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Athens Neutron Monitor Station

NM BANGLE Model for GLEs real-time analysis

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Overview

- Cosmic Ray Variation Model
- The NM-BANGLE Model
- Off-line application to GLE 69 and GLE70
- The real-time concept
- Conclusions

Cosmic Ray Variation Model

The method of coupling coefficients (Dorman, 1957)

Intensity of any CR component of type i, observed at a cut-off rigidity $R_c(t)$ at level h_0 in the atmosphere at some moment t:

$$N_i(R_c(t), h_0(t), t) = \int_{R_c(t)}^{\infty} D(R,t) m_i(R, h_0(t), g(t), T(h,t), E(h,t)) dR$$

Primary CR spectrum **Integral multiplicity**

Possible time variation of observed CR intensity can be caused by the variation of any of the three parameters : R_c, D or m

$$\delta N_i(R_c(t), h_0(t), t) / N_{io} = \int_{R_{co}}^{\infty} \frac{\delta m_i(R, h_0(t), g(t), T(h,t), E(h,t))}{m_{io}} W_i(R_{co}, R) dR$$

$$-\delta R_c(t) W_i(R_{co}, R_{co}) + \int_{R_{co}}^{\infty} \frac{\delta D(R,t)}{D_0(R)} W_i(R_{co}, R) dR$$

where:

$$W_i(R_{co}, R) = \frac{D_0(R) m_{io}(R, h_0(t), g_0(t), T_0(h,t), E_0(h,t))}{N_{io}}$$

is the **coupling function** between secondary CR of type i and primary CR

The NM-BANGLE Model

Neutron Monitor Based Anisotropic GLE Model

(Plainaki et al., J. Geophys. Res., 2007)

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \frac{\int_{R_c}^{R_u} W(R,h,t_0)\frac{\boxed{\delta D}}{D_{GCR}}(t,R)dR}{\int_{R_C}^{R_u} W(R,h,t_0)dR}$$

Solar Cosmic Rays differential spectrum

- **Neutron monitor coupling functions**:

$$W(R,h,t_0)dR = \begin{cases} W_T(R,h,t_0)dR, & E \geq 2GeV \\ W(R=2.78GV,h,t_0)\left(\frac{E}{2GeV}\right)^{3.17} dR, & \\ & E < 2GeV \end{cases}$$

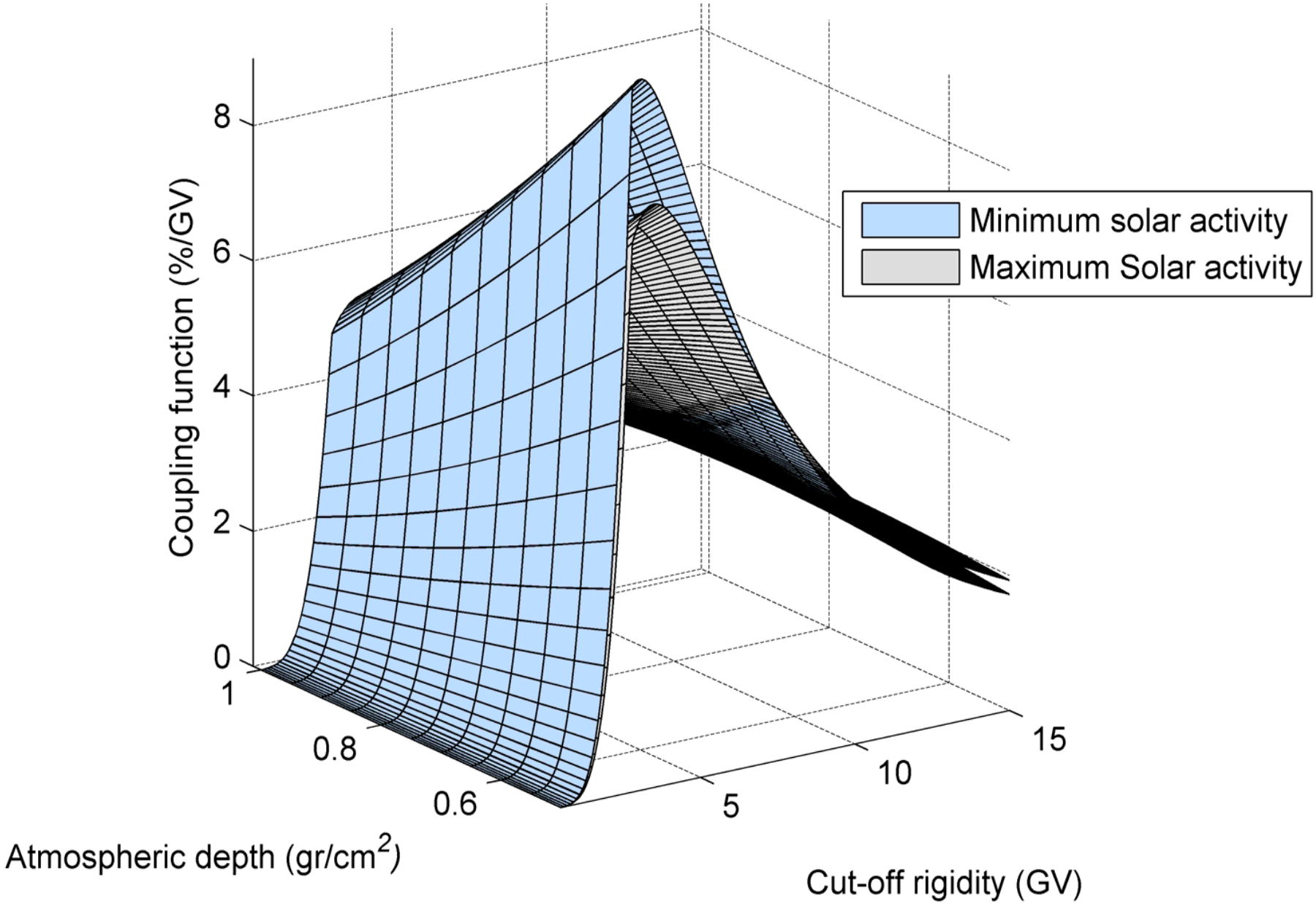
where

$$W_T(R,h,t_0) = a\cdot(k-1)\cdot\exp(-a\cdot R^{-k+1})R^{-k}$$

is the **Dorman** function

(Dorman, 2004;Clem and Dorman, 2000; Belov and Struminsky, 1997; Belov et al., 2005)

Neutron Monitor Coupling Functions



The NM-BANGLE Model

Taking into consideration long-term variation and/or possible Forbush effect, coupling functions become:

$$W(R,h,t_0)dR = \begin{cases} W_T(R,h,t_0)[1+\delta_{t0}(R)]dR & , \quad E \geq 2GeV \\ W(R=2.78GV,h,t_0)\left(\dfrac{E}{2GeV}\right)^{3.17} dR & , \quad E < 2GeV \end{cases}$$

where $\delta_{to}(R) = a_o \cdot \dfrac{b_w + (10)^{\gamma_o}}{b_w + R^{\gamma_o}}$ is a typical GCR spectrum

- **Solar Cosmic Ray Spectrum**:

$$\delta D = b \cdot f(R,E) \cdot \Psi$$

anisotropy function

For $f(R,E)$ and Ψ there is a variety of choices depending on the **characteristics** of each specific GLE event.

Power-law rigidity dependence gives: $f(R) = R^{\gamma}$

The NM-BANGLE Model

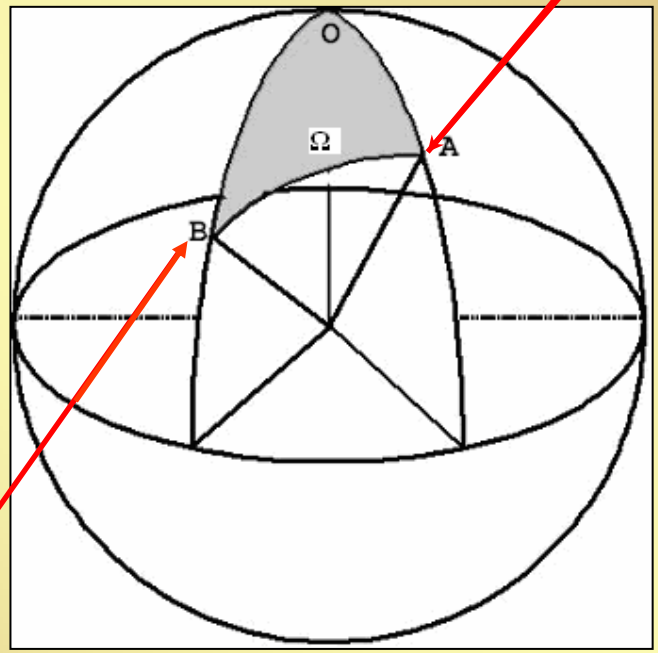
- SCR Anisotropy

$$\Psi(\Omega) = \exp(-n^2 \sin^2 \Omega)$$

axis-symmetric **anisotropy function**

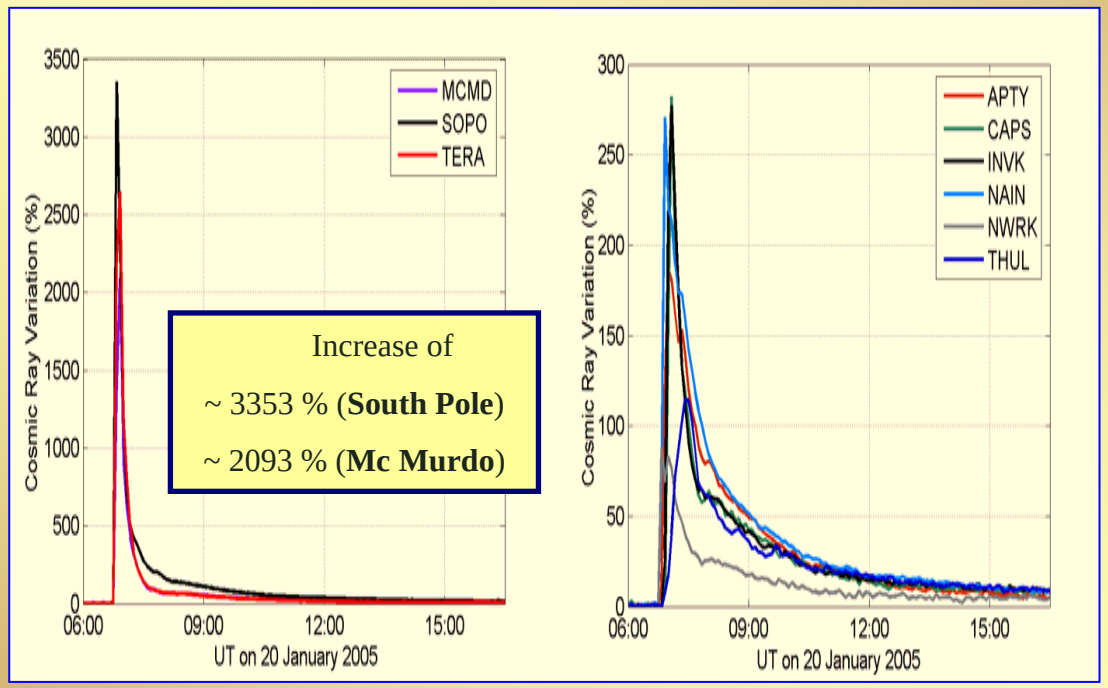
Definition of angular parameter Ω

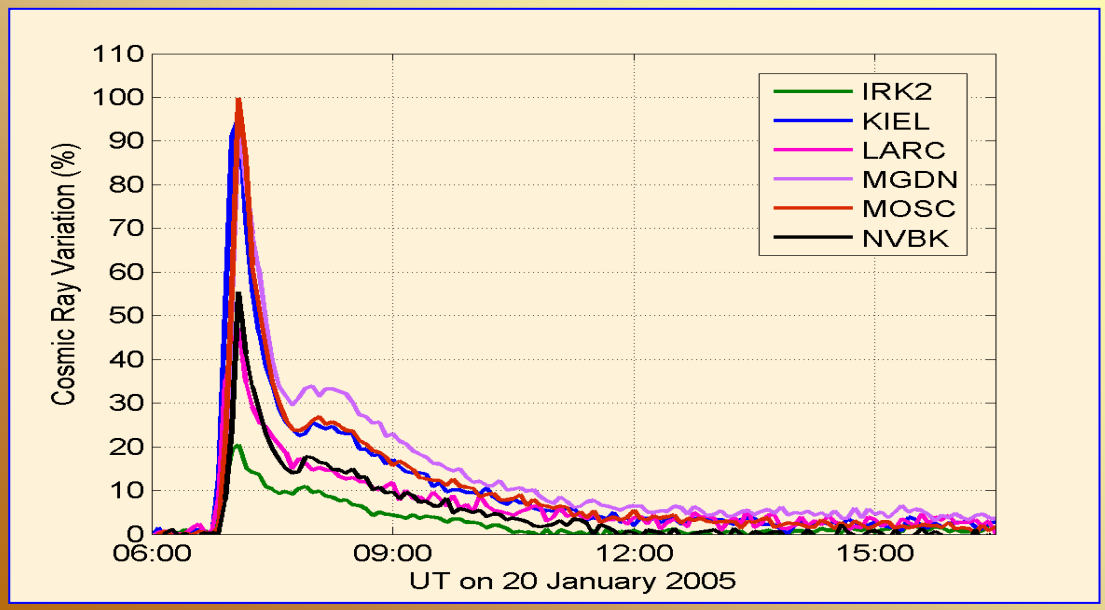
Point of observation defined by the asymptotic coordinates of the NM Station



Location of the anisotropy source

The GLE of 20 January, 2005 (GLE 69)





- GLE **onset** for most stations: 06:50 – 07:00 UT
- Different time of **maximum flux** among the stations.

First maximum recorded at South Pole (06:50 UT).

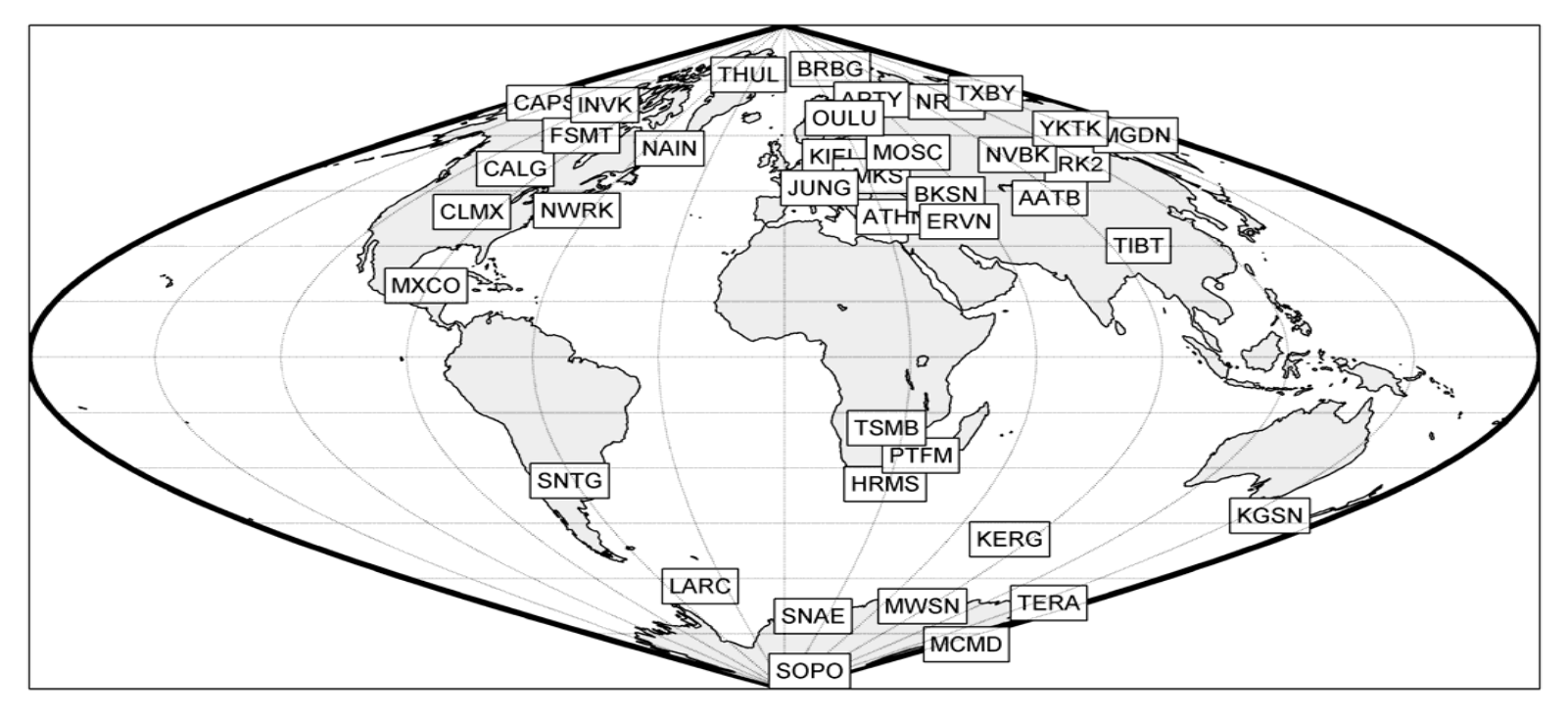
Last maximum recorded at Thule (07:30 UT)

- Biggest maximum was observed at South Pole.
- Maximum rigidity of solar particles arriving in the vicinity of Earth at least 14.1 GV !
- **Evidence of anisotropy** :

Two orders of magnitude difference in maxima between **McMurdo** (south hemisphere) and **Thule** (north hemisphere).

(Plainaki et al., J. Geophys. Res., 2007)

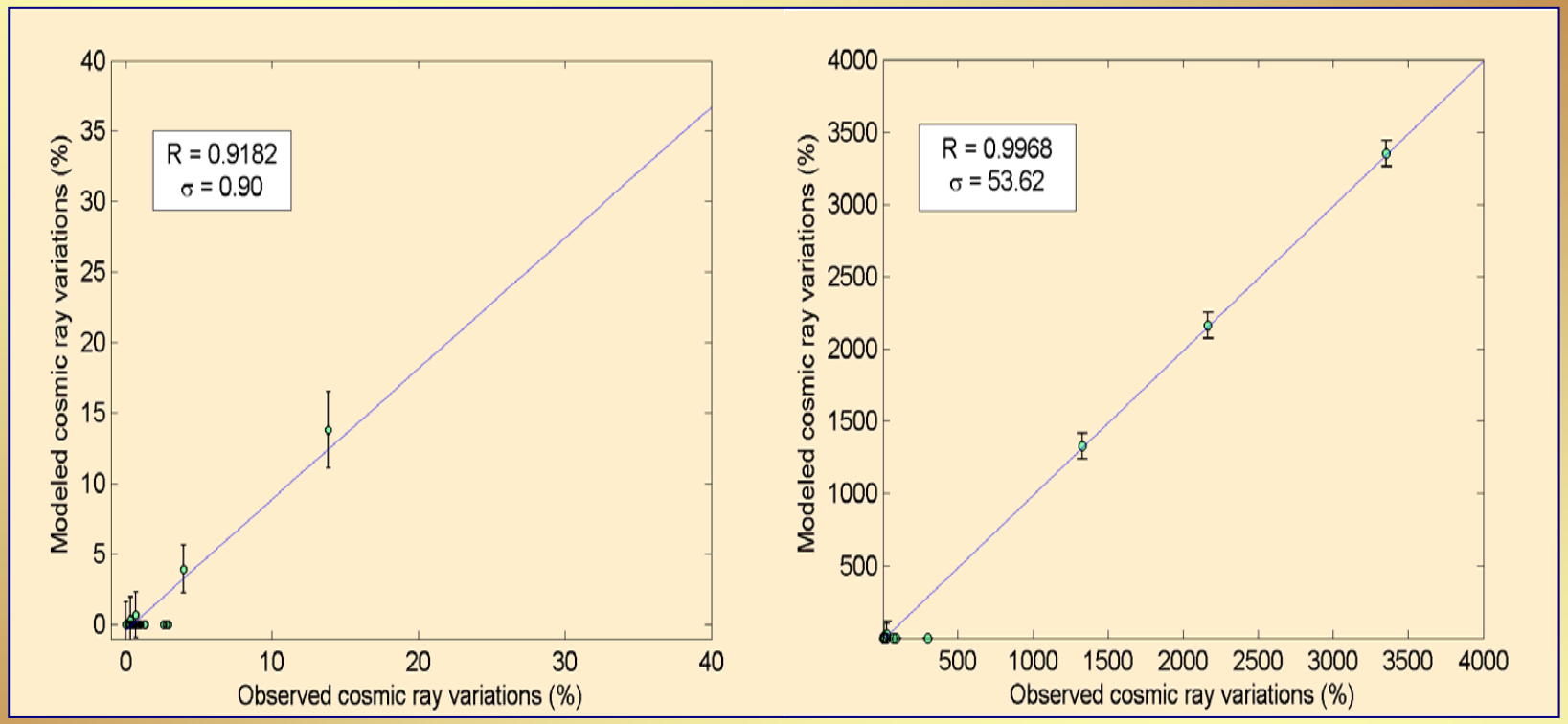
Application of the NM-BANGLE Model to GLE 69



- Five minute data from **41 NM stations** widely distributed around the Earth
- Magnetospheric field configuration according to Tsyganenko89 model
- Calculation of the Neutron Monitors asymptotic directions of viewing.
- Levenberg-Marquardt non-linear optimization algorithm

Results

Goodness of our fit for the first time intervals of the event



Later, the dispersion between observed and calculated CR variations was reduced, whereas the correlation coefficient remained big enough.

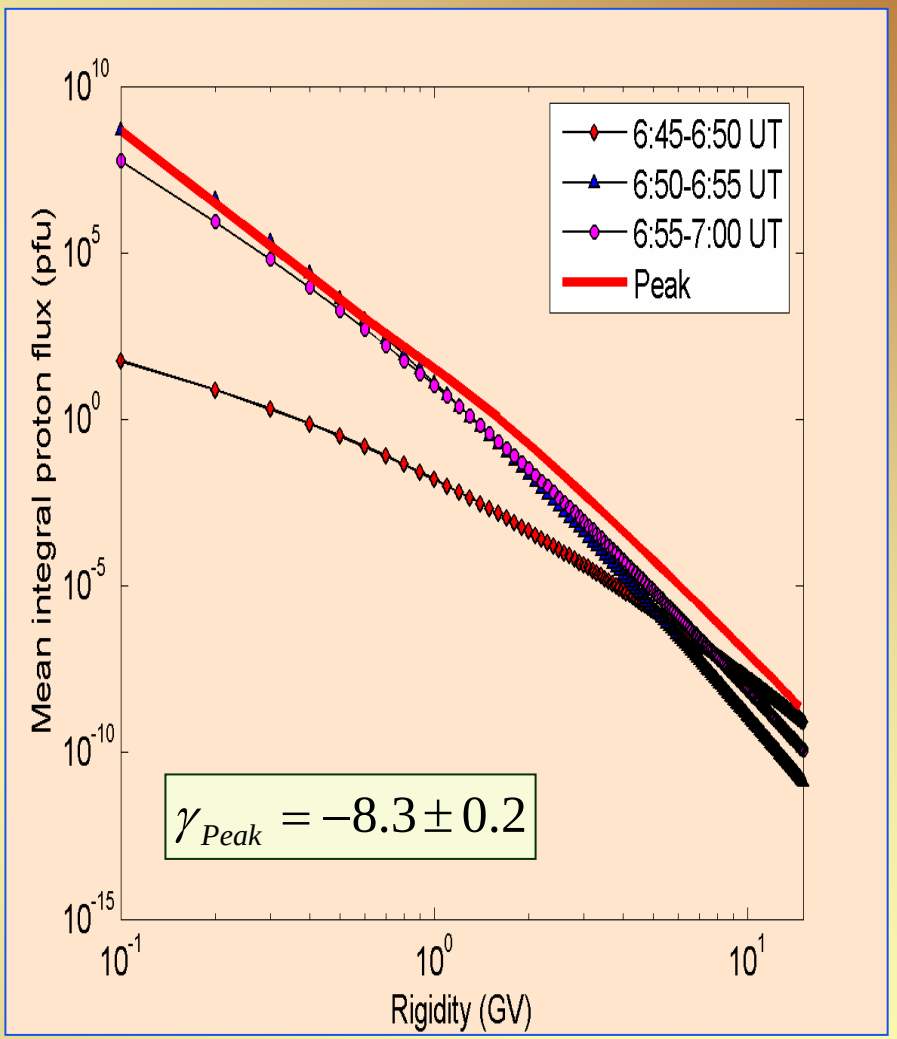
Rigidity Spectrum

- Contribution of **higher energy** particles in 6:45 – 6:50 UT

- Initially **hard spectrum-** significantly **softer** in the second 5min-interval- **hardened** during the third one → quite an unexpected behavior!

- **Peak spectrum** quite close to power law
→ Contrary to the 15 June 1991 event, the form of peak and emission spectra during GLE 69 **cannot be supposed as coincided**!

- Even in case of a full scatter-free propagation the peak spectrum cannot be affirmed to be very representative of the injection spectrum shape because of the possible **influence of the magnetic field**
→ Additional study required

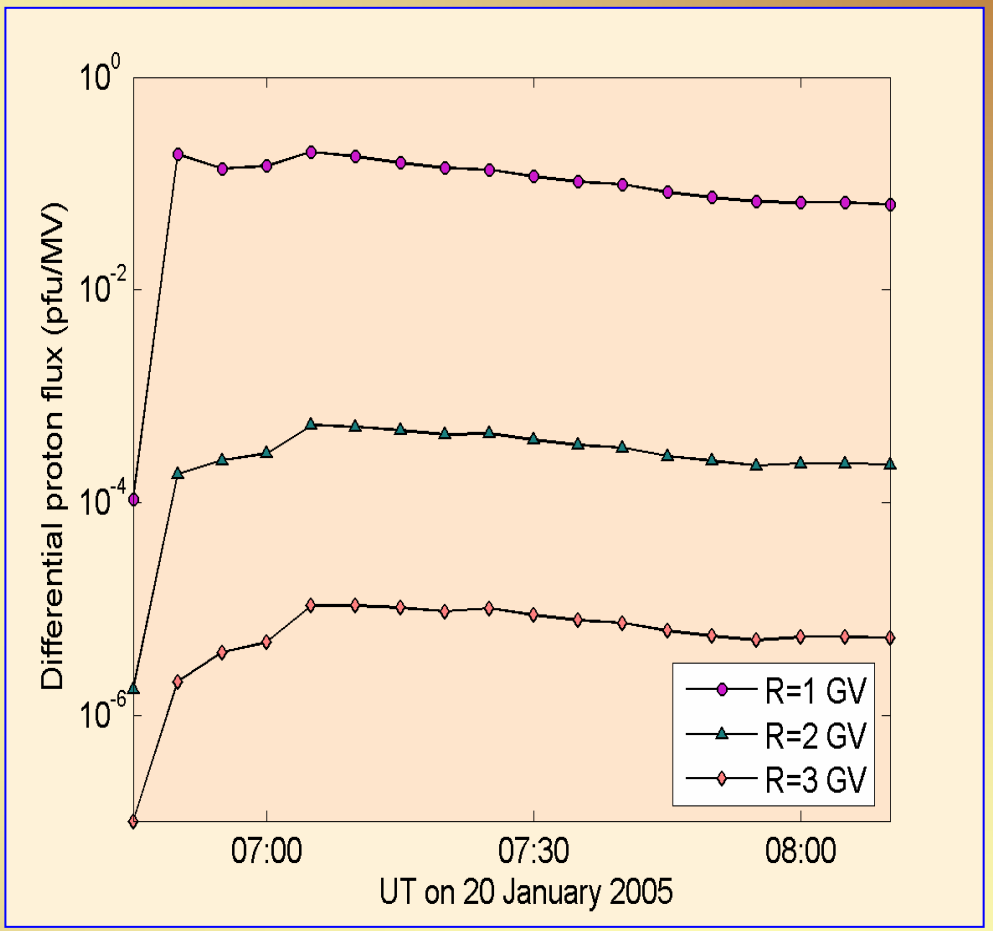


Differential proton fluxes

- Peak time turned out to be the **same for all higher rigidity particles** (1GV, 2GV and 3GV)

- The proton enhancement in the vicinity of Earth for solar particles must have been of very short duration.

- A difference in the profiles for 1GV and 2GV might be an argument for two episodes of the acceleration.



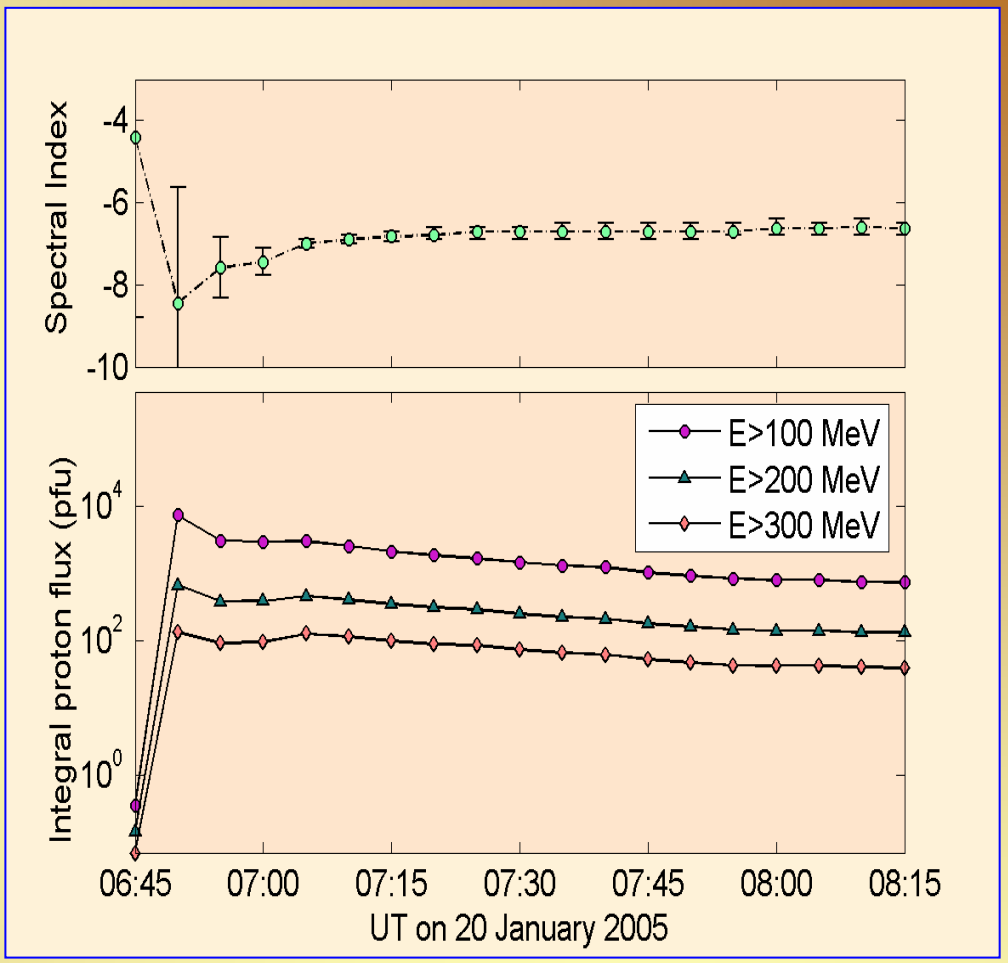
Integral proton fluxes

- Big mean integral flux during the first time intervals of the event

- Good agreement of the calculated mean integral flux with the satellite observations.

- According to our model, all three fluxes of lower energy particles remain at a surprisingly high level during the first hour of the event. **This is also testified by the satellite observations.**

- The estimated flux for particles with energy >100 MeV exceeds only by a factor of ~2 the flux recorded on 29 September 1989 (~600 pfu) and on 14 July 2000.



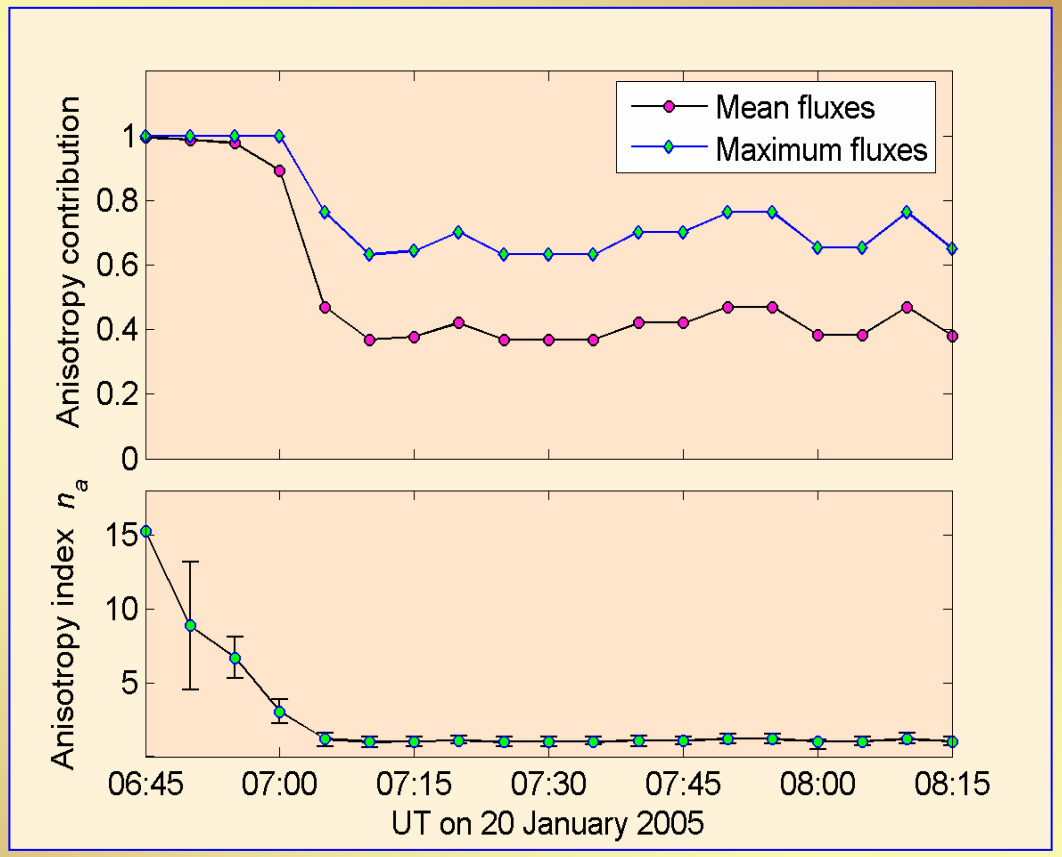
Results displayed for energies greater than 100 MeV, 200 MeV and 300 MeV are obtained by extrapolation

Solar Cosmic Ray Anisotropy

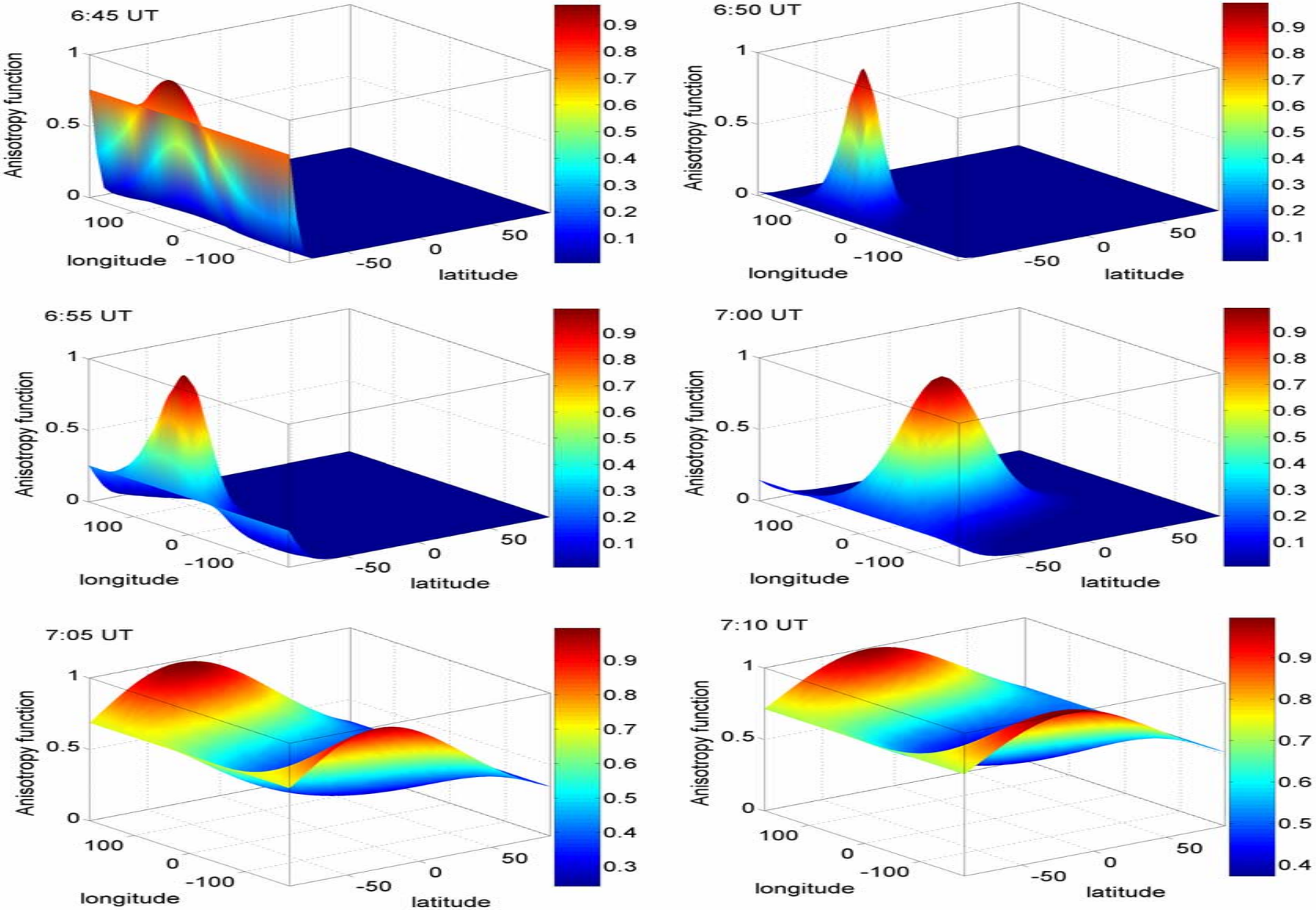
- Strong anisotropy during the first moments of the event. The anisotropy contribution in mean fluxes coincides with that in maximum fluxes.

- The angular distribution is narrow during the time interval 6:45 UT – 7:00 UT, with an index taking values between 3 and 15.

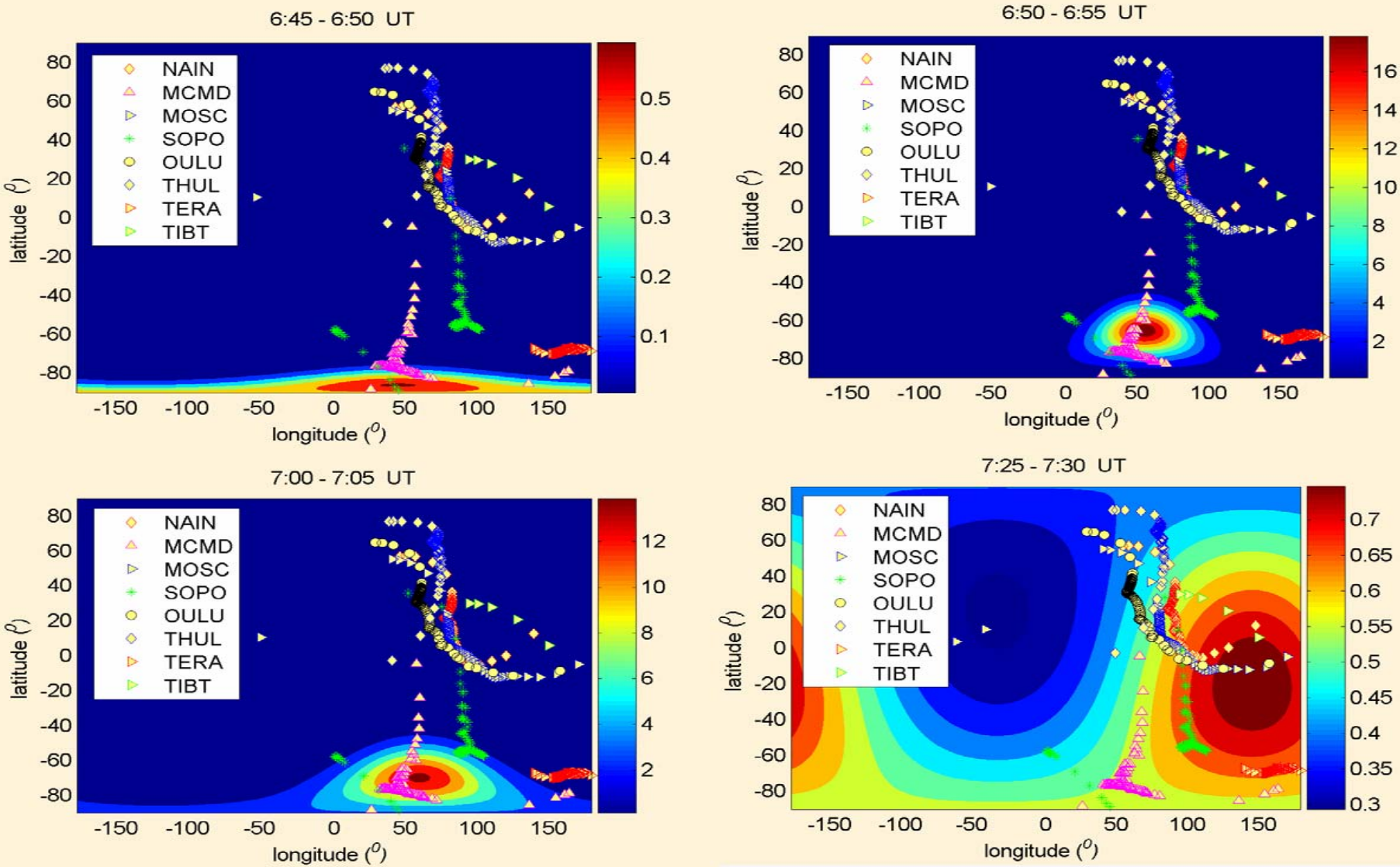
- After 7:00 UT anisotropy index becomes smaller (~1), suggesting a wider angular distribution of SCR particles



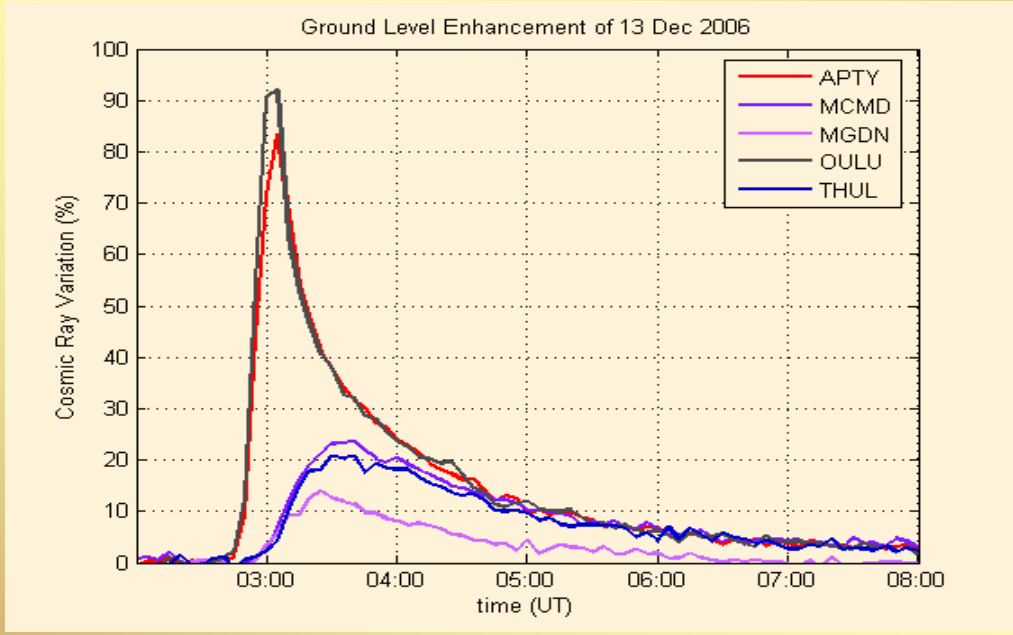
Longitudinal distribution of the anisotropy

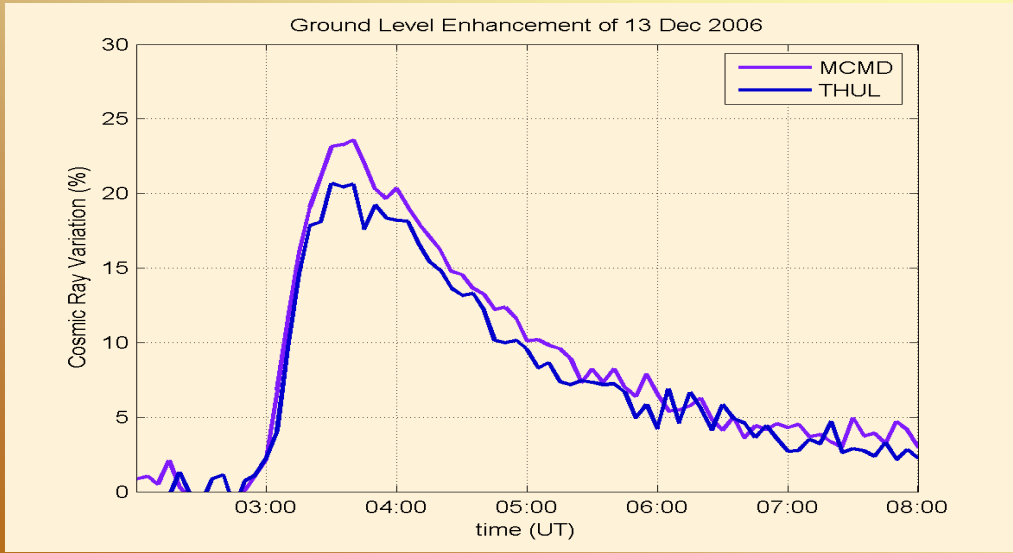


Contour areas of equal fluxes of particles with rigidity>1 GV together with NM asymptotic viewing directions



Application of the NM-BANGLE Model to GLE 70

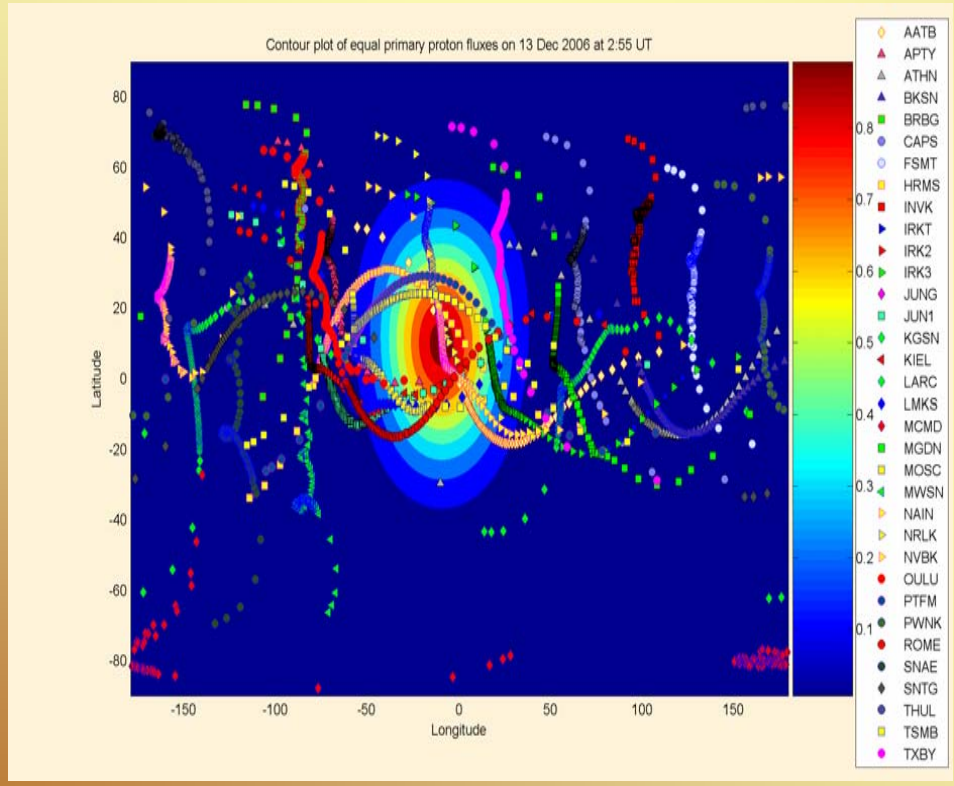


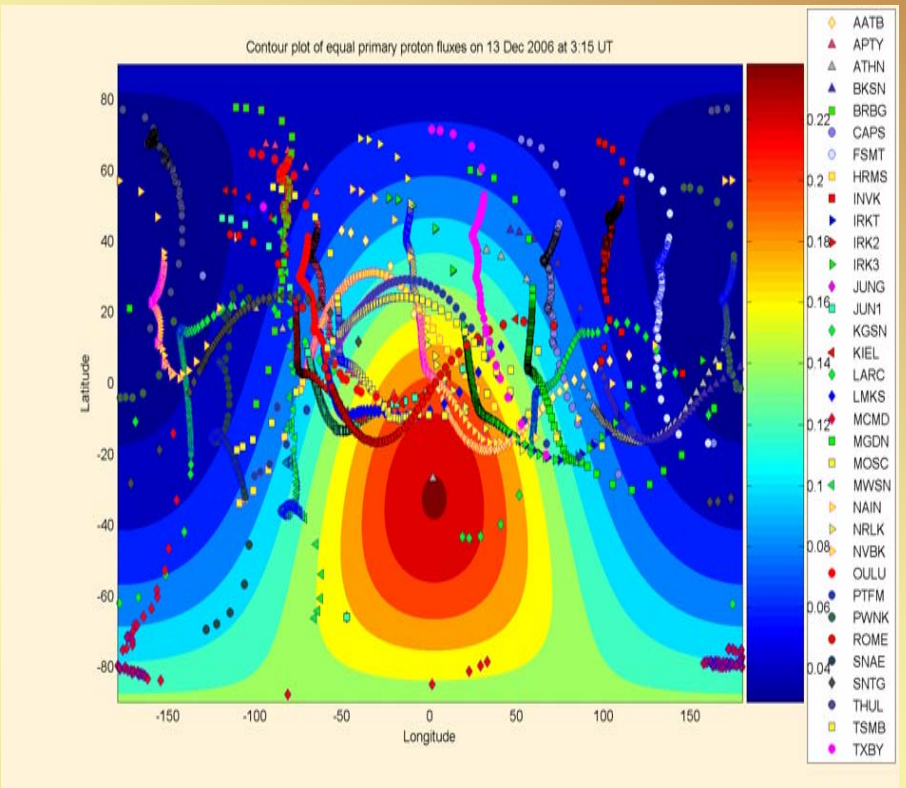


The GLE of 13 December, 2006

- One of the biggest GLE in 23rd cycle (behind Apr. 15 2001 and Jan. 20 2005 only) in minimum phase of solar cycle.
- Slow and unpronounced onset for so big GLE. It is difficult to define surely onset time (2:45-2:52).
- Very anisotropic enhancement.
- Maximum enhancement is not on subpolar stations as usual, but on lower latitudes→ Source of anisotropy near ecliptic plane.
- No big NS-assymetry.

Application of the NM-BANGLE Model to GLE 70
Preliminary Results





13 Dec, 2006 02:55 UT

13 Dec, 2006 03:15 UT

The real-time concept

Real-time definition of the onset and the characteristics of GLEs can be extremely useful since

⇨ they denote the arrival of solar energetic particles with impacts on

- Astronauts and aircrews
- Electronic Devices and Systems on the satellites
- Telecommunications

⇨ they indicate the presence of solar particles with energy >500 MeV/nucleon, whereas particles of **lower energy** arrive more than 30-60 minutes later

GLEs can be used as a tool for predicting the arrival of solar plasma of moderate energy, still very dangerous for human health and electronic devices

NM BANGLE Model in real-time

Step-1: **One-minute data collection**

The intensity $I_m(i)$ of one (or more) CR components recorded by at least ***M*** independent registration systems (e.g. neutron monitors widely distributed around the globe) is retrieved (via internet), at some specific time i.

Step-2: **Data Process → Transformation to GLE-input format**

Calculation of the average values $<I_m(i)>$ and the standard deviations $<\sigma_m(i)>$, on the basis of 60 one-minute data and derivation of quantity:

$$\delta I_m(i) = (I_m(i) - <I_m(i)>) / <I_m(i)>$$

and the corresponding standard deviations $\sigma(\delta I_m(i))$.

NM BANGLE Model in real-time

Step-3: **Calculation of the NM-asymptotic cones**

a) **Definition of the level of geomagnetic activity**

The value of Kp-index at moment i is retrieved via internet.

b) **Calculation of the asymptotic directions of viewing**

Using a model for the geomagnetic field (e.g. Tsyganenko 1989) in combination with the output of Step-3a, the asymptotic directions of viewing for each NM station used in the analysis are derived.

NM BANGLE Model in real-time

Step-4: **Application of the NM-BAGNGLE Model Equation**

Using the outputs of Step-2 and 3 a set of M independent equations is derived, on the basis of the NM-BANGLE Model:

$$\delta I_m(i) = \frac{\int_{R_c^m}^{R_u} W_m(R,h_m)\frac{\delta D}{D_{GCR}}(i,R)dR}{\int_{R_c^m}^{R_u} W_m(R,h_m)dR} \qquad m = 1,\ldots M$$

where R_c^m is the cut-off rigidity of the *m*-th NM and

$W_m(R,h_m)$ is the coupling-function of the *m*-th NM placed at atmospheric depth h_m

For a SCR differential spectrum of the form $f(R) = R^{\gamma}$

and anisotropy function $\Psi(\Omega) = \exp(-n^2 \sin^2 \Omega)$

the total number of **free parameters** to be defined by the model is 5.

NM BANGLE Model in real-time

Step-5: **Solution of the optimization problem**

Application of the effective Levenberg-Marquardt algorithm for non-linear problems leads to the **real-time exact definition** of several specific GLE parameters:

- Spectral index
- Anisotropy index (characterizing the width of solar particle beam
- Position of the anisotropy source above the atmosphere
- Amplitude of the SCR differential spectrum

Furthermore important quantities characterizing the GLE event can be also derived in real-time:

- Primary SCR integral flux on the top of the atmosphere
- Angle between the direction of the anisotropy and the Interplanetary Magnetic Field
- SCR flux distribution around the globe

NM BANGLE Model in real-time

Step-6: **Result presentation in internet**

All results are set available to the scientific community via internet.

The outputs of the NM-BANGLE Model will be

- stored in FTP Server and
- presented in graphical form

Conclusions

- GLEs can be used as a tool for predicting the arrival of solar plasma of moderate energy still very dangerous for human health and electronic devices.

- The **NM-BANGLE Model**, based on the coupling coefficient method (Dorman, 1957), can lead to the definition of several SCR parameters during a GLE event.

- As an input the model uses data from a big number of neutron monitors widely distributed around the globe.

- Application of the **NM-BANGLE Model** to the most recent GLEs (**GLE69** and **GLE70**) renders it reliable since it predicts with great precision the values of several parameters characterizing these two events.

- **On-line** function of the NM-BANGLE Model will render it an important tool for **space weather** monitoring and prognosis since it will be possible to define in real-time a variety of solar cosmic ray parameters.

- For real-time application of the NM-BANGLE Model the existence of an extended neutron monitor database is necessary.

Thank you

Websites

http://cosray.phys.uoa.gr