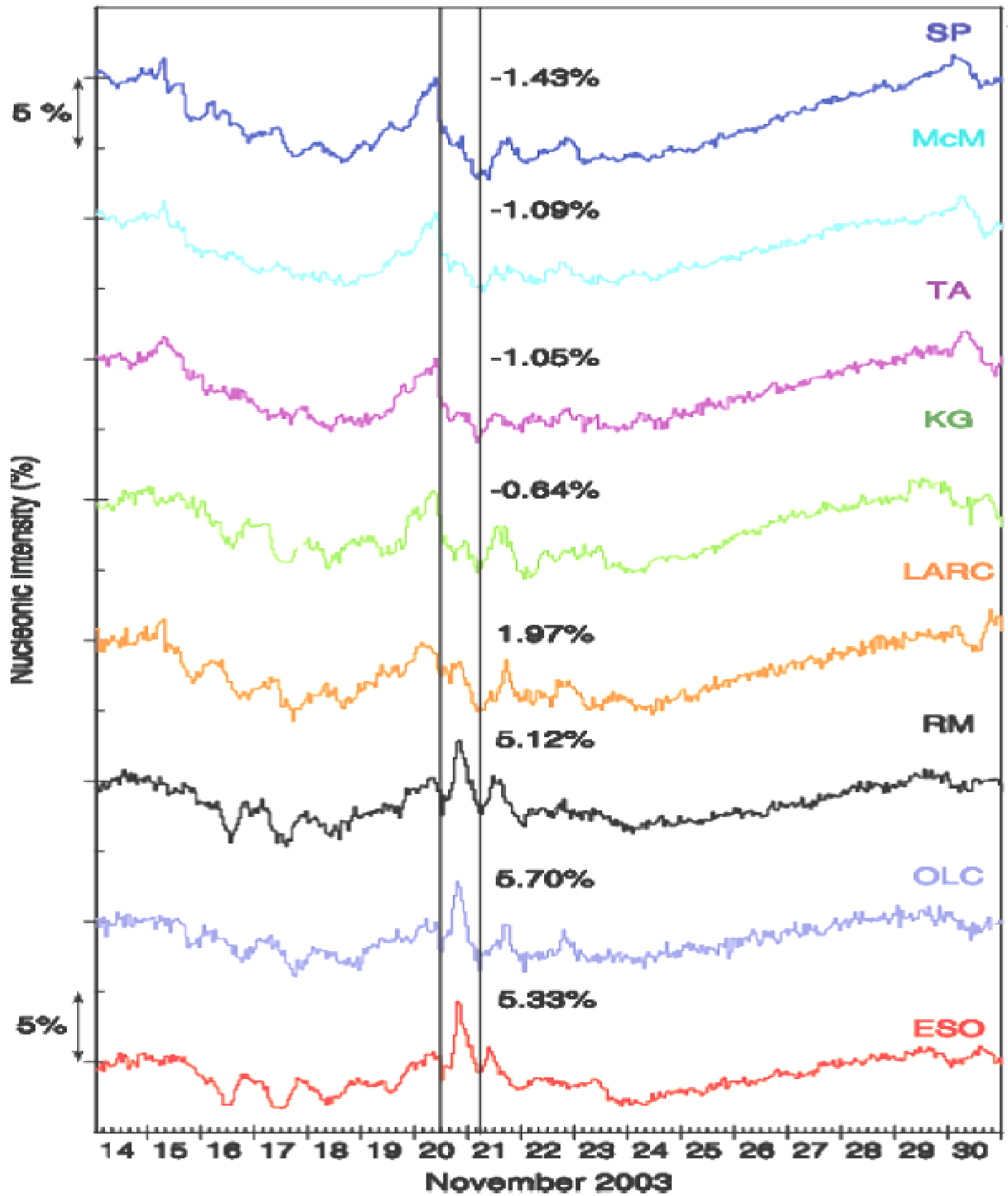

The “global transmission function”: the fraction of the Earth’s surface at which the vertical access of cosmic rays for $R > R_c$ is allowed for different epochs.

Earth was in the past exposed to cosmic rays in changing manners.

## *4. External current sources, examples during geomagnetic disturbances.*

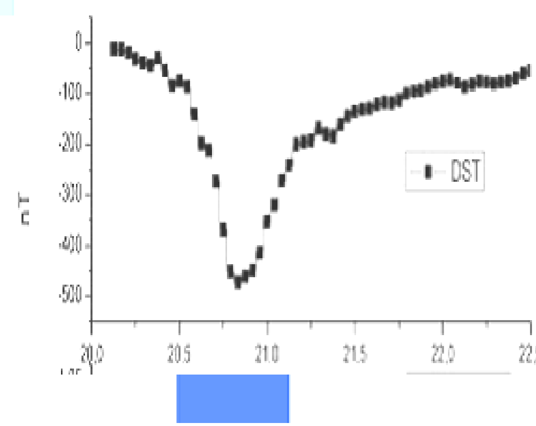
***Different models for strong disturbances of magnetosphere give different results on cosmic ray cut-offs.***

Time profile of cut-off depression, asymptotic directions and transmissivity function are different for different models.




During a strong geomagnetic storm, due to improved transmissivity of the magnetosphere for cosmic rays (reduction of cut-off rigidities) along with Forbush decrease seen at high latitude stations (South Pole, McMurdo) an increase especially at middle and low latitude neutron monitors is seen (Rome, Los Cerillos, ESO).

(*Storini, M. et al., EGU 2006*).



Similarly to that case the increase at Tibet neutron monitor (nominal vertical cut-off ~14.1 GV) was observed during a couple of geomagnetic storms (*Miyasaka H. et al, Proc. ICRC Tsukuba, 6, 3609-3612, 2003*).

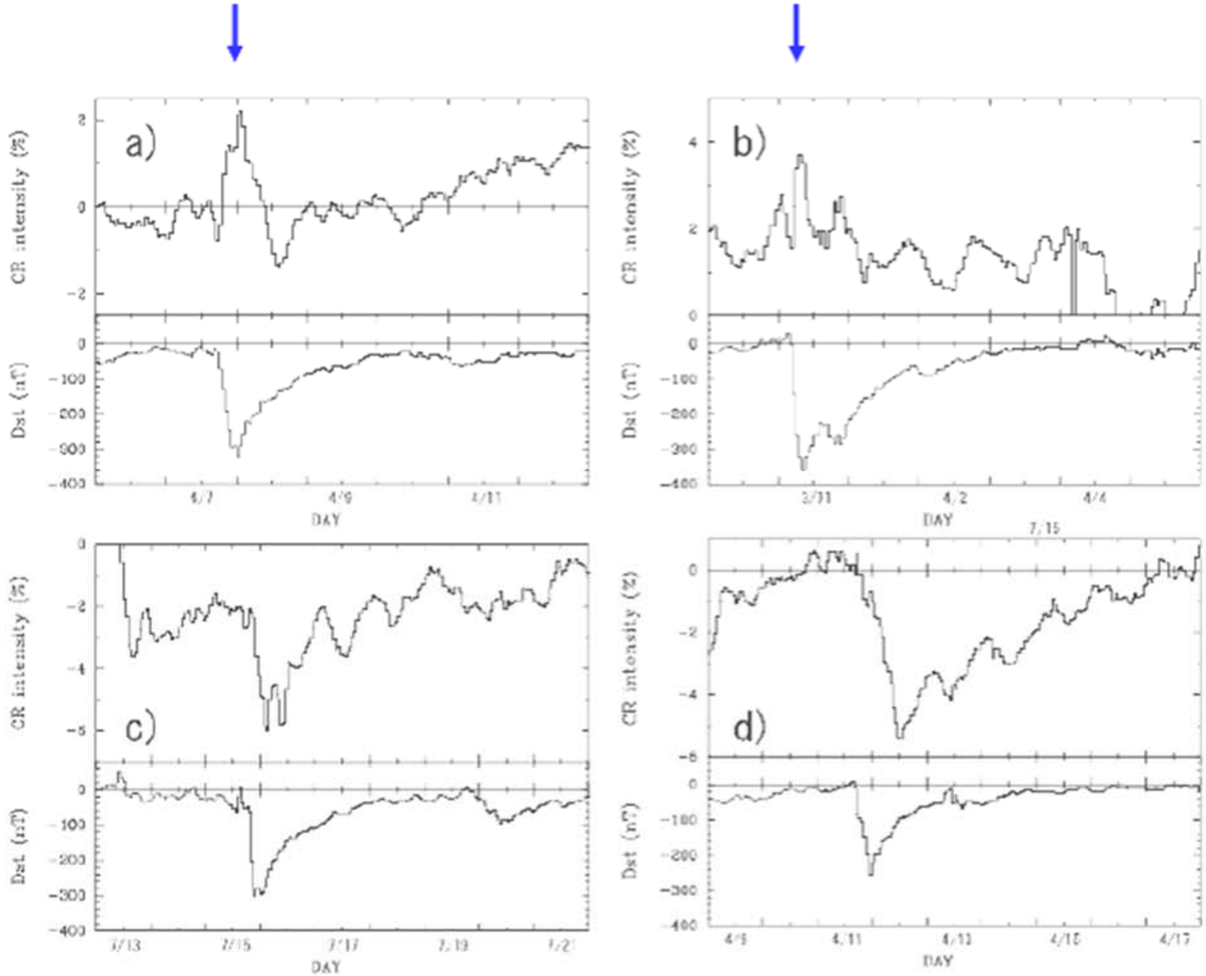
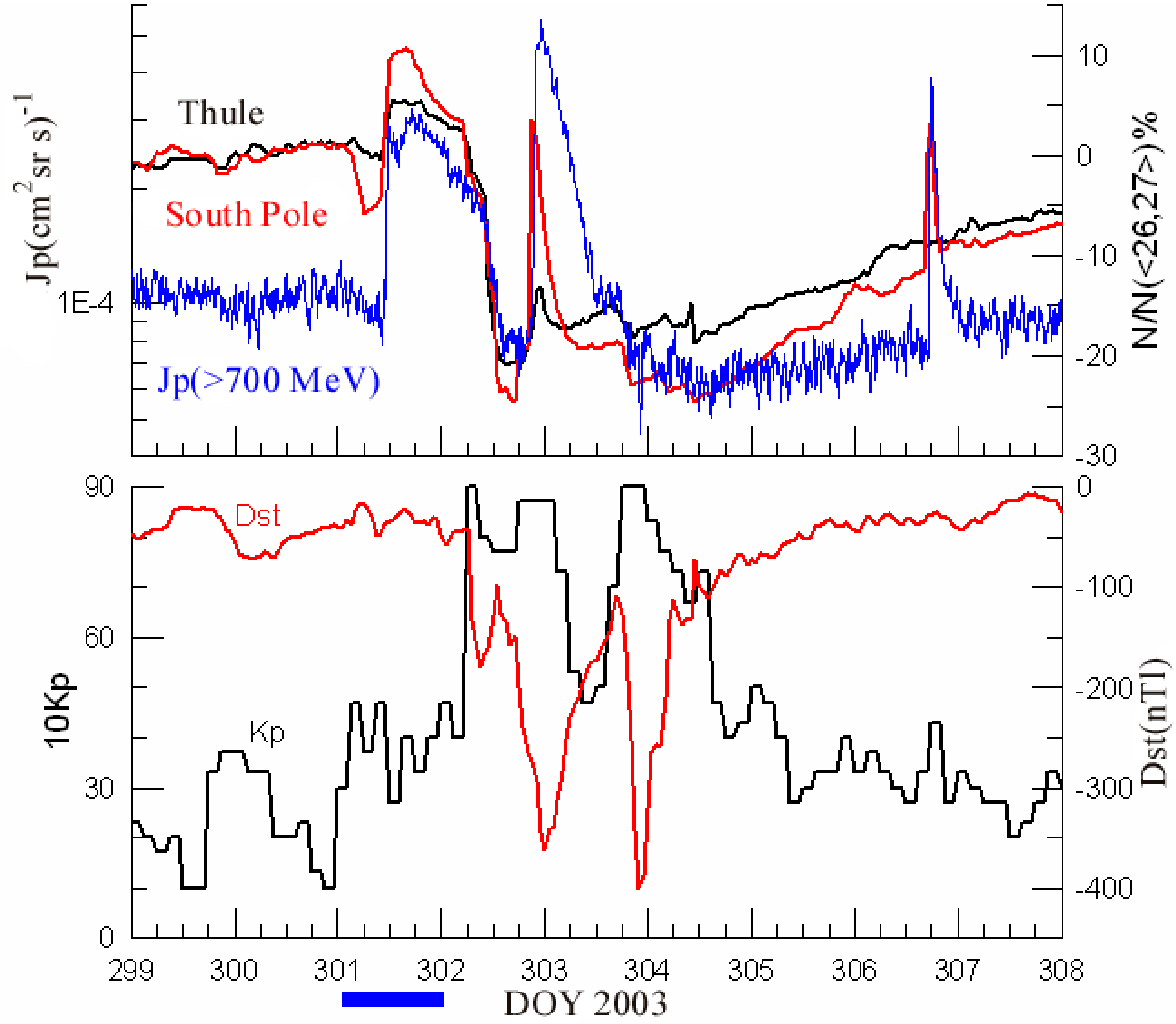



Fig. 1. Cosmic ray intensity (%) observed at TIBET neutron monitor and Dst value (nT) are shown. Each of the figure shows the magnetic disturbance occurred at (a)2000/04/07, (b) 2001/03/31, (c) 2000/07/15 and (d) 2001/04/11.

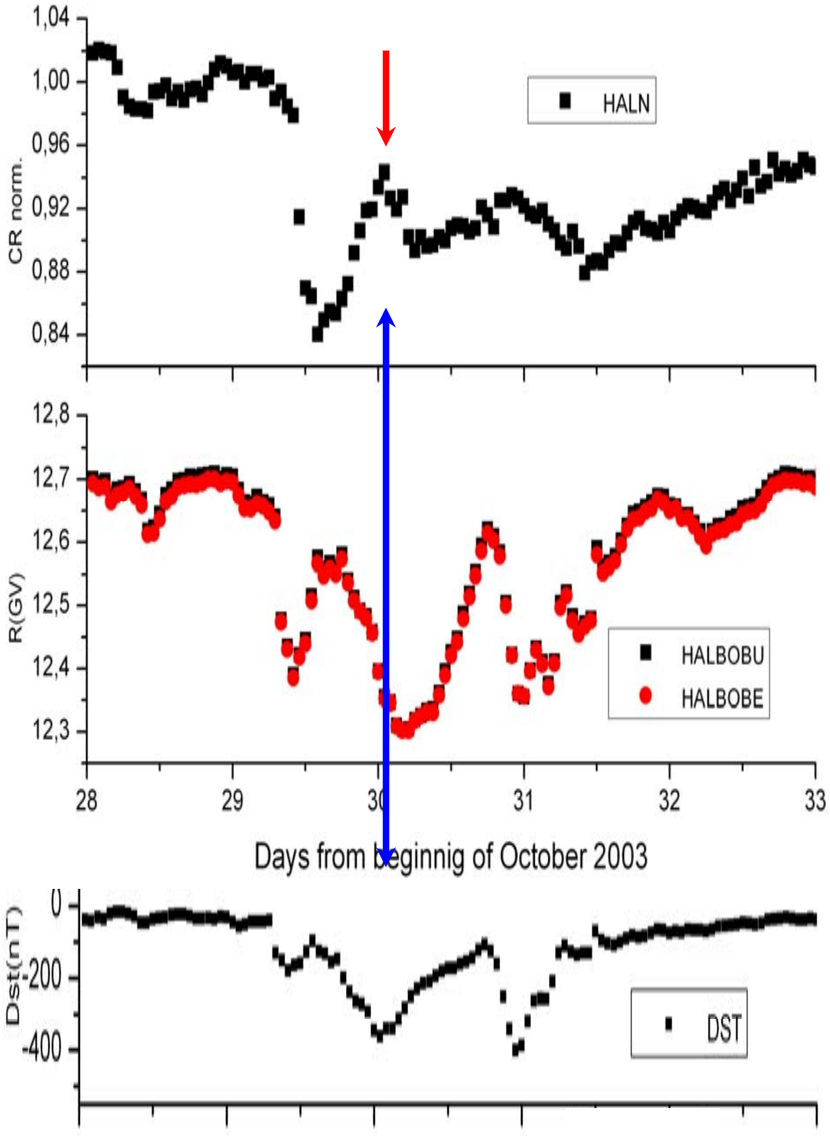
## *a. October 28 – November 1, 2003*

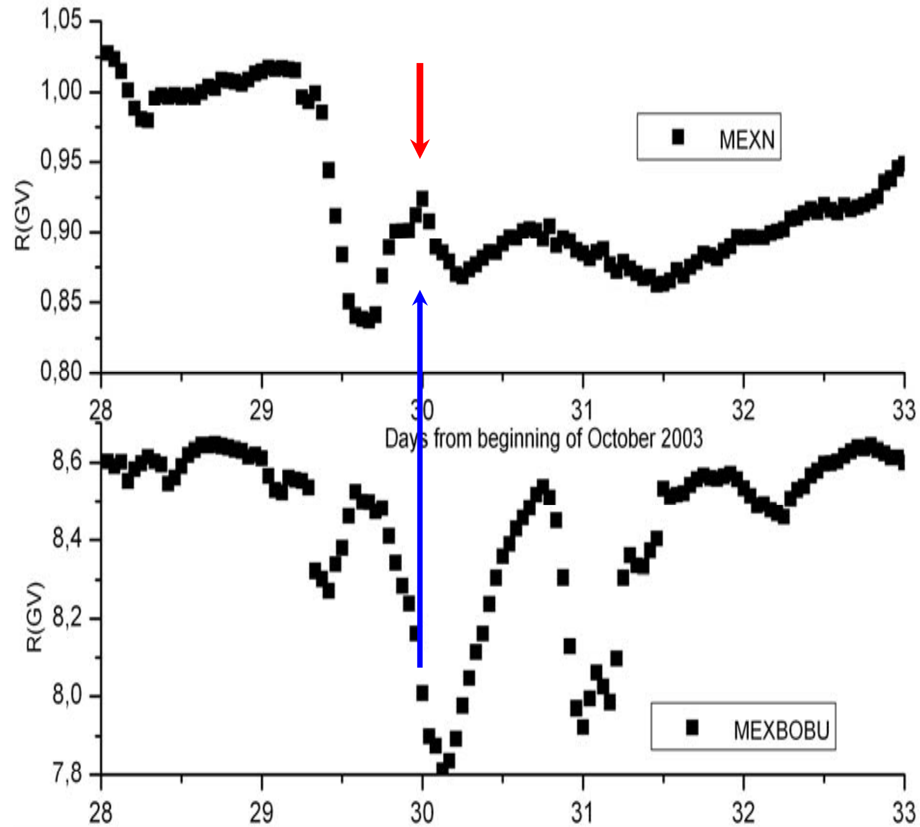
NM intensity at high latitudes, high energy proton data by GOES and geomagnetic indices for the period of October 26 until November 3, 2003



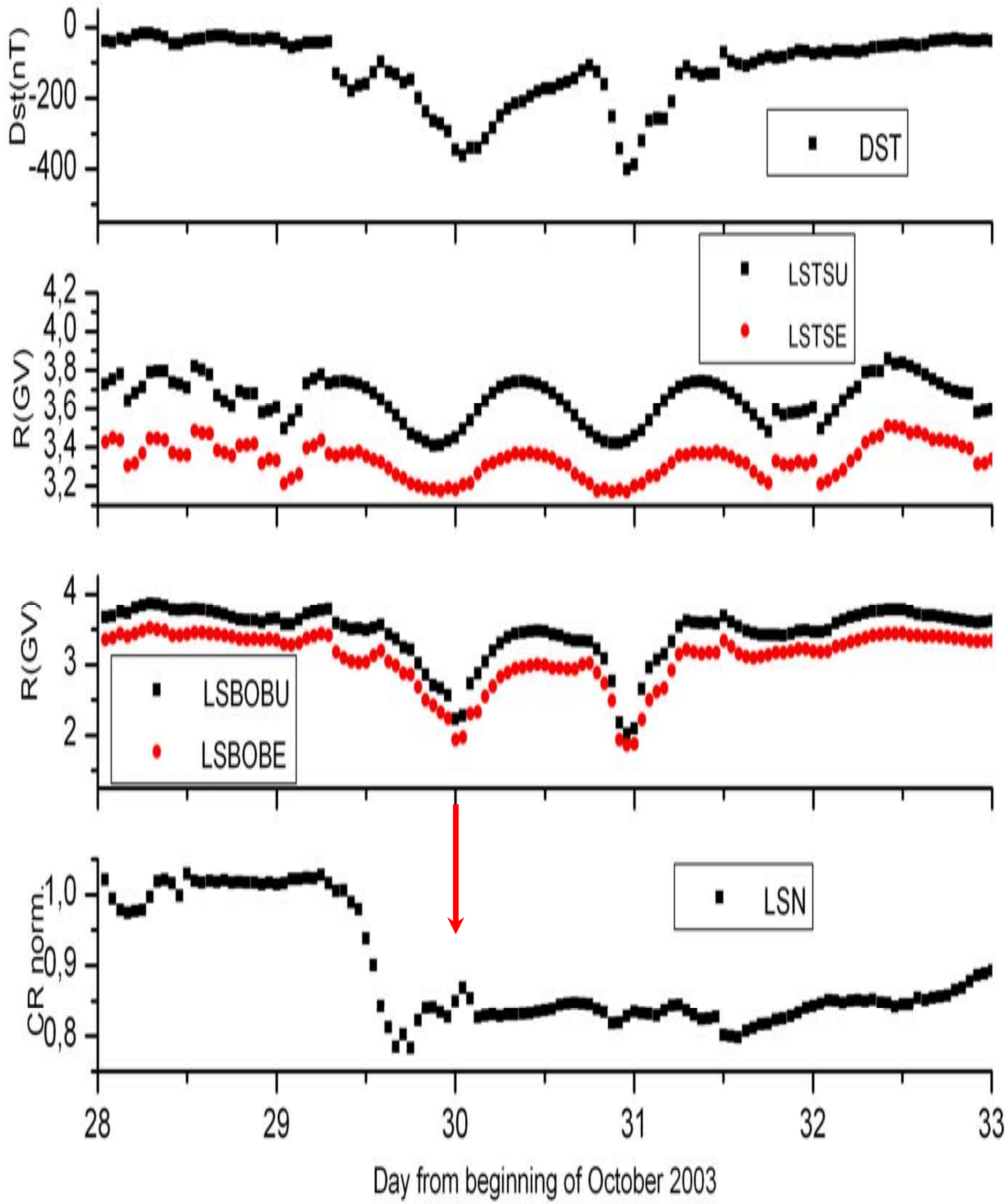

Oct. 28

CR increases *during first Dst depression* at high cut-off rigidity stations. Two Dst minima on Oct. 30: at 01 UT (Dst=-363nT) and at 23 UT (Dst = -401nT).

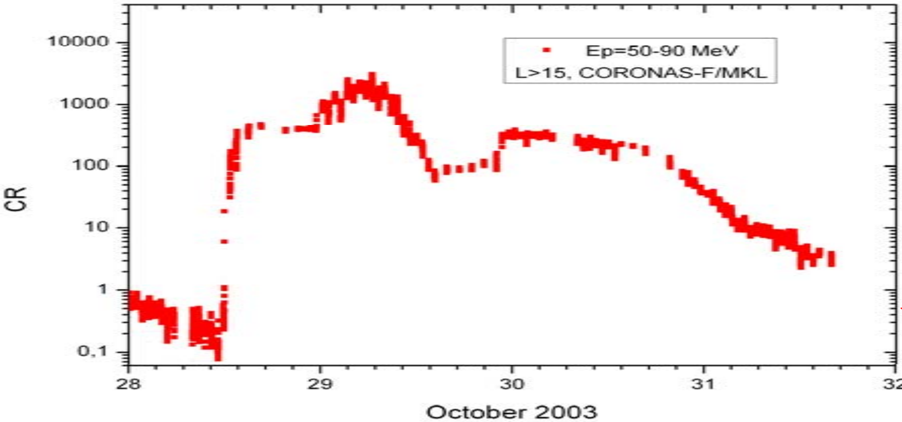


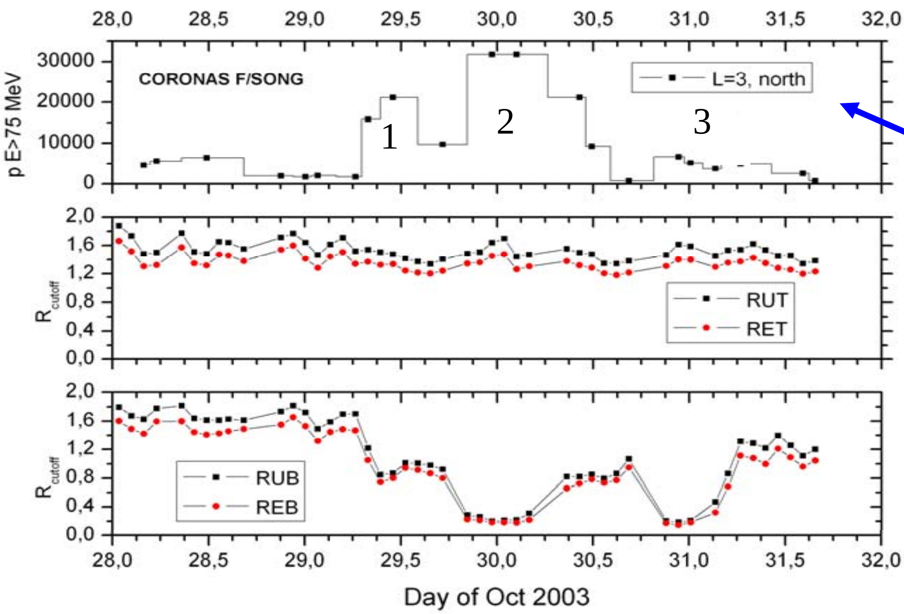

Upper panels: Haleakala (HALN) and Mexico (MEXN) NM normalized CR intensity. Middle:vertical cut-off rigidity (upper-U and effective-E by Ts89+Dst model)




Increase is smaller at middle latitudes (Lomnický Štít). Dst; upper-U and effective-E vertical cut-off rigidities by Ts89 (LSTS) and Ts89+Dst model (LSBOB).




Penetration of solar protons to lower L is seen on low altitude satellite CORONAS-F (experiments SONG, MKL – SINP MSU and IEP SAS, PI S.N. Kuznetsov)




The event seen differently at high latitudes

and at L=3.

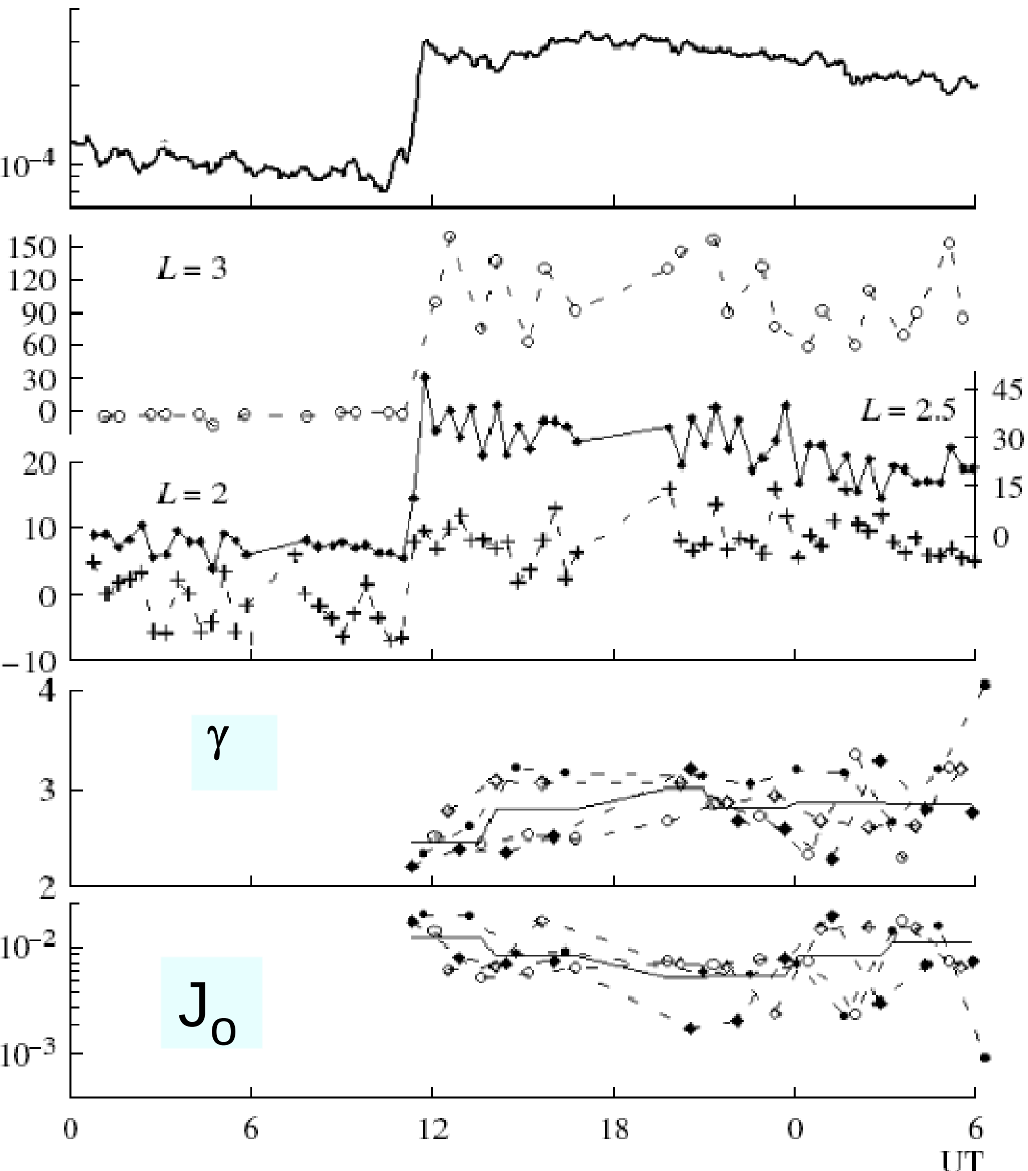
Computed vertical cutoffs for Ts89

Cutoffs for Ts89+Dst


Position of penetrating boundary of protons 50-90 MeV.

No input data for Ts04 model

Energy spectra from CORONAS-F using geomagnetic changes ***(large geom. factor***)




*From Kuznetsov et al, 2007*

GOES flux of protons E > 700 MeV $(cm^2.s.sr)^{-1}$

Fluxes of protons E > 90 MeV observed ad various L crossings by SONG/CORONAS-F. Linear scale, relative units vs background (ΔN/N %)

Assuming spectral shape

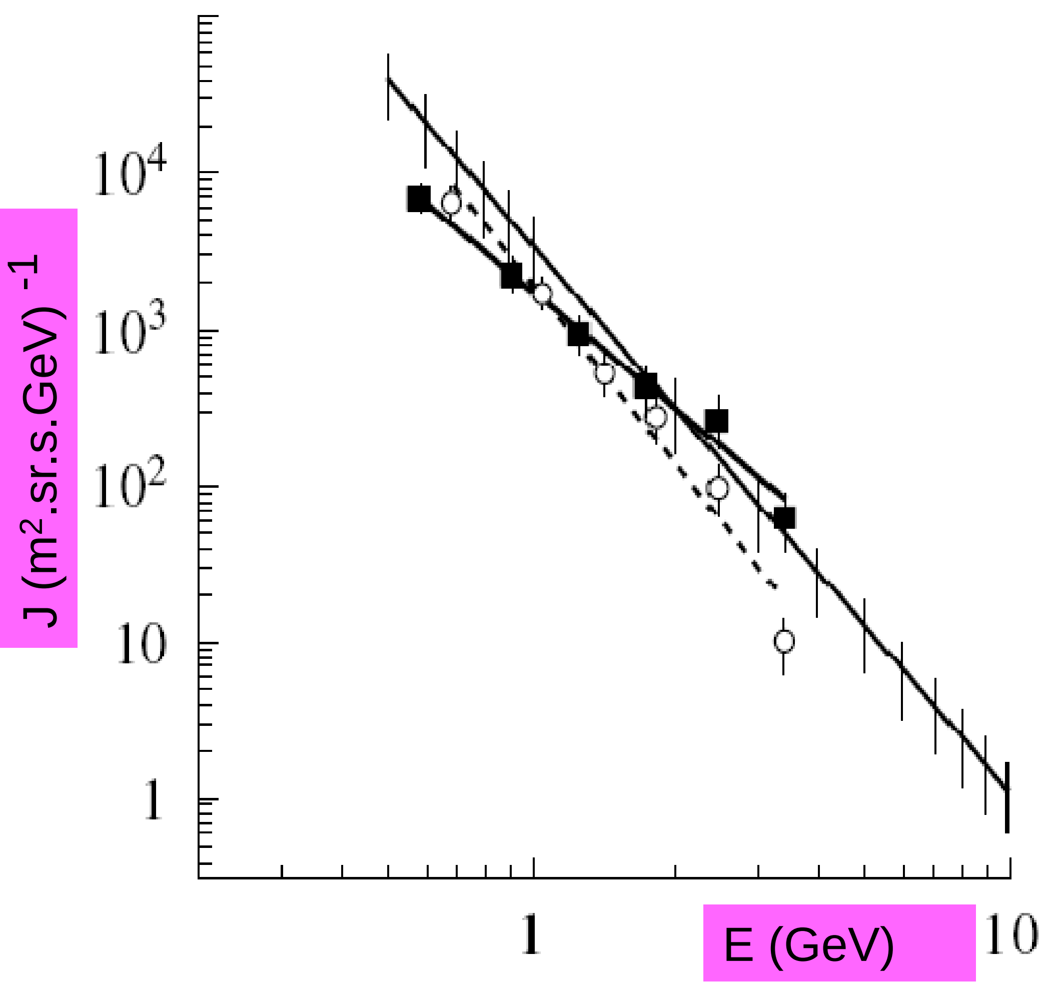
$$J\ (>E) = J_o\ .\ E^{-\gamma}$$

Values are fitted for all crossings. Circles and white romboids – morning sector (north, south)

Dots and black romboids – evening sector (north,south)

Lines – 3 h averages

For trajectory (at L=1.75, 2.0, 2.25, 2.75, 3.0 and 3.5) the vertical cutoff rigidities were computed at each point according to Ts'89 model (*Tsyganenko, PSS, 1989; Boberg et al, 1995*), more details in paper by *Kuznetsov et al, Czech. J. Phys., 2006*). Using power-law energy spectra, values $J_o$ and $\gamma$ were obtained. *Yushkov, B. et al, ICRC 2007*.



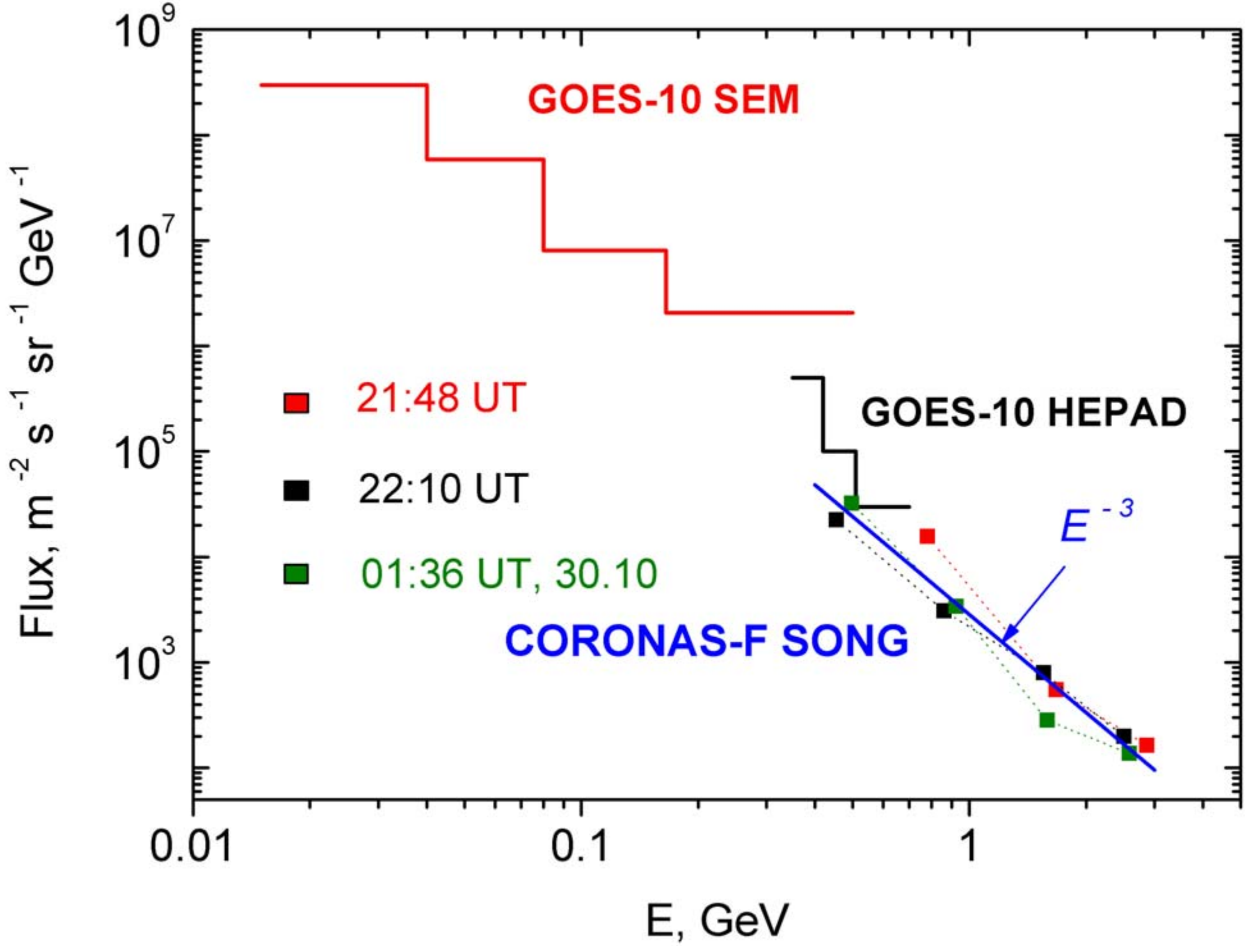

Two examples of the energy spectra obtained from SONG data:

at 1142-1146 UT evening sector (black squares) and at 1204-1209 UT morning sector (circles)

Comparison with NM data (line > 400 MeV) according to *Vashenyuk et al (Izv. RAN, 2005*) and *Miroshnichenko et al. (JGR, 2005*)

Increase during event 29.10. – more complicated – strong magnetic activity

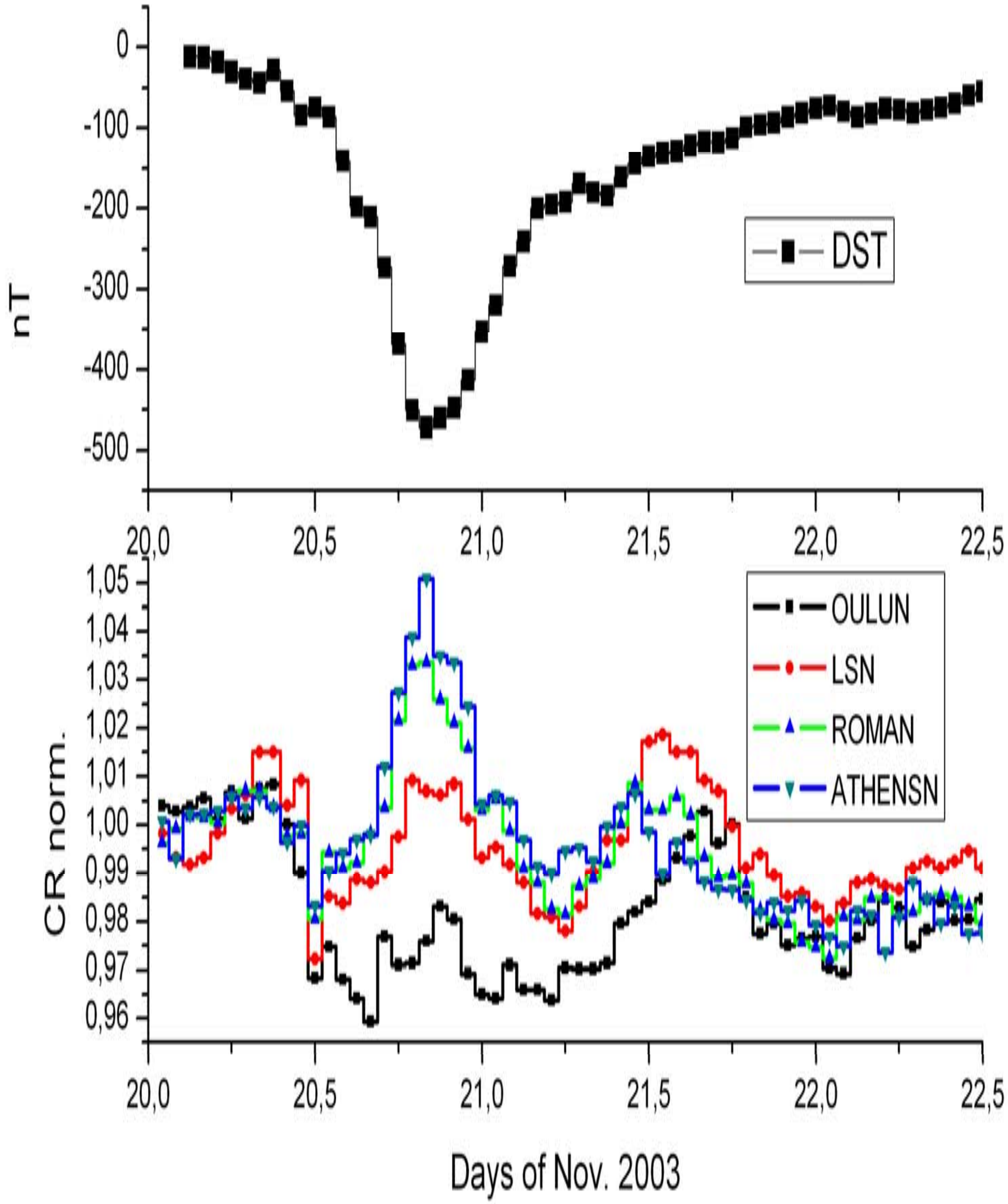
For event November 2 fit $\gamma$ ~3.5 (around 2128 UT)




Comparison of estimated part of energy spectra by SONG on October 29-30, 2003 with lower energies from GOES SEM and HEPAD from http://spidr.ngdc.noaa.gov/spidr/ and http://goes.ngds.noaa.gov/data/ averaged over 22 UT 29.X - 01 UT 30.X.

Background level was calculated over 14-21 UT on 29.X.

***b. November 20-22, 2003. Isolated Dst depression.***




Improvement of magnetospheric transmissivity is clearly seen at NMs with high cut-off rigidities.

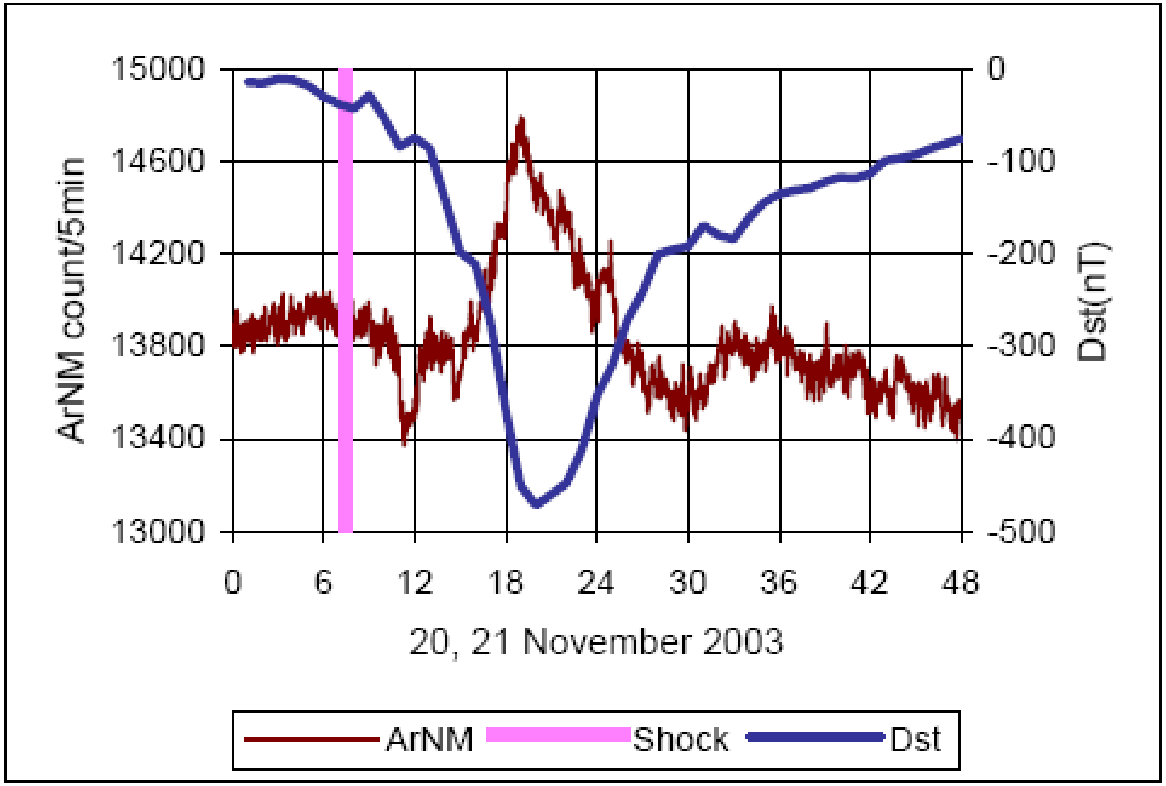
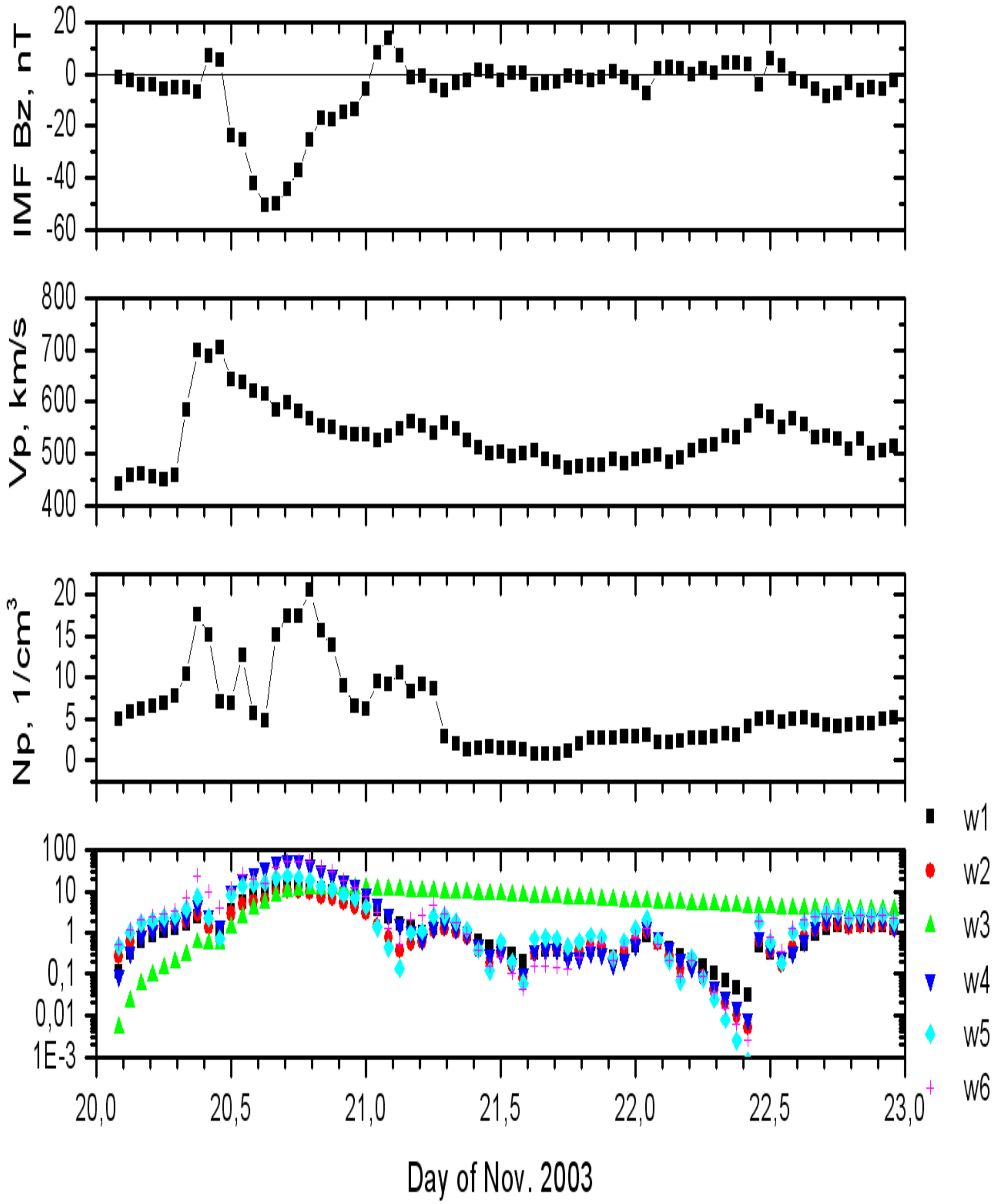



**Figure 1.** Aragats Neutron Monitor 5-minute count rate and Dst-index for November 20, 2003 event.

*Important for high cut-off stations (From paper by Zazyan and Chilingarian, Pune 2005)*

For interval 2 data for using Ts04 model are available. Differences in transmissivity of CR in different models can be tested.

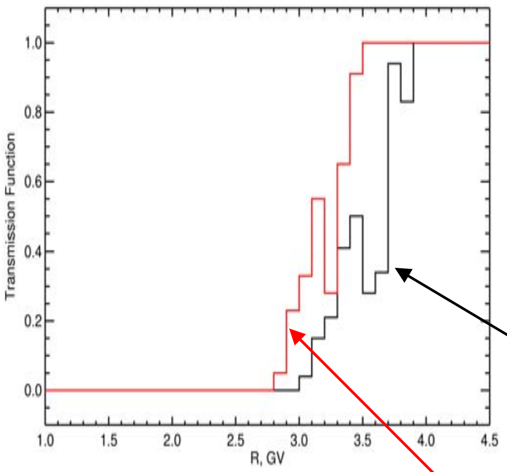



Tsyganenko 04 model uses "prehistory" of geomagnetic storm.
Input parameters
W1(inner tail current),
W2(outer tail current),
W3(symmetrical ring current),
W4 (partial ring current),
W5 (FAC- region 1),
W6 (FAC-region 2).
Constructed from the time profiles of $N_p$, $V_p$, IMF $B_z$ by *Tsyganenko and Sitnov, 2005* formula (7) modified for one – hour data.

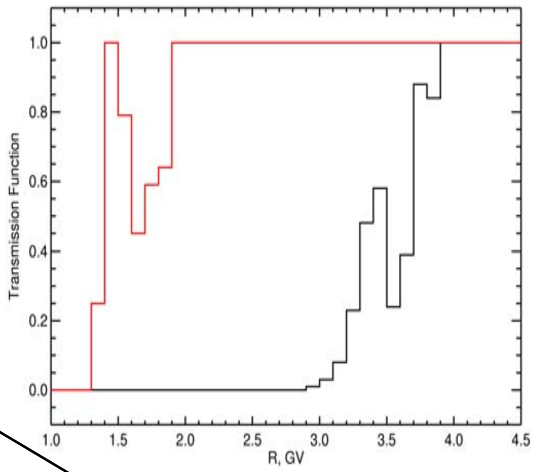
***Differences of Ts89, Ts89+Dst, Ts04:***

***<u>1. Transmissivity function:</u>***

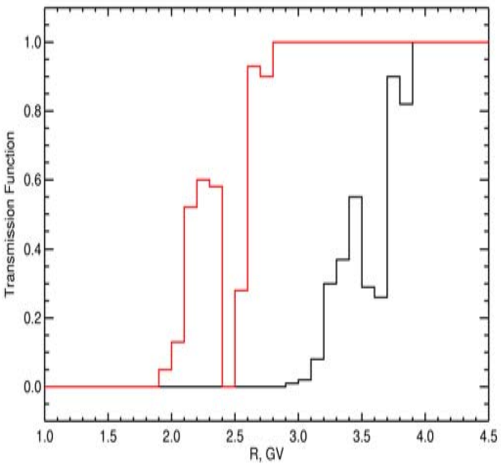
Ts89



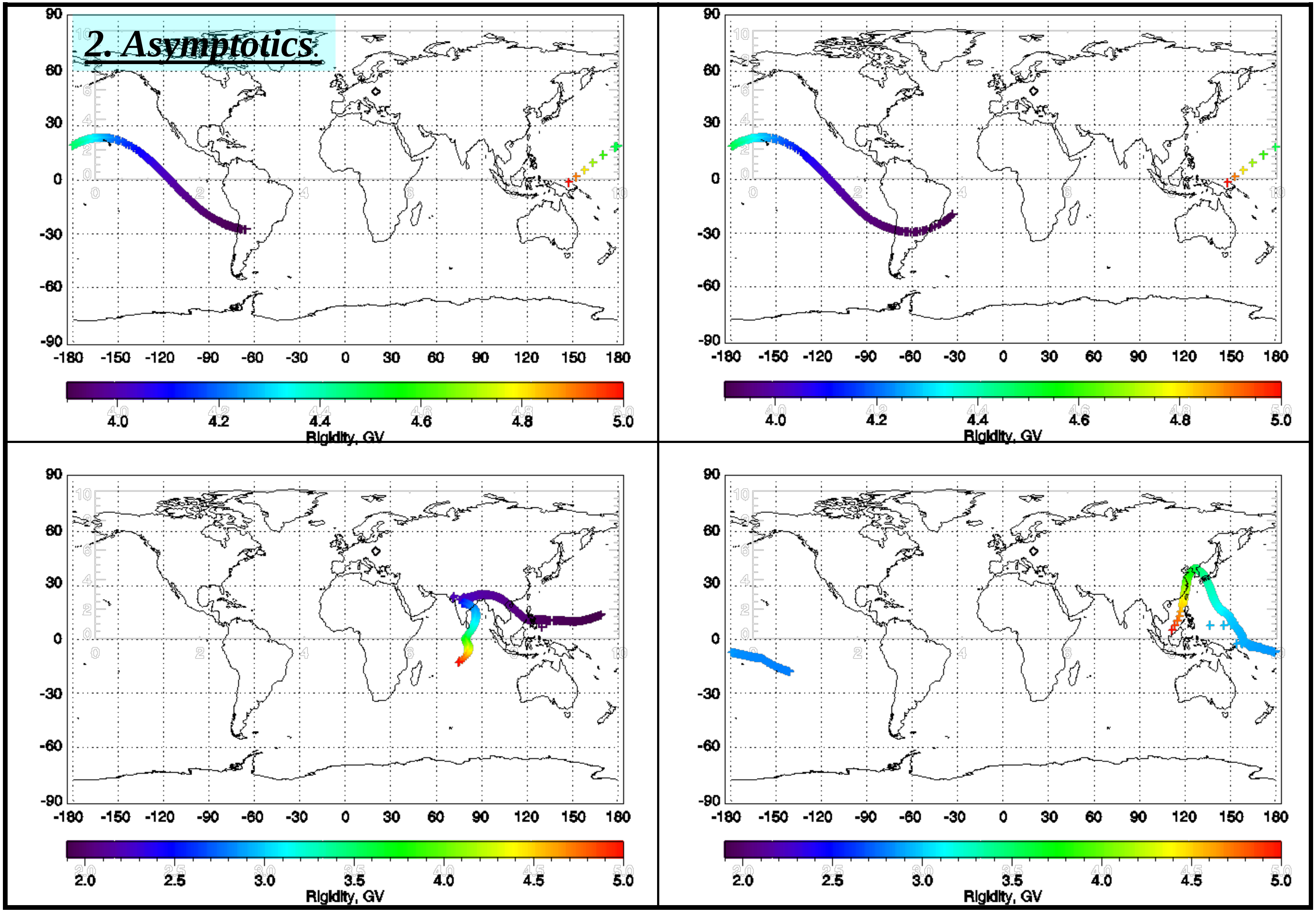

Ts89+Dst




Ts04

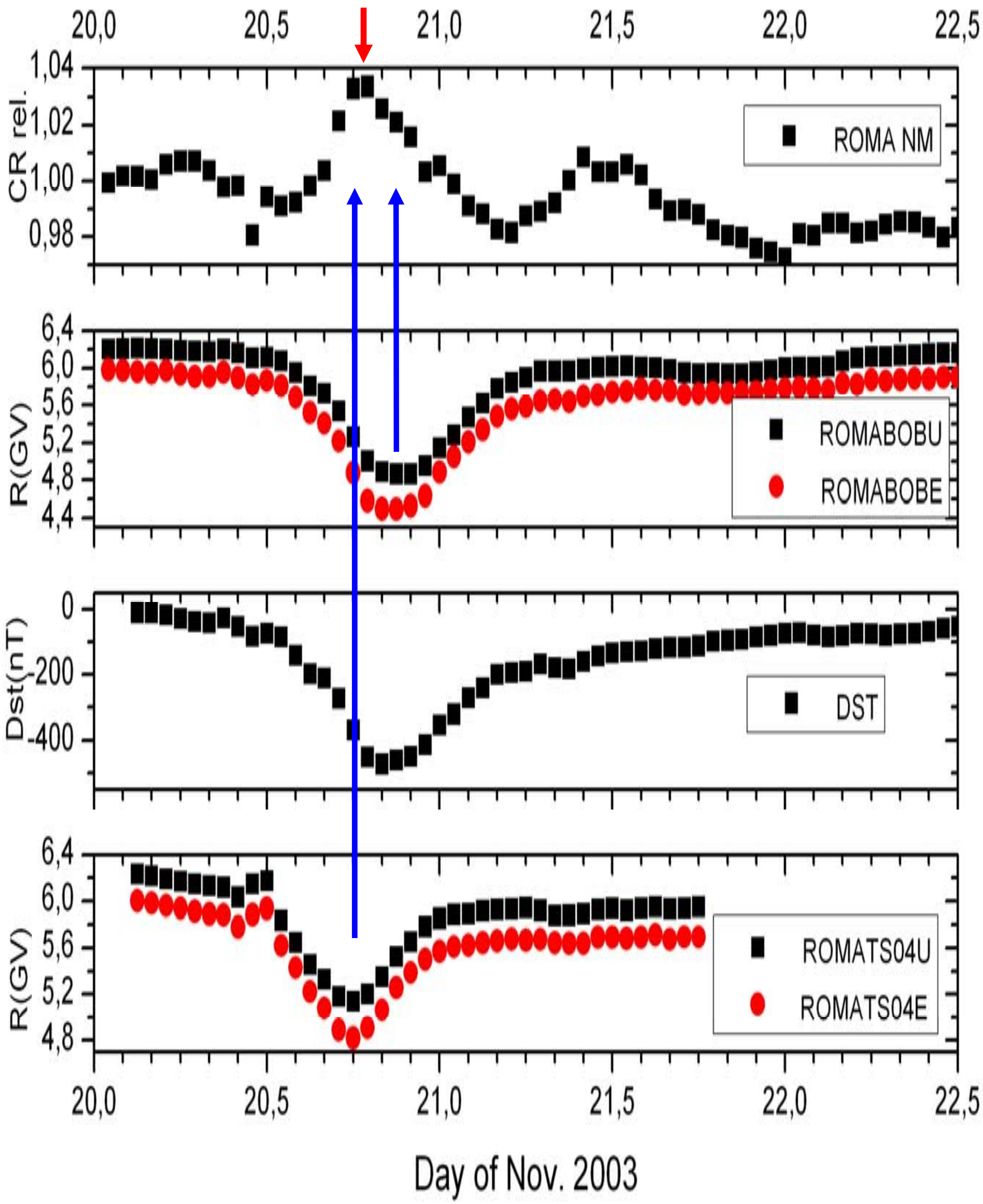



TF (for vertical direction) for Lomnický Štít **before the onset** of the storm (Nov. 20, 2003, 02 UT, **black**) and **during the Dst minimum** (19 UT, **red**) for three models.




Asymptotic directions for Lomnický Štít *before* the disturbance (*upper* panels, Nov. 20, 2003, 02 UT) and at *minimum Dst* (*lower* panels, 19 UT) for Ts89+Dst (*left*) and Ts04 (*right*).

## *3. Timing of minimum cut-off rigidity.*



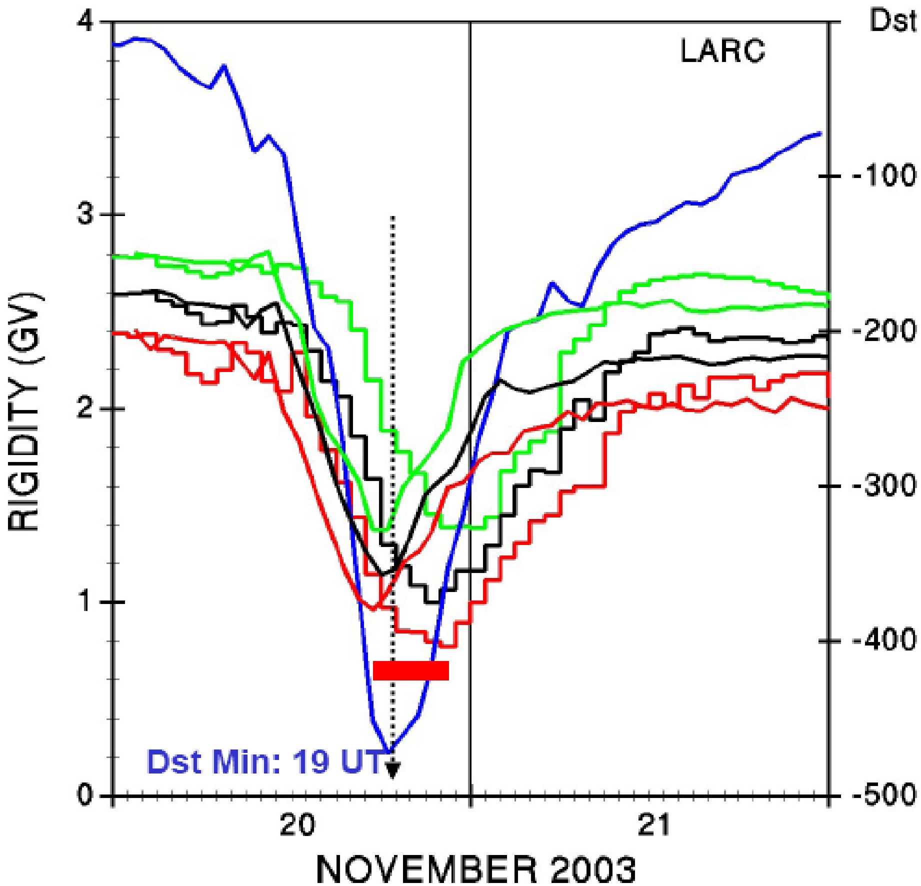

Rome neutron monitor. Increase in CR is matching better the cut-off decrease for Ts04 model than that for Ts89 + Dst.

# VERTICAL CUT-OFF CHANGES DURING NOVEMBER 20-21, 2003

**GREEN: Upper Cut-off**
**BLACK: Effective Cut-off**
**RED: Lower Cut-off**
**BLUE: Dst index**

**Staircase: Ts89Kp/Dst (Boberg et al., GRL 22 (9), 1133, 1995).**

**Continuous line: Ts04 (Tsyganenko & Sitnov, JGR 110, 2005, A03208, doi:10.1029/2004JA010798).**



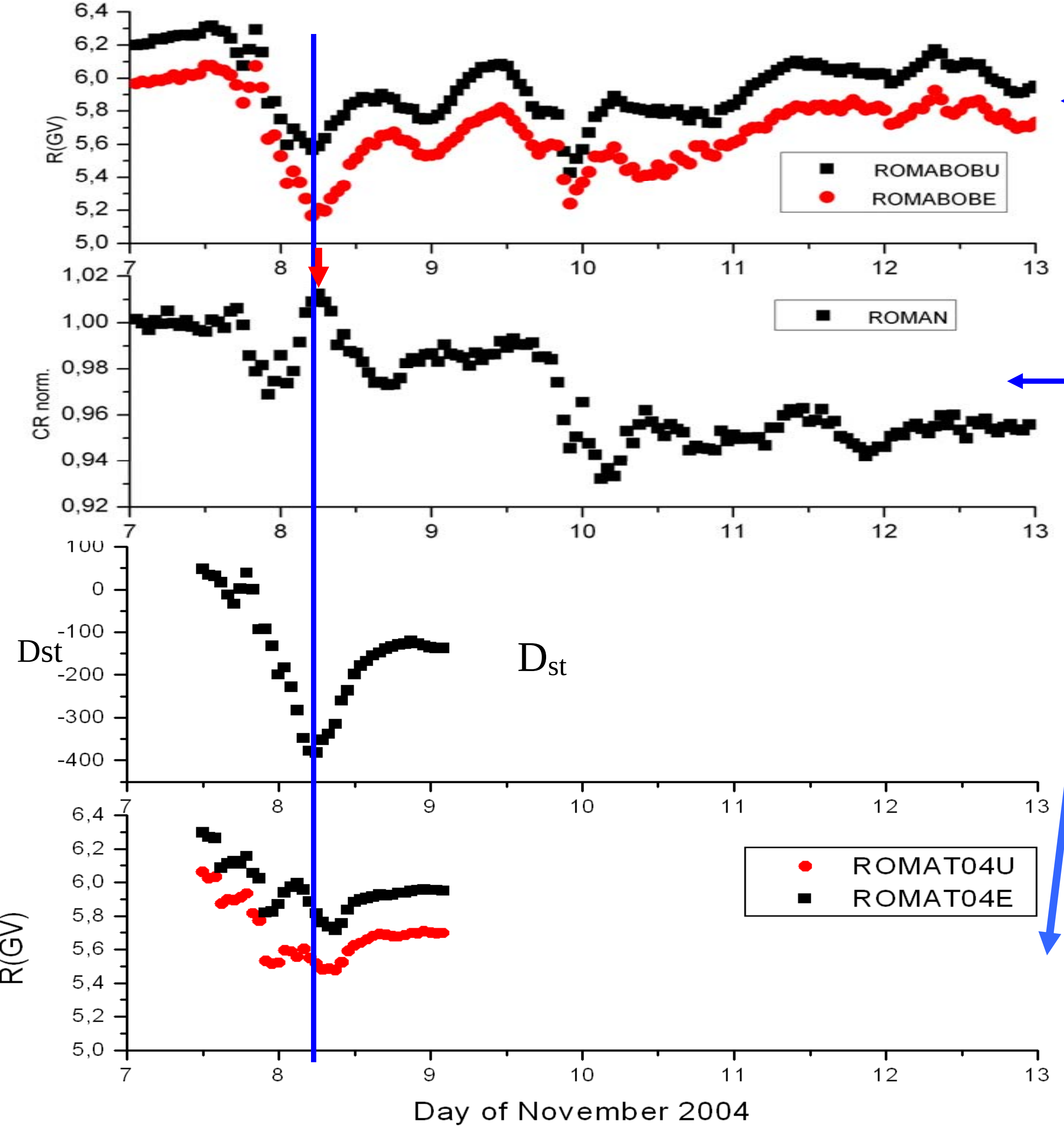

**ABSOLUTE RIGIDITY**

| Cut-off | LOWER | UPPER | EFFECTIVE |
|---|---|---|---|
| Ts89Kp/Dst | 0.77: 22 UT - | 1.38:24 UT - | 1.00:21 UT |
| Ts04 | 0.96:18 UT - | 1.37:18 UT - | 1.14:18 UT |

- **Results from Ts04 gave stable time for minimum rigidity cut-off (18 UT), preceding 1 h the Dst minimum, while the ones for Ts89Kp/Dst follow the Dst minimum from 2 to 5 h.**

Different time of minimum cut-off for LARC station for two models. The time of maximum CR increase is better matching model Ts04 than Ts89+Dst. (*Storini et al, EGU 2006*).

## *c. November 7-8, 2004.*

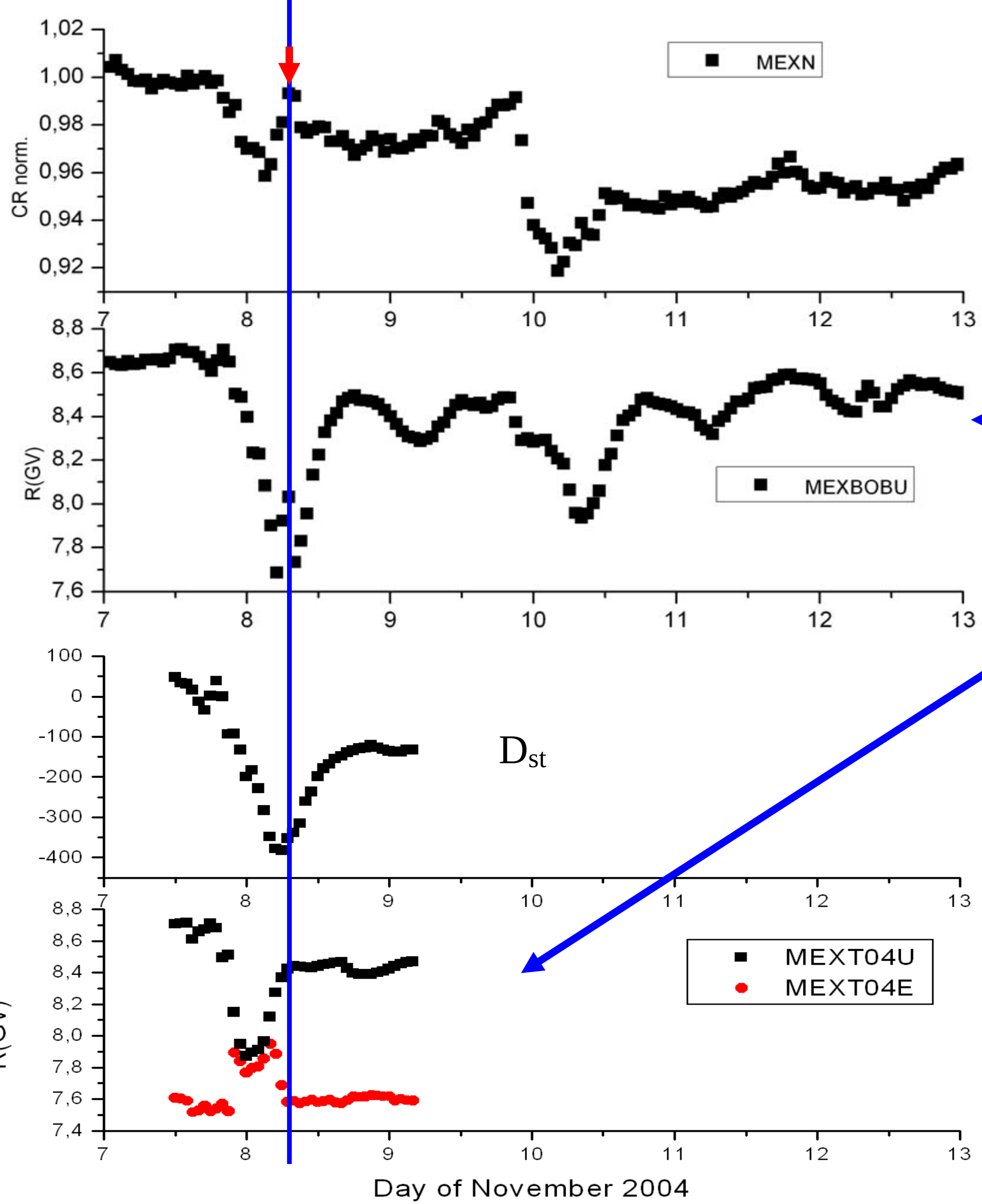



Cutoff rigidities $R_U$ and $R_E$ according to Ts89+Dst

Ts04 model.

Rome NM intensity (normalized to 00-12 Nov.7).

Timing of CR maximum increase is matching better Ts89+Dst model than Ts04.

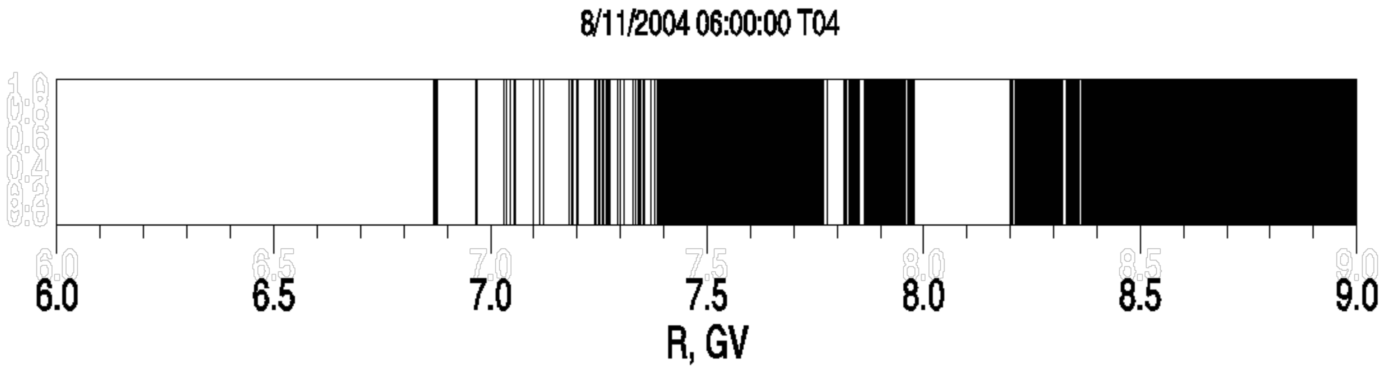



Mexico NM CR intensity
(normalized to 00-12 Nov.7, 2004)

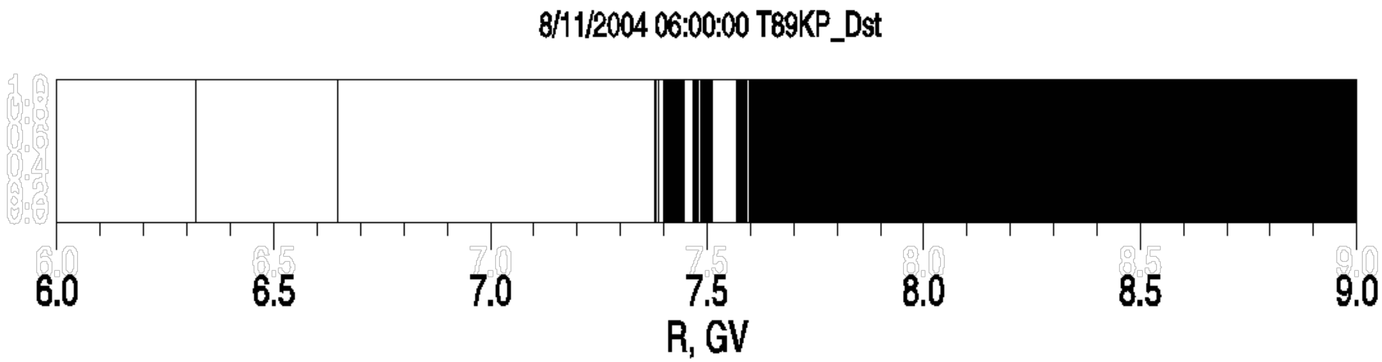
Cut-off rigidity according to Ts89+Dst and Ts04 model.

Complicated structure of cut-off time change.

Time of maximum CR increase is not matching Ts04 expectation of minimum cut-off.

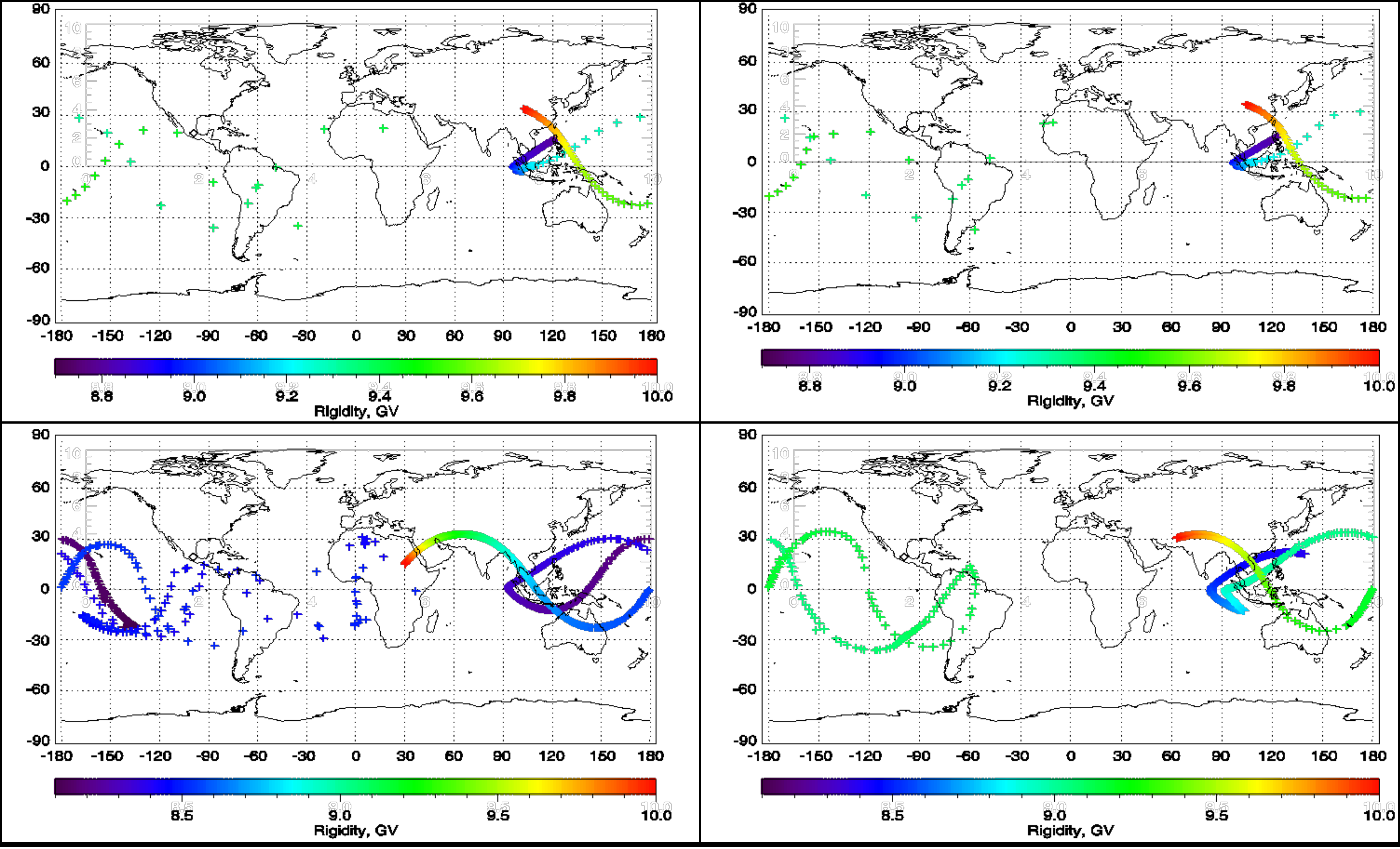



Ts04




Ts89+Dst

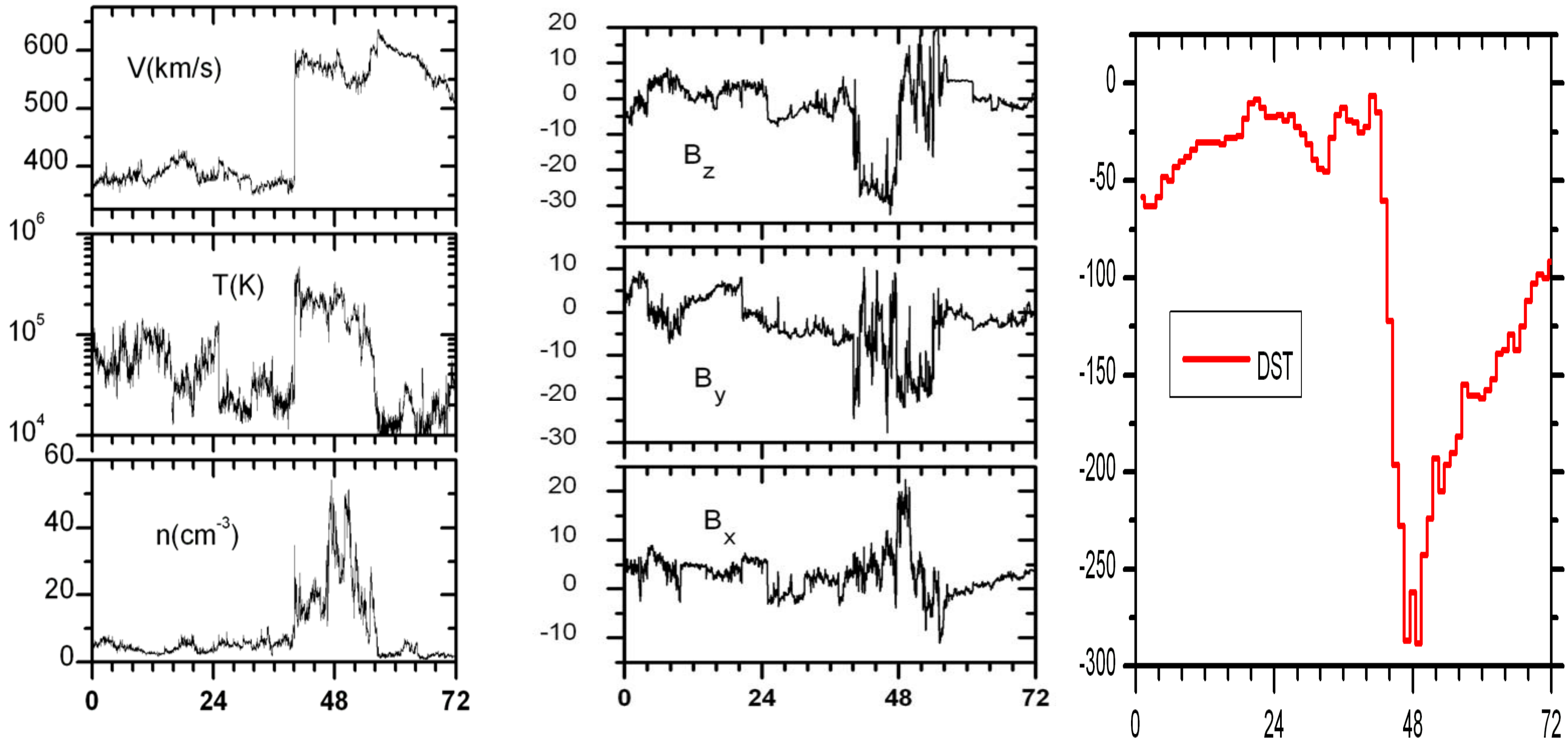
Penumbra structure for high nominal cut-off rigidity station (Mexico) during the storm is complicated and depends on the model. TFs are different.




Asymptotic directions for Mexico ($R>R_U$) *before* the disturbance (*upper* panels, Nov. 7, 2004, 12 UT) and at *minimum Dst* (*lower* panels, Nov. 8, 06 UT) for Ts89+Dst model (*left*) and Ts04 model (*right*).

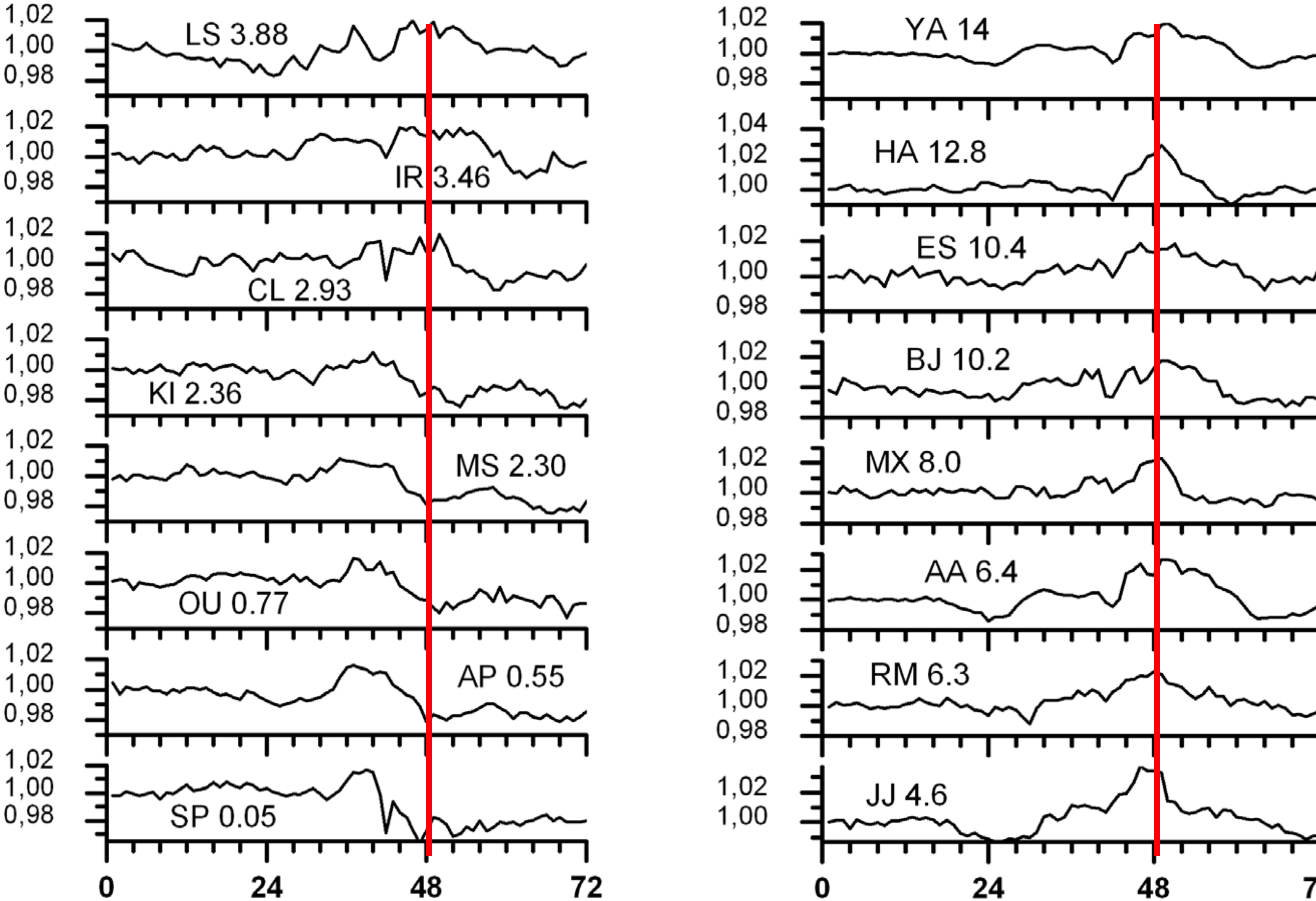
***d. April 6, 2000.***

Rather strong, isolated in time, disturbance of magnetosphere.



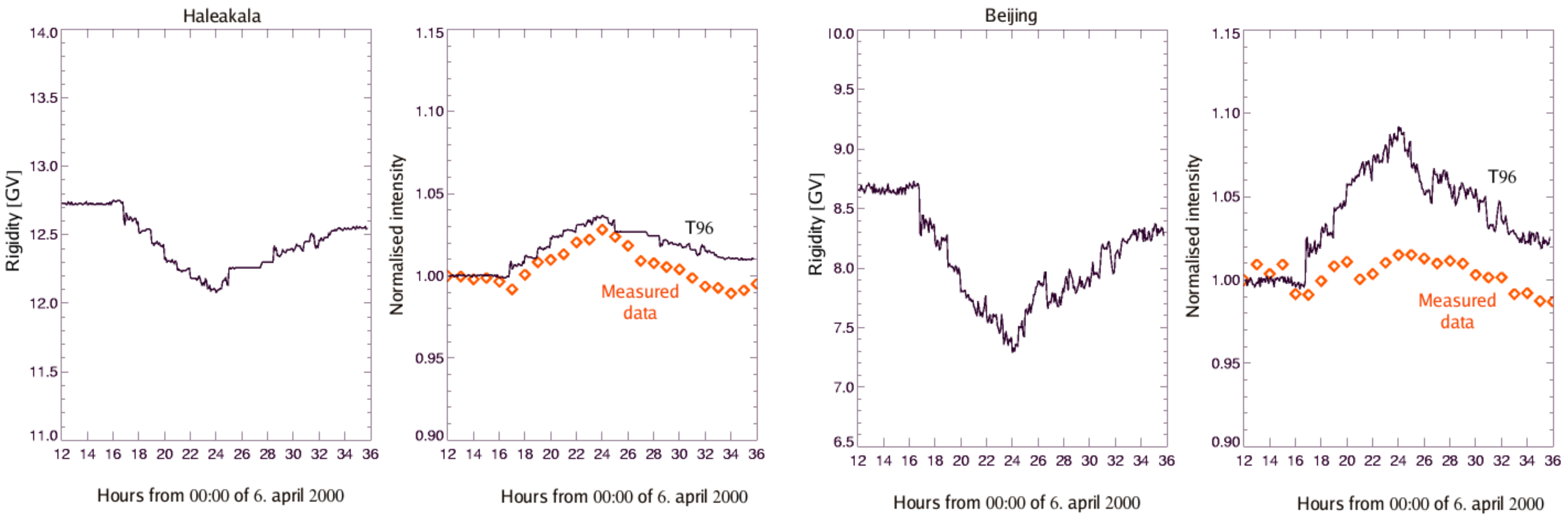

ACE measurements of solar wind characteristics (left), IMF components (middle, nT) and Dst (right). Plots constructed from data at http://www.sec.noaa.gov/ace/. Time interval from 00 UT on April 5 until 00 UT on April 7, 2000.

This event was earlier analyzed by *Desorgher et al, (2005, IUGG)* using Ts 04 model. Recently this event is included in paper by *Desorgher et al ( 2007*)

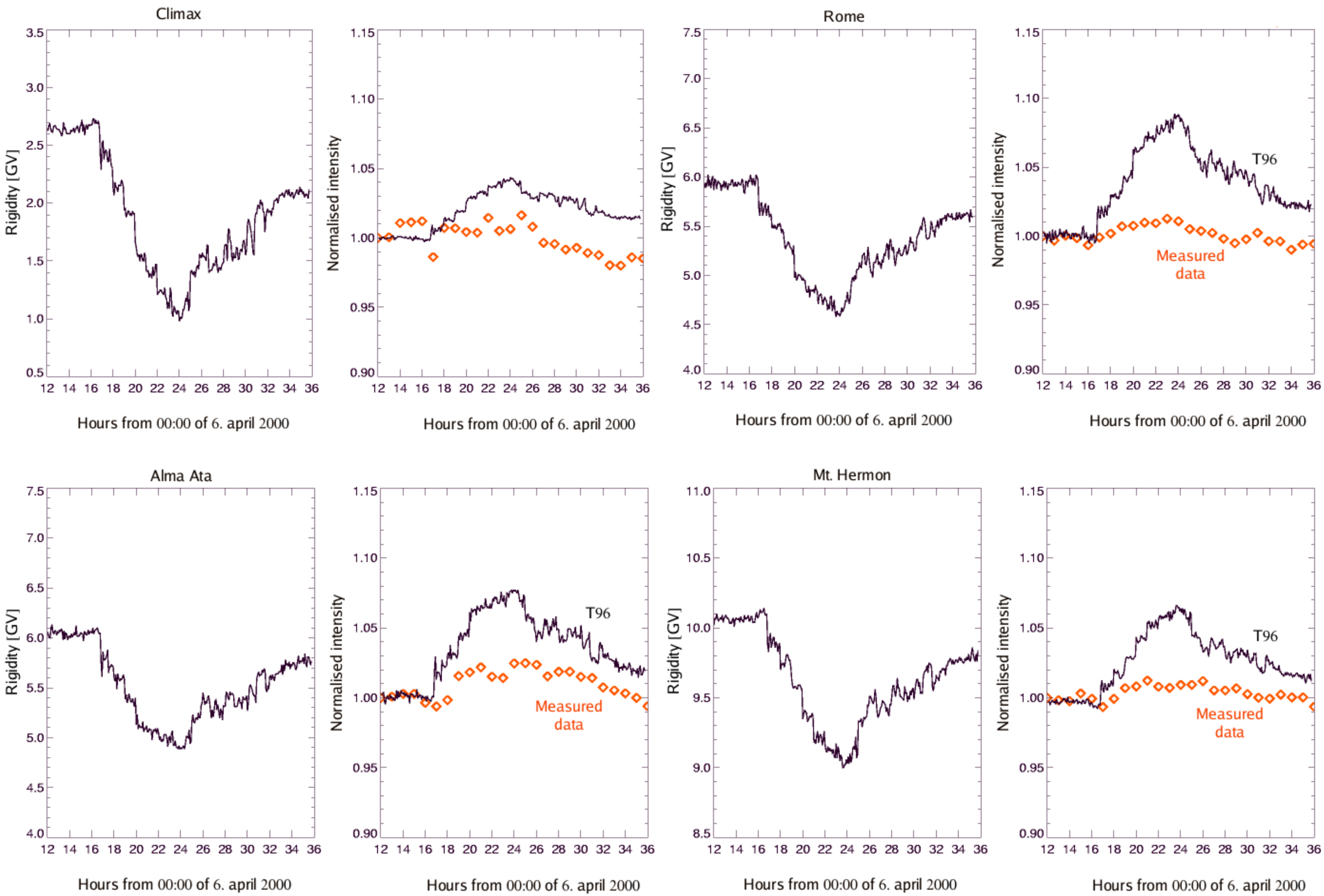



Cosmic ray NM hourly intensity at different cutoff rigidity normalized to 00-12 UT, April 5. Nominal vertical effective cutoff in IGRF model is in the plot (GV). Minimum Dst is in red. Decrease at high latitudes, increase due to cutoff depressions at middle and low latitudes. Acronyms of NMs in acknowledgement.

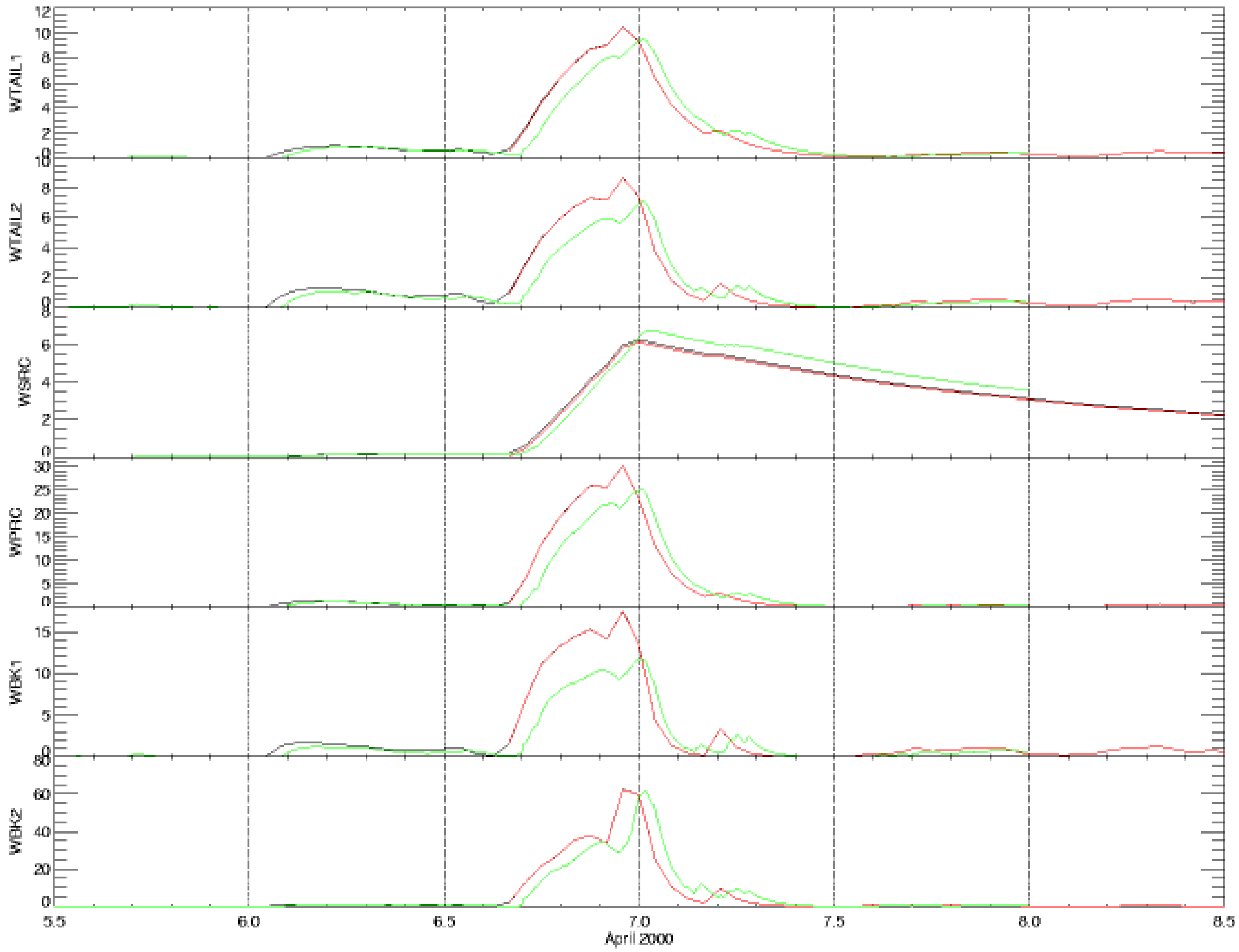
Predictions of cutoff rigidity changes by Ts96 model.



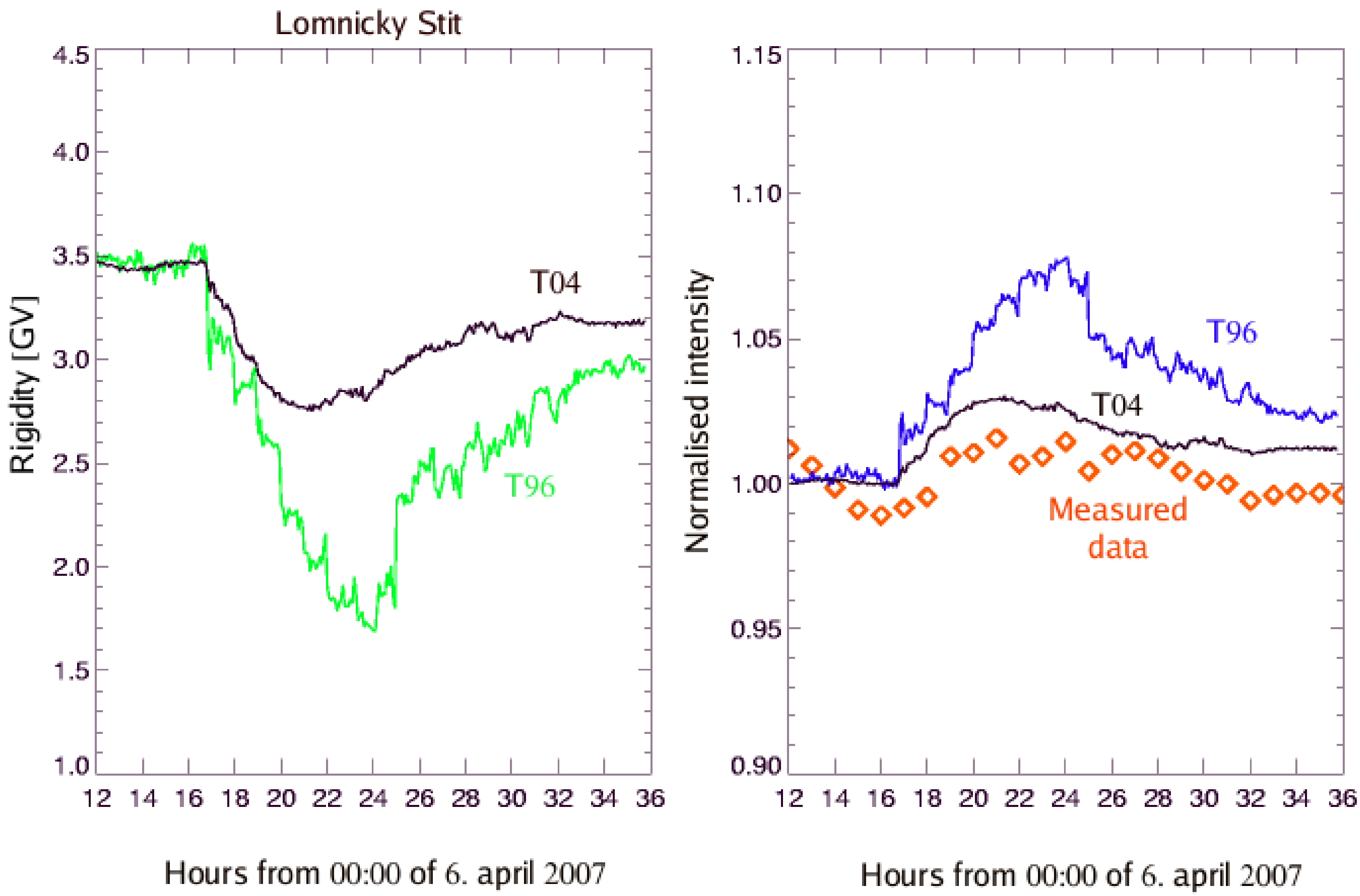

Effective vertical cutoff computed for Ts96. Normalized intensity (to 00 UT on April 6) is estimated using the curve on effect of cutoff changes on neutron monitor count rates in [4].


Climax
Rome
Alma Ata
Mt. Hermon
Rigidity [GV]
Normalised intensity
Hours from 00:00 of 6. april 2000
T96
Measured data

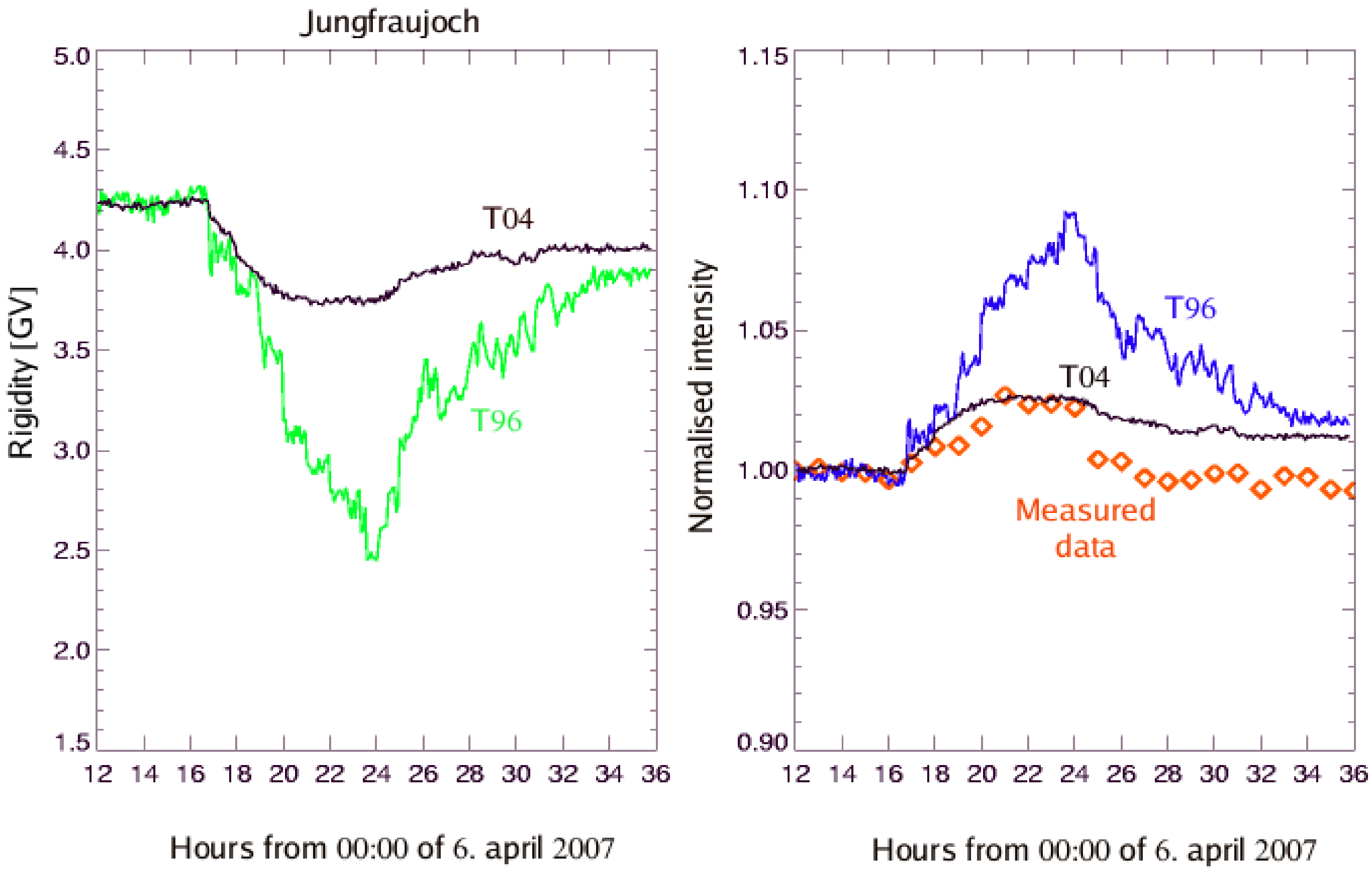
Predictions of cutoff rigidity by Ts04 model.



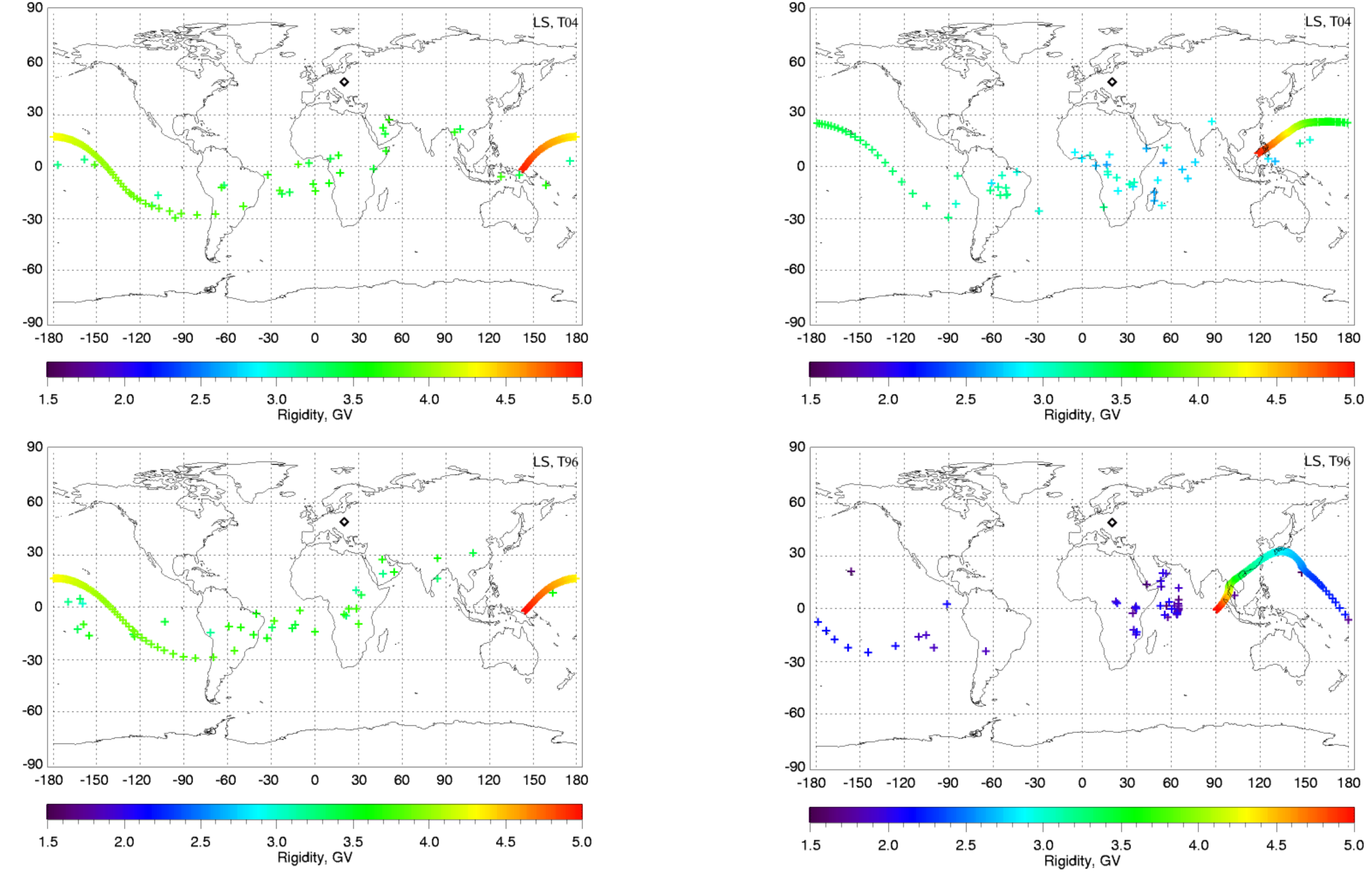

Parameters W1-W6 used for Ts04 model: red curve is putting beginning of the storm 6 April 16 UT and using hourly data from OMNIweb. Green is using 5min SW and IMF data. Putting different times for beginning of the storm is not affecting W1-W6 parameters.



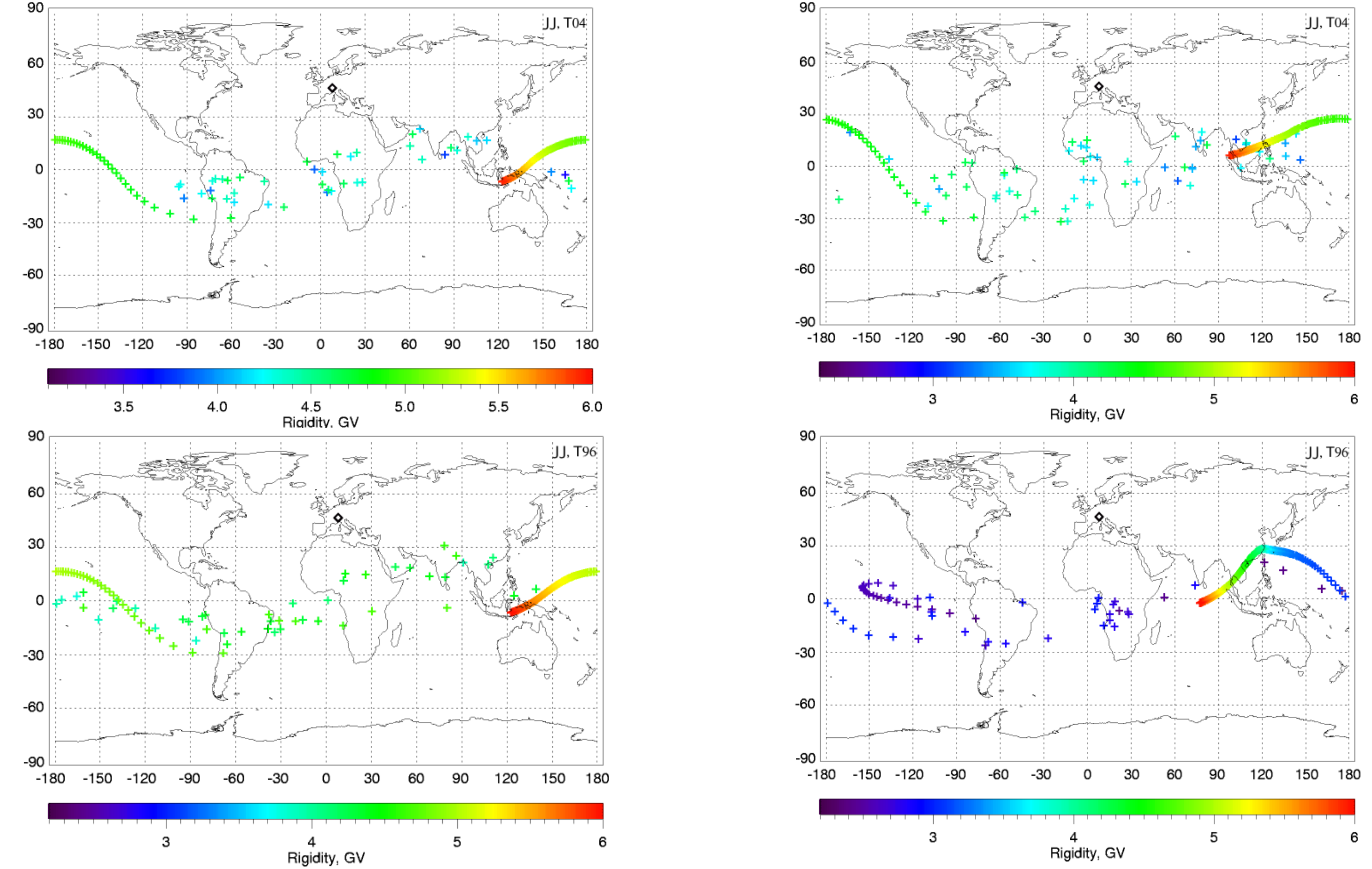

Comparison of cutoff predictions by two models for Lomnický Štít.




Comparison of cutoff predictions by two models for Jungfraujoch.




Asymptotic directions for vertical access of cosmic rays to Lomnický Štít at 12 UT on April 6 (left) and at minimum Dst (right) for two geomagnetic field models. Calculations with rigidity step 10 MV.




Asymptotic directions for vertical access of cosmic rays to Jungfraujoch at 12 UT on April 6 (left) and during minimum Dst (right) for two geomagnetic field models. Calculations with rigidity step 10 MV.

## 5. Discussion and summary.

Before the geomagnetic field models with external current systems were constructed, the local time (longitudinal) changes of cut-offs due to magnetospheric field perturbations were checked (e.g. *Flückiger, Smart and Shea, J. Geophys. Res., 88, A9, 6961-6968, 1983*) and related to ring current effects.

Changes of cut-offs and of asymptotic directions depending on longitude during enhanced geomagnetic activity were described (*Flückiger, Smart and Shea, J. Geophys. Res., 91, A7, 7925-7930, 1986)*

*Kudo et al, J. Geophys. Res., 92, A5, 4719-4724, 1987* showed for 17 storms the local time dependence of CR increase at various NMs.

*New magnetospheric models:* ***can CR measurements by the NM network be helpful in checking their validity during geomagnetic storms****?*

Different models of magnetic field (external sources) during strong geomagnetic disturbances give different estimates of

(a) Time profile of cut-off rigidities at a particular ground station
(b) Transmissivity function for particles coming from outside magnetosphere
(c) Asymptotic directions

CR increases at middle and high nominal cut-off NMs are observed superposed on FD (earlier papers in appendix). Model with prehistory (Ts04) and model with Dst give *different results for two storms* (comparison of CR peak time vs time of maximum cut-off depression). *No general conclusion about validity of models from this limited study*.

How to check validity of geomagnetic field models by CR during geomagnetic storms?

Timing of maximum CR increase vs minimum predicted cut-off at many stations (?)

Very simplified: simultaneous change of CR anisotropy in interplanetary space (CME passing Earth's orbit)

Spaceship Earth (*Bieber J.W., P. Evenson, ICRC, 1995*), ring of NM at high latitudes – anisotropy at low energies (not strongly affected by magnetospheric disturbance – asymptotic directions in narrow interval of longitudes, close to ecliptic, changes below atmospheric cutoff) – *reference for **IP anisotropy at LE*** ?

Network of muon directional telescopes (*Munakata K. et al., Adv. Space Res., 2005*) studies anisotropy at energies above NM (~50 GeV), not strongly affected by changes in magnetosphere – *reference for **IP anisotropy at HE** ?*

Using predictions of different models (disturbed field) for ***(a) time profile of vertical cut-offs, (b) asymptotic directions and (c) transmissivity function for low and middle latitude NMs plus coupling functions***

and

***Anisotropy estimate at "middle energies"*** *from interpolation between anisotropy in IP space by Spaceship Earth (LE) and by Muon Telescope Network (HE)*

***To estimate CR time profiles at various NMs (middle, low latitudes), to compare with measurements*** **by** ***NM network ?***

***Problems, simplifications***: energy spectra of primary particles, only vertical direction assumed.

***In addition: proton detector(s) with high geometric factor at low orbits can check the consistency of transmissivity functions at two altitudes (model dependent).***

More systematic studies needed: different storms, network of NMs, better temporal resolution of NMs.

# Concluding remarks

CR measured by ***NM at middle and low latitudes*** can probably help in testing validity of geomagnetic field models during strong disturbances.

IP anisotropy deduced from lower energies (Spaceship Earth) and high energies (muon telescopes) as well as low altitude polar orbiting satellite(s) with large geometrical factor for energetic particles are useful for that.

**_Acknowledgement._**

*The author wishes to acknowledge the LOC of FORGES 2008 for invitation.*

*PIs of NM Haleakala, Mexico, Rome are acknowledged for providing data.*

*Some of the computations were done by P. Bobík and R. Bučík.*

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## References.


Alldredge, L.R., Geomagnetic parameters derived from an analytic description of the Earth's magnetic field, J. Geomag. Geoelectr., 40, 207-219, 1988

Boberg, P.R., A.J. Tylka, J.H. Adams, Jr., E.O. Flückiger, E. Kobel, Geomagnetic transmission of solar energetic protons during the geomagnetic disturbance of October 1989, Geophys. Res. Lett., vol. 22, No 9, 1133-1136, 1995

Bobik, P., M. Storini, K. Kudela, The influence of magnetospheric disturbances on the charged particle access to Inuvik station, Conf. Proc., vol. 68 "What are the prospects of Cosmic Ray Physics in Italy", ed. A. Aiello, A. Blanco, p. 39-44, SIF, Bologna, 2000

Clem, J.M., J.W. Bieber, P. Evenson, D. Hall, J.E. Humble, M. Duldig, Contribution of obliquly incident particles to neutron counting rate, J. Geophys. Res., vol. 102, No A12, 26,919-26,926, 1997

Cooke, D.J., J.E. Humble, M.A. Shea, D.F. Smart, N. Lund, I.L. Rasmussen, B. Byrnak, P. Goret, N. Petrou, Il Nuovo Cimento, vol. 14 C, N 3, 213-233, 1991

Chilingarian, A; Reymers, A, Investigations of the response of hybrid particle detectors for Space Environmental Viewing and Analysis Network (SEVAN), Ann. Geophysicae, 26, 2, 249-257, 2008

De Wit Dudok, A. Chilingarian, G. Karpetyan, Techniques for characterizing weak transients in cosmic ray records, as measured by neutron monitor networks, Acta Geophysica, 07, 2008

Dudok de Wit, T.; Chilingarian, A. A.; Karapetyan, G. G., Source separation techniques for characterising cosmic ray transients from neutron monitor networks, eprint arXiv:0807.4475**,** 07/2008

Desorgher, L., E.O. Flückiger et al, IUGG presentation, 2005

Dorman, L.I., G. Villoresi, N. Iucci, M. Parisi, M.I. Tyasto, O.A. Danilova, N.G. Ptitsyna, J. Geophys. Res., vol. 105, No A9, 21,047-21,056, September 1, 2000

Feynman, J., Geomagnetic and solar wind cycles, 1900-1975, J. Geophys. Res., vol. 87, 6135-6162, 1982

Flückiger, E. O., Effects of asymmetric magnetospheric currents on cosmic radiation, AFGL-TR-0177, ERP No 783, pp. 36, 1982

Flückiger, E. O., Effects of asymmetric magnetospheric currents on cosmic radiation, AFGL-TR-0177, ERP No 783, pp. 36, 1982

Flückiger, E.O., D.F. Smart, M.A. Shea, A procedure for estimating the changes in cosmic ray cutoff rigidities and asymptotic directions at low and middle latitudes during periods of enhanced geomagnetic activity, J. Geophys. Res., vol. 91, No A7, 7925-7930, 1986

Flückiger, E.O., D.F. Smart, M.A. Shea, The effect of local perturbations of the geomagnetic field on cosmic ray cutoff rigidities at Jungfraujoch and Kiel, J. Geophys. Res., vol. 88, No A9, 6961-6968, 1983

Heinrich, W., A. Spill, Geomagnetic shielding of cosmic rays for different satellite orbits, J. Geophys. Res., vol. 84, No A8, 4401-4404, 1979

Humble, J.E., D.F. Smart, M.A. Shea, Empirical model for the Earth's cosmic ray shadow at 400 km: prohibited cosmic ray access, Proc. ICRC , SH 6.1-14, 1985

Iucci, N., G. Villoresi, L.I. Dorman, M. Parisi, Cosmic ray survey to Antarctica and coupling functions for neutron component near solar minimum (1996-1997) 2. Determination of meteorological effects, J. Geophys. Res., vol. 105, No A9, 21,035-21,045, September 1, 2000

Kassovicova, J. and K. Kudela, On the computations of cosmic ray trajectories in the geomagnetic field, preprint IEP SAS, Space Physics Dept., pp. 12, May 1998

Kobel, E, E.O. Flückiger, A model of the steady state magnetic field in the magnetosheath, J. Geophys. Res., vol. 99, No A12, 23,617-23,622, 1994

Kudo, S., M. Wada, P. Tanskanen, M. Kodama, Local time and cutoff rigidity dependences of storm time increase associated with geomagentic storms, J. Geophys. Res., vol. 92, No A5, 4719-4724, 1987

Leske, R.A., R.A. Mewaldt, E.C. Stone, T.T. von Rosenvinge, Observations of geomagnetic cutoff variations during solar energetic particle events and implications for the radiation environment at the Space Station, J. Geophys. Res., vol. 106, No A12, 30,011-30,022, December 1, 2001

McCracken, K.G., U.R. Rao, B.C. Fowler, M.A. Shea, D.F. Smart, IQSY Instruction manual No 10, Cosmic Ray Tables (Asymptotic directions, variational coefficients and cut-off rigidities), Issued by IQSY Committee, 6 cornwall Terrace, London NW1, 183 pp, May 1965

Nagashima, K., S. Sakakibara, K. Murakami, I. Morishita, Response and yield functions of neutron monitor, galactic cosmic ray spectrum and its solar modulation, derived from all available world-wide surveys, Il Nuovo Cimento, vol. 12 C, N 2, 1989

Ostapenko, A.A., Y.P. Maltsev, Relation of the magnetic field in the magnetosphere to the geomagnetic and solar wind activity, J. Geophys. Res., vol. 102, No A8, 17,467-17,473, 1997

Pchelkin, V.V. and E.V. Vashenyuk, Effects of quasi-drift and problem of penumbra of cosmic rays (in Russian), Izv. AN, ser. Fiz., 65, 416-421, No 3, 2001

Peredo, M., D.P. Stern, N.A. Tsyganenko, Are existing magnetospheric models excessively stretched?, J. Geophys. Res., vol. 98, No A9, 15,343-15,354, 1993

Peredo, M., D.P. Stern, On the position of the near-earth neutral sheet: a comaprison of magnetic model predictions with empirical formulas, J. Geophys. Res., 19,521-19,524, 1991

Pfitzer, K.A., The effect of magnetic field models on cosmic ray cutoff calculations, in Quantitative Modeling of Magnetospheric Processes, Geophysical Monograph 21, AGU, Washington, D.C., p. 242-252, 1979

Regan, R.D., P. Rodriguez, An overview of the external magnetic field with regard to magnetic surveys, Geophysical Surveys, 4, 255-296, 1981

Shea, M.A., and D.F. Smart, Vertical cutoff rigidities for cosmic ray stations since 1955, Proc. 27th ICRC, Hamburg, p. 4063-4066, 2001

Shea, M.A., D.F. Smart, H. Carmichael, Summary of Cutoff Rigidities Calculated with the IGRF for various epochs, AFGL-TR-76-0115, Env. Res. Pap., No 561, pp. 97, May 1976

Shea, M.A., D.F. Smart, H. Carmichael, Summary of cutoff rigidities calculated with IGRF for various epochs, AFGL-TR-76-0115, ERP No 561, pp. 97, 1976

Shea, M.A., D.F. Smart, L.C. Gentile, Estimating cosmic ray vertical cutoff rigidities as a function of the McIlwain L-parameter for different epochs of the geomagnetic field, *Phys. Earth and Planet. Interiors*, 48, 200-205, 1987

Shea, M.A., D.F. Smart, Supplemental summary of cutoff rigidities calculated using the IGRF for various epochs, AFGL-TR-82-0320, ERP No 802, pp. 60, 1982

Shea, M.A., D.F. Smart, Vertical cutoff rigidities for cosmic ray stations since 1955, Proc. 27th ICRC, Hamburg, 4063-4066, 2001

Smart, D.F. and M.A. Shea, A comparison of the Tsyganenko model predicted and measured geomagnetic cutoff latitudes, Adv. Space Res., vol. 28, No 12, 1733 – 1738, 2001

Smart, D.F., M.A. Shea and J.E. Humble, Characteristics of cosmic ray cutoffs for a satellite at 400 km; The effect of the solid Earth, Adv. Space Res., vol. 1, 165-168, 1981

Smart, D.F., M.A. Shea, N. Lund, I.L. Rasmussen, B. Byrnak, N.J. Westergaard, Cosmic ray penumbral patterns derived from the trajectory calculations for the HEAO-C satellite, Proc. 16th ICRC, Kyoto, Japan, vol. 12, 237-242, 1979

Stern, D.P., N.A. Tsyganenko, Uses and limitations of the Tsyganenko field models, Eos Transactions, AGU, vol. 73, No 46, November 17, p. 489, 493-494,1992

Storini, M., M.A. Shea, D.F. Smart, E.C. Cordaro, Cutoff variability for the Antarctic Laboratory for cosmic rays (LARC: 1955-1995), Proc. 26th ICRC, Salt Lake City, paper SH 3.6.30, 1999

Storini, M., P. Metteo, G. Moreno, Effects of geomagnetic secular variations on cosmic ray access to the terrestrial environment, Adv. Space Res., in press, 2007

Villoresi, G., L.I. Dorman, N. Iucci, N.G. Ptitsyna, Cosmic ray survey to Antarctica and coupling functions for neutron component near solar minimum (1996-1997) 1. Methodology and data quality assurance, J. Geophys. Res., vol. 105, No A9, 21,025-21,034, September 1, 2000

Zazyan, M., A. Chlingarian, Calculation of the Aragats Space Environmental Center monitors response to galactic and solar cosmic rays, ICRC Pune, 2007.