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CR Tramsmissivity in Variable Magnetosphere

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1. Numerical solution of equation of particle motion.

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

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

This equation leads to system of 6 linear differential equations with unknown values (x, y, z, dx/dt, dy/dt, dz/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*).

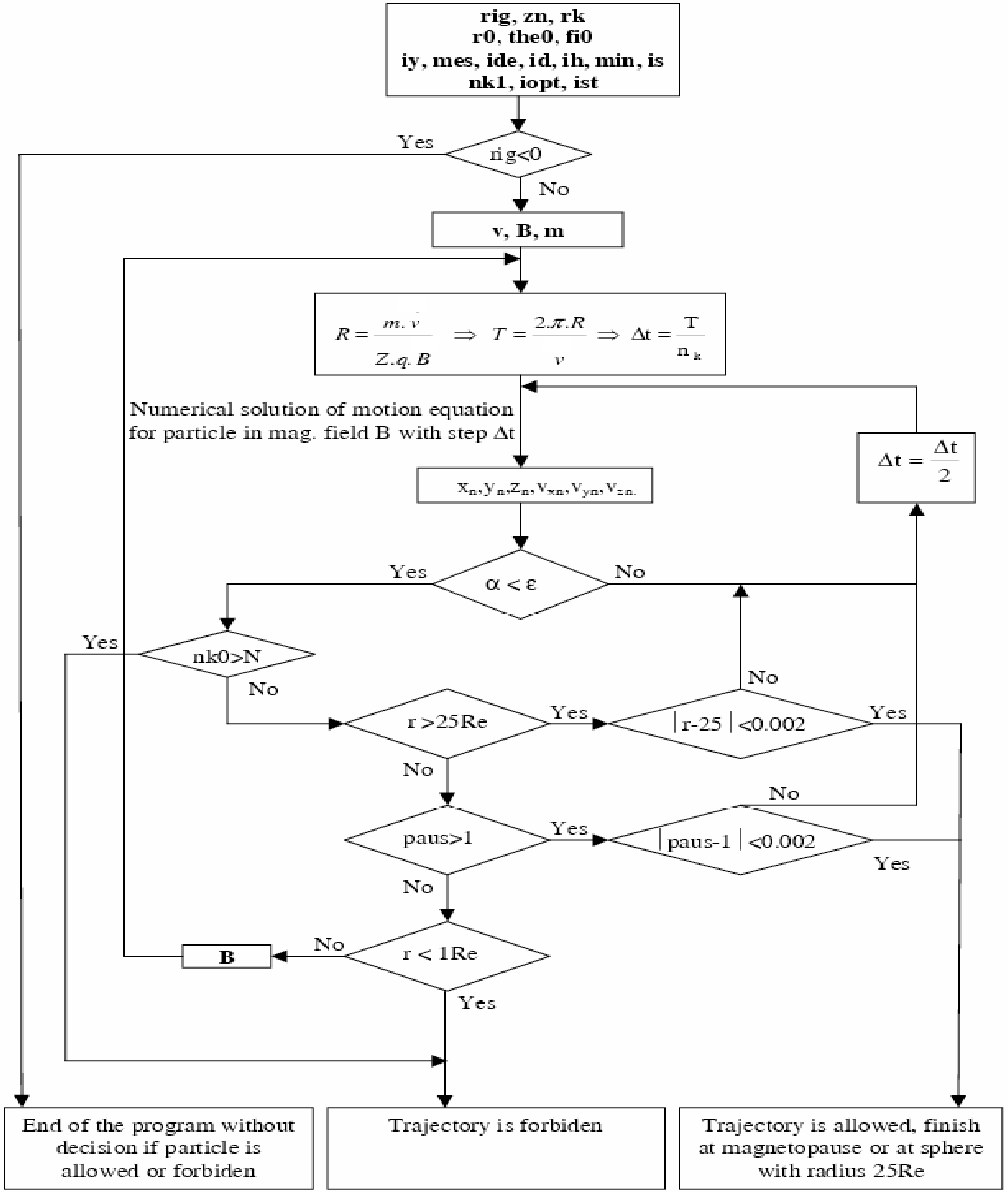
Initial conditions: rigidity (velocity), charge, direction of access (zenith, azimuth angle) $\Rightarrow$ (x,y,z,v_x,v_y,v_z), back tracing numerical integration of (1) in given **B** (x,y,z) from the point of observation in given direction with charge sign reversed.

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

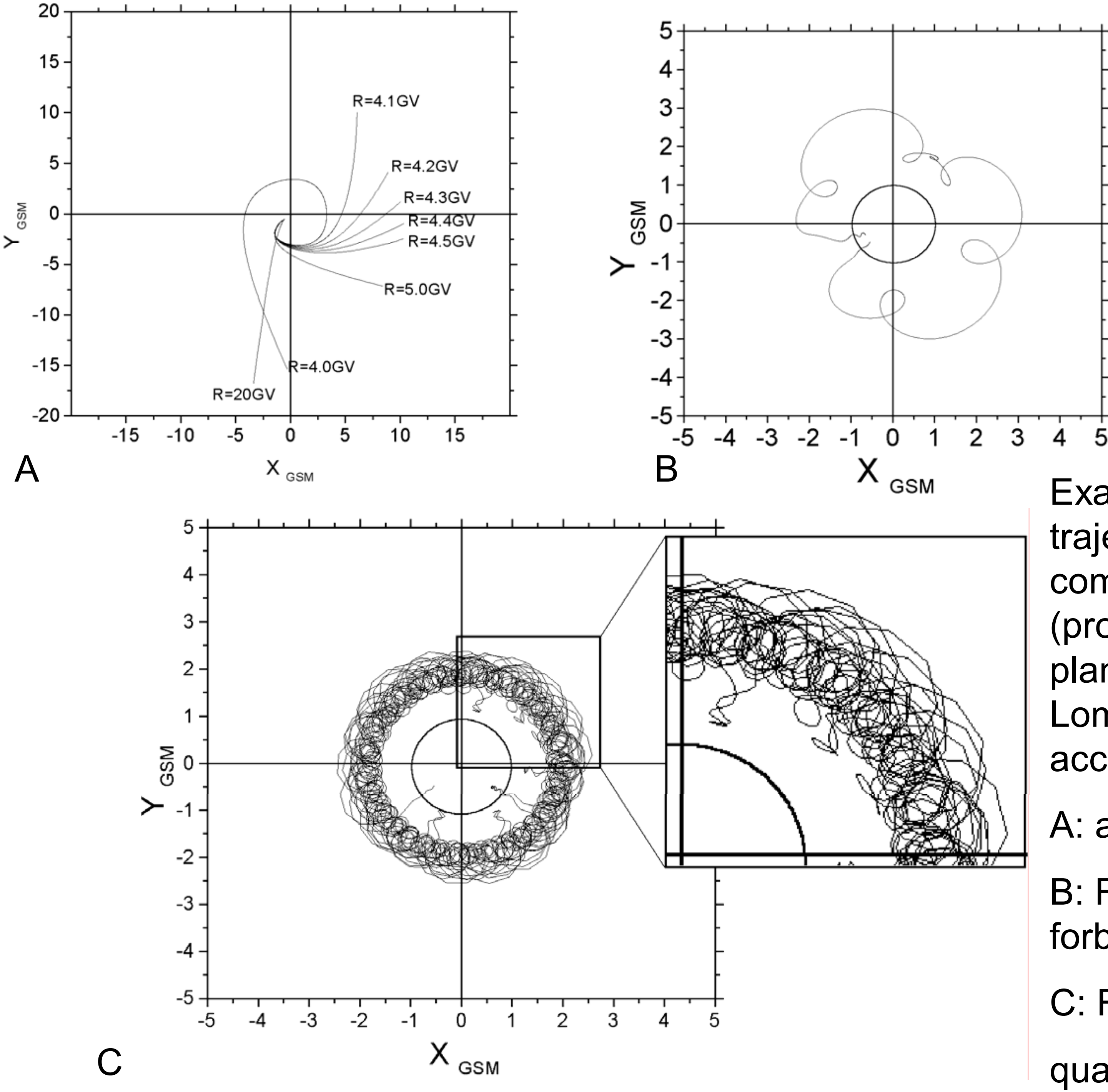
Conditions for smoothness of trajectory (angle between two subsequent elementary straight lines on trajectory < α, usually α = 0.001 rad)

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)



Scheme of trajectory computations



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

A: allowed traj.

B: R=3.25 GV forbidden

C: R=2.25 GV

quasitrapped

2. Geomagnetic field models used for cosmic ray trajectory computations.

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:*

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

where *r, θ, λ* are geocentric coordinates (*r* is the distance from the centre of the Earth, *θ* is the co-latitude, i.e. 90° - latitude, and *λ* is the longitude), *R* is a reference radius (6371.2 km); $g_n^m(t)$ and $h_n^m(t)$ are the coefficients at time *t* and $P_n^m(\theta)$ are the Schmidt semi-normalised associated Legendre functions of degree *n* and order *m*. The main field coefficients are functions of time and for the IGRF the change is assumed to be linear over five-year intervals. For the upcoming five-year epoch, the rate of change is given by predictive secular variation coefficients.

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)

Structure of allowed and forbidden trajectories is different for different periods of time in the internal field approach.

From paper (*Storini, M. et al, Proc. ICRC, Rome, vol. 4, p. 1074-1077, 1995*)

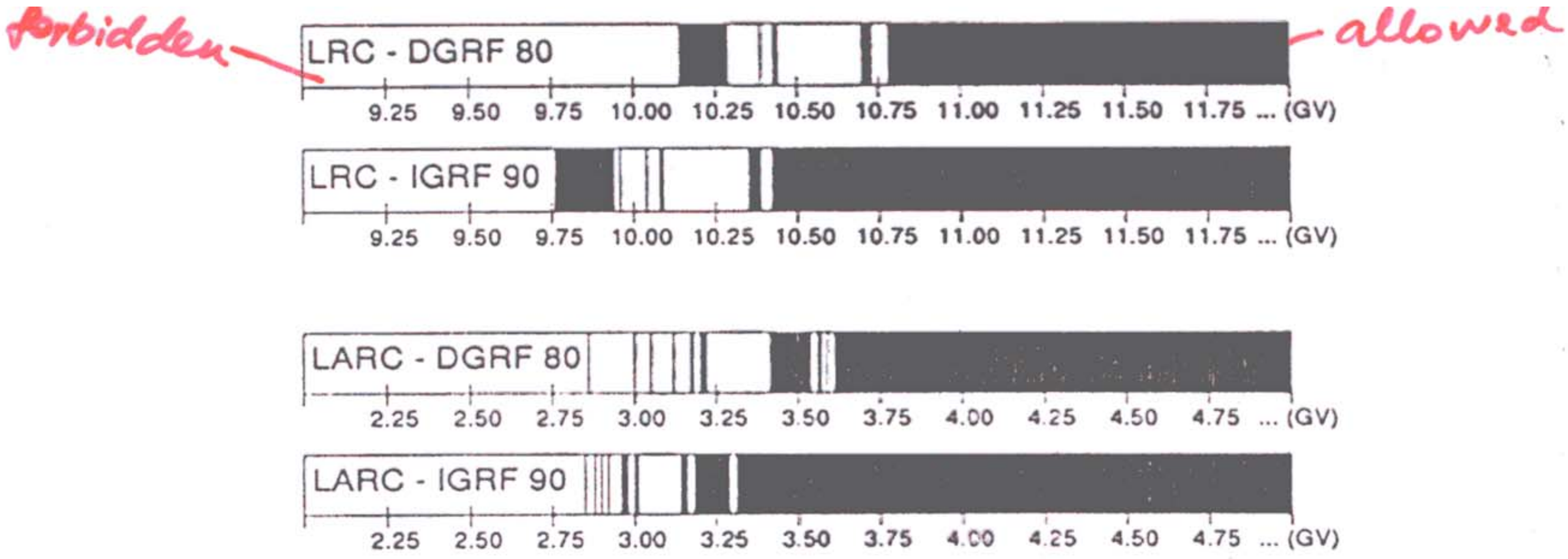


Figure 2. Illustration of charged-particle access at LRC (Los Cerrillos, Santiago) and LARC (King George Island, Antarctica). Allowed particle rigidities are reported as dark areas and the forbidden ones by white areas.

STORINI et al, 1995

Structure of penumbra is depending on the model (epoch)

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*).

Cut-offs for non-vertical directions.

For correct interpretation of responses of ground based cosmic ray measurement by detectors with omnidirectional chracteristics of acceptance (as NM are, part 3), the obliquely incident particle 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*). An “apparent” cut-off is defined:

Apparent cut-off is that rigidity which, if uniform over the whole sky, would yield the same neutron monitor counting rate as the real, angular dependent cutoff distribution. Cut-off sky-maps are computed.

While this approach requires large computing time, In paper (*J.W. Bieber et al, Proc. ICRC, Durban, 2, 389-392, 1997*) simplification is checked: effective cutoffs are computed for 9 directions (vertical and ring 30 degrees off vertical with 8 directions by azimuth) and apparent cutoff is computed with corresponding statistical weights (vertical cutoff ½,other cutoffs with weight 1/16 each).

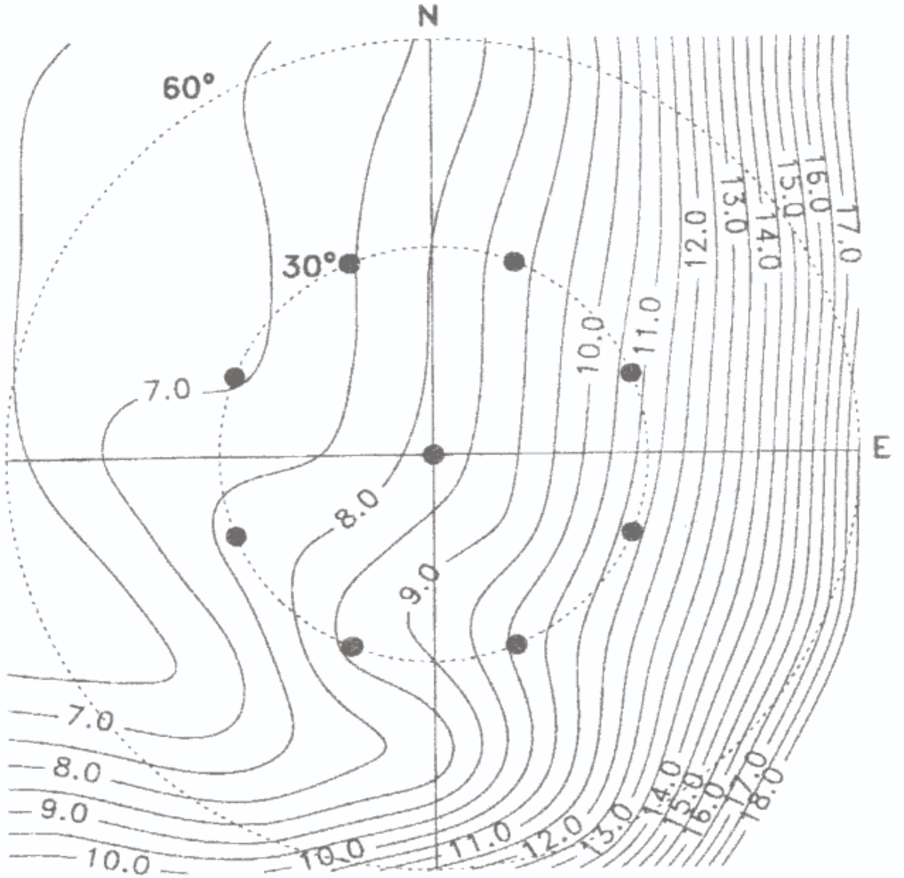


Figure 2: Effective cutoff map for 43.92 S, 76.64 W. Vertical cutoff is 8.23 GV and apparent cutoff is 8.65 GV. Solid dots show locations where cutoffs are calculated for the ring approximation.

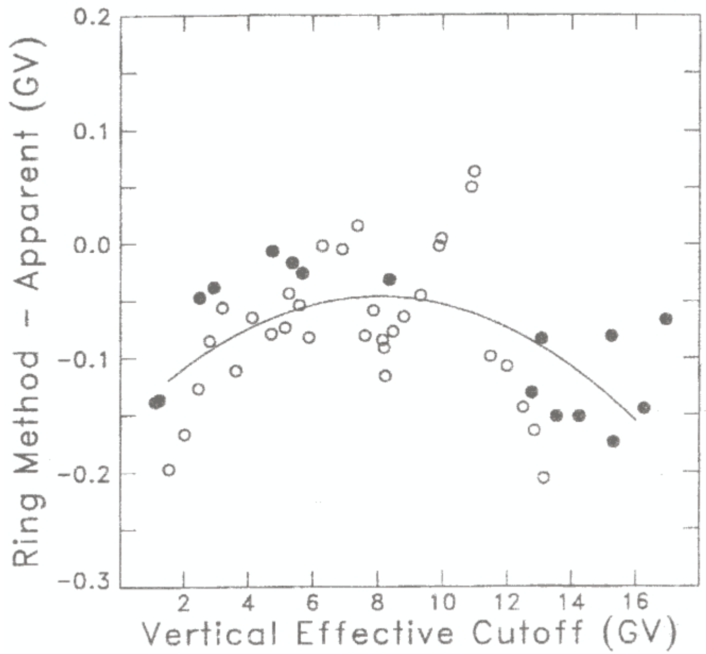


Figure 4: Difference between apparent cutoff calculated with the ring approximation and the full calculation. Symbols and the trend line are discussed in the text.

From paper *(J.W. Bieber et al, Proc. ICRC, Durban, 2, 389-392, 1997)*

External field (contributions of external current systems).

We use

A. Tsyganenko'89 model (*Tsyganenko, N.A., Planet. Space Sci., vol. 37, No 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) as a parameter depending on Dst, an approach to geomagnetic transmission during the disturbances in October 1989 was proposed (*Boberg, P.R. et al., 22, No 9, 1133-1136, 1995*).

C. *Tsyganenko'96 model*

(code at http://modelweb.gsfc.nasa.gov/magnetos/data-based/T96.html)

Input parameters: solar wind pressure, Dst, By, Bz of IMF; dipole tilt angle; x, y, z position in GSM

D. *Tsyganenko 2001 model*

Input parameters: Dipole tilt angle; solar wind pressure; Dst; IMF By and Bz components; two IMF-related indices G1 and G2 taking into account the IMF and solar wind conditions during the preceding 1-hour interval

(their definition is in paper available online from anonymous

ftp://nssdcftp.gsfc.nasa.gov/models/magnetospheric/tsyganenko/2001paper/)

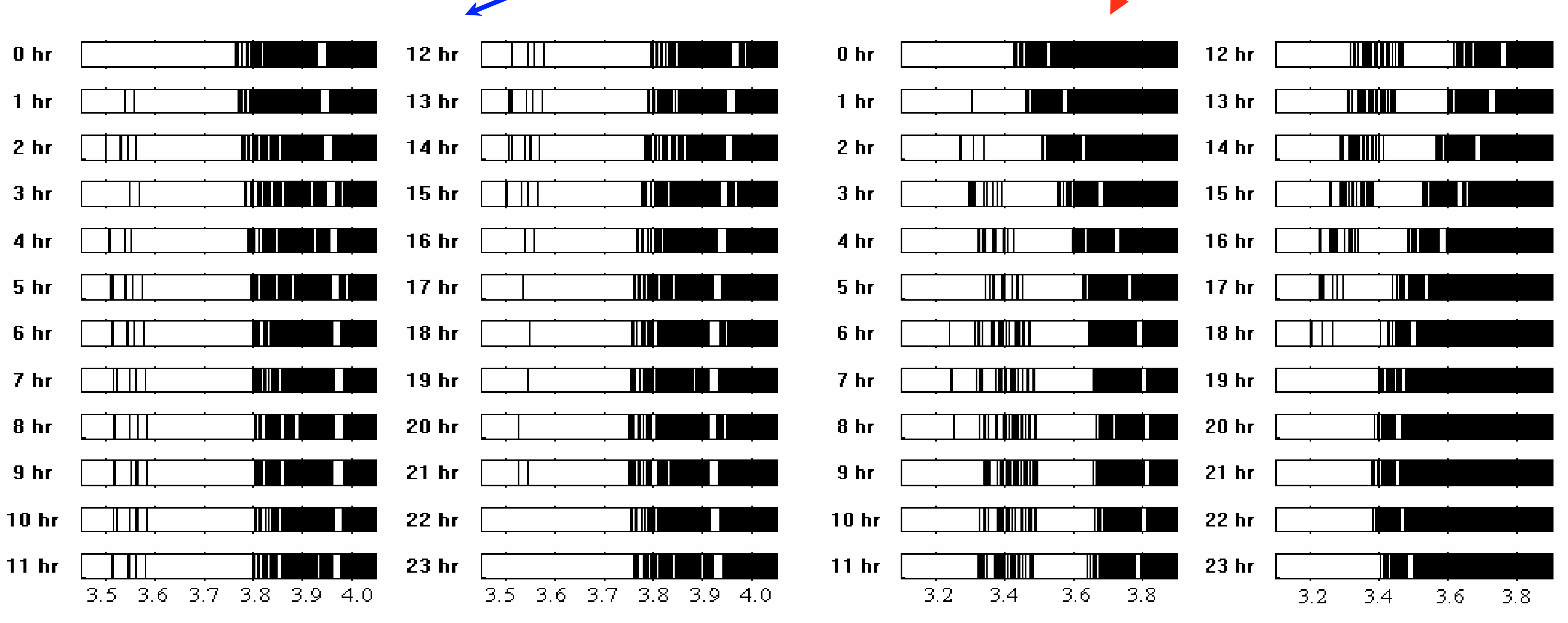
E. *Tsyganenko 2004 model*

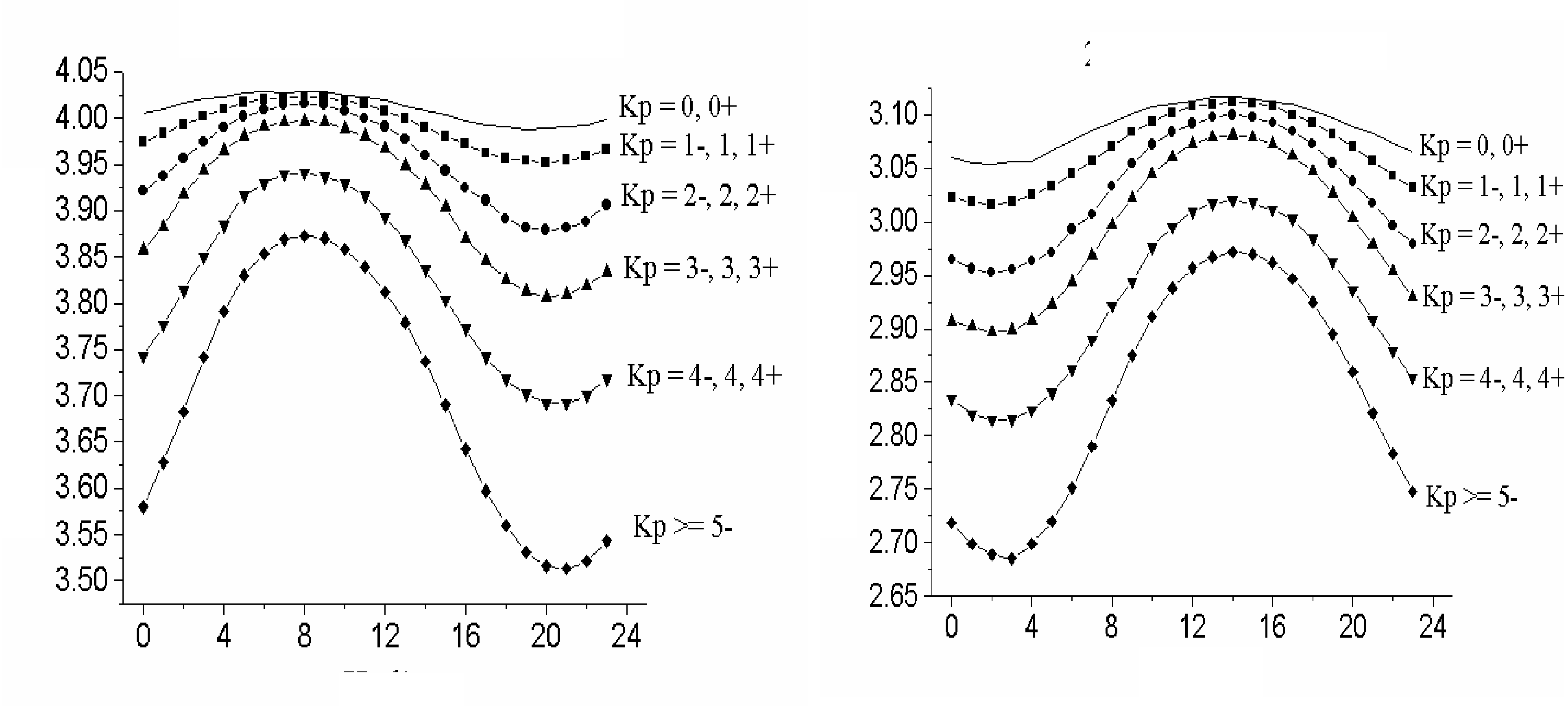
Model of the external (i.e. without earth's contribution) part of the magnetospheric field, calibrated by solar wind pressure; Dst; By of IMF; Bz IMF and indices W1 – W6 calculated as time integrals from beginning of a storm (Bz, n, v; described in *N. A. Tsyganenko and M. I. Sitnov, Modeling the dynamics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

3. Effects of magnetosheric disturbances on cosmic rays.

Diurnal variation of the cut-off rigidity.

While IGRF is not sensitive to local time of measurements, the external field models assume the local time asymmetry of magnetosphere. For a middle latitude station Lomnický Štít the structure of allowed (black) and forbidden (white) trajectories is depending on local time and on level of geomagnetic disturbance (Left for IOPT=1, right IOPT=6, 21.3.1990), vertical directions. Ts89 model (A) is used (*P. Bobík, PhD thesis, 2001*).

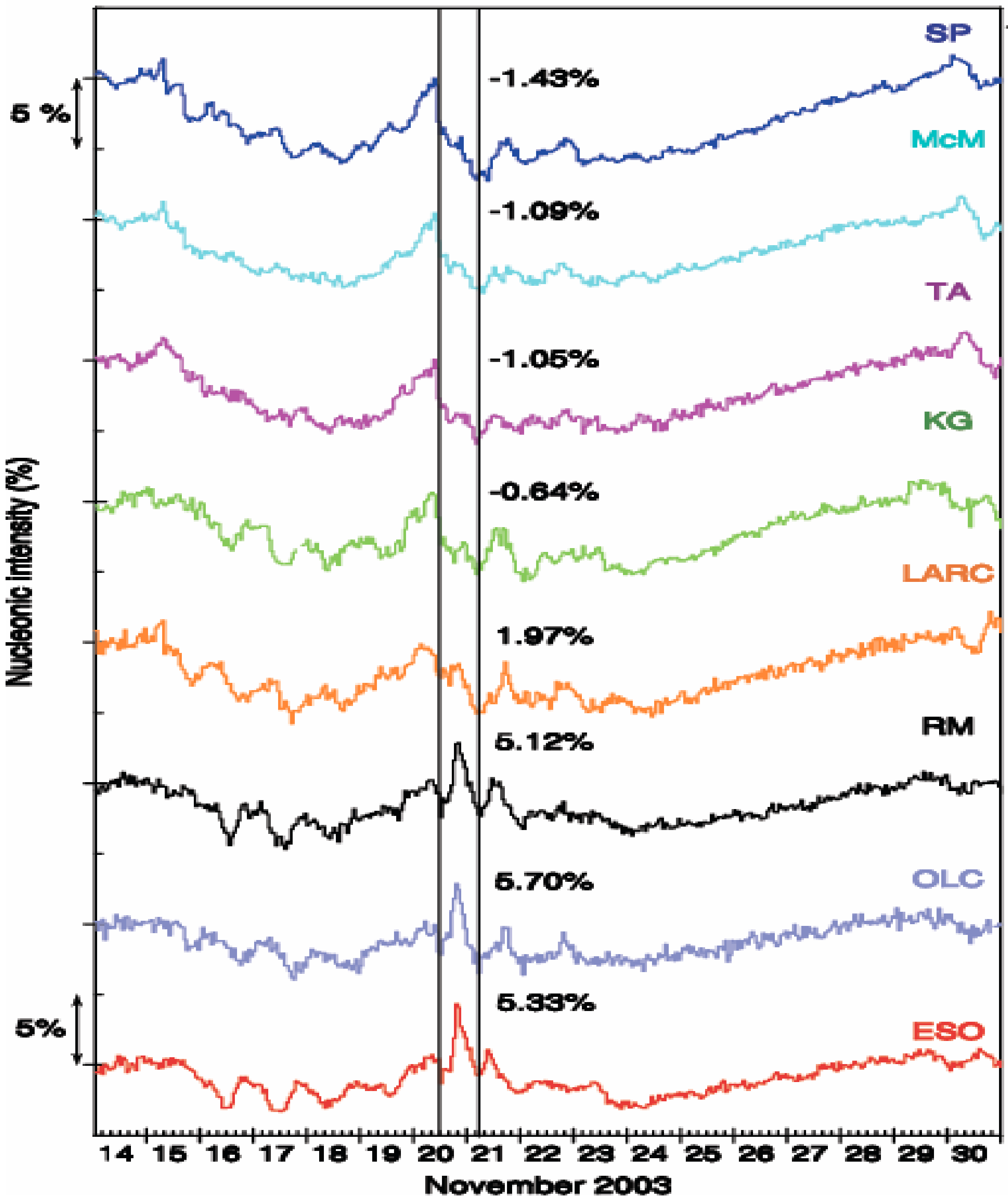




Variation of R_E (effective vertical cut-off rigidity in GV) for position of Lomnický Štít (left panel) and LARC (right panel) with local time of measurements according to Ts89 model (A). Computations are done for January 21, 1986.

At high latitude stations the diurnal variation of cut-off rigidity is not important since the cut-off rigidity is below the atmospheric one (about 400 MeV kinetic energy p).

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



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*).

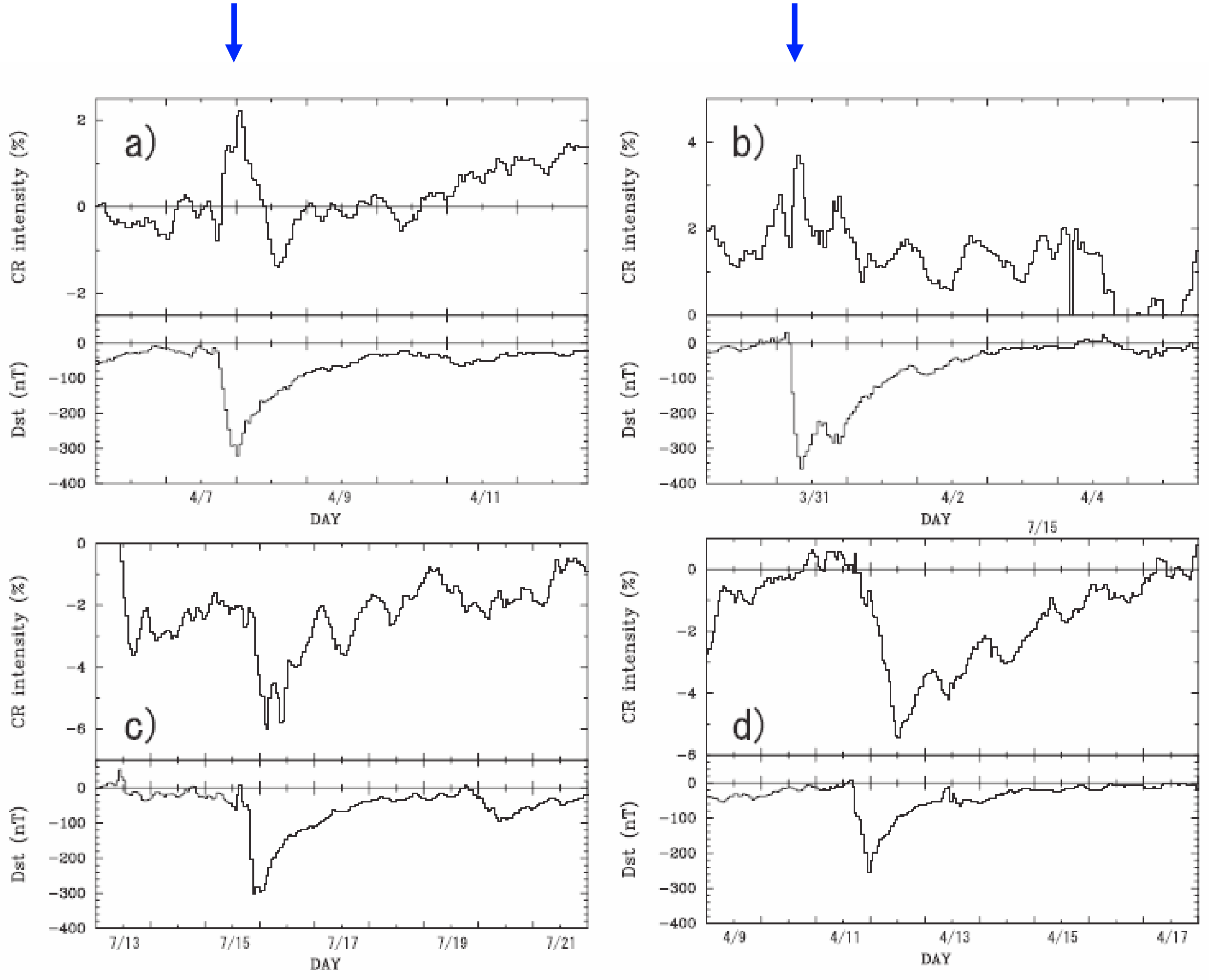
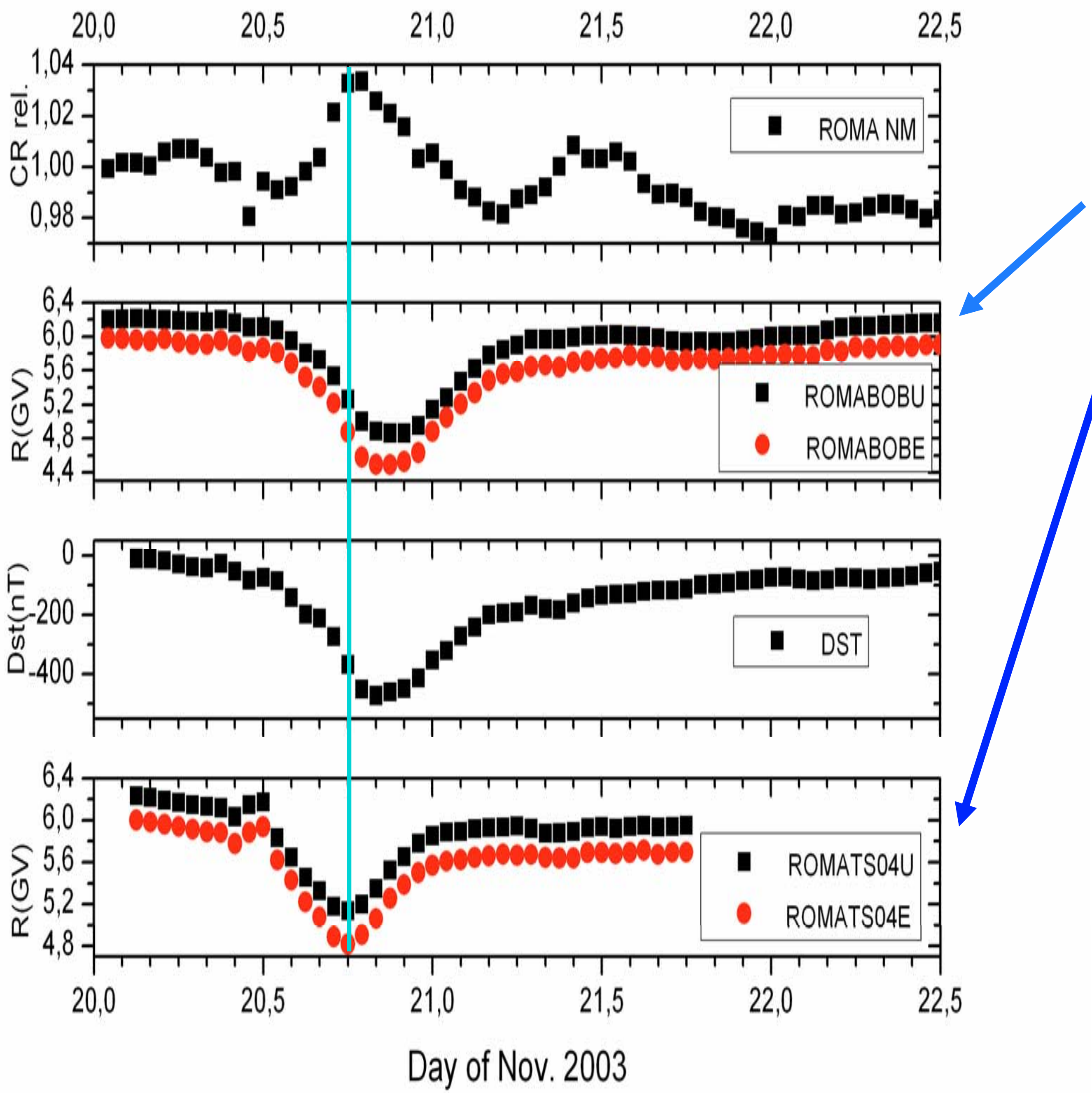
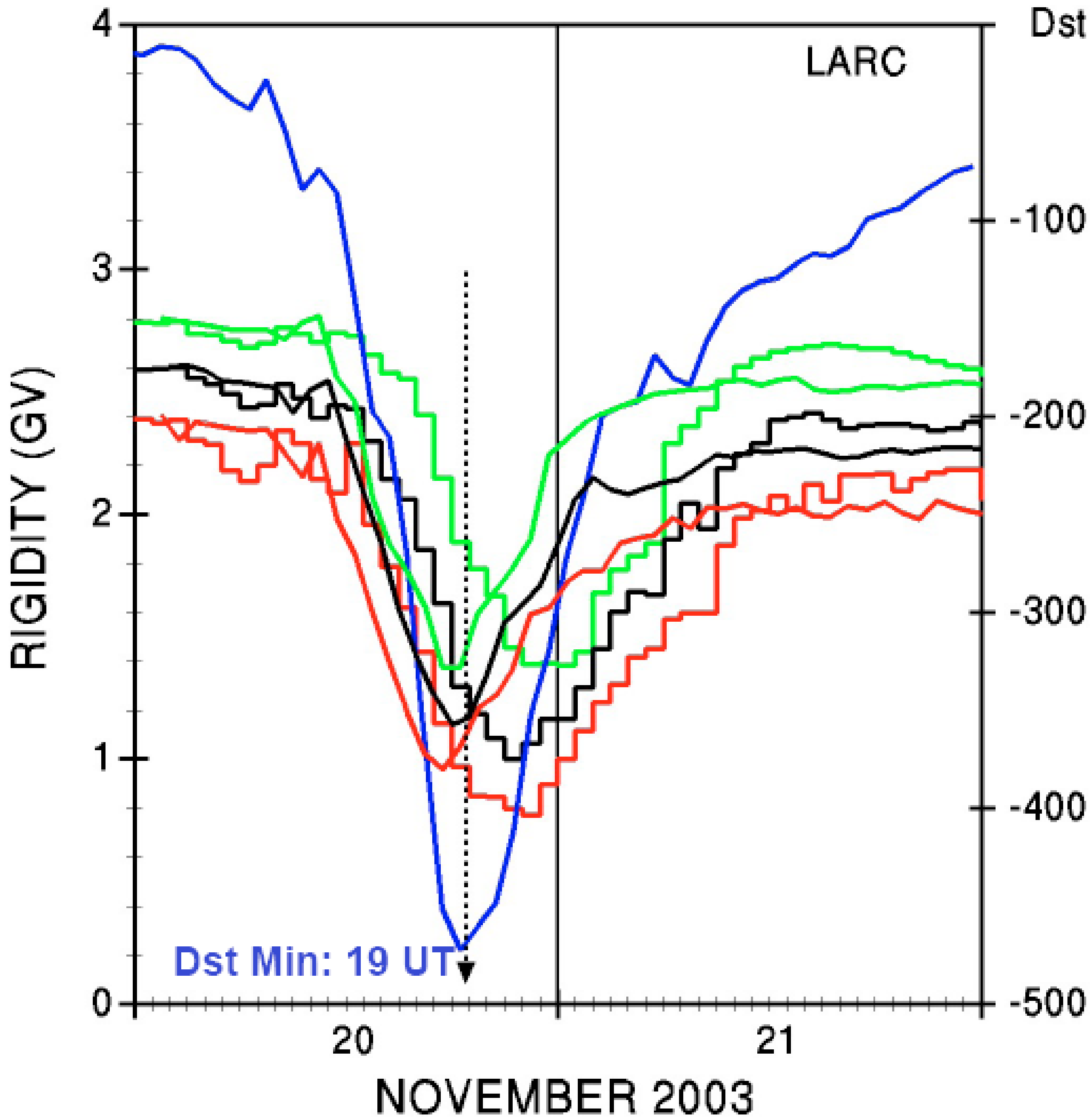


Fig. 1. Cosmic ray intensity (%) observed at TIBET neutron monitor and Dst value (nT) are shown. Each of the figure shows the magnetic disturbance occurred at (a)2000/04/07, (b) 2001/03/31, (c) 2000/07/15 and (d) 2001/04/11.



Comparison of cutoff rigidity profiles by model (B) Ts89+Dst and Tsyganenko 2004 (E) for position of Rome NM.

(*computations by R. Bučík, 2005*)



Model E (continuous line) predicts minimum cut-off rigidity by 4-5 hours shift with respect to model B (staircase).

Green (R_U), black (R_E), red (R_L) - vertical cutoffs.

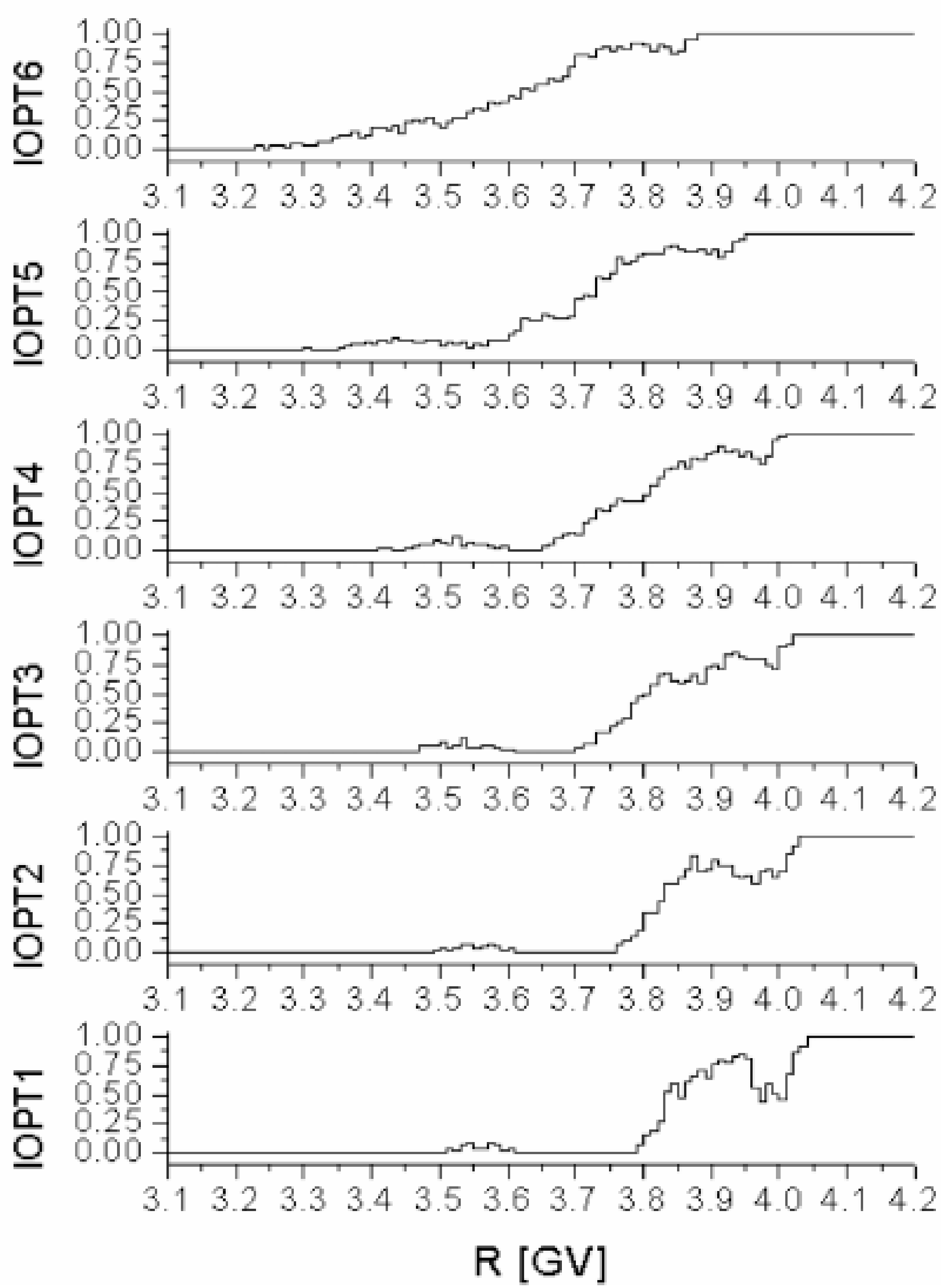
Paper (*Storini, M. et al, EGU 2006*)

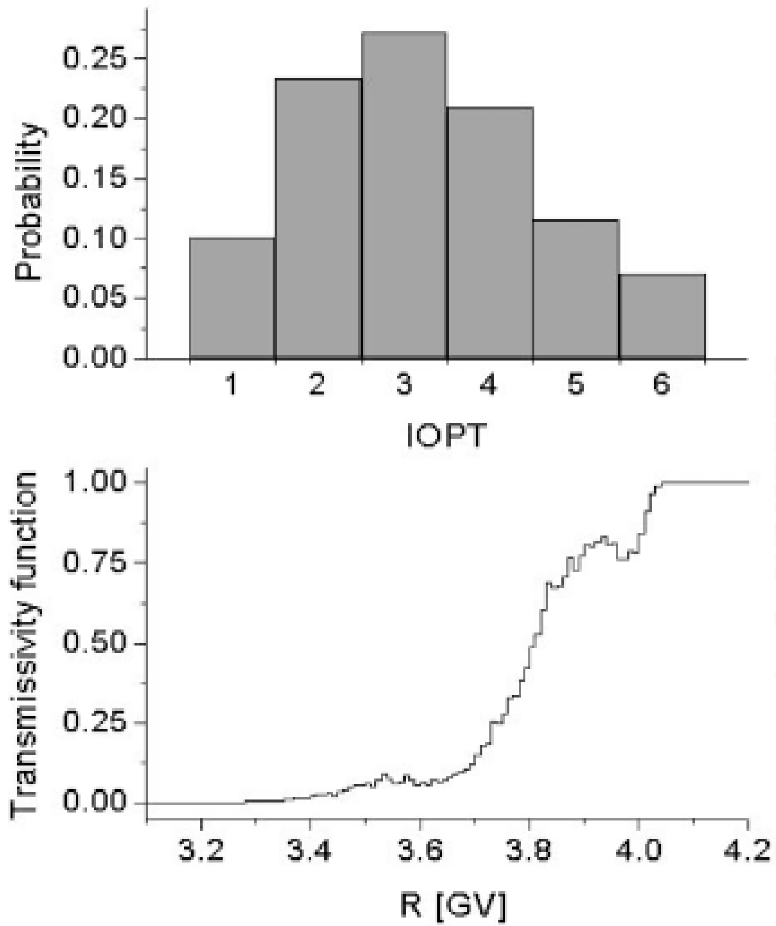
Average transmissivity.

Computing trajectories with small step in rigidity (0.0001 GV) gives the probability that particle having rigidity e.g. in the interval (R,R+0.01) GV can access the site. TF (transmissivity function) is used for such probability.

TF computed for Lomnický Štít, 24 hour averaged for different levels of geomagnetic activity (Ts89 model (A) used).

Kudela,K. and Usoskin,I.G, Czech. J. Phys, 54, 239-254, 2004.

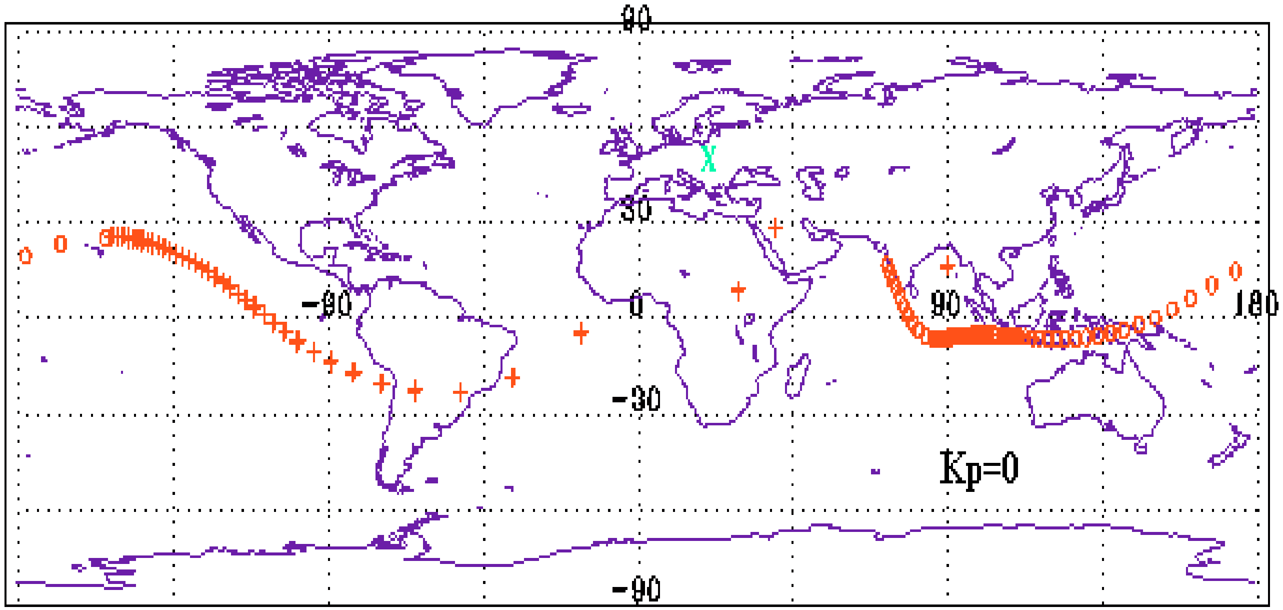


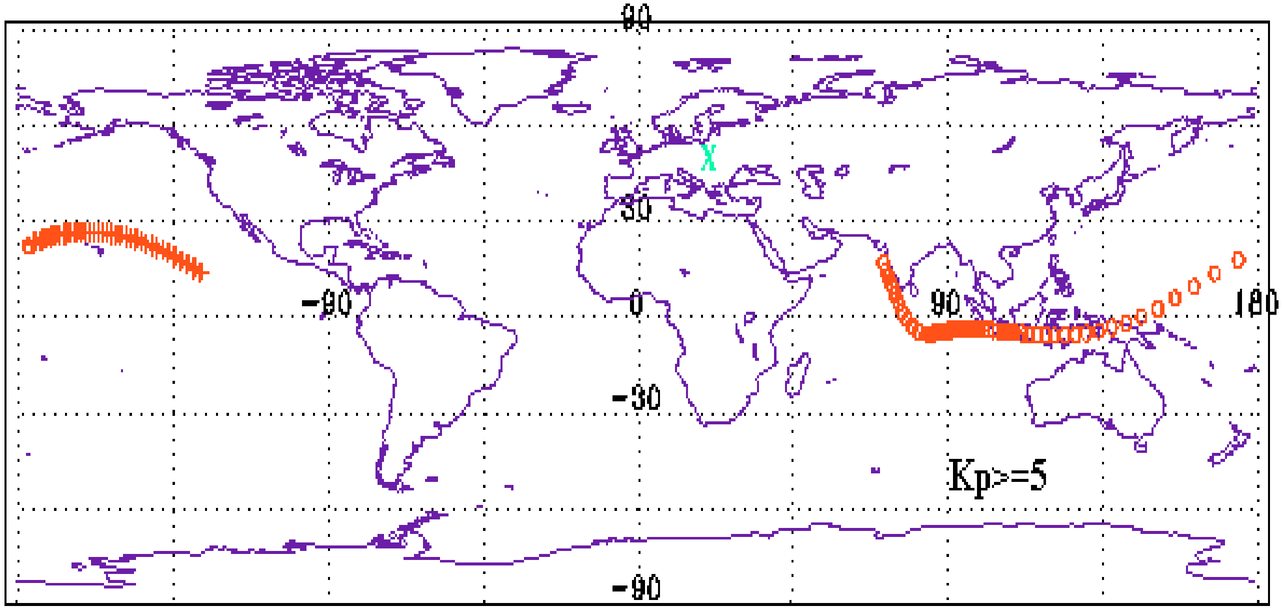


. Upper panel: probability of occurring of various *IOPT* during the period 1980–1990 (histogram from data available at `http://nssdc.gsfc.nasa.gov/omniweb`). Lower panel: The transmissivity function for Lomnický Štít weighted by the probabilities displayed in the upper panel.

Transmissivity function for Lomnický Štít averaged over long time period with different Kp indices and over diurnal change of the cut-off rigidities.

TF can be used for analysis of long term variations of cosmic rays observed at a particular station.





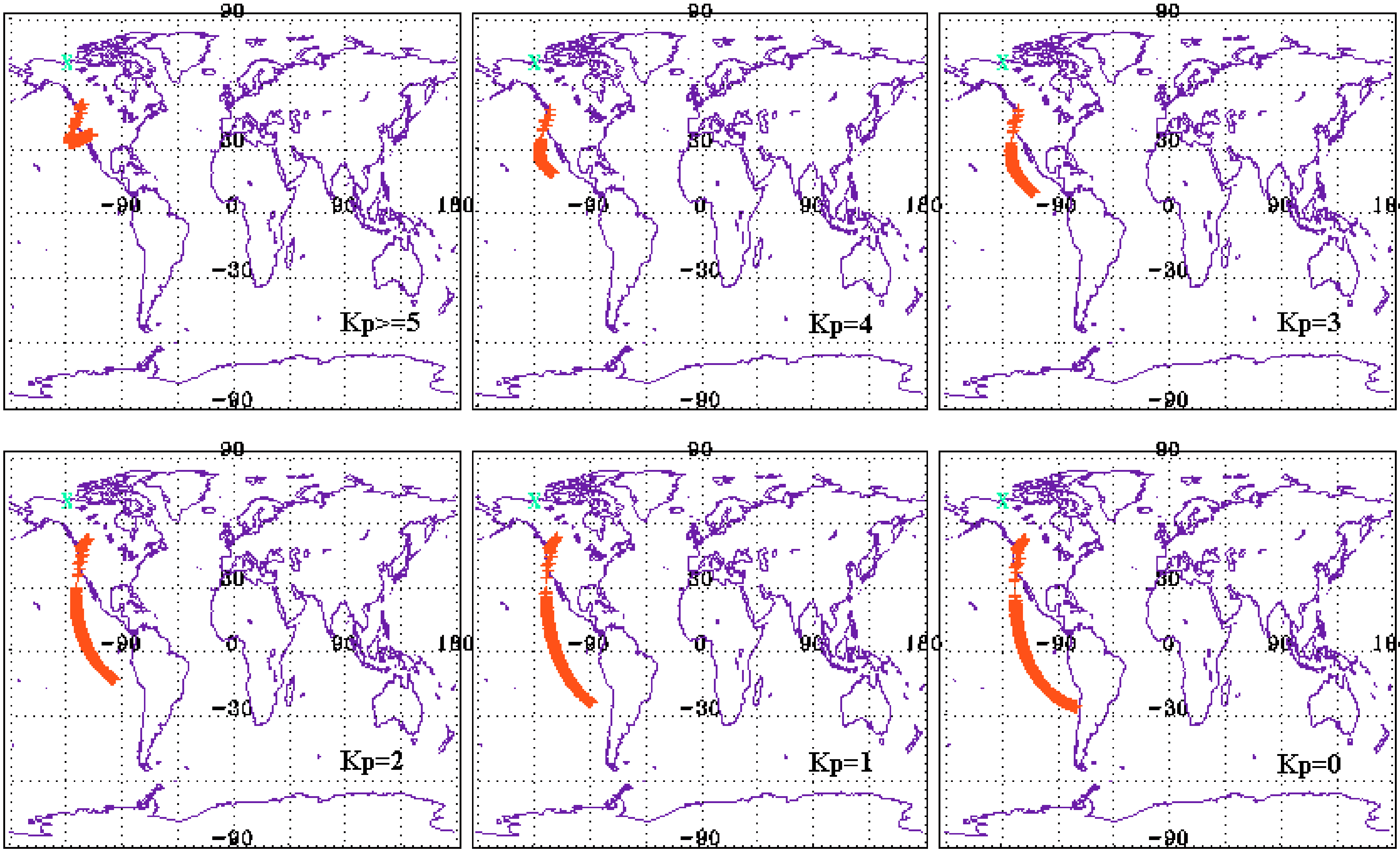
<u>Changes of asymptotic directions due to geomagnetic activity</u>.

Asymptotic directions for particles vertically accessing Lomnický Štít for low and high geomagnetic activity level.

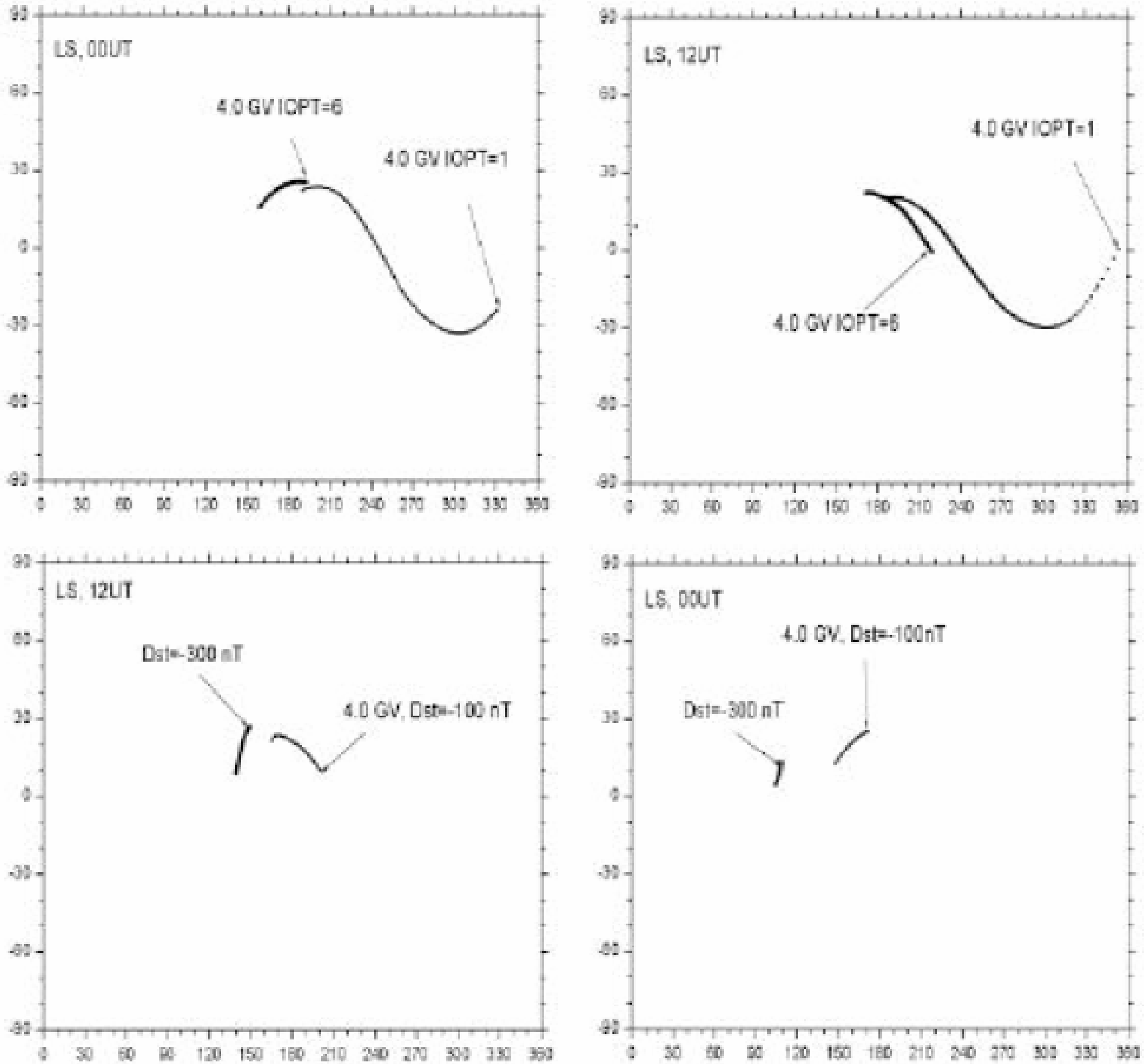
Ts89 model (A) is used.

Rigidities 4.1-4.5 GV are marked by crosses, interval 4.5-20 GV by circles.

(*Bobík, P., PhD thesis, 2001*)



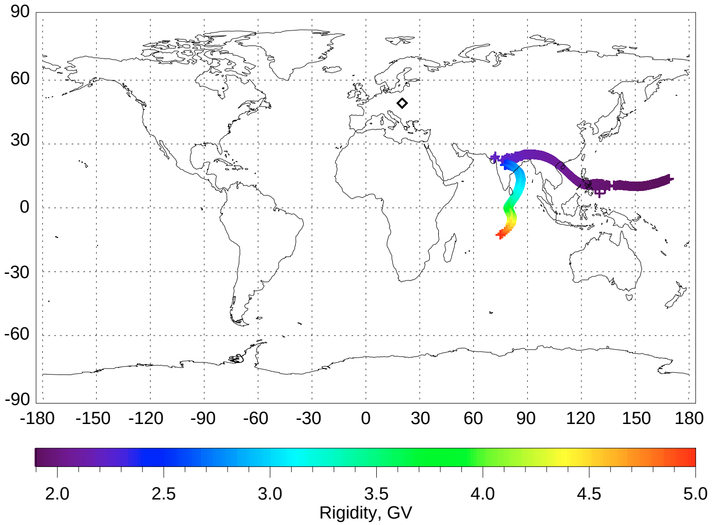
Change of asymptotic directions at a high latitude station (Inuvik) in dependence on geomagnetic activity level. Rigidities 0.3 - 20 GV are displayed (*P. Bobík, PhD thesis, 2001*)

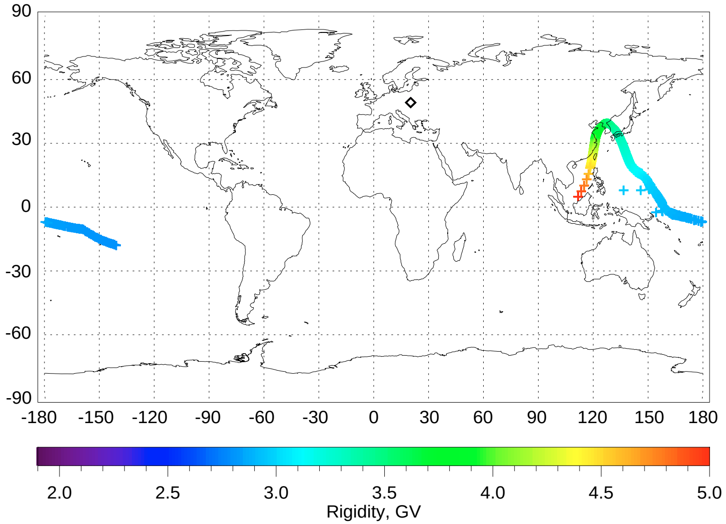


Asymptotic directions of (4.0–4.5) GV primary cosmic rays accessing vertically Lomnický Štít position at midnight and noon for different geomagnetic conditions. The epoch for internal field is January 21, 1986. The arrows correspond to asymptotic directions at 4.0 GV at each line.

Asymptotic directions for middle latitude station at low rigidity interval for different models of the magnetic field. Upper panels are for Ts'89 model (A); lower panels are for the model with Dst extension (B). The different asymptotics are seen also for local noon and midnight.

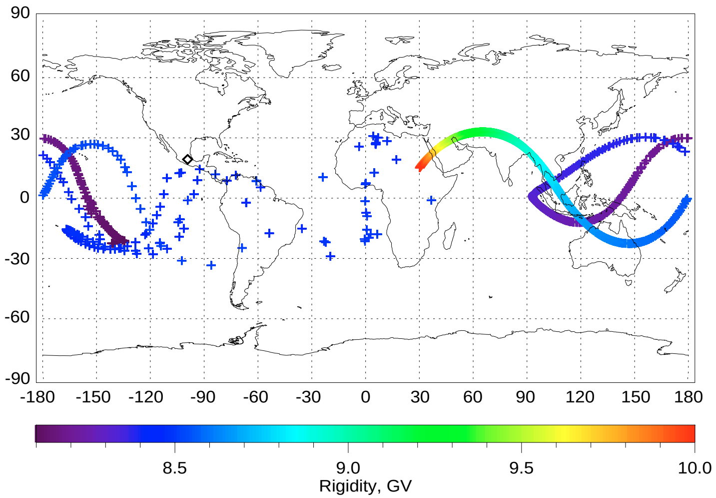
Different models give different asymptotic directions during high level of geomagnetic activity (computations by *R. Bučík, 2005*).

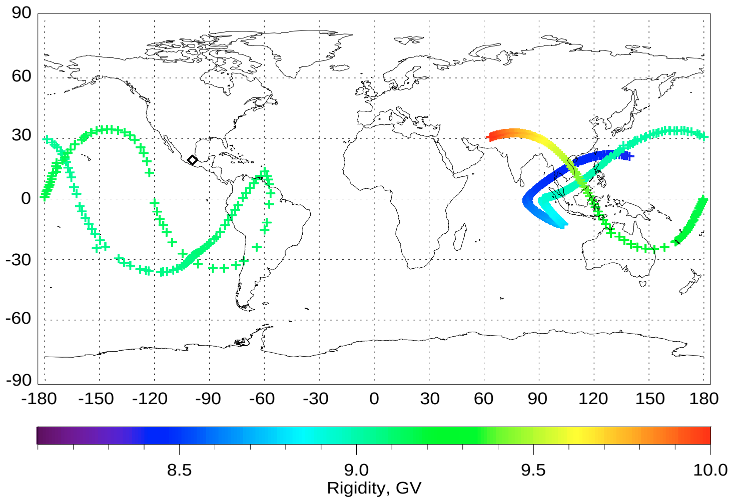




Model B, 20.11.03, 19 UT

Model E, 20.11.03, 19 UT Lomnický Štít





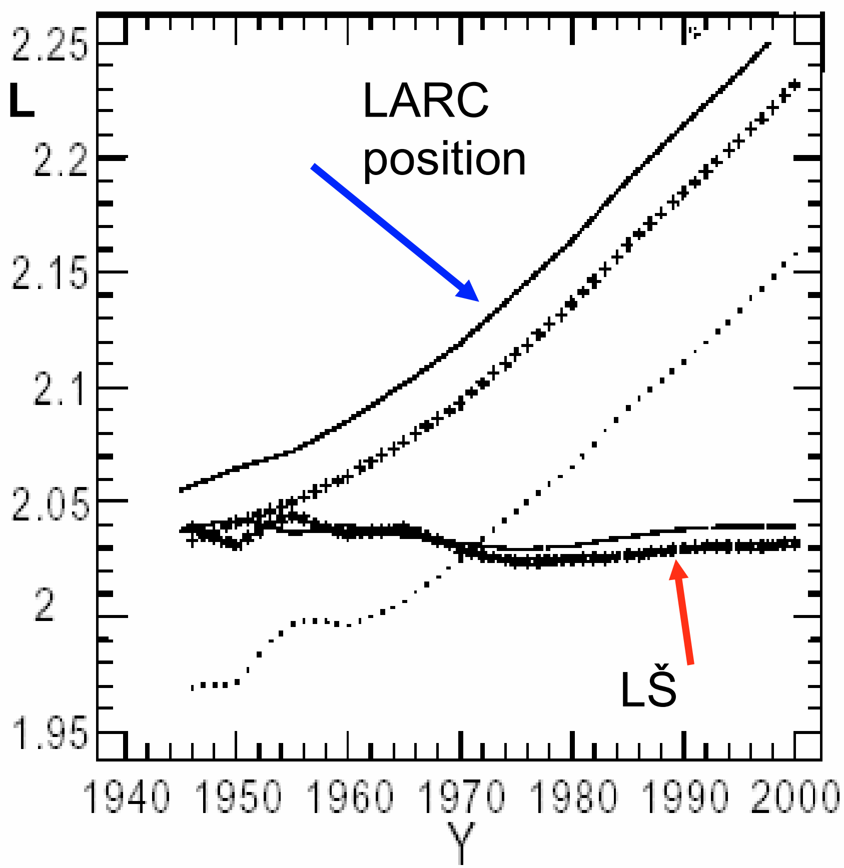
Model B, 8.11.04, 06 UT

Model E, 8.11.04, 06 UT Mexico

4. Long term variability of CR access to vicinity of Earth.

Parts 2 and 3 are based on models of the geomagnetic field valid for the recent period. However, geomagnetic field was changing on long time scales.

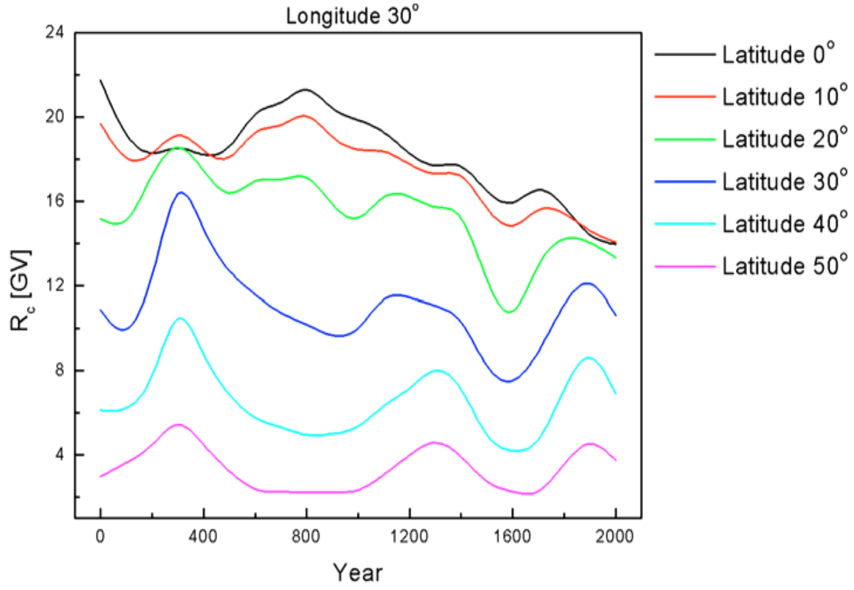
There are positions on the earth where the geomagnetic cut-offs are changing over past century more dramatically than in another positions.

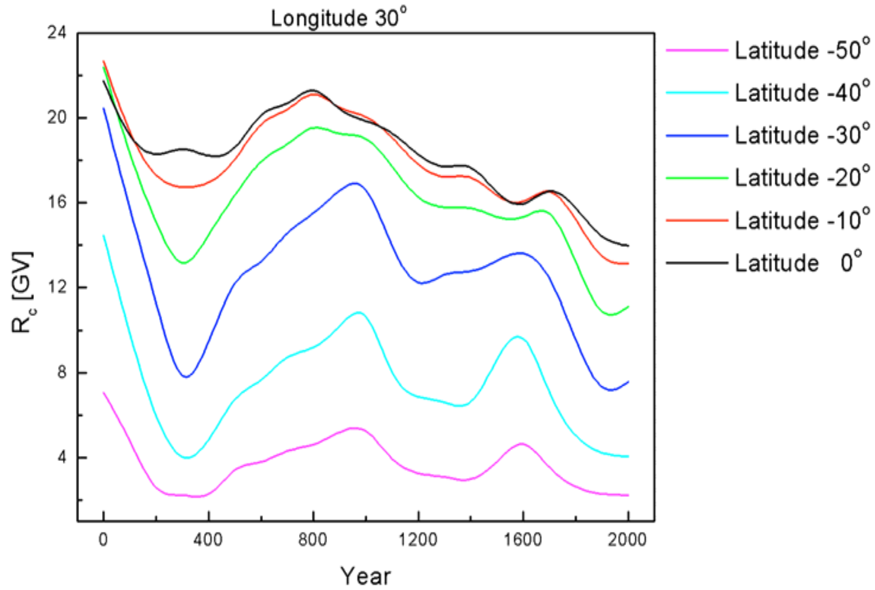


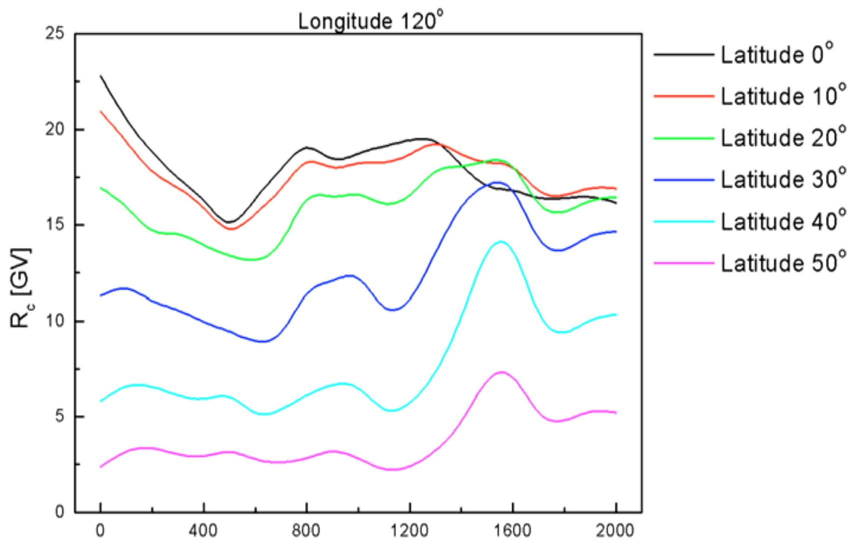
The vertical cut-off can be approximated as a function of L, McIlwain's parameter (e.g. *Shea, M. A. et al, Phys. Earth and Planet. Interiors, 48, 200-205,1987*).

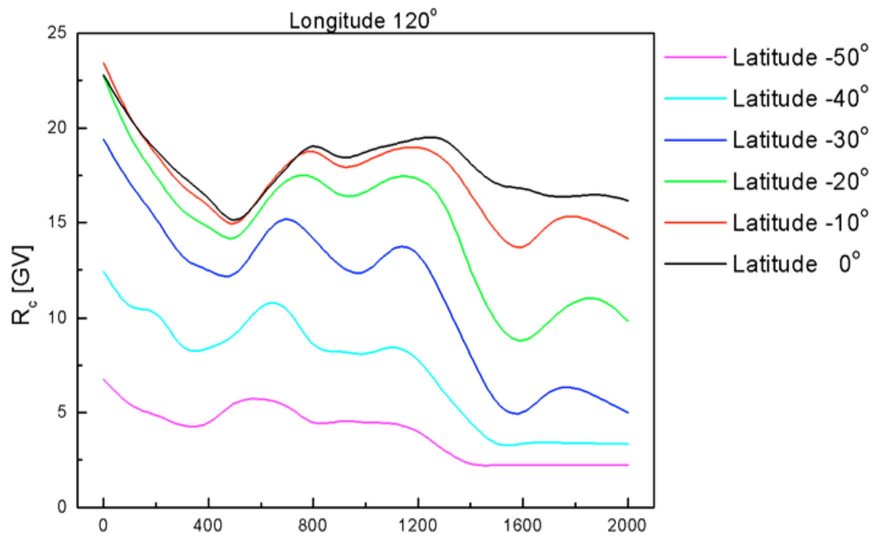
While around 1950 positions of LŠ and LARC (in opposite hemispheres) had almost the same value L, by the end of last century L at LARC was significantly higher (lower cut-off) than at LŠ (*Kudela,K. and M. Storini, Proc. ICRC, Hamburg, 9,4106-4109, 2001*)

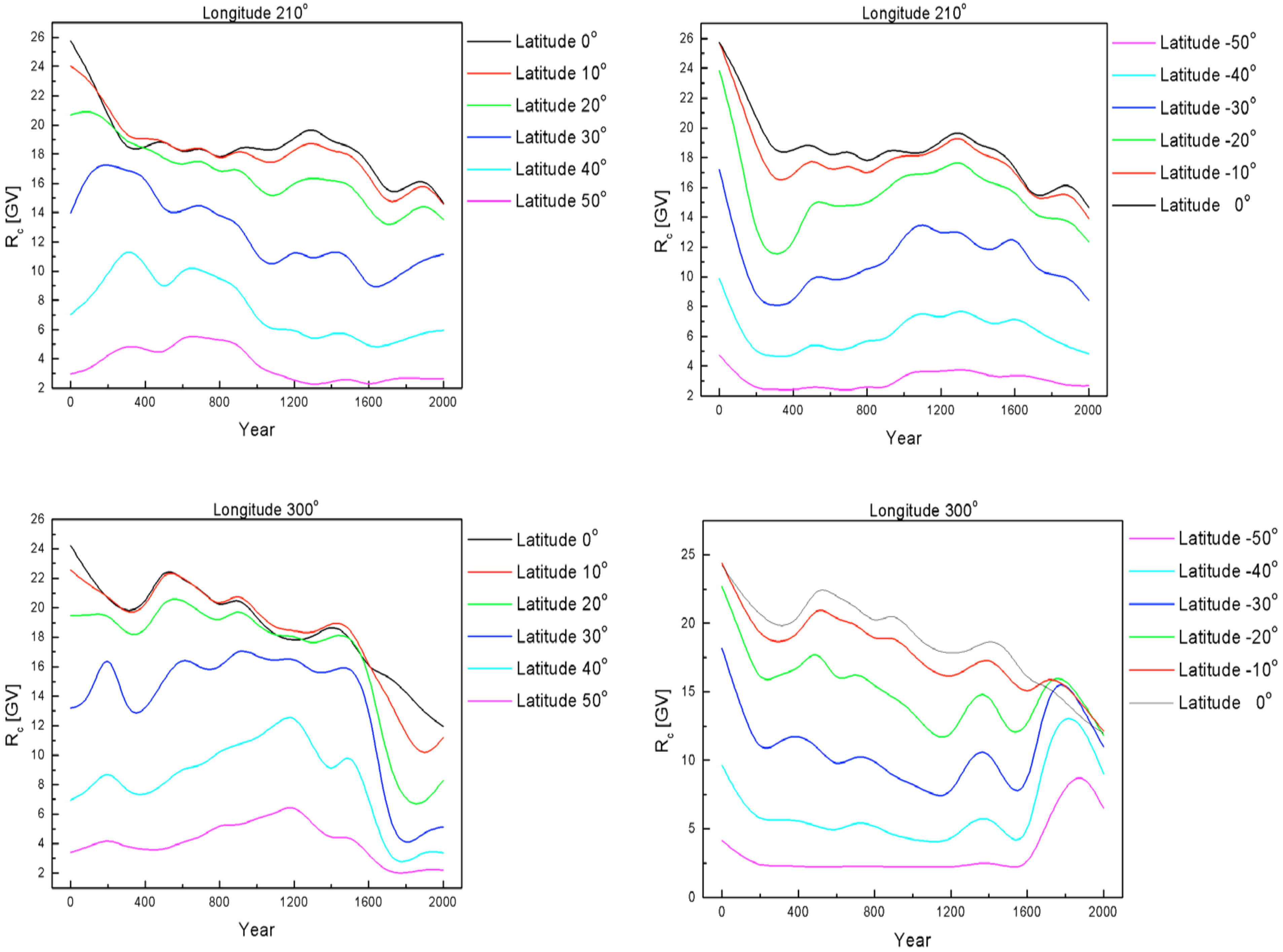
Changes of geomagnetic cut-offs in the past: available models of geomagnetic field are used (e.g. *Kudela, K., Bobík, P., Solar Phys., 224, N 1-2, 423 – 431, 2004*). Different positions on earth had different cut-off rigidity time changes.











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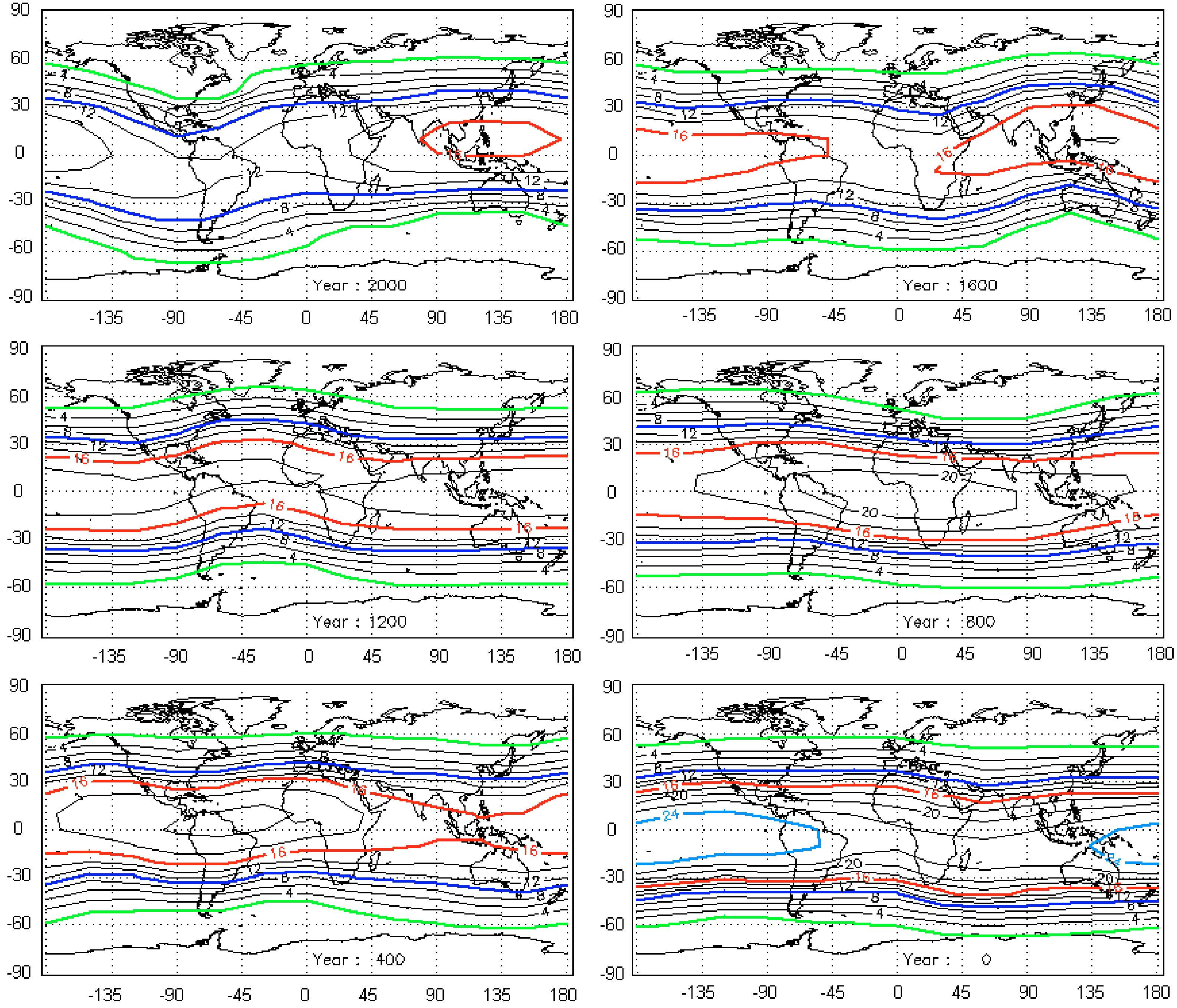
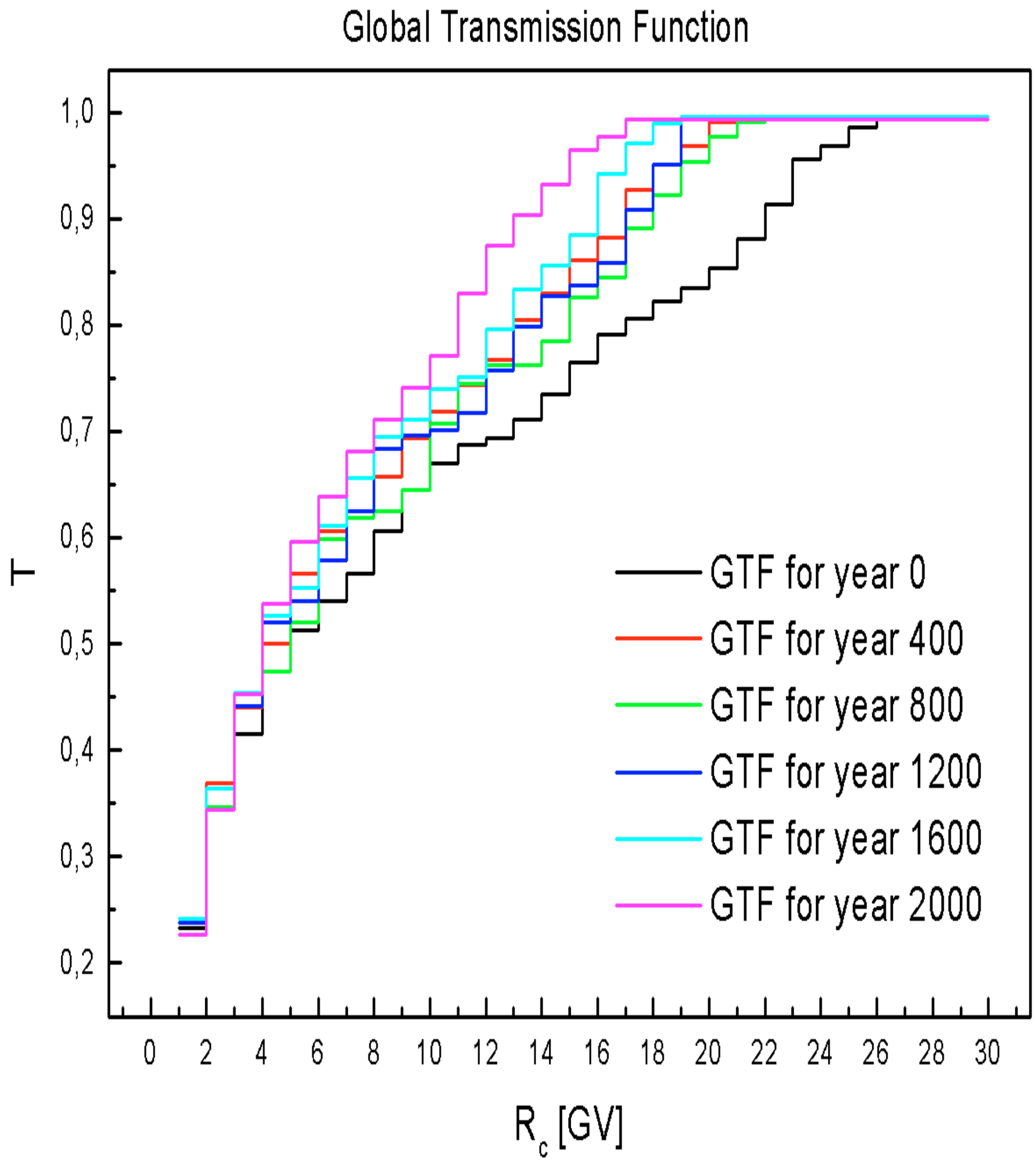
Latitude -30°
Latitude -20°
Latitude -10°
Latitude 0°



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.