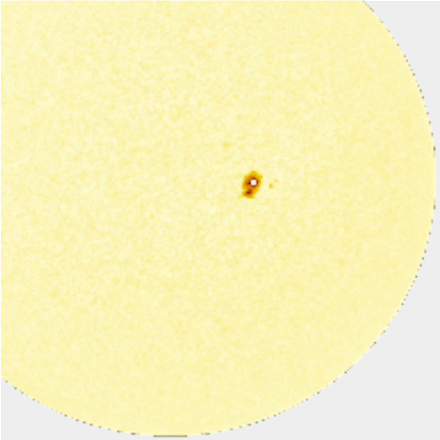

22 ECRS 2010

Turku, Finland, 3-6 August, 2010

Features of relativistic solar proton spectra derived from GLE modeling

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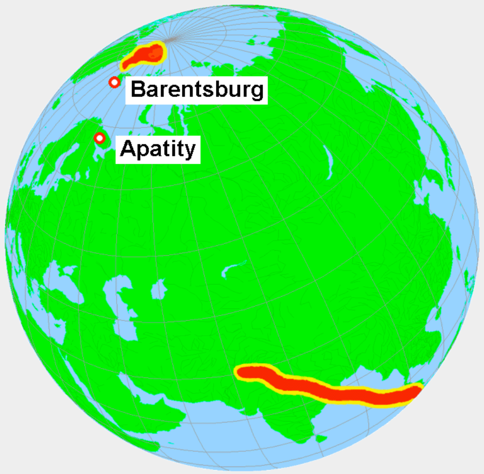
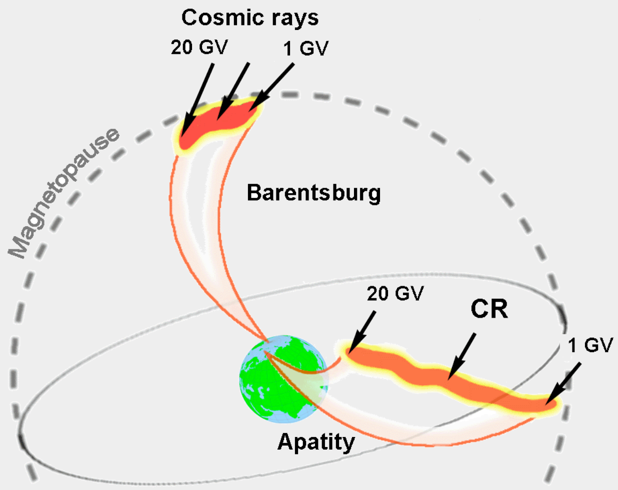




INTRODUCTION

The neutron monitors (NMs) long since and down to the present time remain the basic means of relativistic solar cosmic rays study. These particles are observed in rather rare Ground Level Enhancement (GLE) events. The rate of GLEs occurrence is ~ 1 per year. For 68 years from the first GLE registered on 28 February, 1942, only 70 events occurred up to now.

The worldwide network of neutron monitors can be considered as a multidirectional cosmic ray spectrometer. The author's GLE modeling technique employing the optimization methods and modern magnetosphere models allows obtaining characteristics of relativistic solar protons (RSP): rigidity (energy) spectrum, anisotropy axis and pitch angle distribution in the primary solar proton flux. Two distinct populations of RSP: the prompt and delayed ones probably having different origins on the Sun have been revealed.

OUTLINE

- Short information about neutron monitor response function and GLE modeling technique
- Results of relativistic solar cosmic ray events study with the GLE modeling
- Energetic spectra of the prompt and delayed components of relativistic solar protons
- Possible generation schemes and acceleration mechanisms for relativistic solar cosmic rays

GLE modeling technique

The technique of deriving of the characteristics of relativistic SCR from the ground based neutron monitors was at first suggested by D.F. Smart, M.A. Shea and P. Tanskanen, (1971). Then this technique was advanced : M.A. Shea, D.F. Smart, (1982), Cramp et al., (1997). Worth mentioned are also Bieber et al., 2003, Belov et al., 2005, Plainaki et al., 2006

Recently we developed a GLE modeling technique, allowing most precisely, from the nowadays point of view, to derive the characteristics of relativistic solar protons. It uses, in particular, the modern magnetosphere model of Tsyganenko (2002) and allows correctly account the contribution of the oblique particles into the neutron monitor response

Our GLE modeling technique

consists of a few steps:

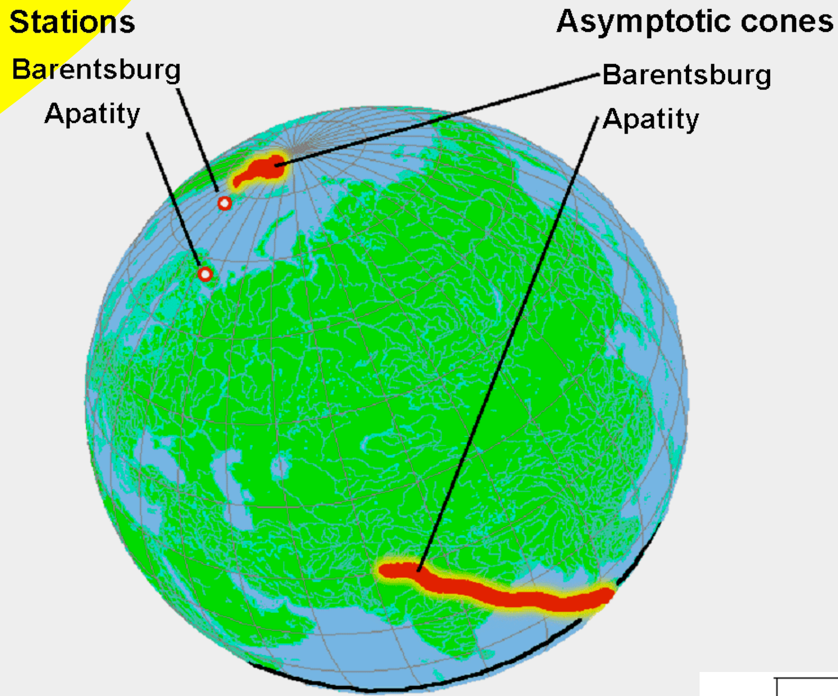
1. Definition of asymptotic viewing cones (taking into account not only vertical but also oblique incident on a detector particles) by the particle trajectory computations in a model magnetosphere (Tsyganenko 2002)

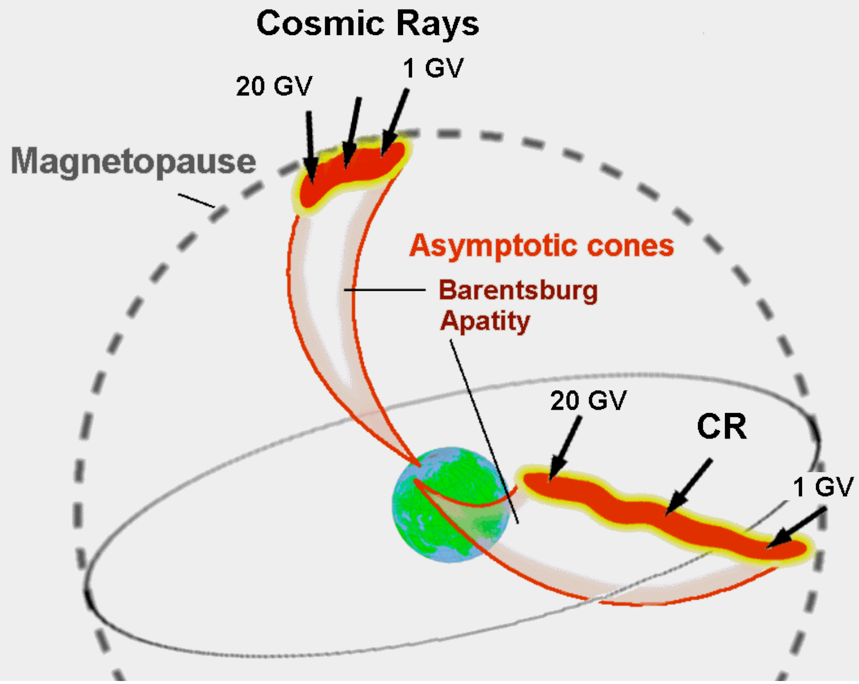
2. Calculation of the NM responses at variable primary solar proton flux parameters.

3. Application of a least square procedure for determining primary solar proton parameters (namely, energy spectrum, anisotropy axis direction, pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations

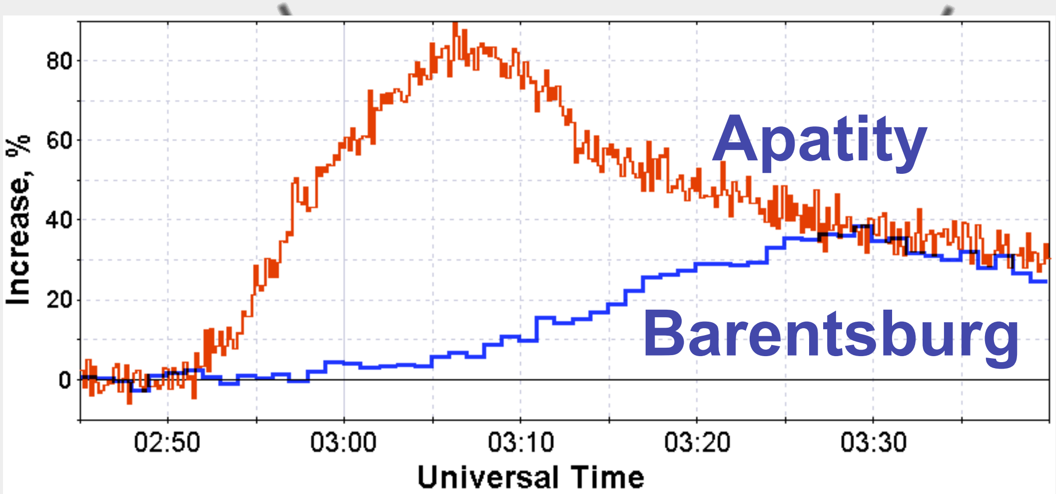
Concept of Asymptotic cone

Asymptotic cones of Barentsburg and Apatity stations are shown in geographic coordinates for representation



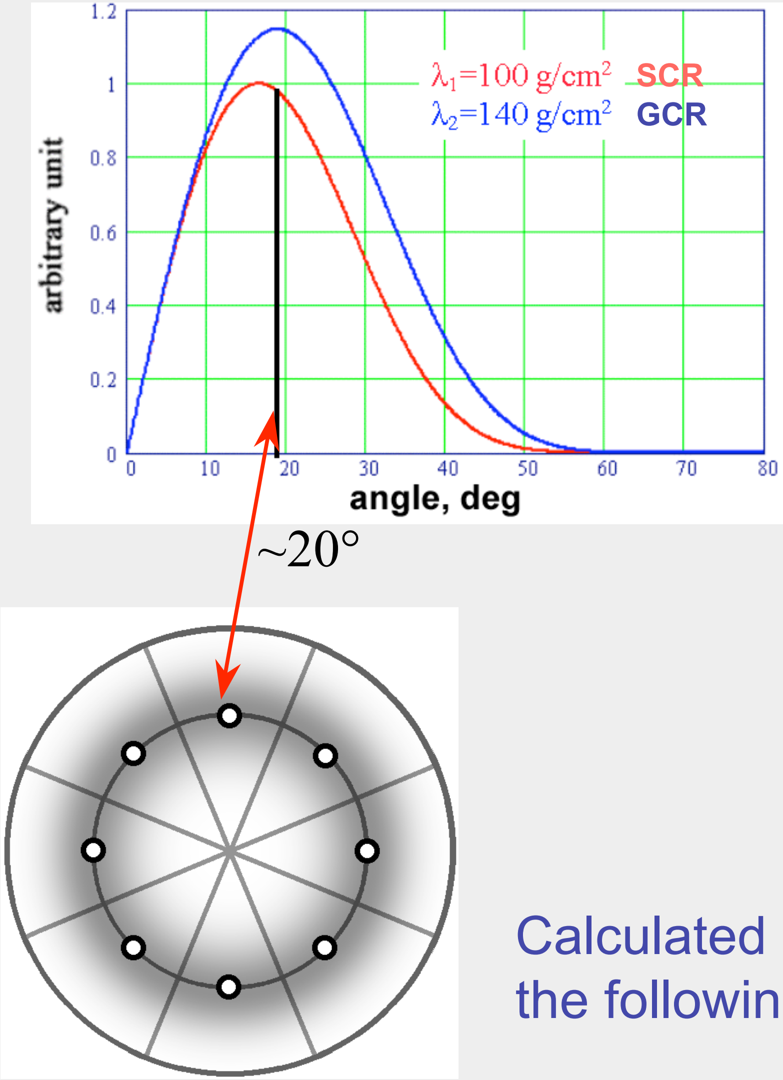


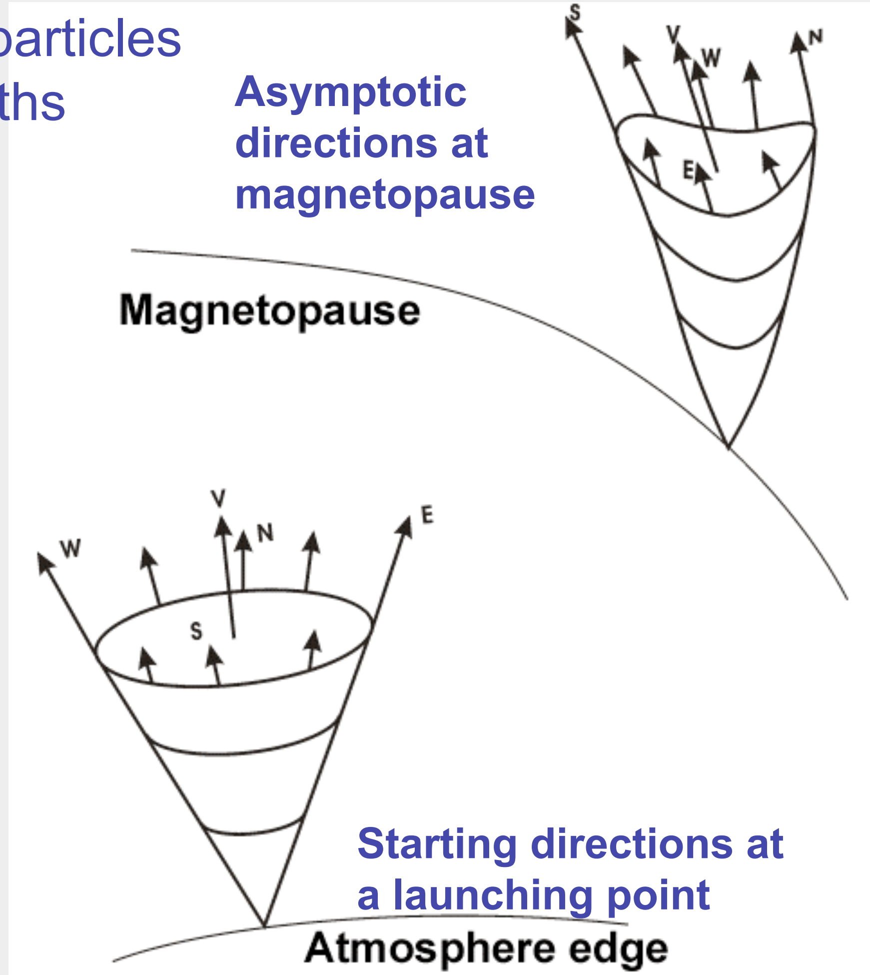
Anisotropy effect during the GLE 13.12.2005



Scheme of asymptotic cones calculations:

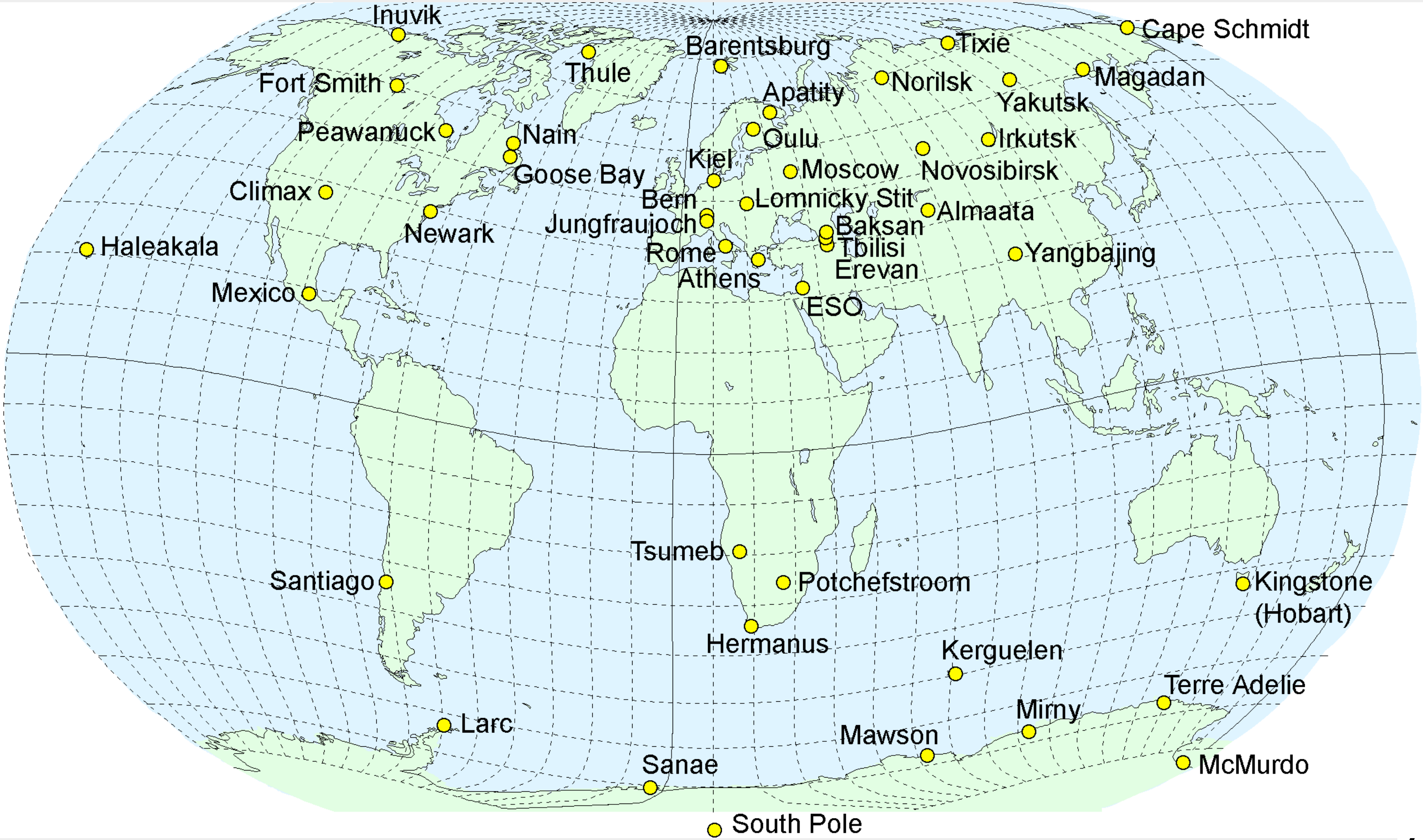
To account the contribution of oblique incident particles we calculate 8 trajectories of particles launched at zenith angle 20^{o} and 8 azimuths





Calculated asymptotic directions are then used in the following modeling of a NM response

The worldwide network of neutron monitors as a multidirectional cosmic ray spectrometer



The response function of a *i-th* neutron monitor to anisotropic flux of solar protons

$$\left(\frac{\Delta N}{N}\right)_i = \frac{1}{8}\sum_{j=1}^{8}\sum_{R=1}^{20\ GV} \mathbf{J(R)\cdot F(\theta_{i,j}(R))\cdot S(R)\cdot \Delta R}$$

$\Delta R = 0.001$ GV

$(dN/N)_i$ is percentage increase effect at a given neutron monitor *i*

- **J(R)** = $J_0 R^{-\gamma^*}$ is rigidity spectrum of RSP flux with changing slope

•$\gamma^* = \gamma + \Delta\gamma \cdot (R-1)$ where $\Delta\gamma$ is increase per 1 GV (Cramp et al., 1997)

- **S(R)** is specific yield function (Debrunner et al., 1984),

- **θ(R)** is pitch angle (angle between the anisotropy axis given

•by **Φ; Λ** parameters)

•**F(θ(R))** ~ $\exp(-\theta^2/C)$ is pitch-angle distribution in a form of Gaussian (Shea&Smart, 1982)

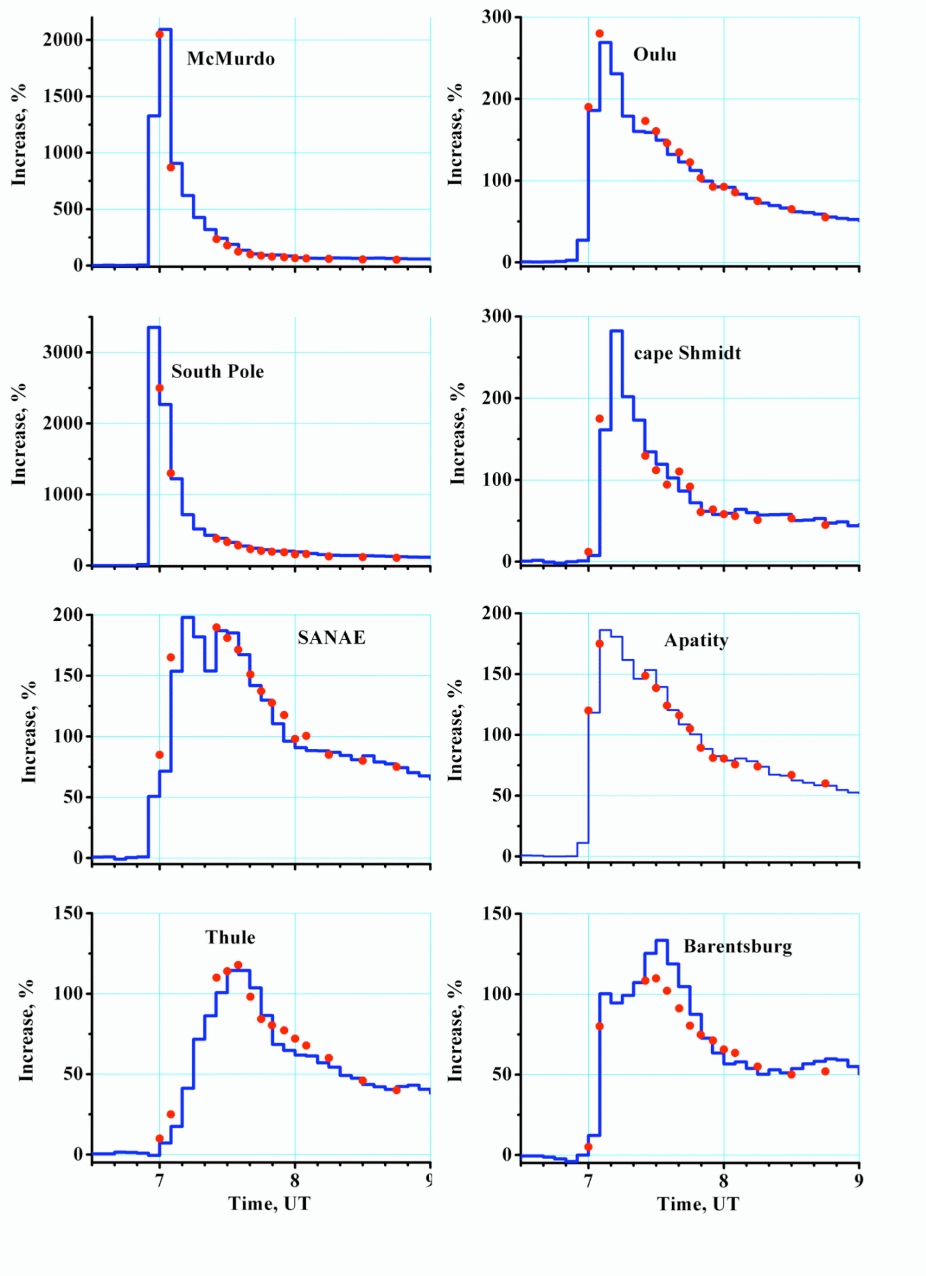
Thus, **6 parameters** (12 for a bidirectional flow) of anisotropic solar proton flux outside magnetosphere:

Φ; Λ, Jo, γ, Δγ, C are to be determined by a solving of the **nonlinear least square problem** by comparison of computed responses with observations

$$SN = \sum_j \left[\left(\frac{\Delta N}{N}\right)_j^{calc} - \left(\frac{\Delta N}{N}\right)_j^{observ} \right]^2 \Rightarrow min$$

As example of such study we consider the GLE on January 20, 2005

GLE 20 January 2005

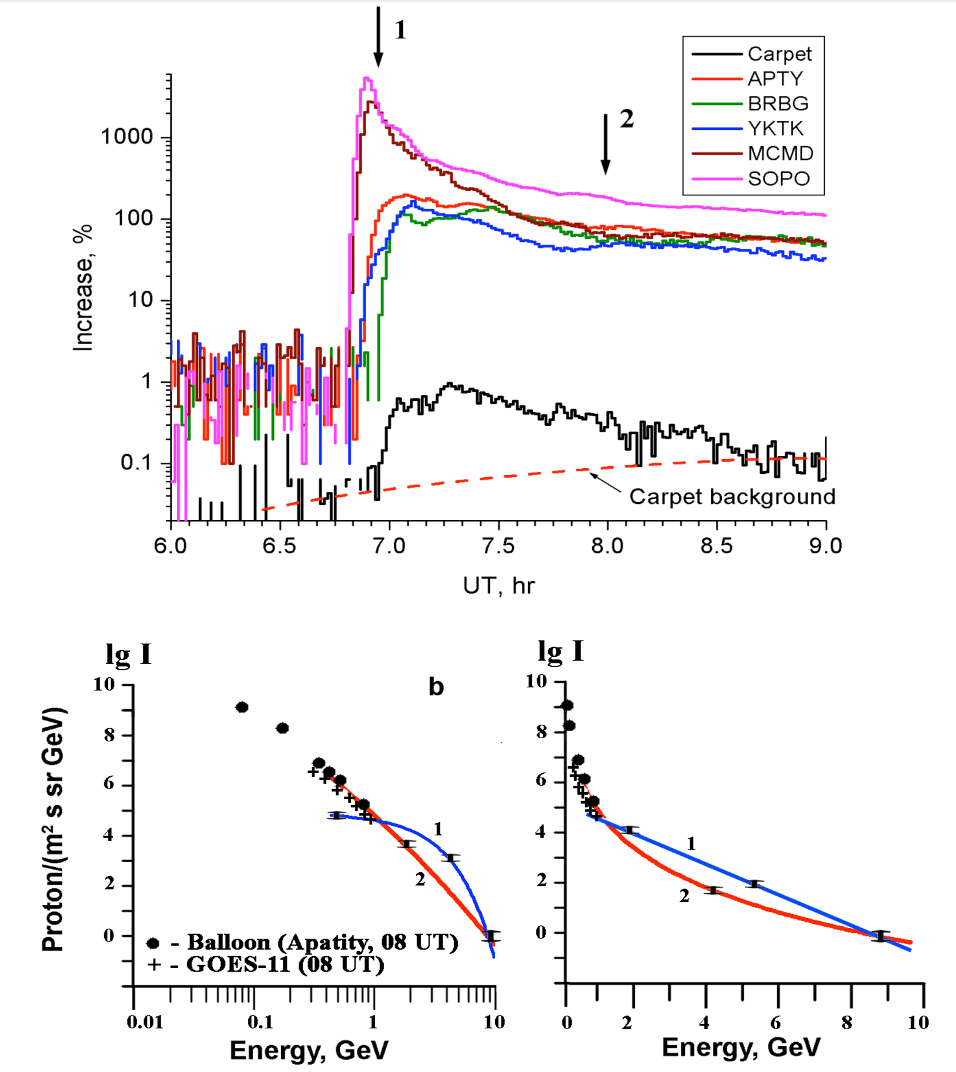


The super GLE 69, 20 January 2005, was the greatest event since 23 February, 1956. The parent solar flare 2B/X7.1, N14, W61.

Figure shows increase profiles as registered by the neutron monitors at a number of NM stations. Data of 36 NM stations were used in the modeling analysis

Quality of modeling can be seen at comparison of observed (blue line) and modeled (red points) responses at a number of neutron monitor stations

GLE 20.01.2005



Increase profiles as registered by a number of NM stations and EAS array "Carpet"(Baksan, North Caucasus)

The spectrum derived in moment (1) when the prompt component was dominated is exponential in energy: $J = 1.5\times10^{5}\exp(-E/0.92)$, and spectrum of delayed component (2) has a power-law form: $J = 7.5\times10^{4}\,E^{-4.9}$.

Points are direct TOM solar proton data of GOES-11 and balloons

(Vashenyuk et al.2006, 2007, Perez-Peraza et al., 2007)

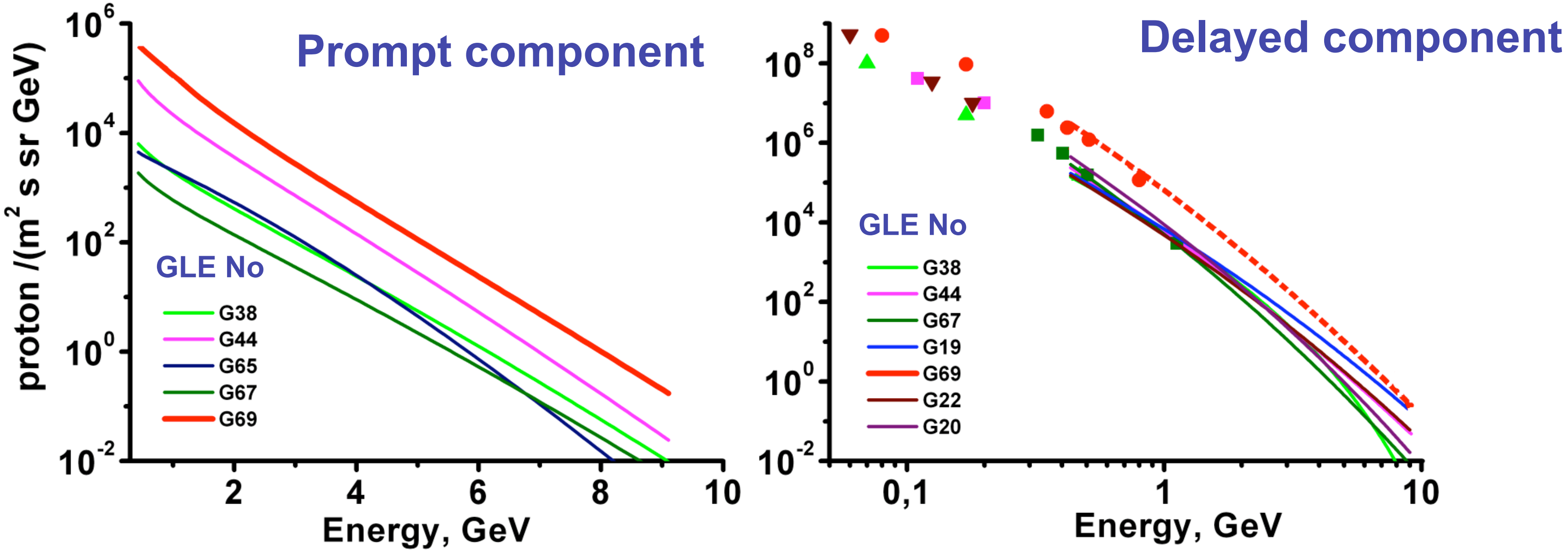
Results of modeling analysis of 32 major GLEs showing existence of two RSP components

Spectrum of prompt component: $J = J_0 \exp(E/E_0)$ E [GeV]

Spectrum of delayed component: $J = J_1 E^{-\gamma}$ J_0, J_1 $[m^2 \text{ s st GeV}]^{-1}$

No	GLE No	Date	Type II onset	Importance	Heliocoordinates	J_0 (PC)	E_0 (PC)	J_1 (DC)	$-\gamma$ (DC)
1	05	23.02.1956	03.36*	3	N23 W80	$7.4 \cdot 10^5$	1.37	$5.5 \cdot 10^1$	4.6
2	08	04.05.1960	10.17	3+	N13 W90	$2.7 \cdot 10^5$	0.65	$1.6 \cdot 10^3$	4.2*
3	10	12.11.1960	13.26	3+	N27 W04	-	-	$7.5 \cdot 10^3$	4.1**
4	11	15.11.1960	02.22	3	N25 W35	-	-	$1.0 \cdot 10^5$	5.3
5	13	18.07.1961	09.47	3+	S07 W59	$5.2 \cdot 10^3$	0.52	$3.6 \cdot 10^3$	6.0
6	16	28.01.1968	07.55	-	N22 W154	$1.4 \cdot 10^4$	0.58	$6.7 \cdot 10^3$	4.7
7	19	18.11.1968	10.26	1B	N21 W87	$1.2 \cdot 10^4$	0.58	$2.6 \cdot 10^3$	5.5
8	22	24.01.1971	23.16	3B	N19 W49	$3.4 \cdot 10^4$	0.45	$8.7 \cdot 10^3$	5.8
9	25	07.08.1972	15.19	3B	N14 W37	$6.6 \cdot 10^2$	1.23	$4.3 \cdot 10^2$	5.0
10	29	24.09.1977	05.55	-	N10 W120	$6.5 \cdot 10^2$	1.14	$9.3 \cdot 10^2$	3.2
11	30	22.11.1977	-	2B	N24 W40	$1.5 \cdot 10^4$	0.77	$1.1 \cdot 10^4$	4.7
12	31	07.05.1978	03.27	1B/2	N23 W82	$3.5 \cdot 10^4$	1.11	$1.3 \cdot 10^4$	4.0
13	32	23.09.1978	09.58	3B/X1	N35 W50	-	-	$7.0 \cdot 10^2$	4.7
14	38	07.12.1982	23.44	1B/X2.8	S19 W86	$5.7 \cdot 10^3$	0.65	$7.2 \cdot 10^3$	4.5
24	52	15.06.1991	08.14	3B/X12.5	N36 W70	-	-	$5.8 \cdot 10^3$	4.6
25	55	06.11.1997	11.53	2B/X9.4	S18 W63	$8.3 \cdot 10^3$	0.92	$8.2 \cdot 10^3$	4.6
26	59	14.07.2000	10.19	3B/X5.7	N22 W07	$3.3 \cdot 10^5$	0.50	$5.0 \cdot 10^4$	5.4
27	60	15.04.2001	13.48	2B/X14.4	S20 W85	$1.3 \cdot 10^5$	0.62	$3.5 \cdot 10^4$	5.3
28	61	18.04.2001	02.17	-	- W120	$2.5 \cdot 10^4$	0.52	$1.2 \cdot 10^3$	3.6
29	65	28.10.2003	11.02	4B/X17.2	S16 E08	$1.2 \cdot 10^4$	0.60	$1.5 \cdot 10^4$	4.4
30	67	02.11.2003	17.14	2B/X8.3	S14 W56	$4.6 \cdot 10^4$	0.51	$9.7 \cdot 10^3$	6.3
31	69	20.01.2005	06.44	2B/X7.1	N14 W61	$2.5 \cdot 10^6$	0.49	$7.2 \cdot 10^4$	5.6
32	70	13.12.2006	02:51	2/3.4	S06 W24	$3.5 \cdot 10^4$	0.59	$4.3 \cdot 10^4$	5.7

Spectra of prompt and delayed solar proton components derived from neutron monitor data for a number of GLEs

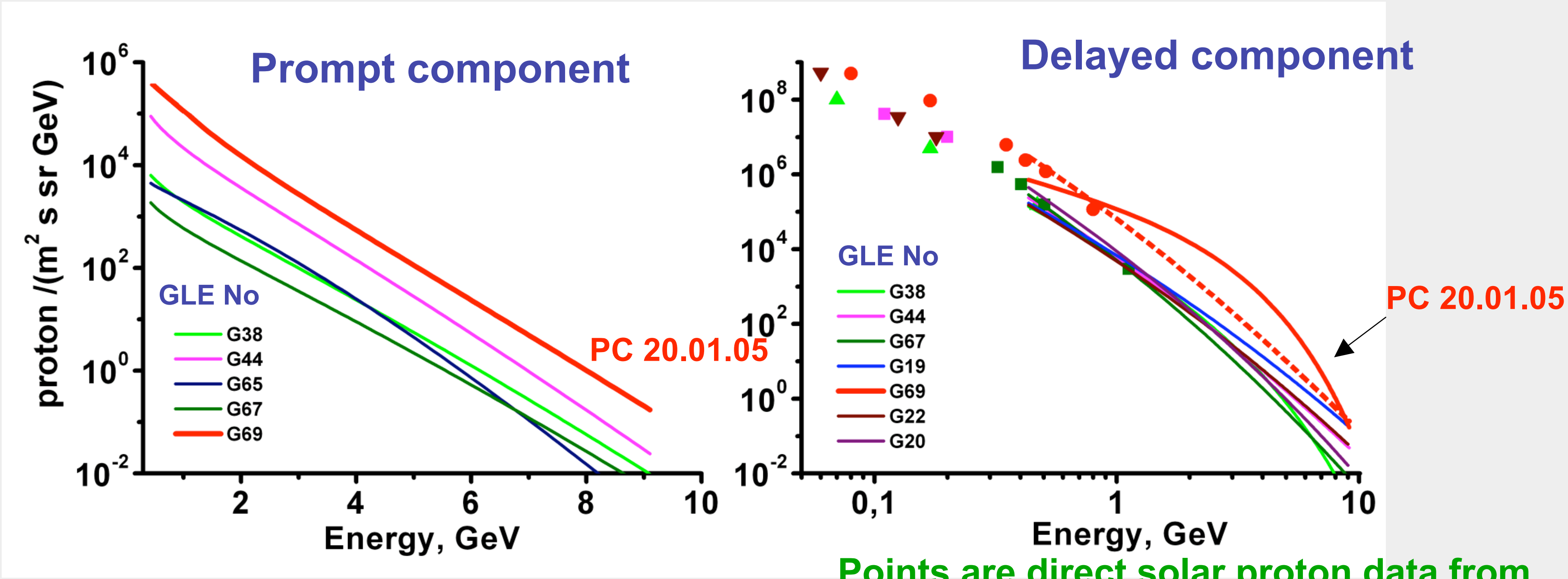


Spectra of the prompt component as a rule have exponential dependence upon energy

Points are direct solar proton data from spacecrafts and balloons

Spectra of the delayed component have close to the power law dependence upon energy

Spectra of prompt and delayed solar proton components derived from neutron monitor data for a number of GLEs

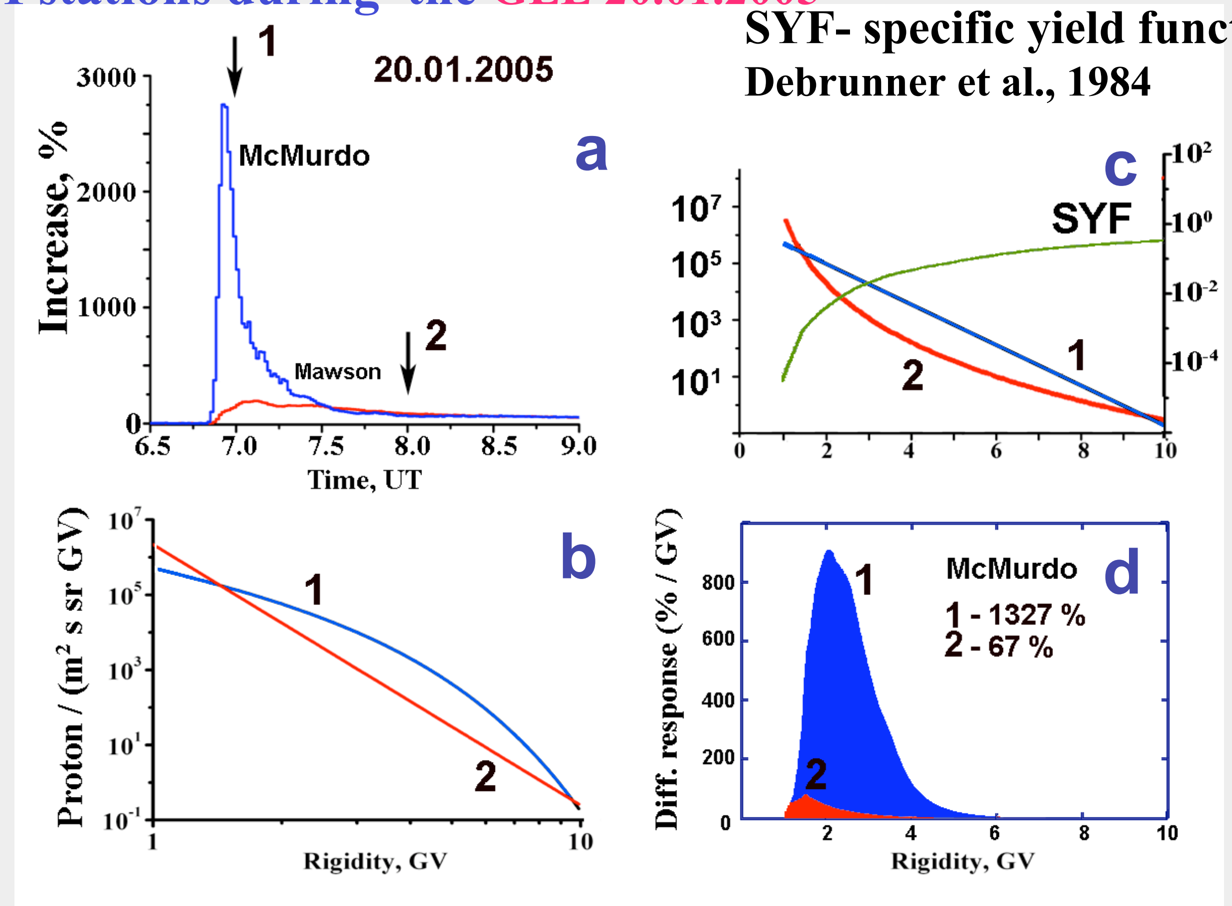


Points are direct solar proton data from spacecrafts and balloons

Spectra of the prompt component as a rule have exponential dependence upon energy

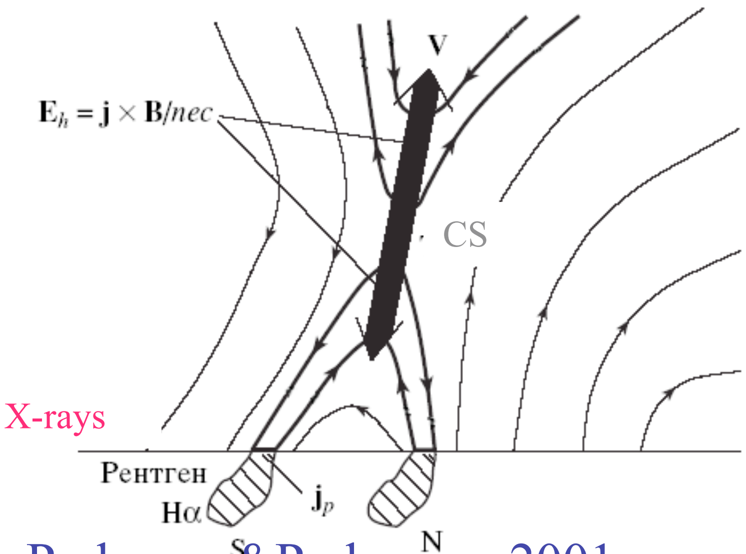
Spectra of the delayed component have close to the power law dependence upon energy

Exponential spectrum of the prompt component was a cause of the giant increase effect at McMurdo neutron monitor and power law spectrum of delayed component produced rather moderate effect at Mawson and other NM stations during the GLE 20.01.2005

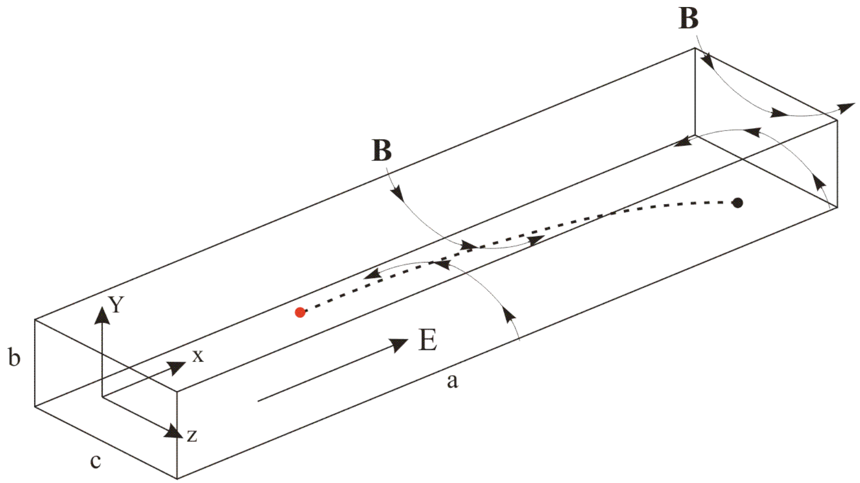


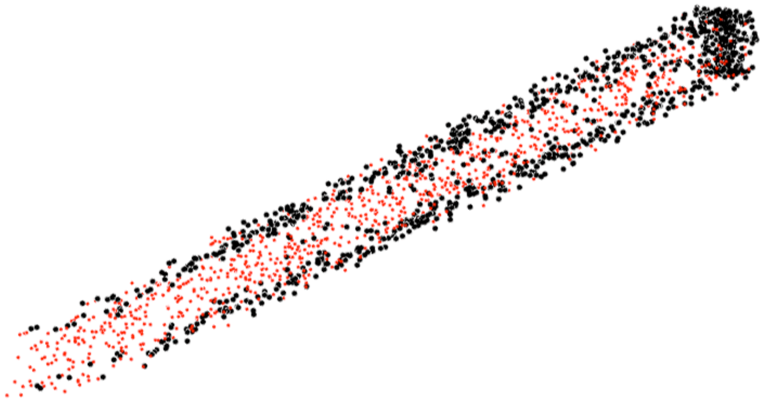
Increase profiles at the McMurdo and Mawson neutron monitors (a), rigidity spectra derived at the moments 07:00 (1) and 08:00 (2) UT (b), SYF and spectra 1 and 2 (c); differential responses (d) of the McMurdo neutron monitor to the exponential spectrum at the moment 1 (blue shading) and to the power-law spectrum at the moment 2 (red shading).

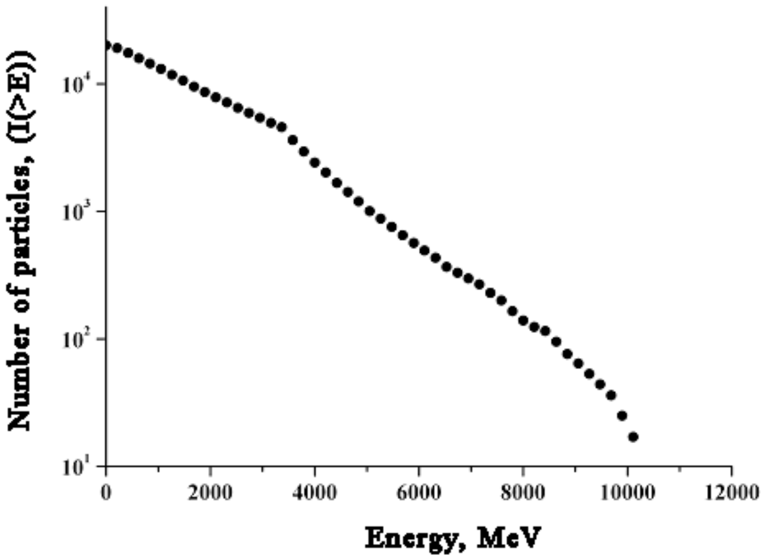
Simulation of Prompt Component formation in a reconnection current sheet
(Bulanov, Sasarov, 1975, Perez-Peraza, Vashenyuk et al, 1992, Balabin et al., 2005)



Podgorny&Podgorny, 2001



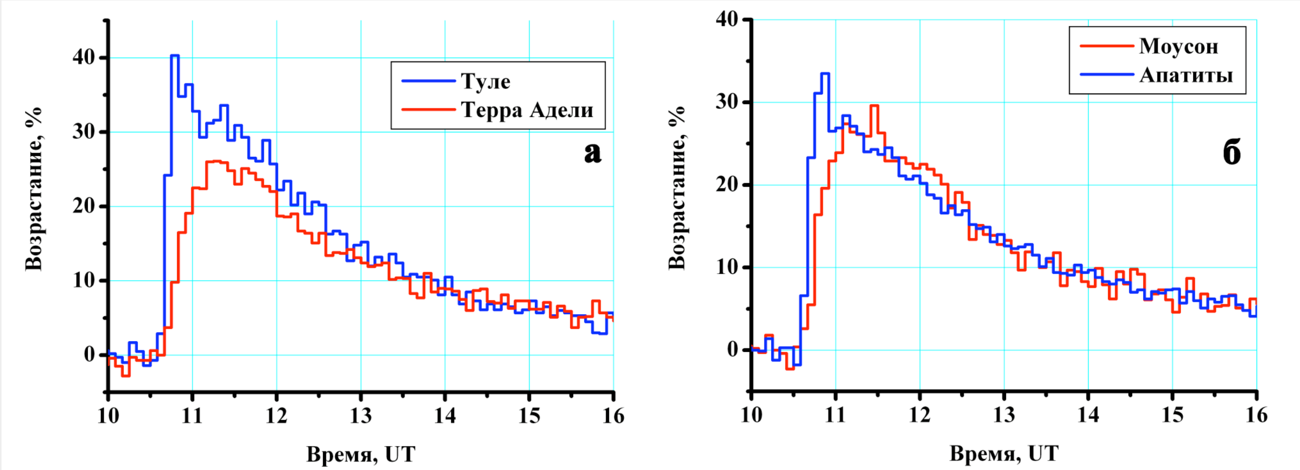




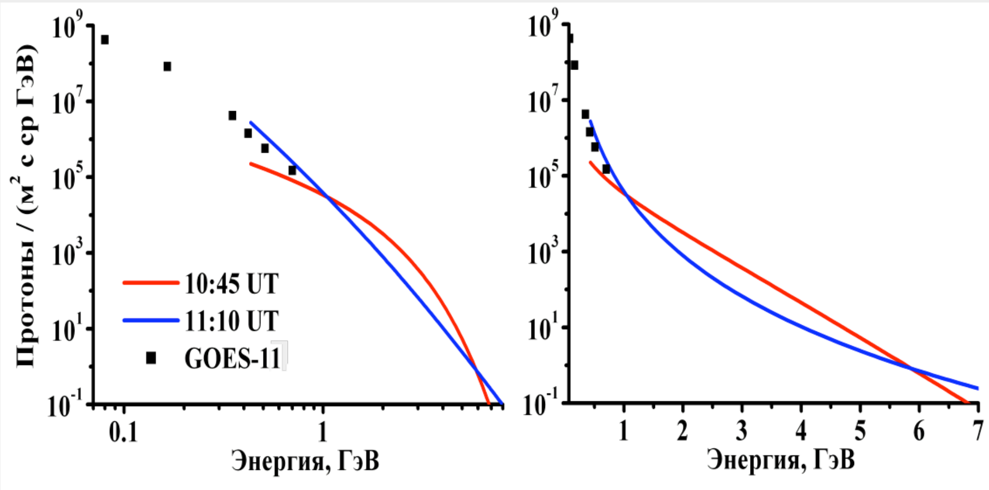
Resulting proton spectrum has nearly exponential form

Bastille day GLE 14.07.2000

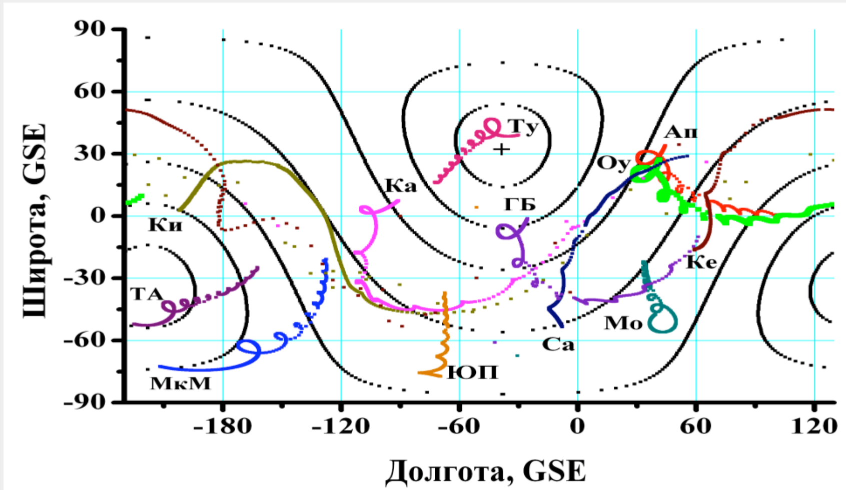
Increase profiles at a number of NM stations



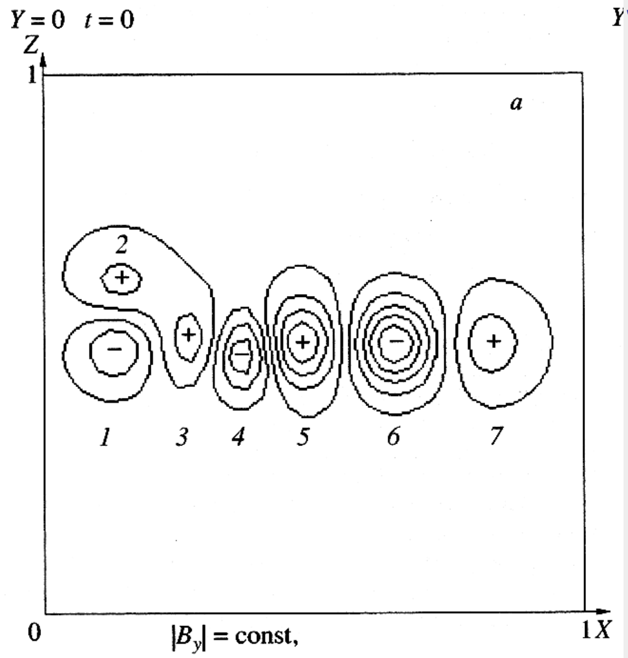
Derived relativistic solar proton spectra: red is PC, blue is DC

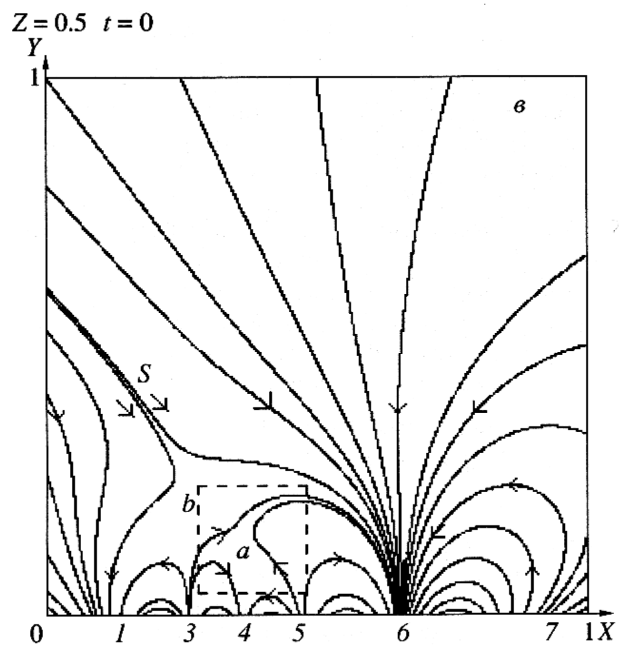


Asymptotic direction map for NM stations



Spectrum of accelerated solar proton simulation in the Bastille day GLE. (Podgorny I.M. at al., 2009)

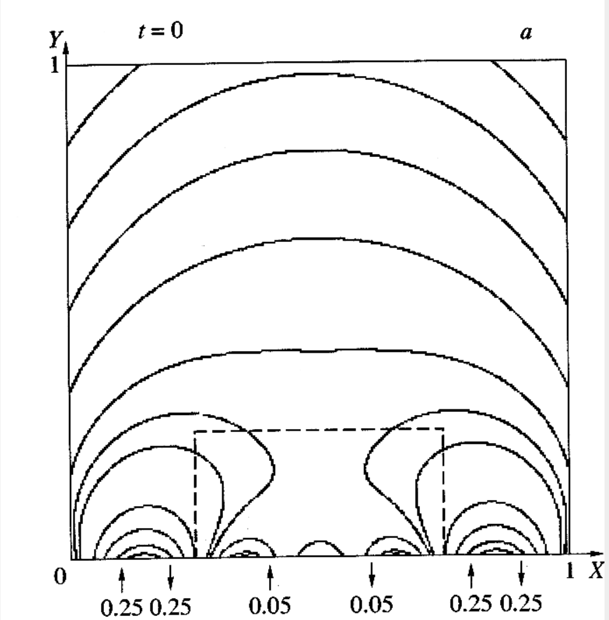


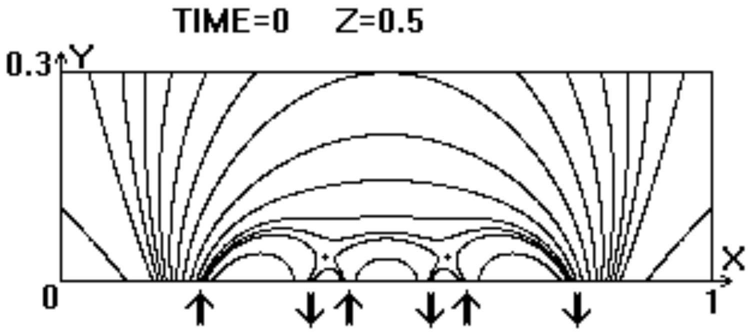


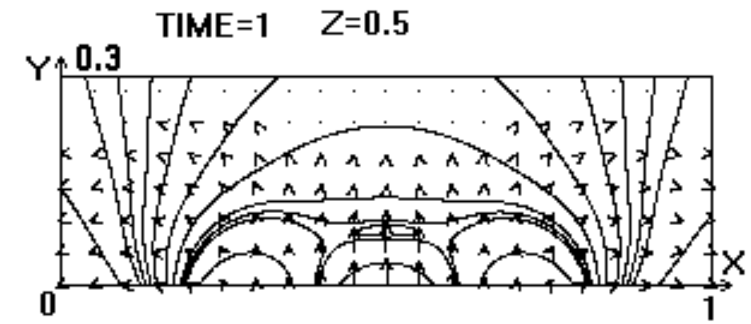
Approximation of the magnetic field in a spot group (on Mt Wilson obs. data)

MHD equation system for compressible plasma is solved to obtain a magnetic configuration in the corona above an active region.

In the modeled configuration of the magnetic field a number of current sheets can be seen. A reconnection can arise in these sheets and protons of surrounding plasma will be accelerated by an electric field in the reconnection area



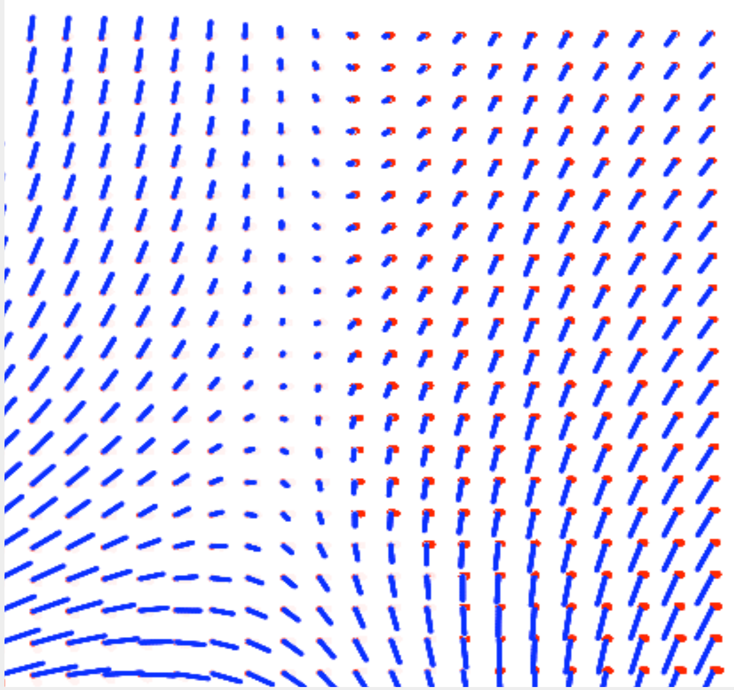




According to observations, before the flare an absorption of a compact positive magnetic flow on the photosphere by a negative flow has occurred.

This process was simulated by the linear reduction of the dipole moments of 3 and 4 magnetic dipoles. At the certain speed of decrease of these moments a formation of the horizontal current sheet and generation of an electric field proceeds.

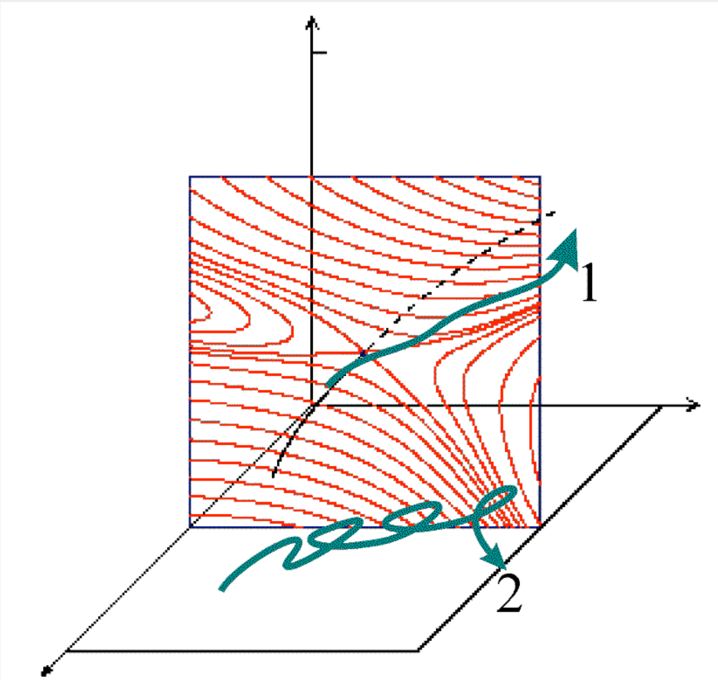
Thus, in a cube with an edge of 260 000 kms the three-dimensional grid (41 points on each side) is given. In each cell the meanings of B and E are determined. The fixed configuration of fields, corresponds to a case of the arisen current sheet.



A distribution of fields in the model. Vectors are shown by red (E) and blue (B) in the acceleration volume (section of the central area).

$$\vec{E} \sim \vec{V} \times \vec{B}$$

By the casual image sets 6 parameters of a particle: its coordinates and components of a vector of speed T ≈ 1000 000 K.

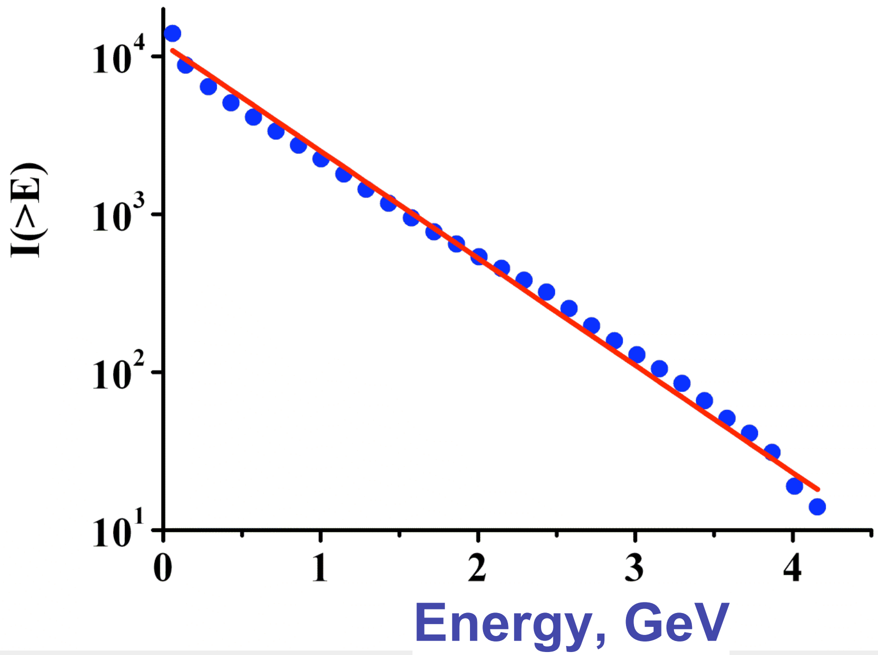


The equation of movement of a particle is solved by a Runge-Kutta method 4-5 order.

The calculations stop after getting by a particle ofa border of cubic area, or upon termination of time T_0.

Energy gain: $dW = e \cdot \vec{E} \cdot \vec{ds}$

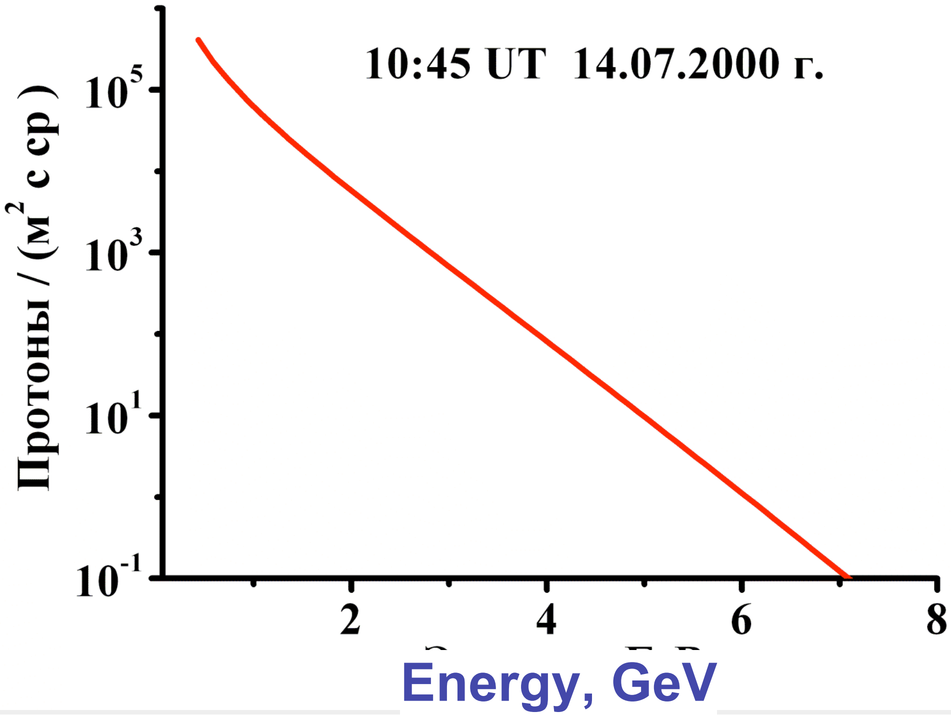
$T_0 \approx$ 1-2 s was estimated from some thousands trajectories



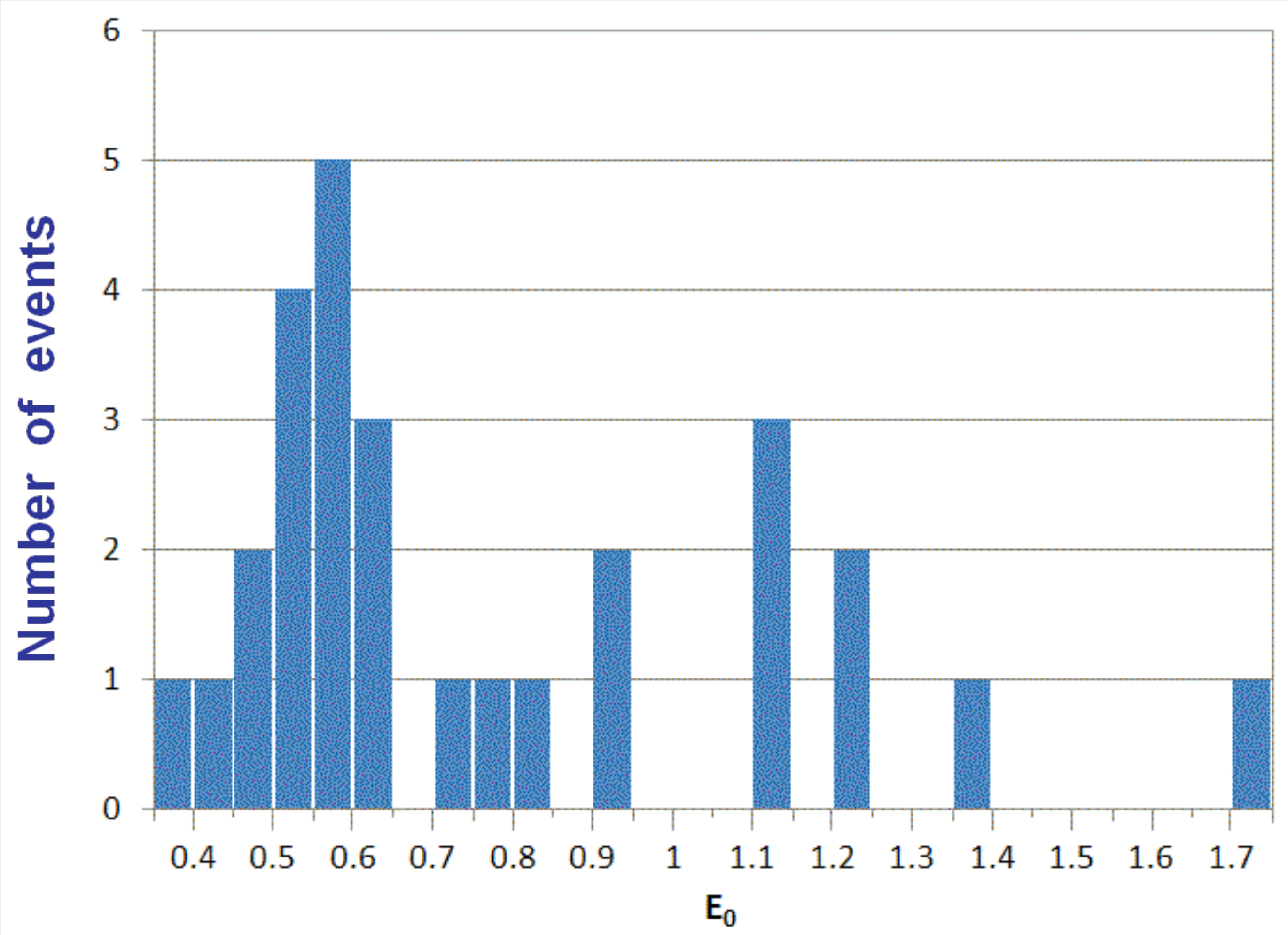
The spectrum obtained by simulations (points):
$I(>E) \sim \exp(-E/E_0)$, where E_0 = 0.59 GeV

Result of solving a least square task on the data of neutron monitors (red line)
$I(>E) \sim \exp(-E/E_0)$,
where E_0 = 0.55 GeV

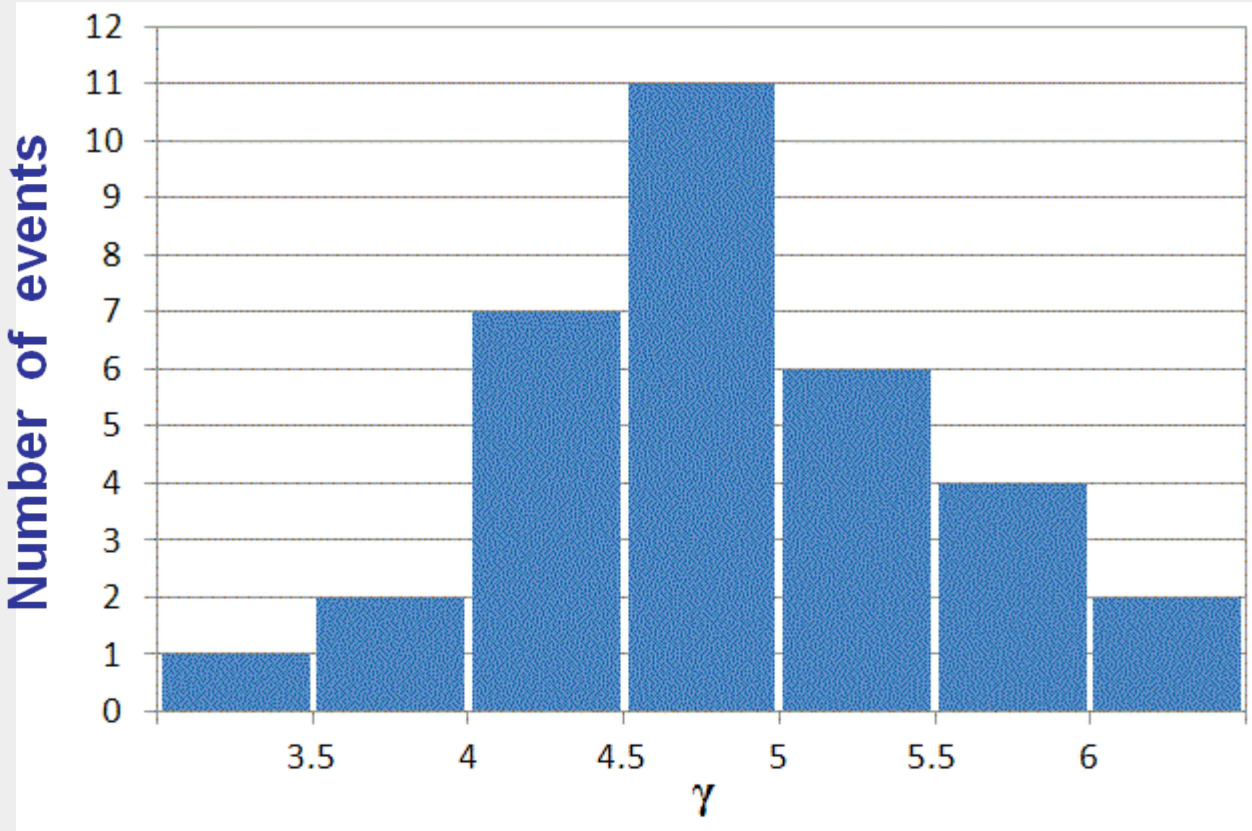
Fitting of the simulated and experimental spectra require the inflow plasma speed $V \sim 10^5$ m/s. The modeling also give the acceleration time of order of seconds



Distribution of E_0



Distribution of gamma



Possible generation mechanisms for the delayed component

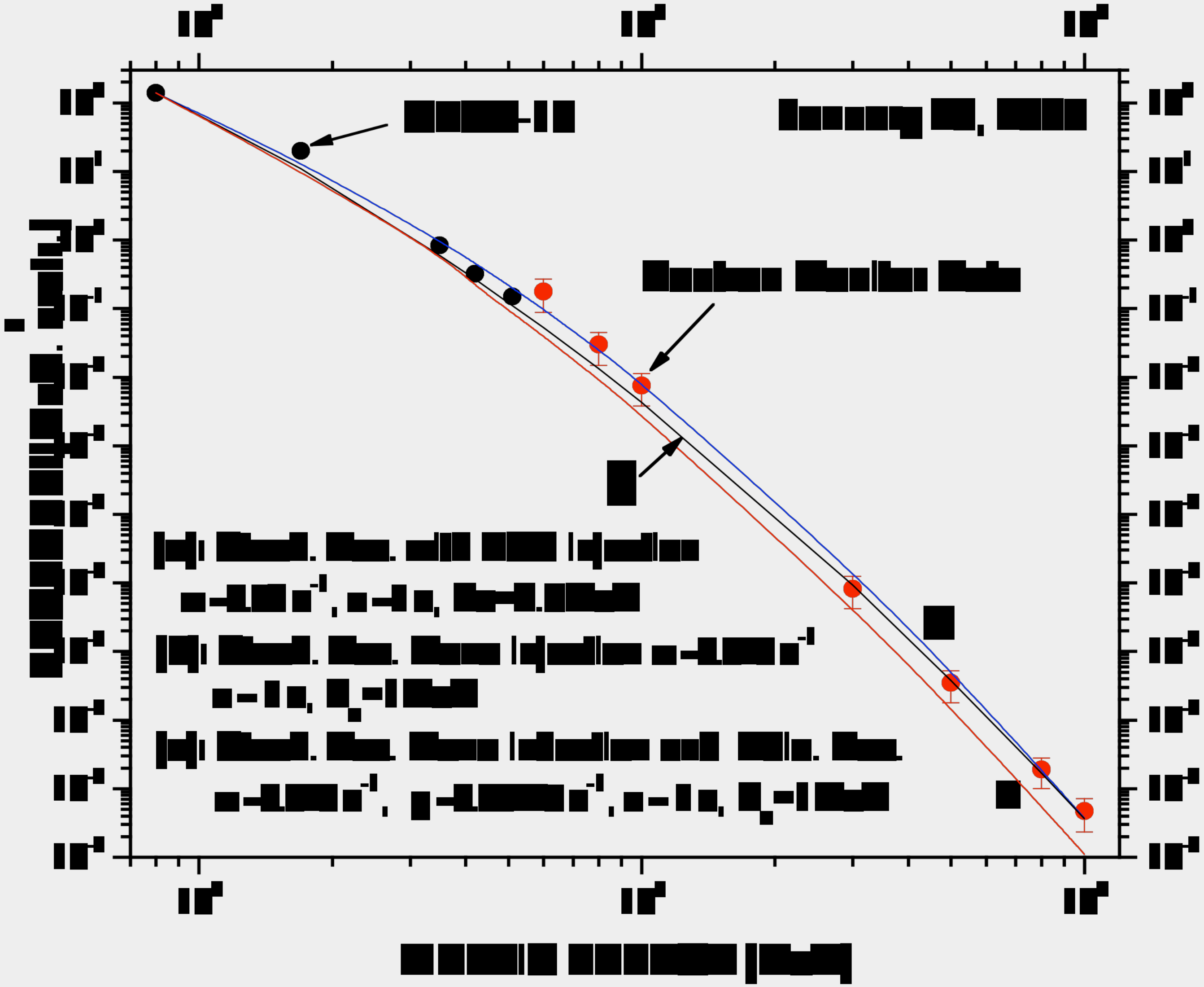
The transport equation describing the evolution of energetic particles in the energy phase-space can be expressed as generalized Fokker-Plank equation

$$\frac{\partial N(E,t)}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}\left[D(E)N(E,t)\right] - \frac{\partial}{\partial E}\left[A(E)N(E,t)\right] - \frac{N(E,t)}{\tau(E,t)} + Q(E,t)$$

Gallegs-Cruz and Perez-Peraza, (1995, Ap.J.446, 400) derived analytical solution of this equation (stationary and time-dependent ones) on basis of WKBJ method. On base of this solution they obtained an analytical expression for an energetic spectrum of protons accelerated by a specific kinds of MHD turbulences in conditions of lower corona. We tried to compare the derived spectra of DC with calculated after above theoretical results: Perez-Peraza et al., JASR,2006,38, 418,

Perez-Peraza J., Vashenyuk E. V., Miroshnichenko L. I., Balabin Yu. V., and Gallegos-Cruz A. IMPULSIVE, STOCHASTIC, AND SHOCK WAVE ACCELERATION OF RELATIVISTIC PROTONS IN LARGE SOLAR EVENTS OF 1989 SEPTEMBER 29, 2000 JULY 14, 2003 OCTOBER 28, AND 2005 JANUARY 20 // Ap. J. 2009, 695, 865.

Spectral form of the particle population accelerated by the stohastic mechanism has a close to the power law form



Perez-Peraza et al., JASR, 41,947, 2008.

Shock acceleration

Diffusive shock acceleration (first-order Fermi acceleration): charged particles stream into magnetic perturbations in the post-shock region, reflect, and are scattered back across the shock by the pre-shock Alfvén waves (Ellison, Ramaty, 1985, Berezhko et al., 2005)

$dE/dt \propto v_c/v$, where E and v are energy and velocity of the particle and v_c is velocity of magnetic compression.

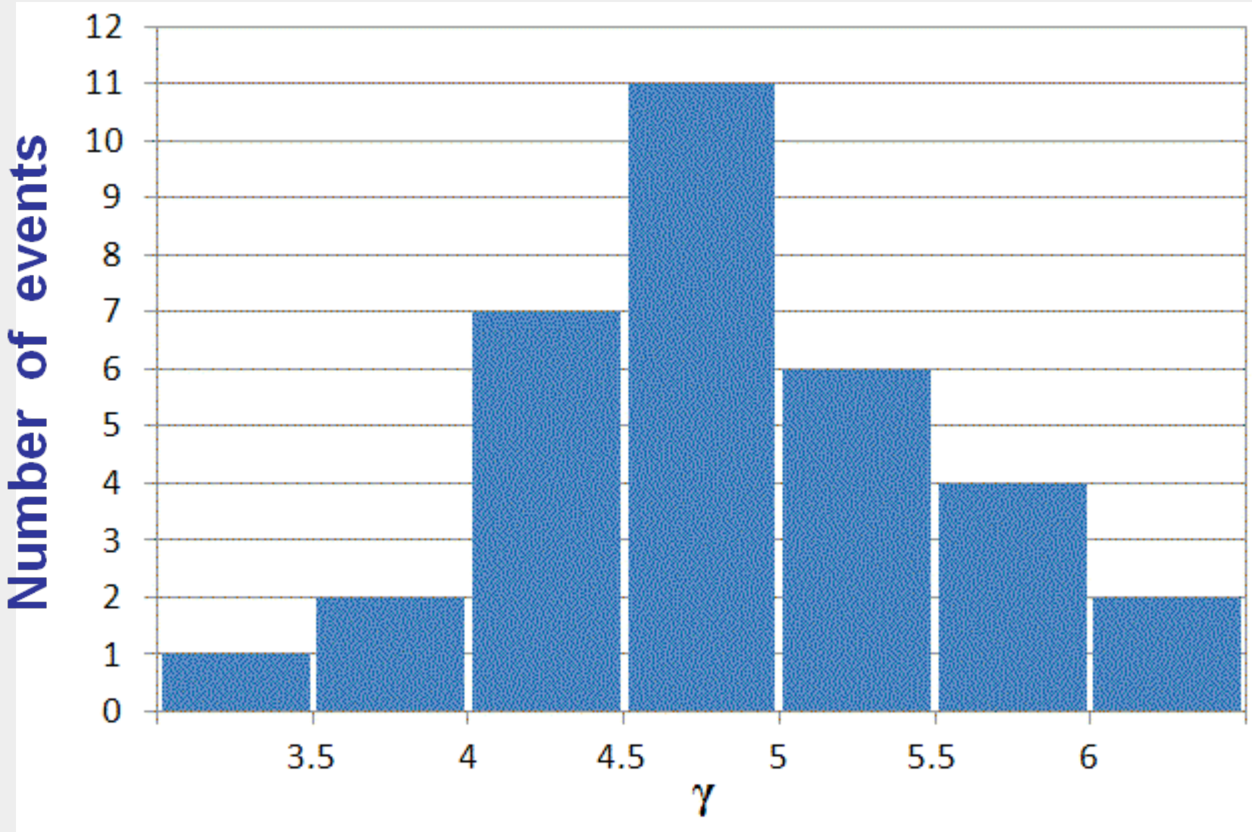
Spectral form:

$$\frac{dJ}{dE} \propto (E^2 + 2Em_0c^2)^{-(\sigma+2)/(\sigma-1)}$$

$\sigma = u_1/u_2$ is the compression ratio; spectral index = $(\sigma+2)/(\sigma-1)$

For $\sigma=2$, $\gamma=4$, $\sigma=3$, $\gamma=2.5$

Distribution of gamma



RESULTS

The modeling analysis of 35 large GLEs occurred in the period 1956-2006 on the data of the worldwide neutron monitors revealed two distinct RSP populations (components):

1. Prompt Component **(PC): the** early collimated impulse-like intensity increase with exponential energy spectrum,

2. Delayed component **(DC):** the late quasi-isotropic gradual increase with a softer energy spectrum of the power law form.

3. The exponential spectrum may be an evidence of the acceleration by electric fields arising in the reconnecting current sheets in the corona. The possible source of delayed component particles can be stochastic acceleration at the MHD turbulence in expanding flare plasma. Another possible source of DC can be acceleration by a coronal shock

For the generation of PC one can suggest a process of magnetic reconnection in the lower corona which precedes the general energy release in a flare, CME eruption and a coronal shock.

Such consequence of processes in a flare related disturbance was described in (Manoharan and Kundu, 2003, Ap.J., 592, 597, 2003).

DC is generated later, during a CME eruption and a coronal shock development

Thank You

for

Your Attention!