Characteristics of relativistic solar cosmic rays in large ground level events

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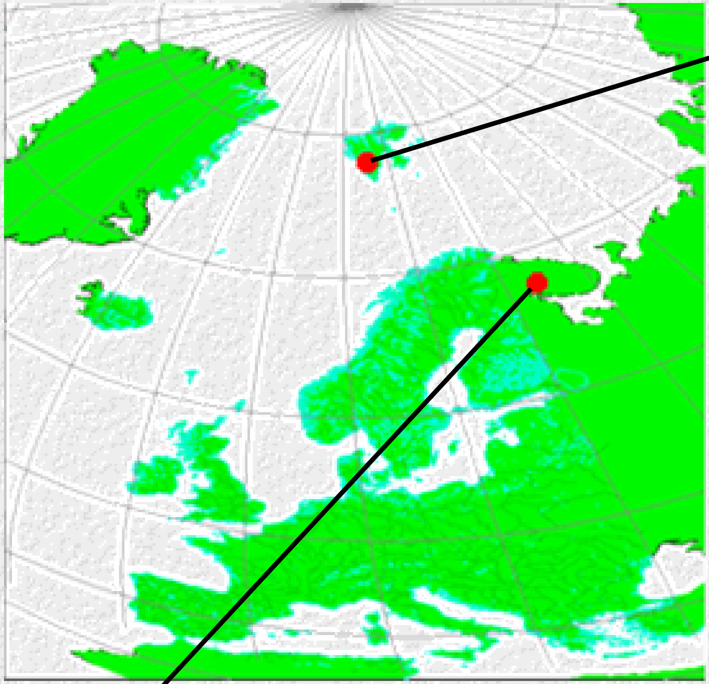
Abstract

By modeling analysis characteristics of relativistic solar cosmic rays (SCR) in 14 largest GLEs has been performed. Using a modeling technique, the parameters of relativistic solar protons (RSP) were obtained from ground-based observations by neutron monitors (NM) and muon detectors. The two particle populations (components), prompt (PC) with high anisotropy and exponential energy spectrum and delayed one (DC) with moderate anisotropy and power-law spectrum, were shown to exist in all cases. Special consideration was done of the greatest GLEs: February 23, 1956 and January 20, 2005. The prompt component was a cause of a giant pulse-like increase at a limited number of NM stations, and the DC caused a gradual increase with moderate amplitude at the most NM stations over the globe. It is argued that only exponential energy spectrum (but not power-law one), in combination with energy dependence of the NM specific yield functions, could cause such great increase effect (~5000%) in both cases.

OUTLINE

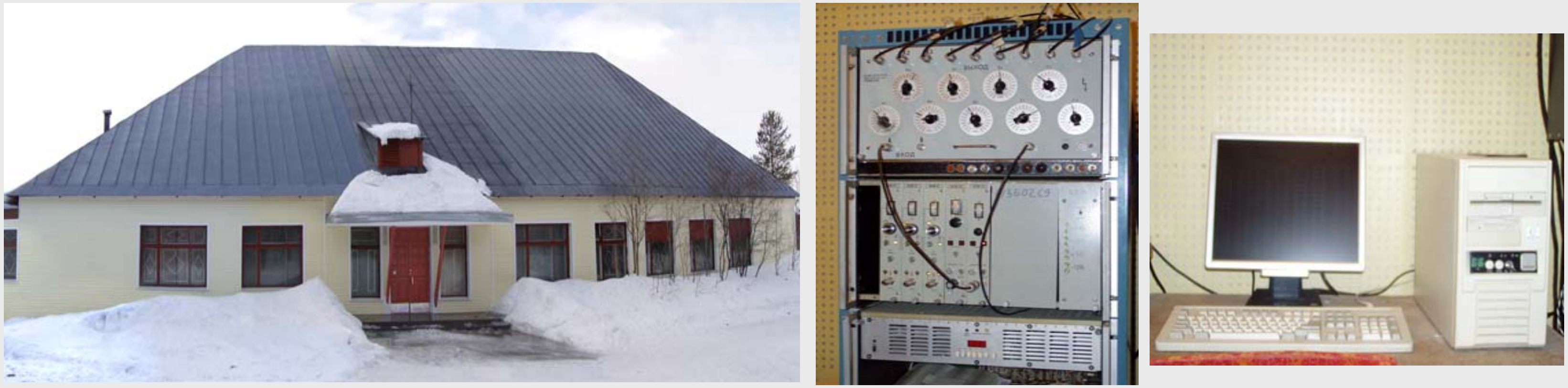
- 1. Short information about cosmic ray (CR) ground based instrumentation and neutron monitor network as a multidirectional CR spectrometer .
- 2.Details of GLE modeling technique and deriving relativistic solar proton (RSP) parameters from ground based observations
- 3. Results of GLE modeling study.
- 4. The greatest in history GLEs 23.02.1956 and 20.01.2005.
- 5. Discussion of possible effects concerning generation RSP on the Sun and interplanetary propagation.

Neutron monitors of the Polar Geophysical Institute

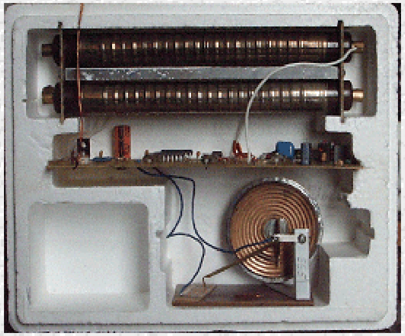


Barentsburg (78.08N 14.12E)

Apatity (67.55N 33.34E)



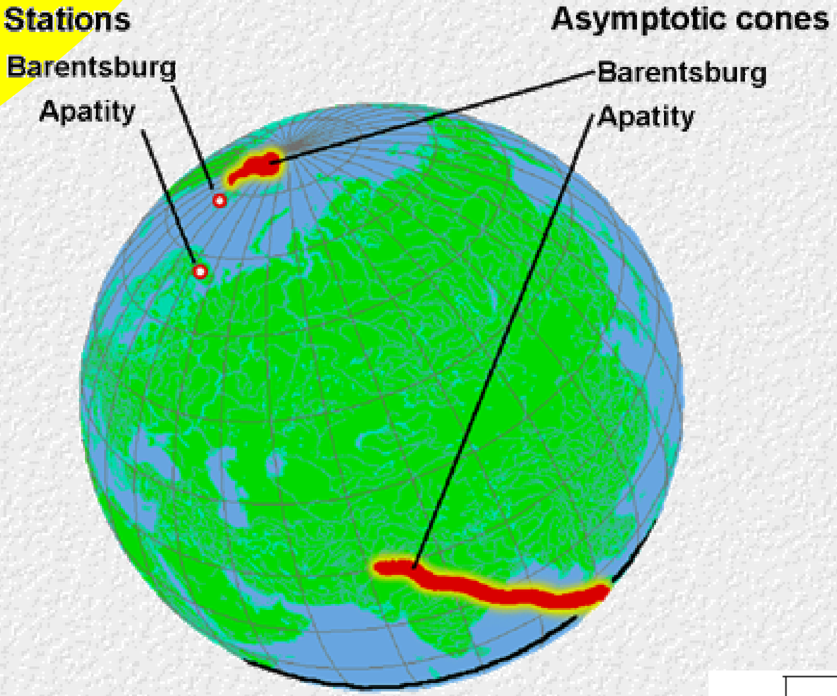
Joint cosmic ray balloon experiment of Lebedev Physical Institute and Polar Geophysical Institute in Apatity

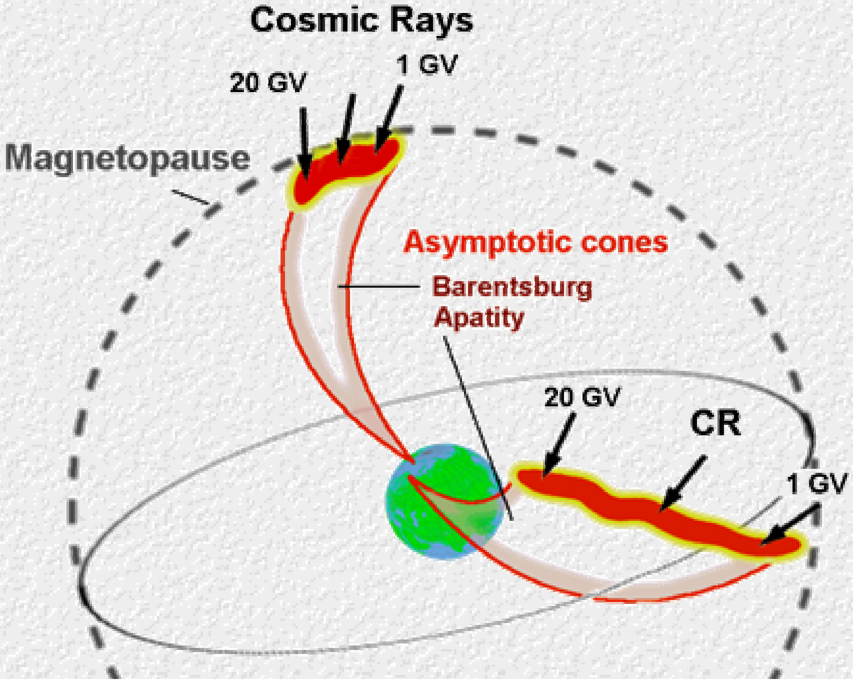


Balloon measurements allow accurate measurements of a spectrum of solar protons in the energy interval from 80-100 to 350-400 MeV (Bazilevskaya &Svirzhevskaya, 1998)

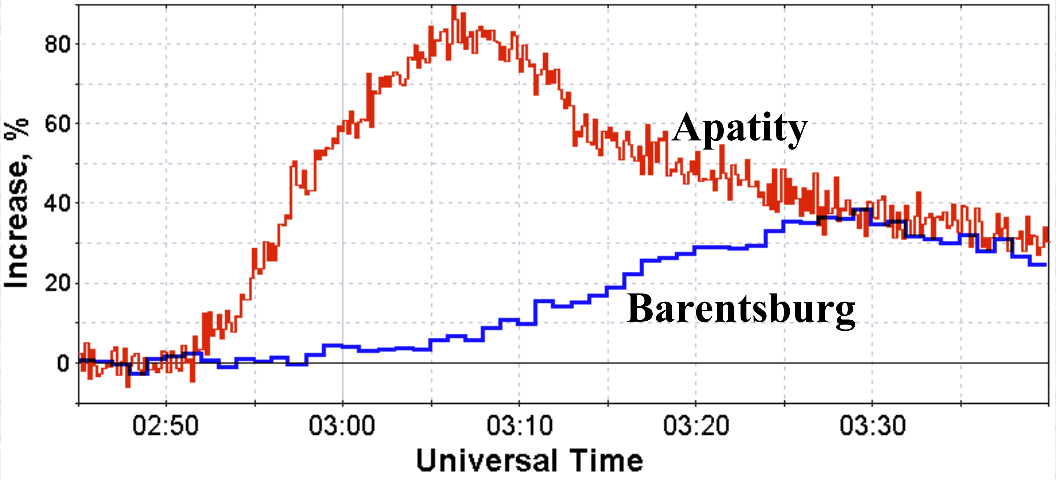
Concept of Asymptotic cone

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





Anisotropy effect during the GLE 13.12.2005



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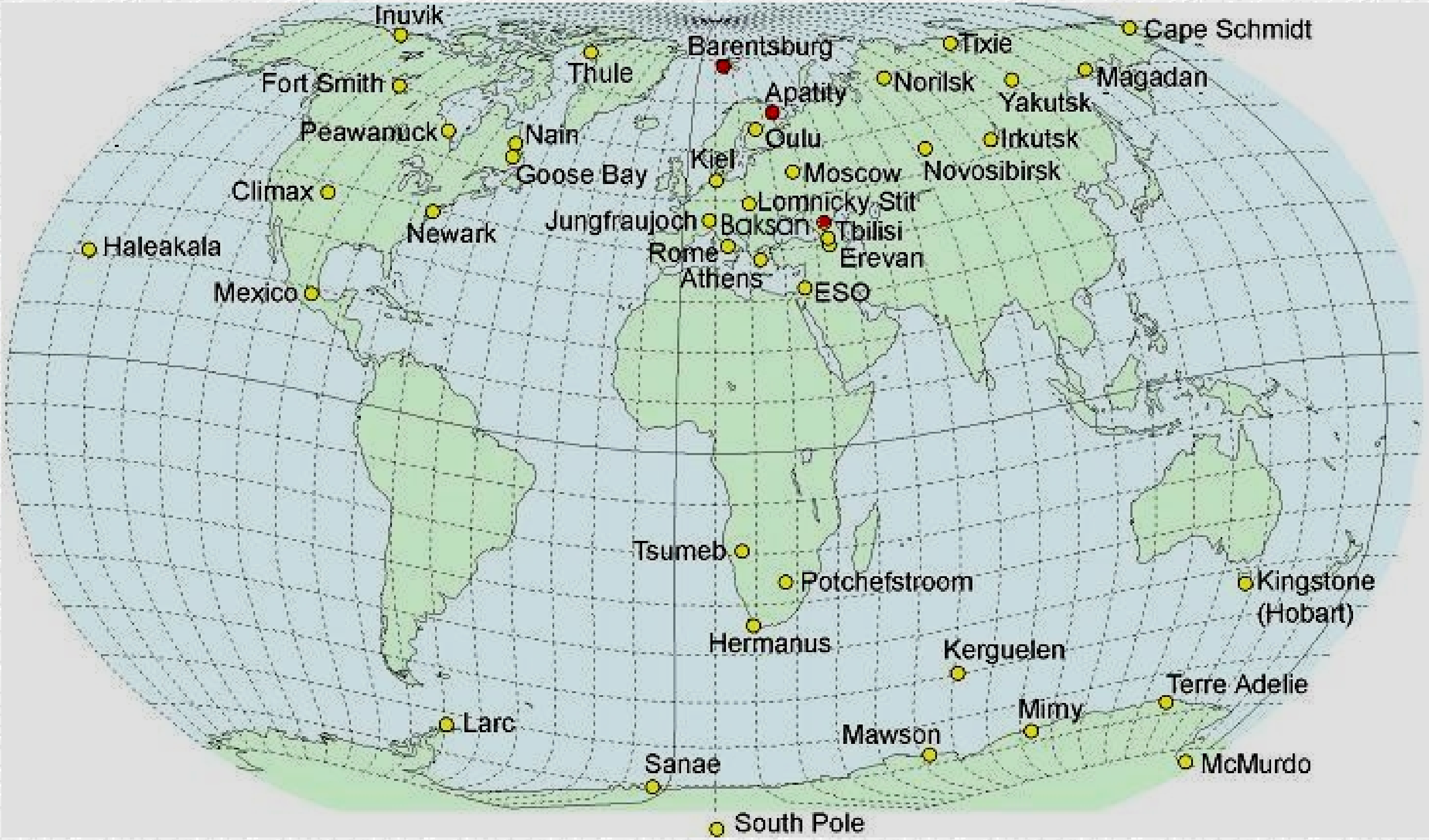
Worldwide neutron monitor network as a multidirectional cosmic ray spectrometer

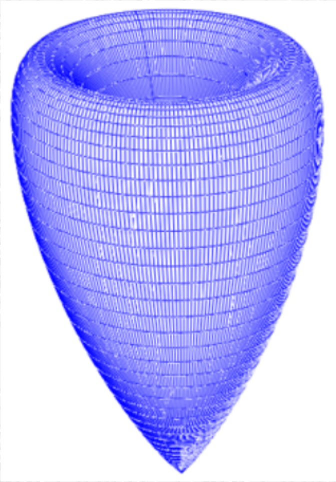


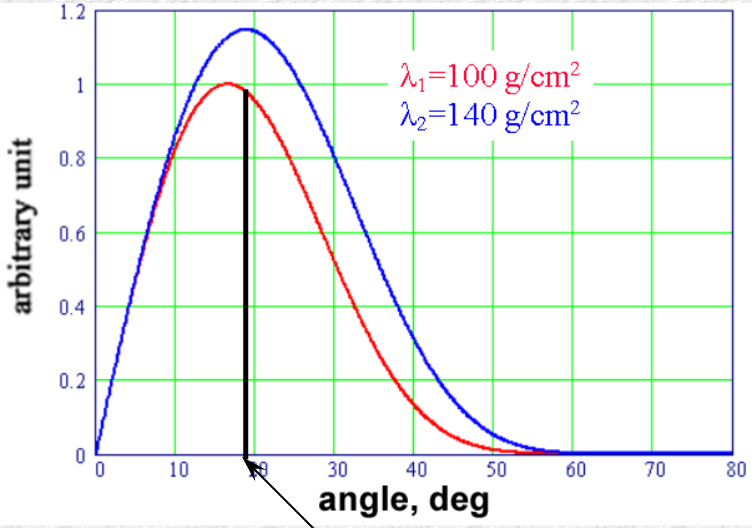
GLE modeling technique

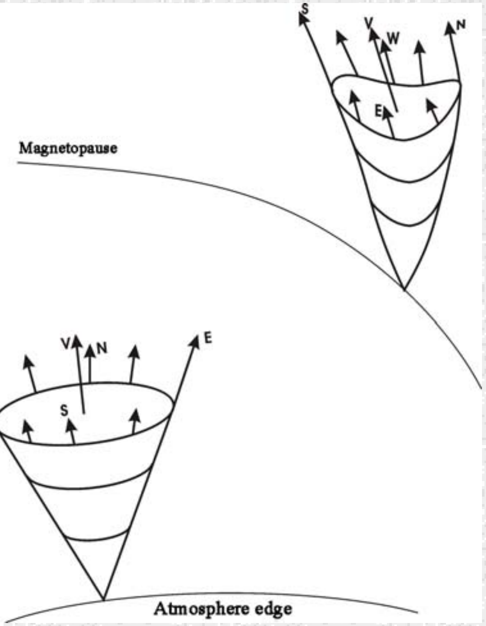
- Modeling technique of the neutron monitor response to an anisotropic solar proton flux were used by many authors:
- Smart , Shea and Tanskanen, 1971, Shea and Smart, 1982, Cramp et al., 1997, Dvornikov and Sdobnov, 1997, Belov et al., 2001, 2005, Plainaki et al., 2007.
- Our methodics of GLE modeling consists of a few steps:
- 1. Definition of asymptotic viewing cones of neutron monitor stations by particle trajectory calculation in a model magnetosphere Tsyganenko 2001 (step in rigidity 0.001 GV) and accounting of contribution of oblique incident particles on a detector
- 2. Calculation of neutron monitor responses at variable primary solar proton flux parameters
- 3. Determination by a least square procedure (optimization) primary solar proton parameters outside magnetosphere by comparison of computed neutron monitor responses with observations.

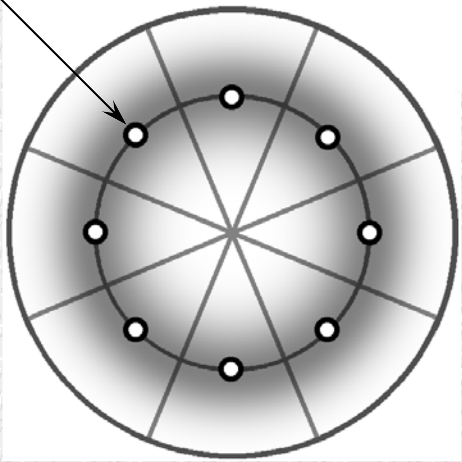
Asymptotic cone calculation: 8 inclined directions

Neutron monitor directivity for solar and galactic cosmic rays

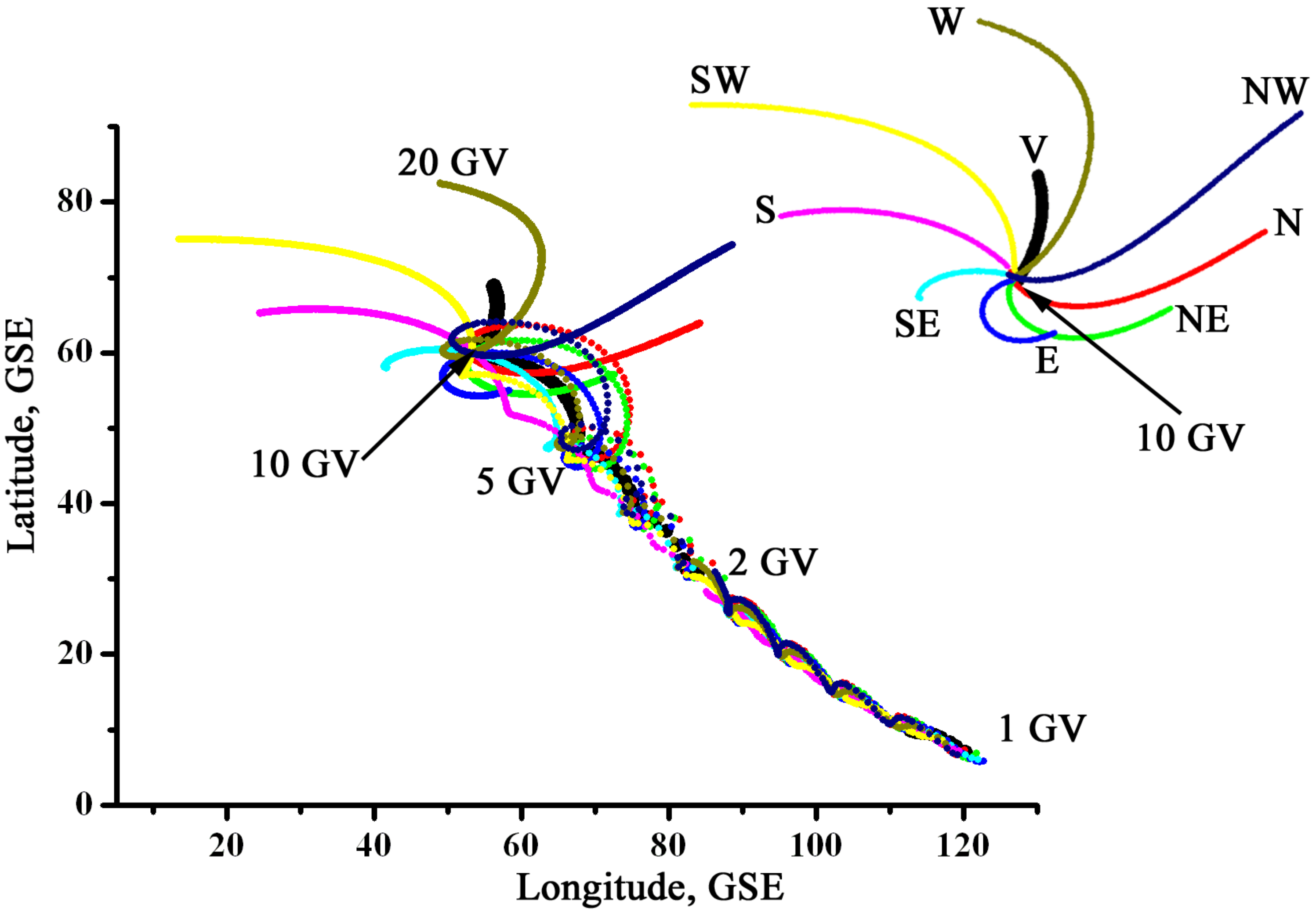








To account the contribution of oblique incident particles we calculate 8 trajectories of particles launched at zenith angle 20° and 8 azimuths



Asymptotic cones for particles launched in vertically (V) and at zenith angle 20 deg. directions: station Apatity
y

Details of modeling technique

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

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

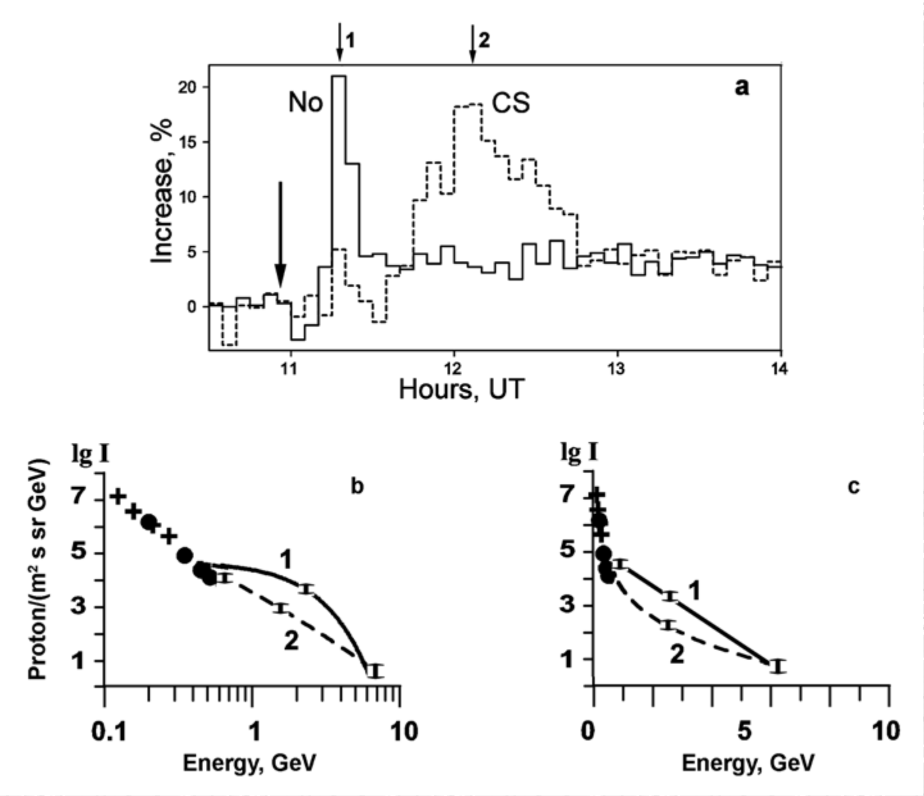
- Where $(dN/N)_J$ is percentage increase effect at a given neutron monitor *j*
- $J_{||}(R) = JoR^{-\gamma^*}$ is rigidity spectrum of RSP flux along the direction of anisotropy axis
- $\gamma^* = \gamma + \Delta\gamma \cdot (R-1)$ where Δγ is increase per 1 GV (Cramp et al., 1997)
- **S(R)** is specific yield function (Debrunner et al., 1984),
- ***θeff(R)*** is pitch angle (angle between the anisotropy axis given by **Φ;** Λ parameters
- **A(R)** = 1 for allowed and 0 for forbidden trajectories
- **$F(\theta(R)) \sim \exp(-\theta^2/C)$** is pitch-angle distribution of RSP (Shea&Smart, 1982**)**
- So **6 parameters** of anisotropic solar proton flux outside magnetosphere:
- **Φ;** Λ, **Jo,** γ, Δγ, **C** are to be determined with a solving of the ***nonlinear least square problem***
- by comparison of computed responses with observations.

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

Prompt and delayed components of relativistic solar protons (RSP)

The GLE 65: 28.10.2003

Increase profiles at NM stations Thule (Th) and Goose Bay (GB). Vertical arrow marks a probable moment of particle generation at the Sun. Numbered arrows 1 and 2 mark the moments of time when the spectra of PC and DC of RSP were derived. The data of direct solar proton measurements are sown by crosses (balloons) and blacked dots (GOES spacecrafts). prompt RSP component and the power law spectrum related to the delayed component.



Spectra of PC (1) and DC(2) in double logarithmic (b) and semi-logarithmic (c) scales. Note an exponential form of the spectrum *1* related to the spectrum 2

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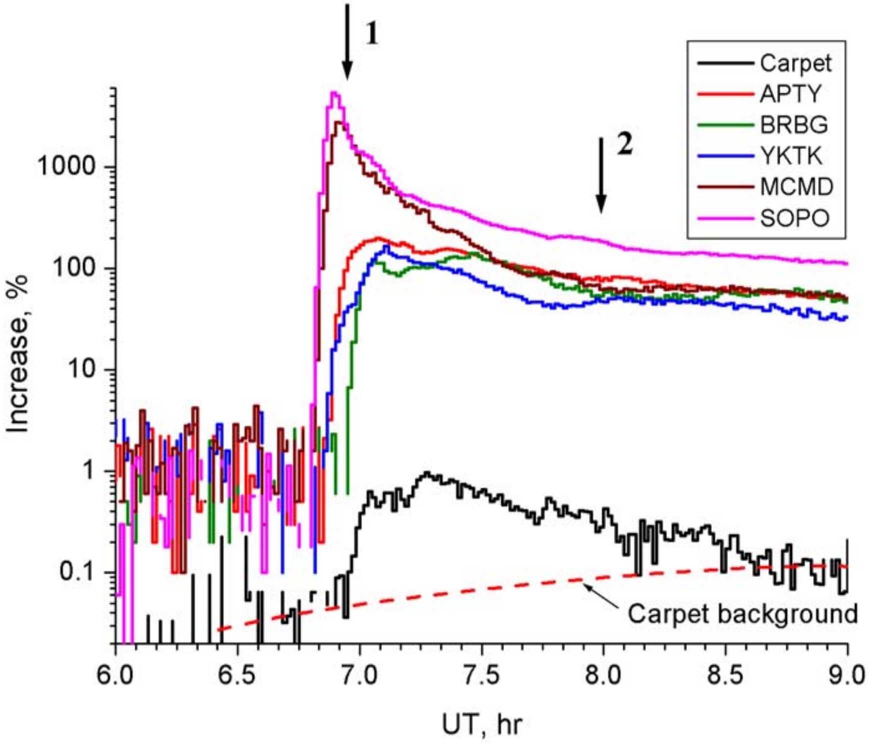
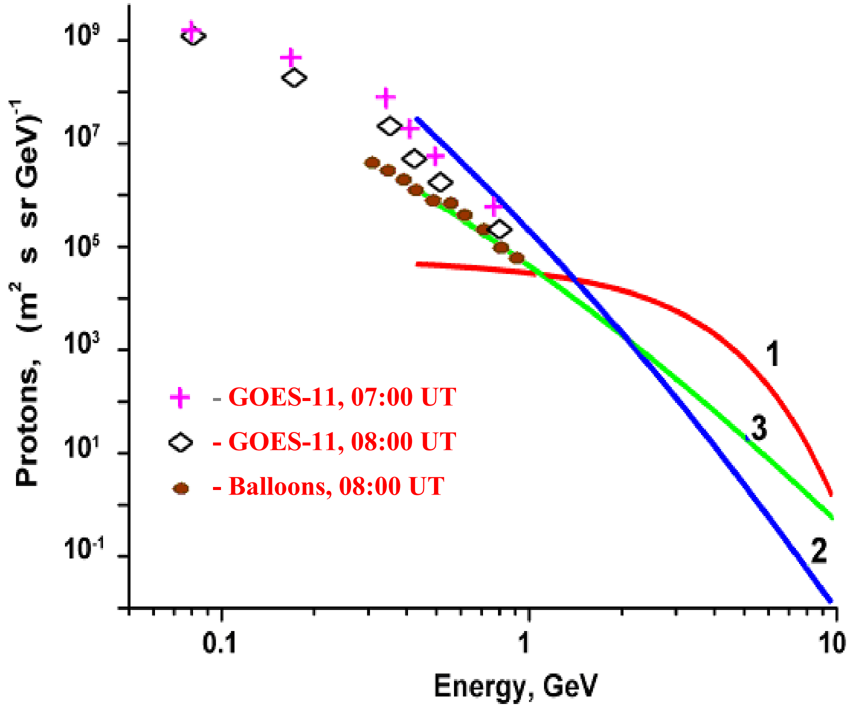
The GLE 69: 20 January 2005 modeling

- **The super GLE 69, 20 January 2005, was the greatest event since 23 February, 1956. The parent solar flare 2B/X7.1, N14, W61. The type II radio onset was reported at 06.44 UT.**

Increase profiles registered by neutron monitors: Apatity (Ap), Barentsburg (BRBG), Yakutsk (YKTK), McMurdo (MCMD), South Pole (SOPO), and EAS array Carpet.
1 and 2 are moments of time when spectra shown in the next figure were obtained

Derived energy spectra of RSP: 1a-:7.00 UT:Flux 1, 2- 7.00 UT, Flux 2,. 3- 8.00 UT. Points are direct solar proton data of GOES-11 and balloons





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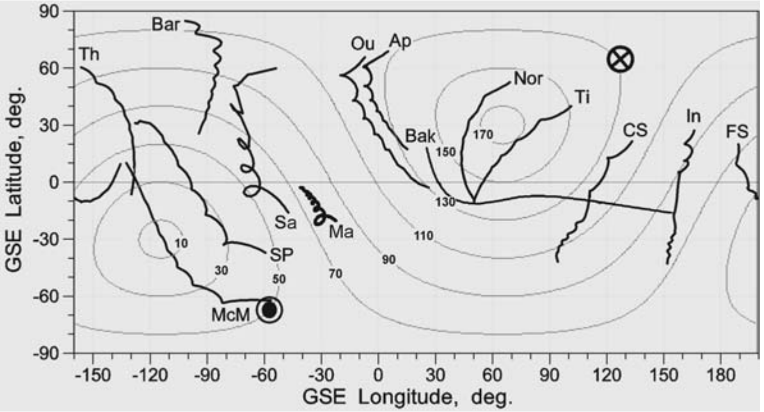
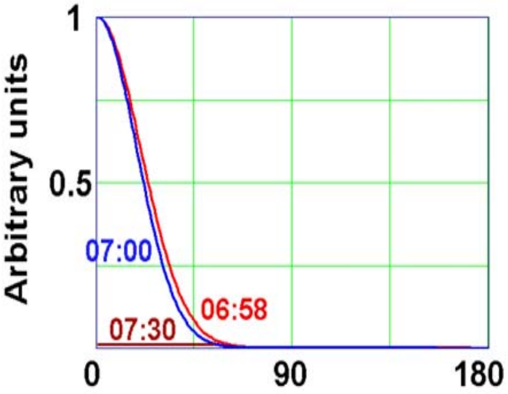
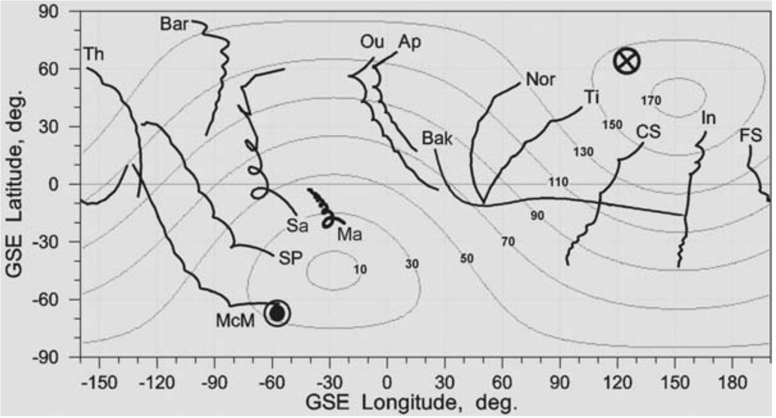
Modeled parameters of anisotropy and pitch angle distributions (PAD) for two particle fluxes

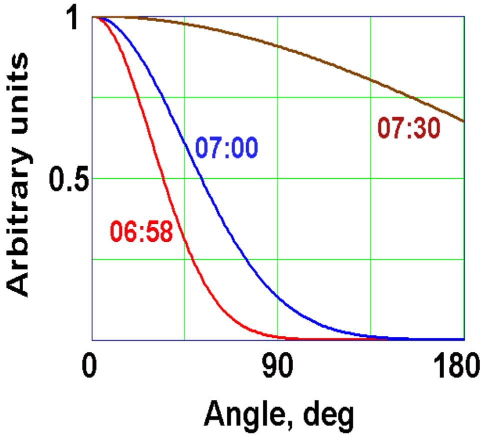
Flux 1





Flux 2





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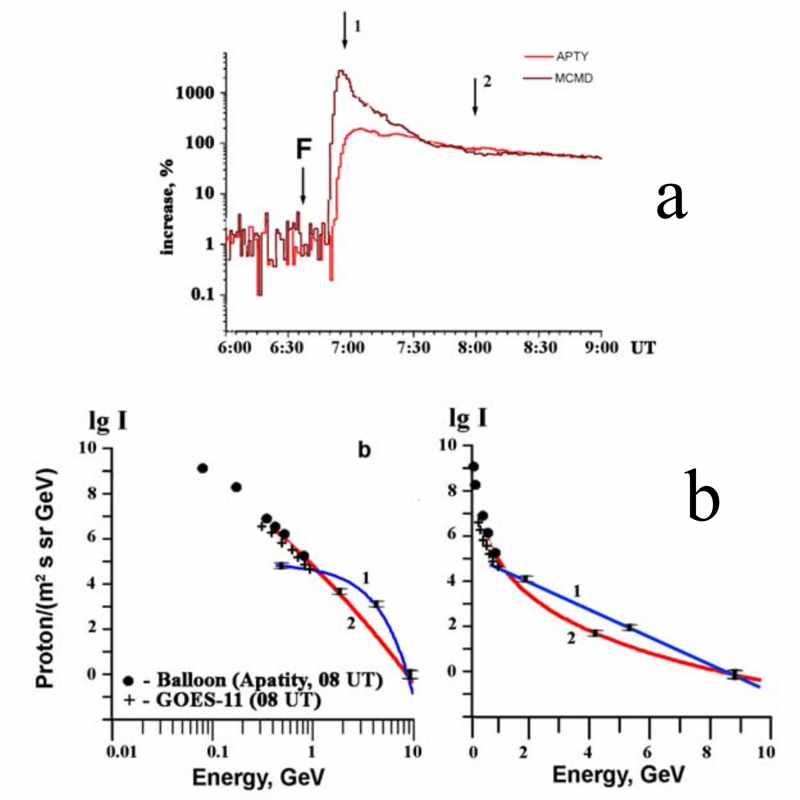
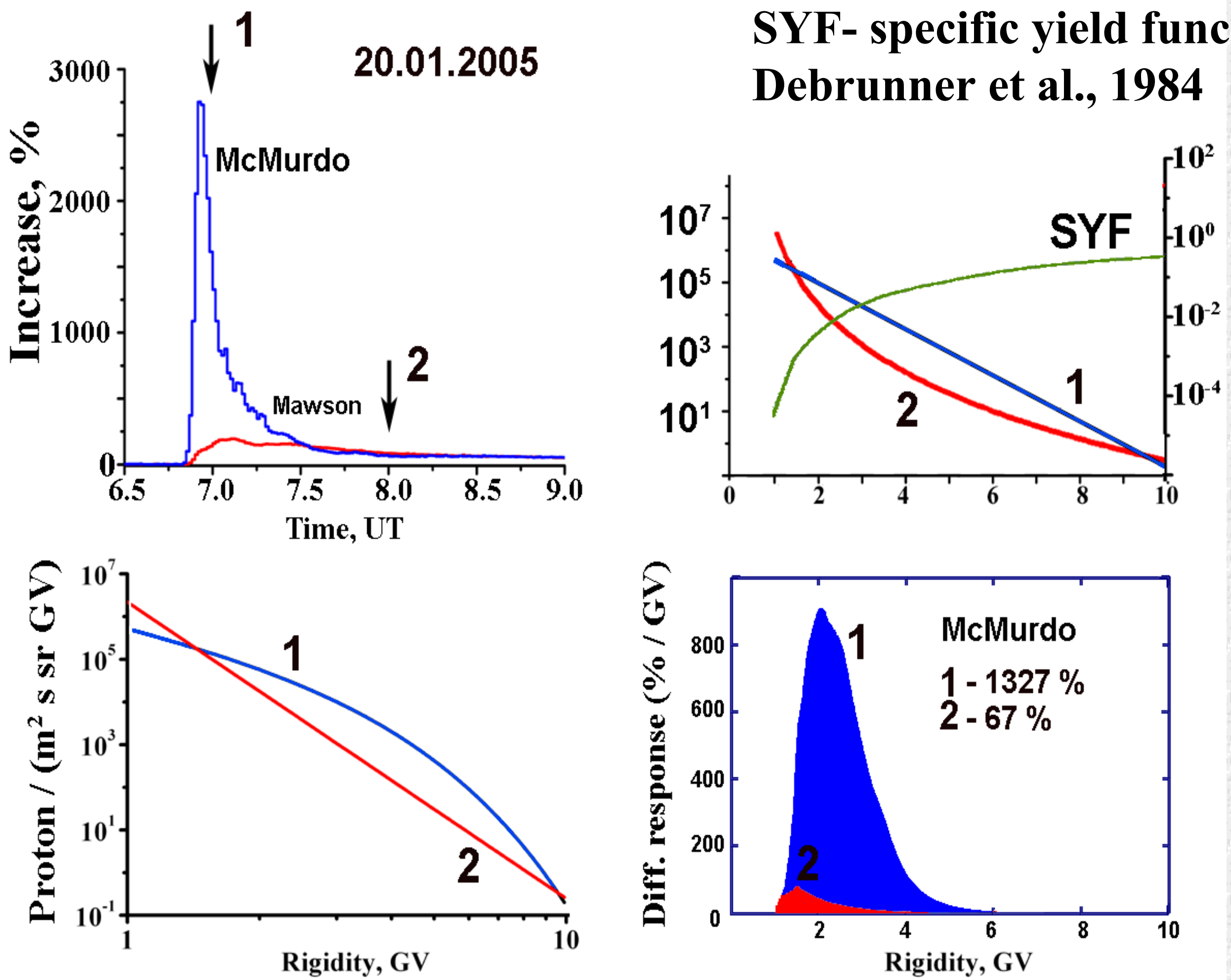
GLE 20.01.2005: energetic spectra for the prompt and delayed components of RSP



a: increase profiles as registered by the neutron monitors at Mc Murdo (McM) and Apatity (AP) stations. The spectrum derived in moment (1) when the prompt component was dominated is exponential in energy: $J = 1.5\times10^{5}\exp(-E/0.0.72)$, and spectrum of delayed component (2) has a power-law form: $J = 7.5\times10^{4}E\text{-}^{6.2}$.

GLE modeling analysis of the 20.01.2005 event Vashenyuk E.V., et al., 2005, 29 ICRC, Pune, India

Neutron monitor responses to the exponential and power law spectra



SYF- specific yield function
Debrunner et al., 1984

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), and differential responses (c) 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.

GLE 05: 23 February, 1956

The GLE of 23 February 1956 (or GLE05), largest for the entire 65-year history of SCR observations was caused by a giant solar flare (3+ or 3B) at 03:31 UT, helioco-ordinates 25°N, 85°W. The 3.3 GHz radio burst onset at 03:34 UT. The event was studied in Dorman, 1957, Dorman and Miroshnichenko, 1968, Miroshnichenko, 2001. Pfotzer, 1958 attempted to separate the “direct” and “indirect” fractions of SCR. This is very like to that we now have done in our modeling analysis. But we call these fractions as prompt and delayed components of relativistic solar cosmic rays Modeling study of the GLE 05 was performed by Smart and Shea, 1990, and recently by Belov et al., 2005. Below we present the results of our modeling analysis of the event

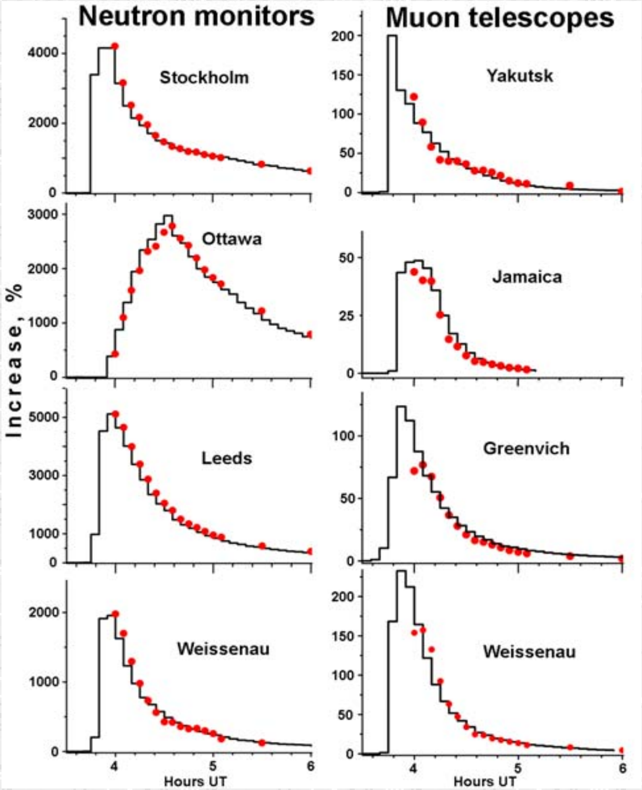


Fig. 2. Increase profiles at a number of neutron monitor (left) and muon telescope (right) stations during the GLE on 23 February, 1956. Points are modeled responses at consecutive 5-min intervals

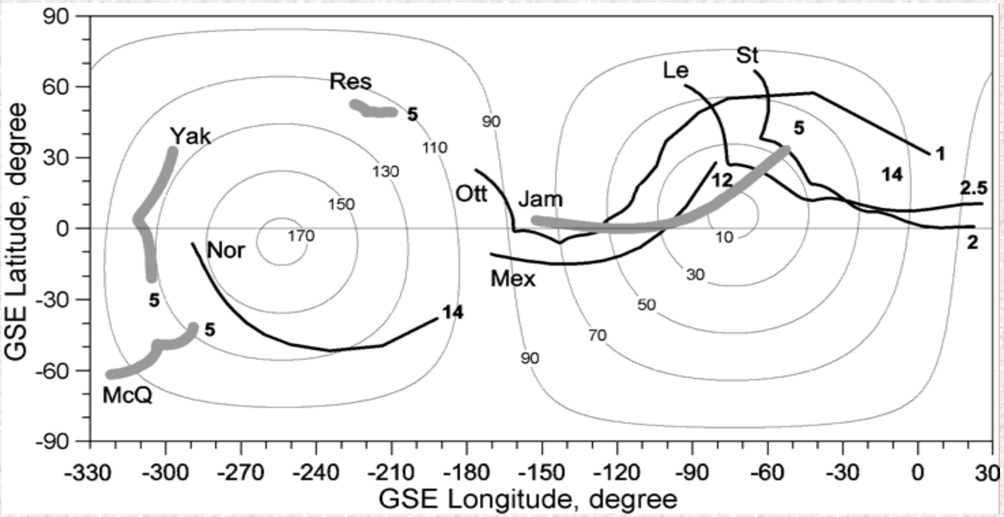
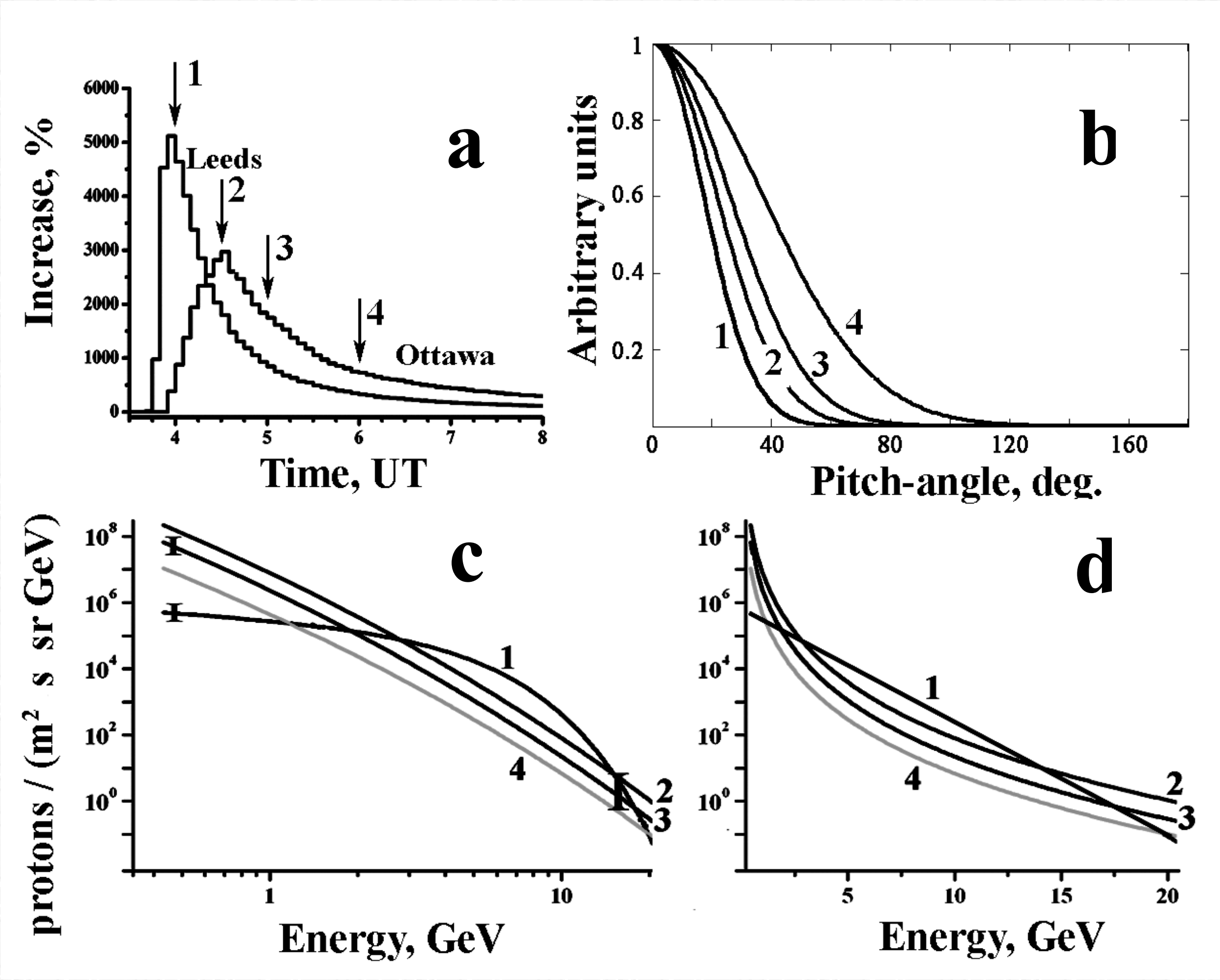
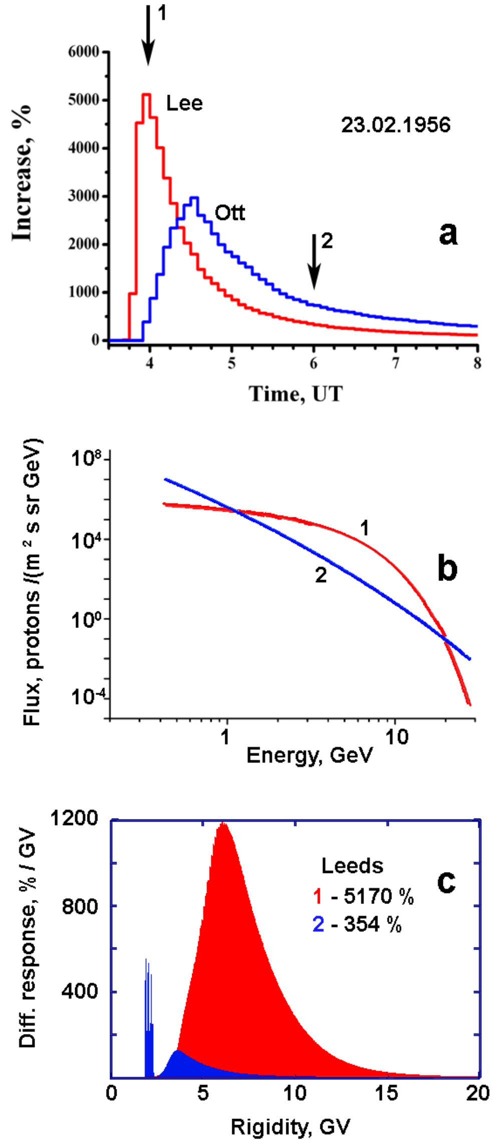


Fig.3. Asymptotic cones of acceptance for a number of neutron monitor stations (solid lines) and muon telescopes (gray shading). Figures denote low rigidity cutoffs in GV. High rigidity (20 GV) asymptotic direction is where abbreviated name of a station: Mac – Macquary Island, Yak – Yakutsk, Nor - Norilsk, Ott – Ottava, Mex - Mexico, Jam – Jamaica, Res - Resolute Bay, Hua - Huancayo, Lee - Leeds, Sto – Stockholm.

Modeling results of the GLE 23 February, 1956



a increase profiles at Leeds and Ottawa NM's, **b** dynamics of pitch angle distribution, **c, d** energetic spectra. Spectrum measured at moment 1 has exponential dependence on energy, spectra 2-4 are of a power law form.



Increase profiles at the Leeds and Ottawa neutron monitors (**a**),

energy spectra derived at the moments 04:00 (1) and 06:00 (2) UT (**b**),

and differential responses (**c**) of the Leeds neutron monitor to the exponential spectrum at the moment 1 (red) and at the moment 2 to the power-law spectrum (blue). By numbers are marked, respectively, the moments when the prompt component (1) or delayed one (2) were dominating. One can see comparable responses of both neutron monitors to the power-law spectrum.

Table1 Parameters of derived solar proton spectra for 14 major GLEs

Spectrum of prompt component: $J=J_0\exp(E/E_0)$, E (GeV); $J_{0,}$ J_1 $(m^2\ s\ st\ GeV)^{-1}$
Spectrum of delayed component $J=J_1E^{-\gamma}$

Table Energetic spectra parameters of relativistic solar protons

№	№ of GLE	Date	Type II radio onset	Flare impor-tance	Helioco-ordi-nates	PC spectrum (exponential)		DC spectrum (power-law)	
						J_0	E_0	J_1	γ
1	05	23.02.1956	03.31*	3B	N23W80	$1.4\cdot10^6$	1.30	$4.2\cdot10^6$	5.2
2	31	07.05.1978	03.27	1B/X2	N23W82	$5.6\cdot10^4$	0.71	$1.2\cdot10^4$	4.1
3	38	07.12.1982	23.44	1B/X2.8	S19W86	$5.7\cdot10^3$	0.65	$7.2\ \cdot10^3$	4.5
4	39	16.02.1984	08.58	-	- W132	-	-	$5.2\ \cdot10^4$	5.9
5	42	29.09.1982	11.33	- /X9.8	- W105	$1.9\ 10^4$	1.54	$3.5\ \cdot10^4$	4.1
6	44	22.10.1989	18.05	2B/X2.9	S27W31	$7.5\ 10^4$	0.87	$1.5\cdot10^4$	6.1
7	47	21.05.1990	22.19	2B/X5.5	N35W36	$6.3\cdot10^3$	0.83	$2.7\cdot10^3$	4.1
8	55	06.11.1997	11.55	2B/X9.4	S18W63	$7.3\ 10^3$	1.20	$5.0\ 10^3$	4.3
9	59	14.07.2000	10.20	3B/X5.7	N22W07	$3.3\cdot10^5$	0.35	$2.0\cdot10^4$	6.4
10	60	15.04.2001	13.19	2B/X14.4	S20W85	$1.3\cdot10^5$	0.53	$3.5\cdot10^4$	5.3
11	65	28.10.2003	11.02	4B/X17.2	S16E08	$1.4\cdot10^4$	0.59	$1.5\cdot10^4$	4.4
12	67	2.11.2003	17.03	2B/X8.3	S14W56	$5.6\cdot10^4$	0.33	$2.7\cdot10^3$	6.6
13	69	20.01.2005	06.44	2B/X7.1	N14W61	$2.5\cdot10^6$	0.49	$7.2\cdot10^4$	5.6
14	70	13.12.2006	02.26	2B/X3.4	S06W24	$1.1\ 10^6$	0.33	$4.4\ 10^4$	5.5

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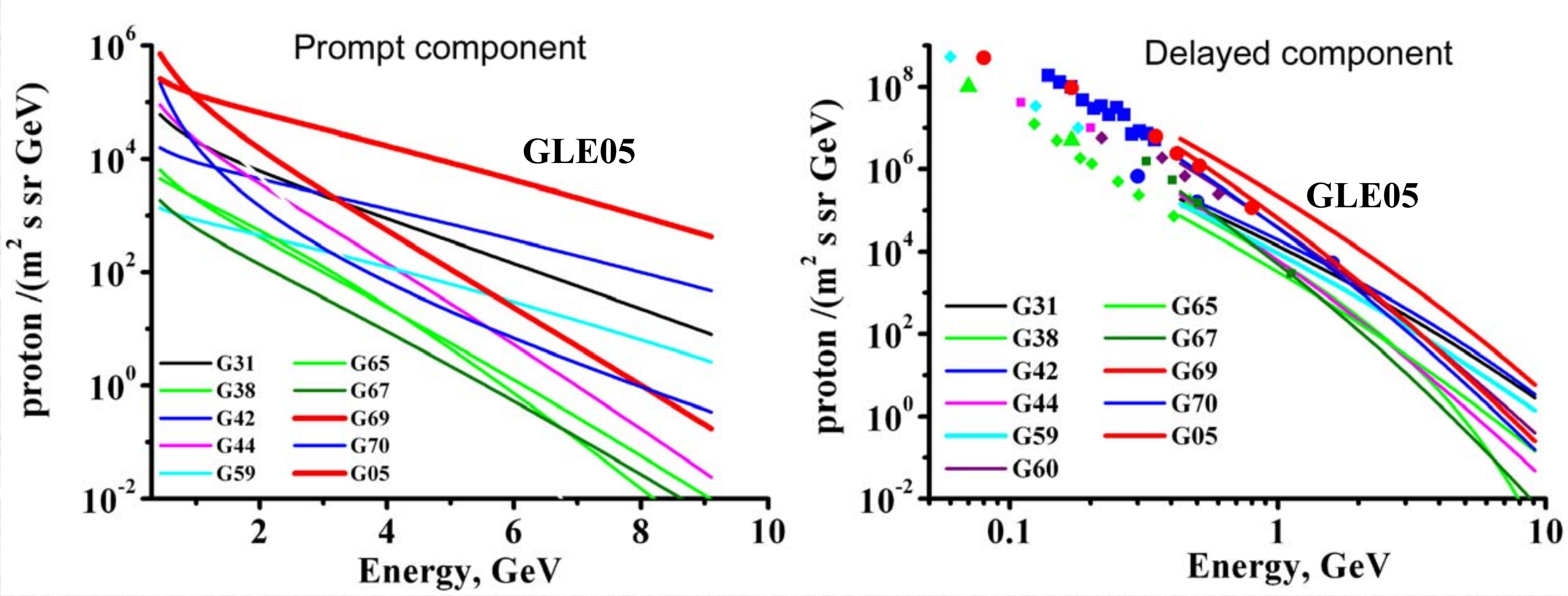
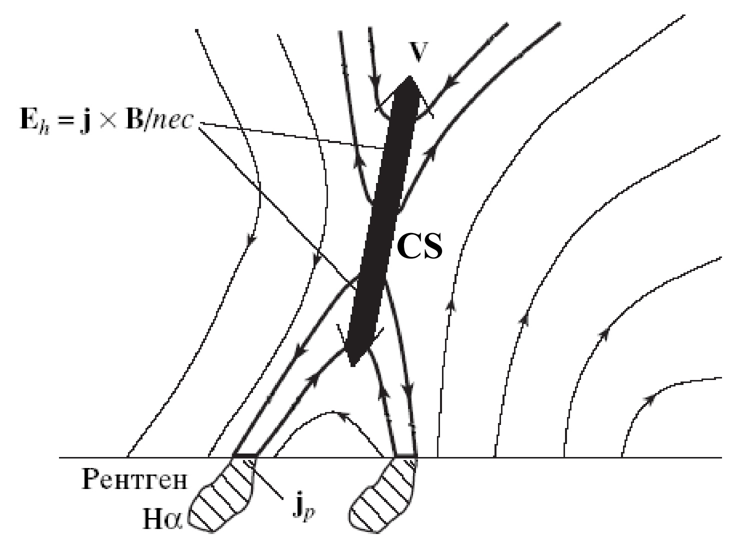
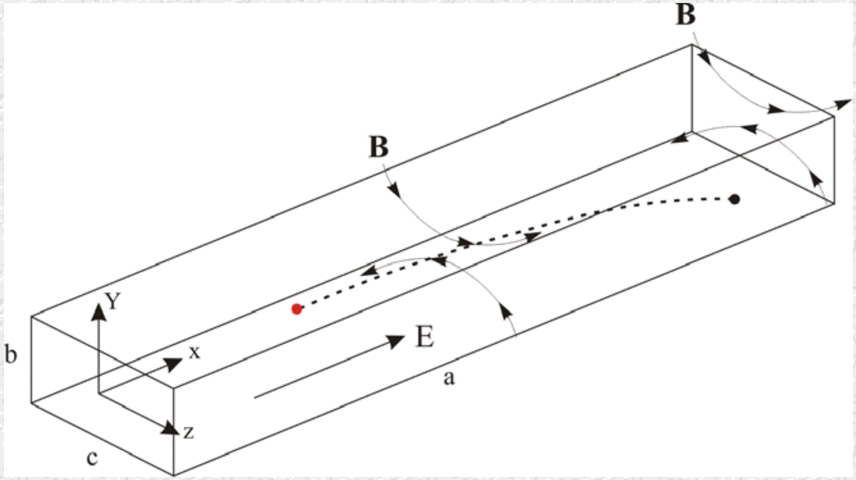

Prompt component
GLE05
proton /(m² s sr GeV)
10^6
10^4
10^2
10^0
10^-2
2
4
6
8
10
Energy, GeV
G31
G38
G42
G44
G59
G65
G67
G69
G70
G05
Delayed component
GLE05
proton /(m² s sr GeV)
10^8
10^6
10^4
10^2
10^0
10^-2
0.1
1
10
Energy, GeV
G31
G38
G42
G44
G59
G60
G65
G67
G69
G70
G05

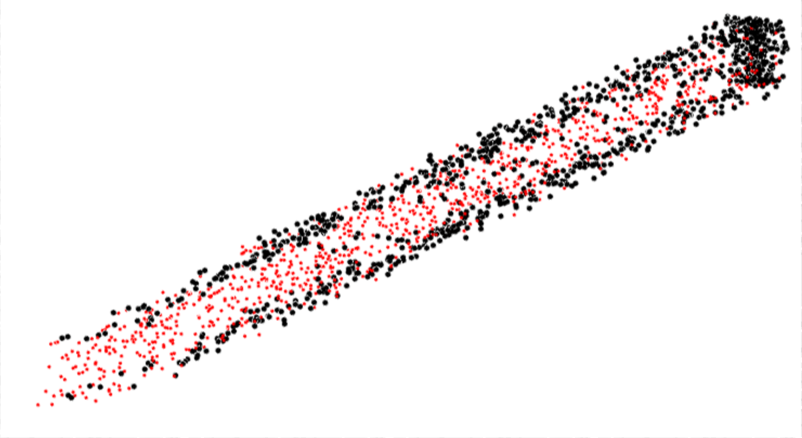
Influence of Interplanetary propagation

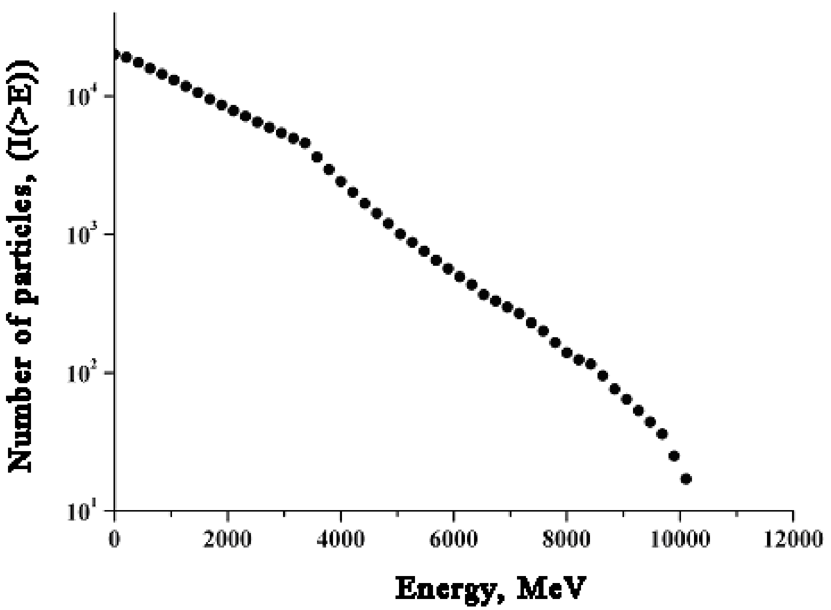
The time of direct flight along an IMF line with a length of 1.2 AU makes for particles with energy about 0.5 GeV and 10 GeV of 13.2 and 10 minutes, respectively. (corresponding ratios $v/c = 0.76$ and 0.996). Hence, relativistic solar protons in the energy range of 0.5-10 GeV come to the Earth within 3-minute interval. In our modeling technique the 5-minute averages of the NM data are used, therefore, obtained solar proton spectrum is suggested to be close under the form to a generation spectrum at the Sun, if only the particles were released simultaneously.

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



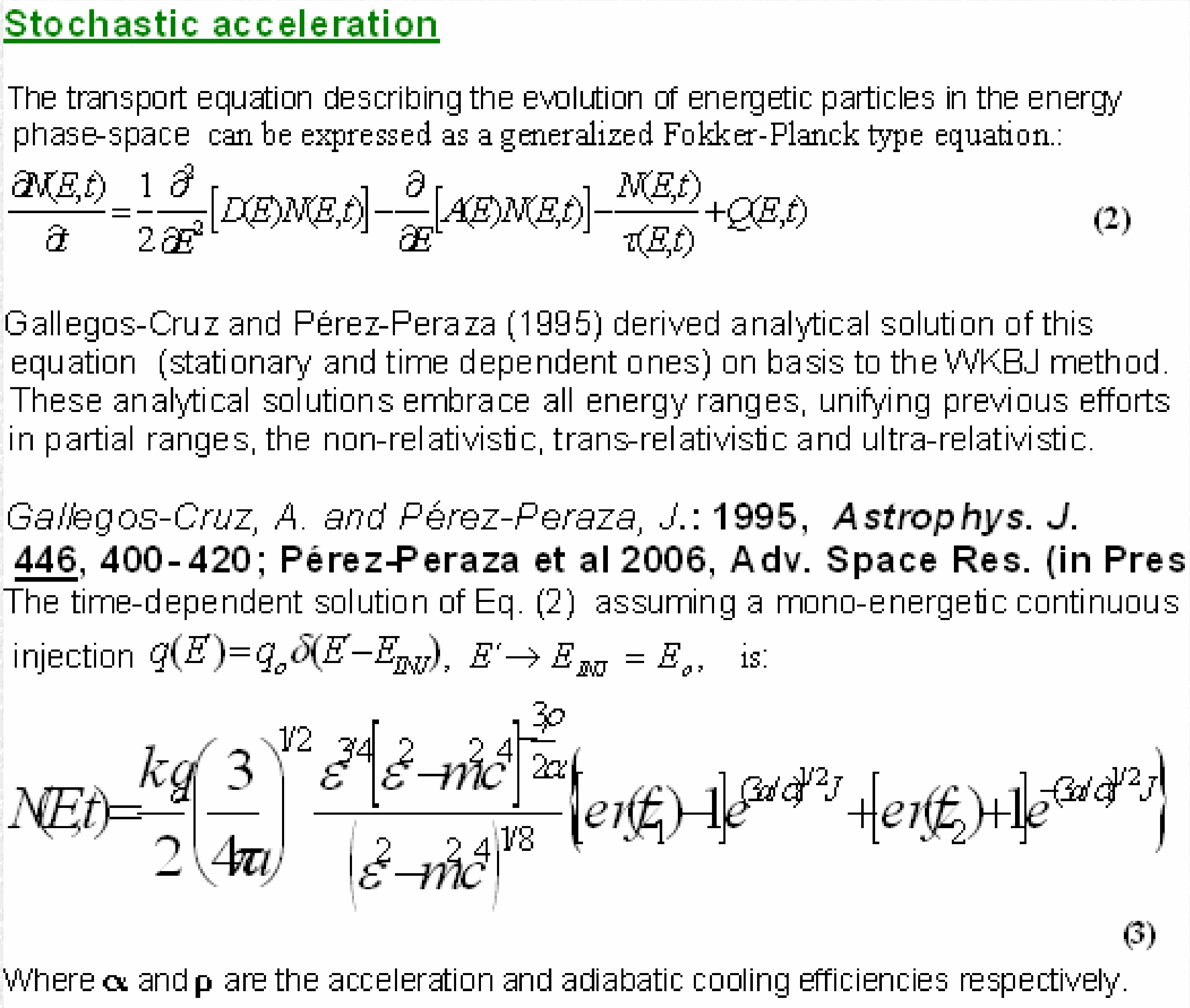






Resulting proton spectrum has nearly exponential form

Possible mechanism generation of delayed component



Stochastic acceleration

The transport equation describing the evolution of energetic particles in the energy phase-space can be expressed as a generalized Fokker-Planck type equation.:

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

Gallegos-Cruz and Pérez-Peraza (1995) derived analytical solution of this equation (stationary and time dependent ones) on basis to the WKBJ method. These analytical solutions embrace all energy ranges, unifying previous efforts in partial ranges, the non-relativistic, trans-relativistic and ultra-relativistic.

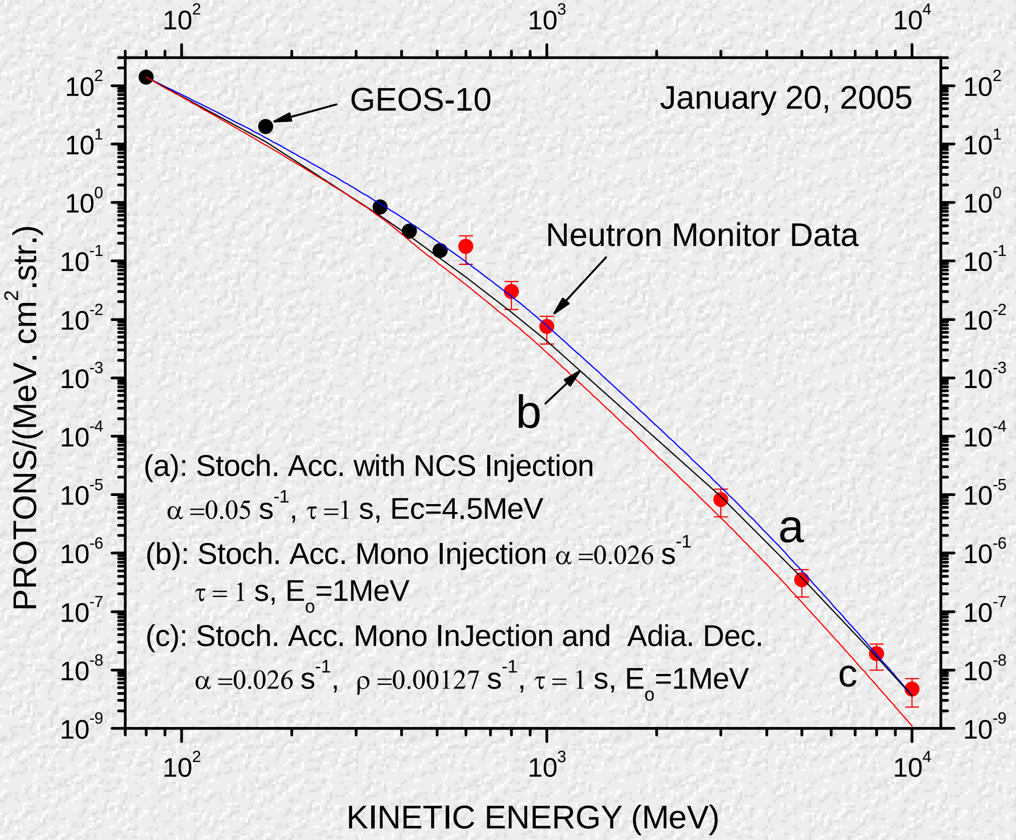
Gallegos-Cruz, A. and Pérez-Peraza, J.: **1995, *Astrophys. J.* <u>446</u>, 400-420; Pérez-Peraza et al 2006, Adv. Space Res. (in Pres**

The time-dependent solution of Eq. (2) assuming a mono-energetic continuous injection $q(E)=q_o\delta(E-E_{INJ})$, $E'\rightarrow E_{INJ}=E_o$, is:

$$N(E,t)=\frac{kq_o}{2}\left(\frac{3}{4\pi\alpha}\right)^{1/2}\frac{\varepsilon^{3/4}\left[\varepsilon^2-m^2c^4\right]^{-\frac{3\rho}{2\alpha}}}{\left(\varepsilon^2-m^2c^4\right)^{1/8}}\left\{\left[erf(\xi_1)-1\right]e^{(3\alpha/\rho)^{1/2}J}+\left[erf(\xi_2)+1\right]e^{-(3\alpha/\rho)^{1/2}J}\right\} \qquad (3)$$

Where α and ρ are the acceleration and adiabatic cooling efficiencies respectively.

Fitting of the different modifications of the stochastic acceleration mechanismt he derived spectrum od delayed component in the GLE 20 January, 2005 (Perez-Peraza et al., 2006)



Results

1. By the modeling technique the 14 large GLEs occurring in the period from 1956 to 2006 have been analysed. The presence of the prompt and delayed components of relativistic solar protons was shown in all cases.
2. Special consideration was devoted to superevents 23.02.1956 and 20.01.2005. Two solar proton components: prompt and delayed ones has been shown in both events.
3. Moreover, the huge increases in both events on a limited number NM stations were caused by the prompt component having an exponential energetic spectrum.
4. The power law spectrum of the delayed component caused increase of moderate amplitude on the majority other stations of a worldwide network.
5. In moderate energies (tens to hundreds MeV) the event 20.01. 2005, and also 23.02.1956 looked as rather ordinary ones.
6. The prompt component was observed almost in all events with relativistic solar protons By distinction of superevents 23.02.1956 and 20.01.2005 was that, the relative intensity of PC in relation to DC was much greater, than for the majority of “ordinary” events. For instance, in the GLE 31 (May 7, 1978) the RSP spectrum during all the event had the clear exponential form in rigidity (Shea and Smart, 1982) but it did not cause such a giant increase effect as in superevent under debate.

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7. The probable mechanism of generation of prompt component is the acceleration by an electric field arising at magnetic reconnection in coronal current sheets. It is necessary to keep in mind that the super GLEs 05 and 20.01.2005 have taken place in the period close to the minimum of a solar cycle. The 23.02.1956 GLE: at early rise phase of the 19th cycle and 20.01.2005: at late decline phase of the 23rd cycle. Then it is possible to assume, that the structure of magnetic fields in the solar corona and interplanetary space could enable generation on the Sun and propagation to the Earth of PC particles of unusually large intensity. Such conditions should be realized rather seldom, as for the period of a half of century only 2 events of scale of GLE 05 and GLE 69 occurred