Dynamics of relativistic solar cosmic rays during December 13, 2006 GLE

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Abstract

The dynamics of relativistic solar cosmic rays during the GLE of 13.12.2006 by modeling technique have been studied. The data of 36 neutron monitors were used in the analysis.

By least square (optimization) methods
parameters of relativistic solar protons:
- rigidity (energetic) spectra,
- anisotropy directions
- pitch-angular distributions

were obtained and their dynamical changes studied.

It is shown that:

In the beginning of the event solar protons arrived at the Earth along the IMF as a narrow collimated beam. These particles caused short-lived peak increase on a number of neutron monitor stations.

On later phase a reverse flux (to the Sun) has appeared and the spectrum became appreciably softer. The rigidity spectral exponent changed from 4 to 6 in course of the event.

Outline

1. GLE 13 December, 2006

2. Neutron monitor network and instrumentation

3. Neutron multiplicity registration

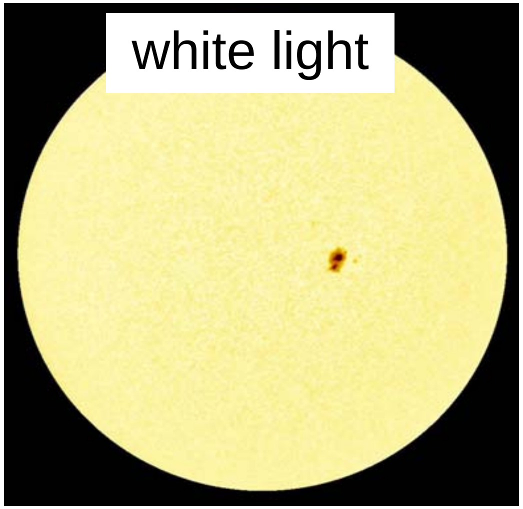
4. GLE modeling technique

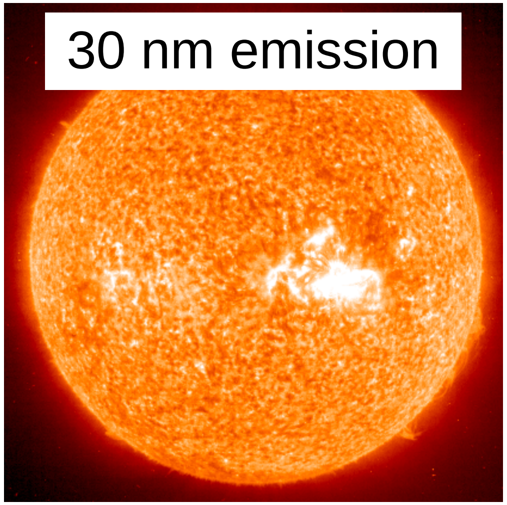
5. Modeling Results of the GLE 13.12.2006:
   parameters of relativistic solar protons

6. Dynamics of energetic spectra and pitch angle
   distribution

The GLE on December 13, 2006

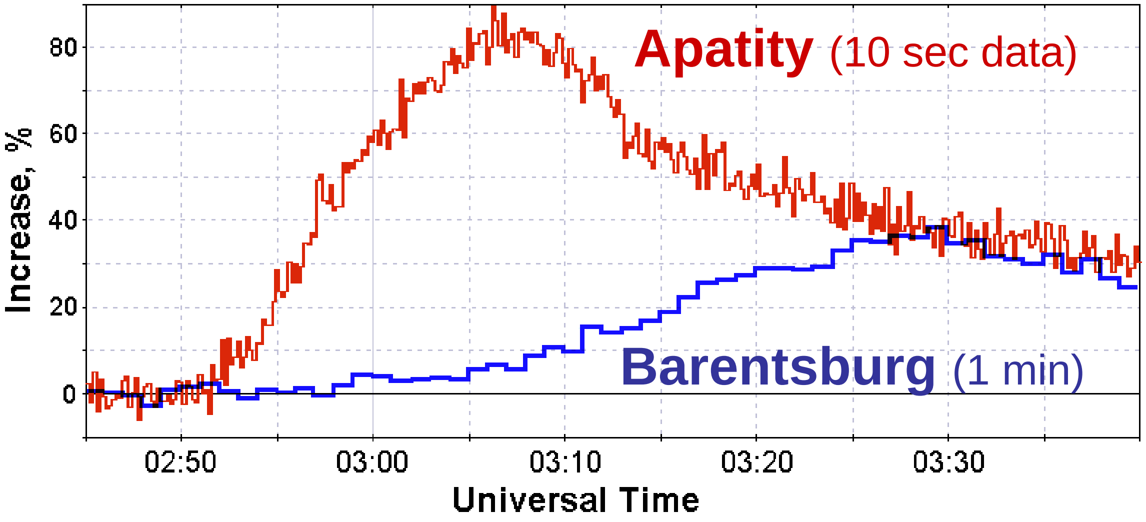
Active region AR10930 on the Sun



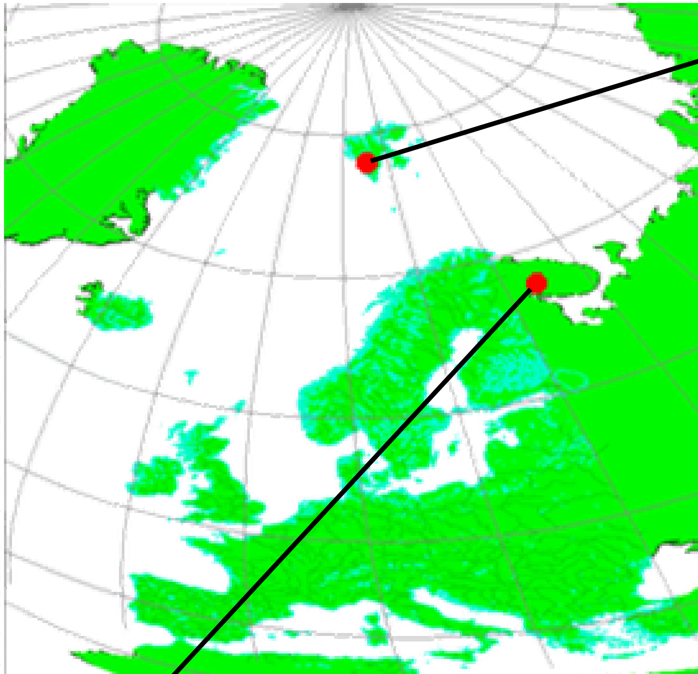


Solar flare X3.4/2B happened at 02:26 UT at S06 W24

Ground level effect registered by neutron monitors



Neutron monitors of the Polar Geophysical Institute



Barentsburg (78.08N 14.12E)

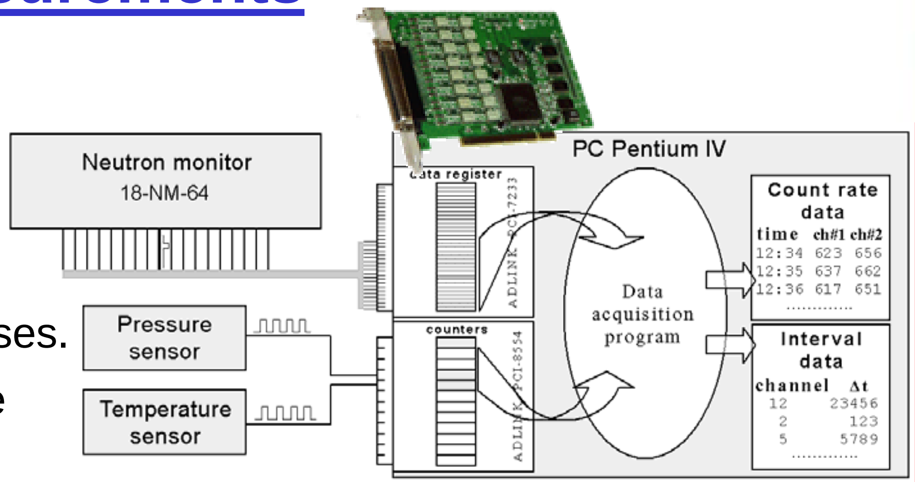
Apatity (67.55N 33.34E)

Multiplicity Measurements

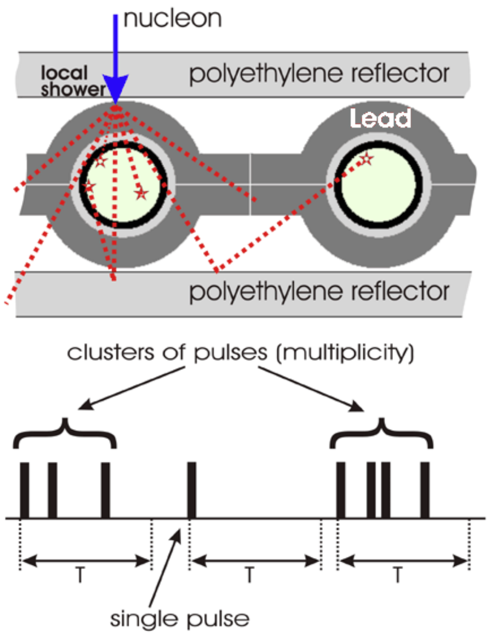
New data acquisition system
- Personal Computer
- digital input card Adlink PCI-7233H
- specially written program

allows to measure intervals between pulses.

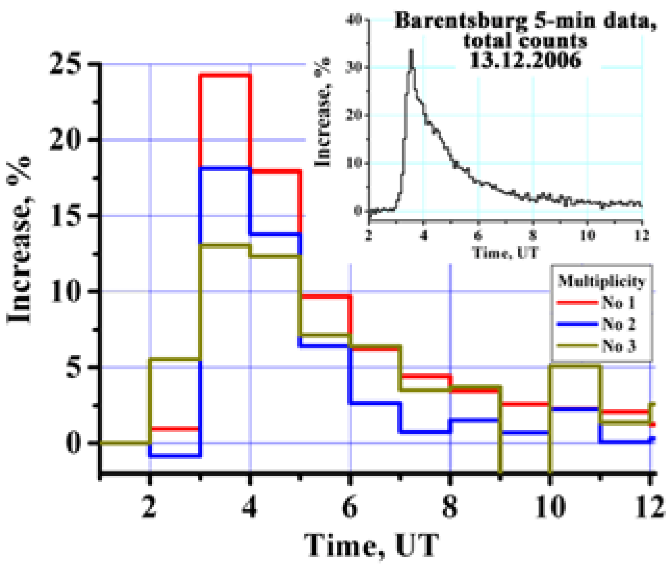
Thus there is a possibility to determine a multiplicity in a neutron monitor



Multiplicity in a neutron monitor

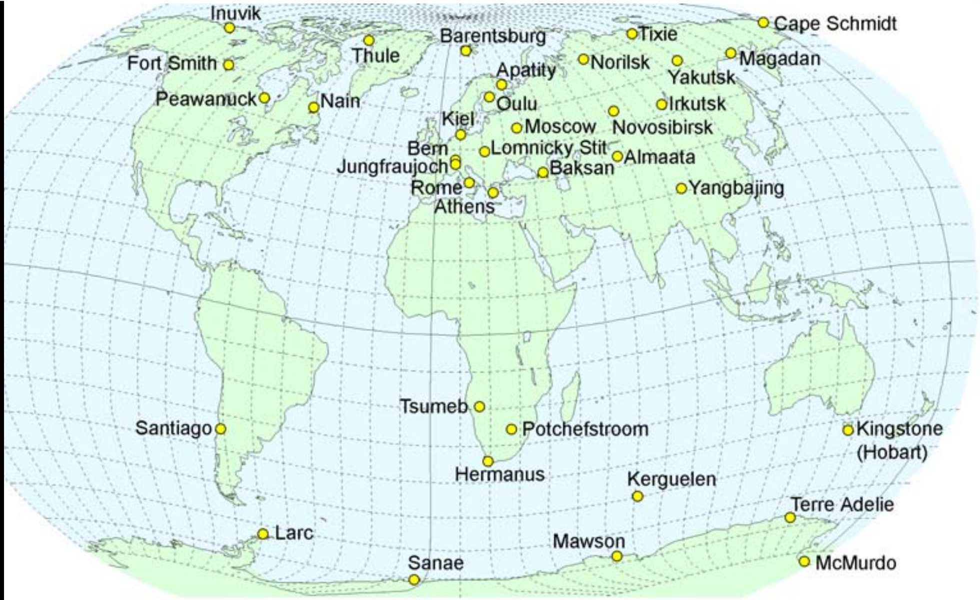


Multiplicity measured on the neutron monitor Barentsburg during 13 December 2006 GLE



Set of neutron monitors used in our analysis

N	Station	Lat	Lon	R_C
1	APATITY	67.55	33.33	0.65
2	ALMAATA-B	43.14	76.60	6.61
3	ATHENS	37.58	23.47	8.72
4	BERN	46.95	7.45	4.53
5	BAKSAN	43.28	42.69	6.40
6	BARENTSBURG	78.12	14.12	0.00
7	CAPE SCHMIDT	68.92	-179.47	0.55
8	FORT SMITH	60.02	-111.93	0.27
9	HERMANUS	-34.42	19.22	4.58
10	INUVIK	68.35	-133.72	0.16
11	IRKUTSK	52.10	104.00	3.56
12	JUNGFRAUJOCH	46.55	07.98	4.53
13	KERGUELEN	-49.35	70.25	1.10
14	KINGSTONE	-42.99	147.29	1.88
15	KIEL	54.30	10.10	2.32
16	LARC	-62.20	-58.96	3.00
17	LOMNICKY STIT	49.11	20.13	3.84
18	McMURDO	-77.51	166.43	0.00
19	MAGADAN	60.10	151.00	2.11
20	MOSCOW	55.47	37.32	2.39
21	MAWSON	-67.60	62.68	0.22
22	NAIN	56.55	-61.68	0.40
23	NORILSK	69.26	88.05	0.57
24	NOVOSIBIRSK	54.80	83.00	2.78
25	SANTIAGO	65.02	25.50	0.81
26	POTCHEFSTROOM	-26.68	27.92	7.00
27	PEAWANUCK	54.98	-85.44	0.35
28	ROME	41.90	12.52	6.24
29	SANAE	-71.67	-02.85	0.86
30	SANTIAGO	-33.49	-70.72	11.0
31	TERRE ADELIE	-66.65	140.00	0.00
32	THULE	76.50	-68.70	0.00
33	TSUMEB	-19.20	17.60	9.21
34	TIXIE BAY	71.60	128.90	0.45
35	YAKUTSK	62.02	129.72	1.63
36	YANGBAJING	30.11	90.53	14.10



Method: Formula

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

N – neutron monitor count rate
R – particle rigidity
θ – pitch angle

i – neutron monitor number
j – direction number

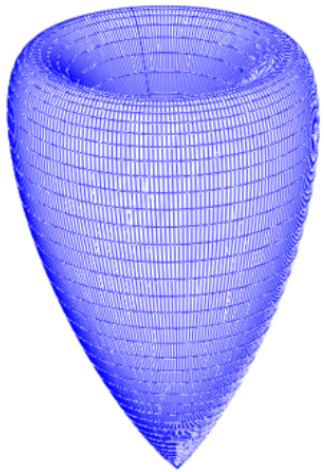
J(R) – rigidity spectrum = $J_0 \cdot R^{-(\gamma+\Delta\gamma\,(R-1))}$
F(θ) – pitch angle distribution = $e^{-\theta^2/C}$
S(R) – specific yield function (Debrunner et al., 2004)

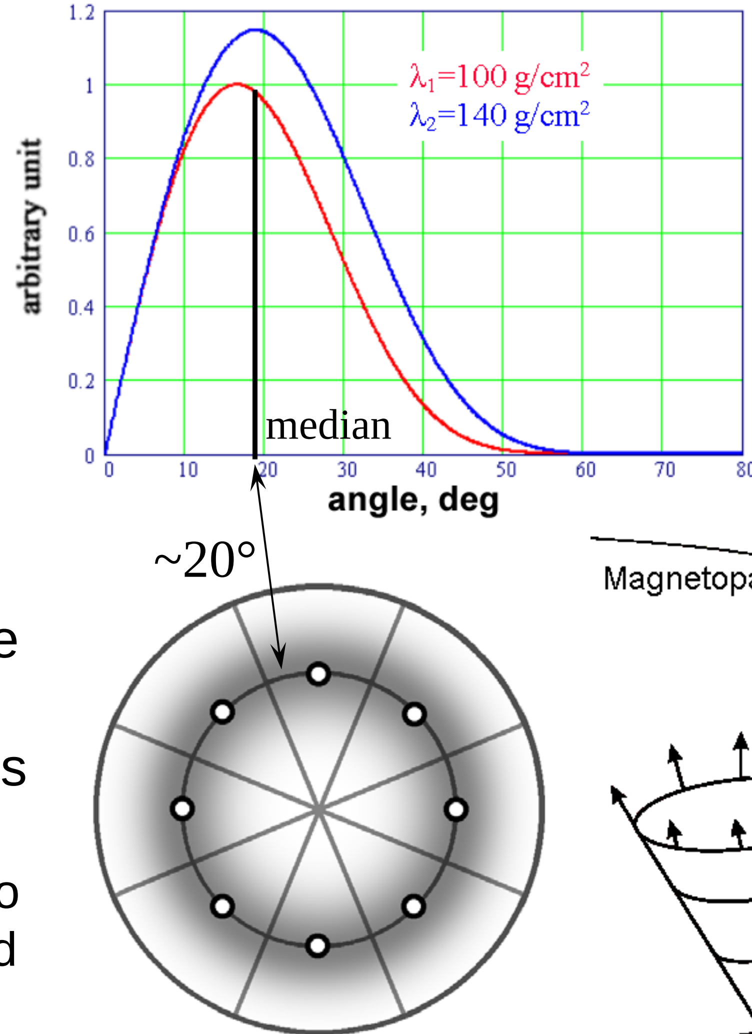
To obtain the parameters
we solve the nonlinear least squares problem:

$$SN = \sum_{\mathbf{i}}\left[\left(\frac{\Delta N}{N}\right)_{\mathbf{i}}^{\mathbf{calc}} - \left(\frac{\Delta N}{N}\right)_{\mathbf{i}}^{\mathbf{observ}}\right]^2 \Rightarrow \min$$

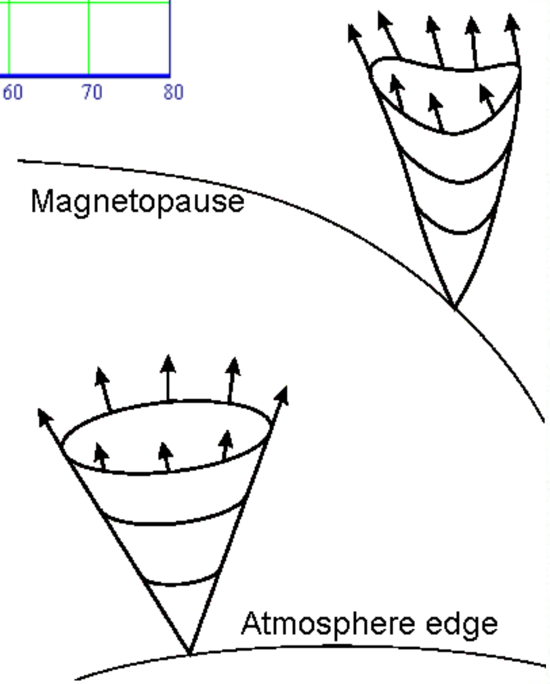
Asymptotic cones calculations

Neutron monitor directivity for solar and galactic cosmic rays





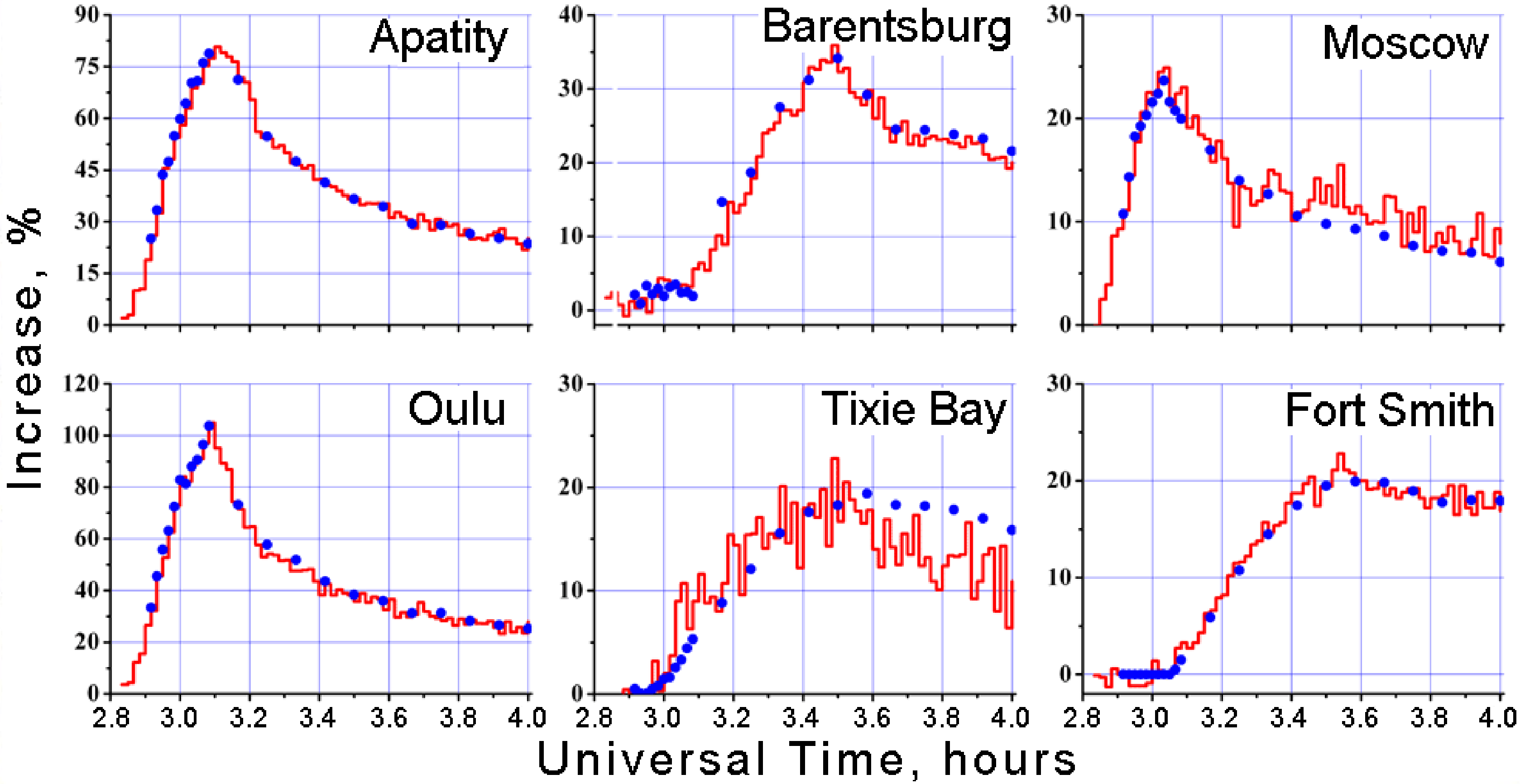
To account the contribution of oblique incident particles we calculate 8 trajectories launched with zenith angle ~20 º. Tsyganenko 2001 model is employed



Modeling result: NM profiles

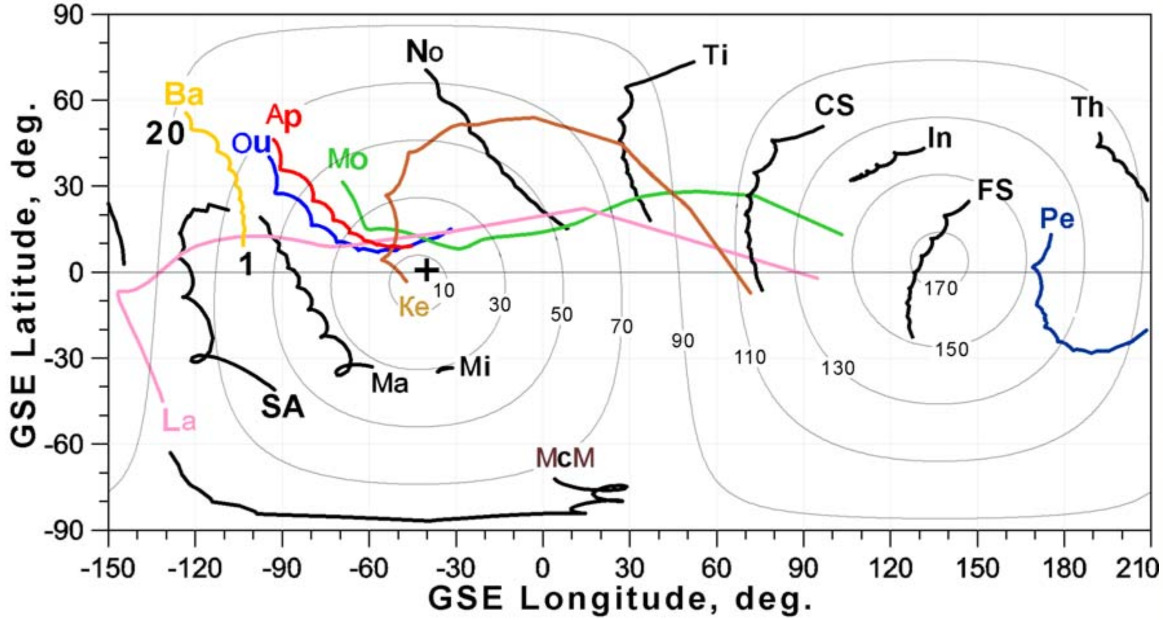
——— real increase profile registered by a neutron monitor

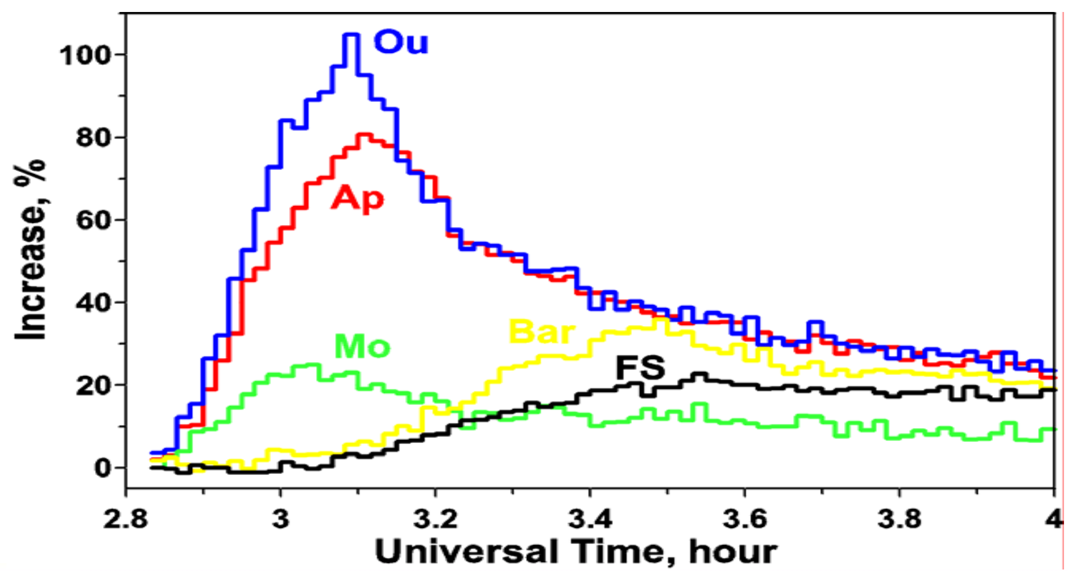
• • • • profile constructed on model parameters



Modeling result: Anisotropy axis

N	UT	Λ deg	Φ deg
1	02:57	-13	-47
2	03:00	-6	-45
3	03:05	0	-43
4	03:20	8	-52
5	03:30	12	-59
6	04:00	1	-47

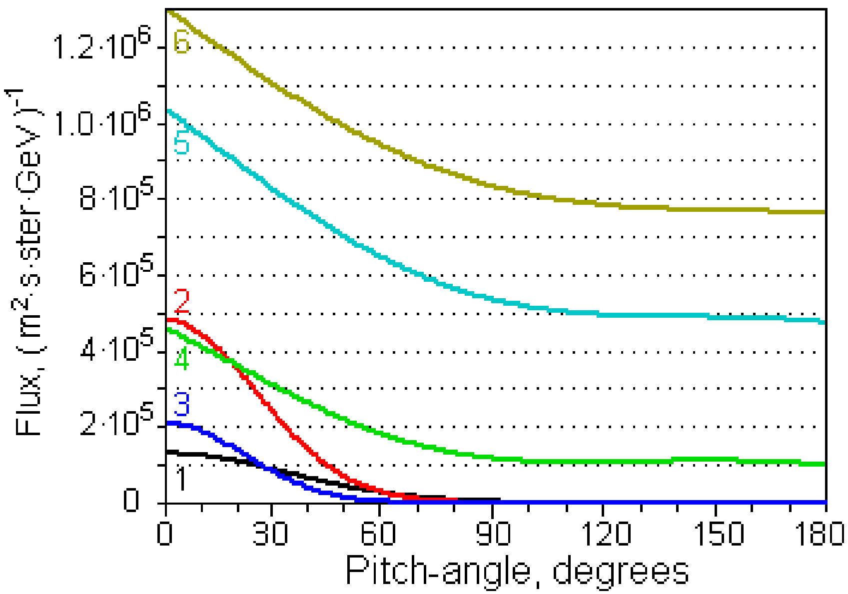


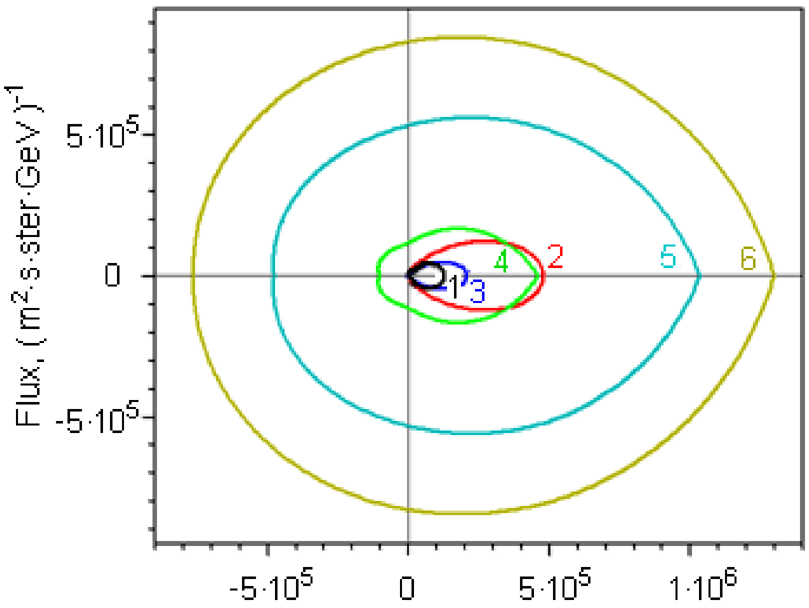


Modeling result: Pitch-angle distribution

$$F(\theta)=J_0\cdot\exp(-\theta^2/C_1)(1-A\cdot\exp(-(\theta-\pi/2)^2/C_2)$$

N	UT	J_0	C_1 rad^2	A	C_2 rad^2
1	02:57	$1.3\cdot10^5$	0.68	0	0
2	03:00	$1.7\cdot10^5$	0.44	0	0
3	03:05	$3.2\cdot10^5$	0.46	0.47	0.35
4	03:20	$8.1\cdot10^5$	6.47	0.79	4.09
5	03:30	$1.8\cdot10^6$	12.6	0.64	6.01
6	04:00	$2.5\cdot10^6$	18.4	0.62	9.63

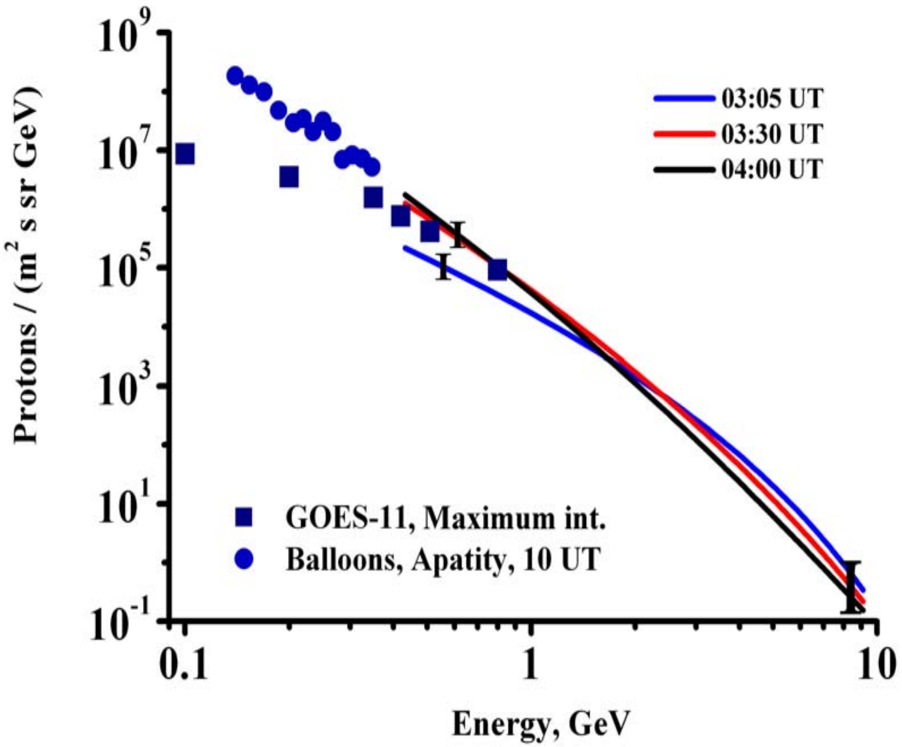




Modeling result: Energy (rigidity) spectra

$$J(R)=J_0 \cdot R^{-(\gamma+\Delta\gamma\cdot(R-1))}$$

N	UT	J_0	$\lvert\gamma\rvert$	$\Delta\gamma$
1	02:57	$1.3 \cdot 10^5$	3.92	0.11
2	03:00	$1.7 \cdot 10^5$	4.73	0.14
3	03:05	$3.2 \cdot 10^5$	3.59	0.35
4	03:20	$8.1 \cdot 10^5$	4.16	0.36
5	03:30	$1.8 \cdot 10^6$	6.06	0.06
6	04:00	$2.5 \cdot 10^6$	6.91	0.00



Reference:

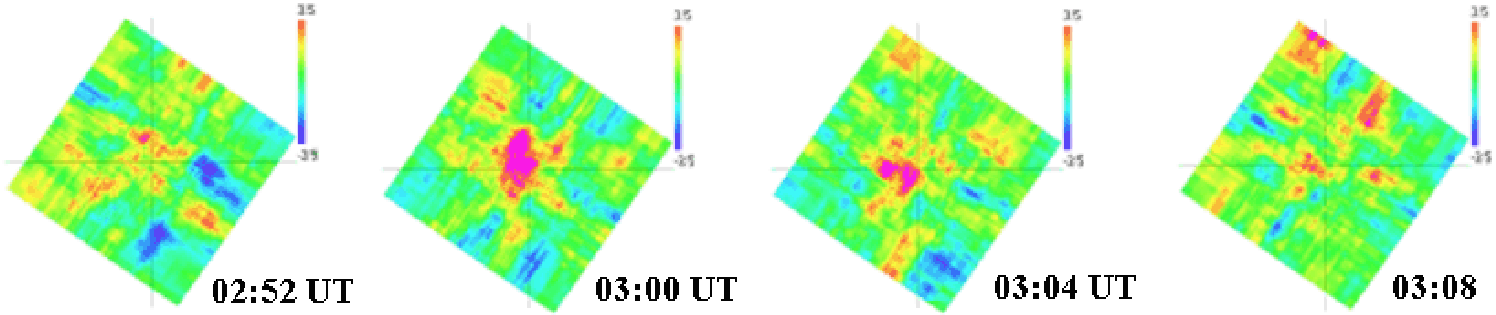
E.V.Vashenyuk, G.A.Basilevskaya, Yu.V.Balabin, B.B.Gvozdevsky, V.S.Makhmutov, Yu.I.Stozhkov, N.S.Svirzhevsky, A.K.Svirzhevskaya, L.I.Schur

The GLE of December 13, 2006 according to the ground level and balloon observations.

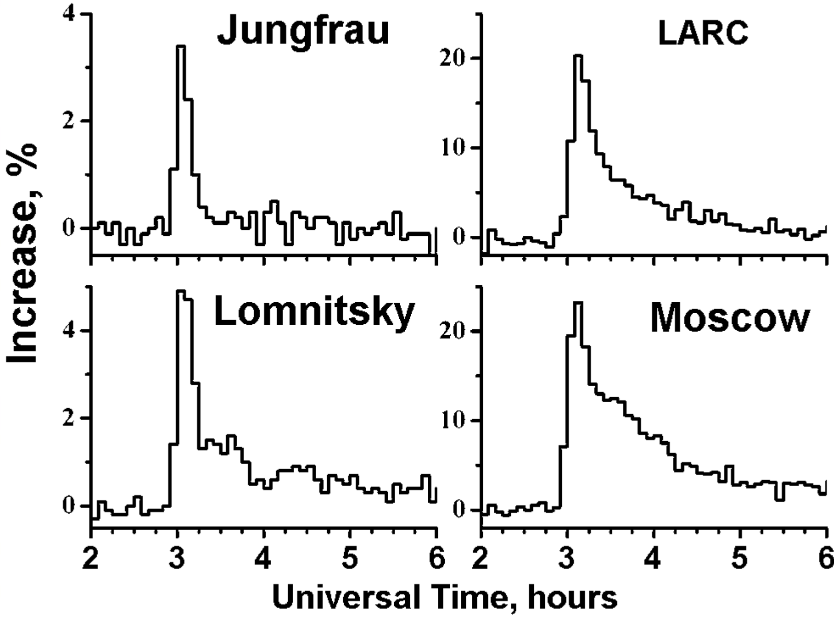
30 ICRC, Paper 0652

Prompt peak

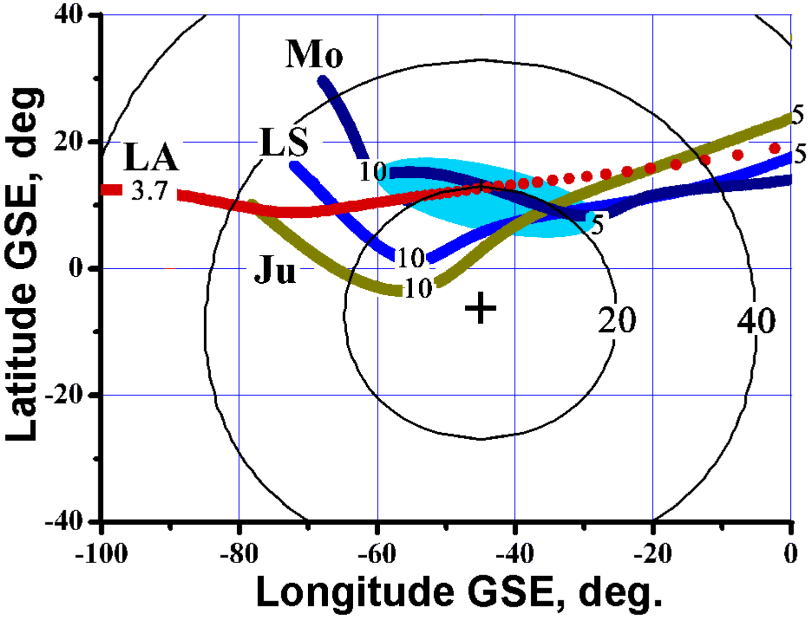
MEPHI Hodoscope (Timashkov D.A. et al. 2007)



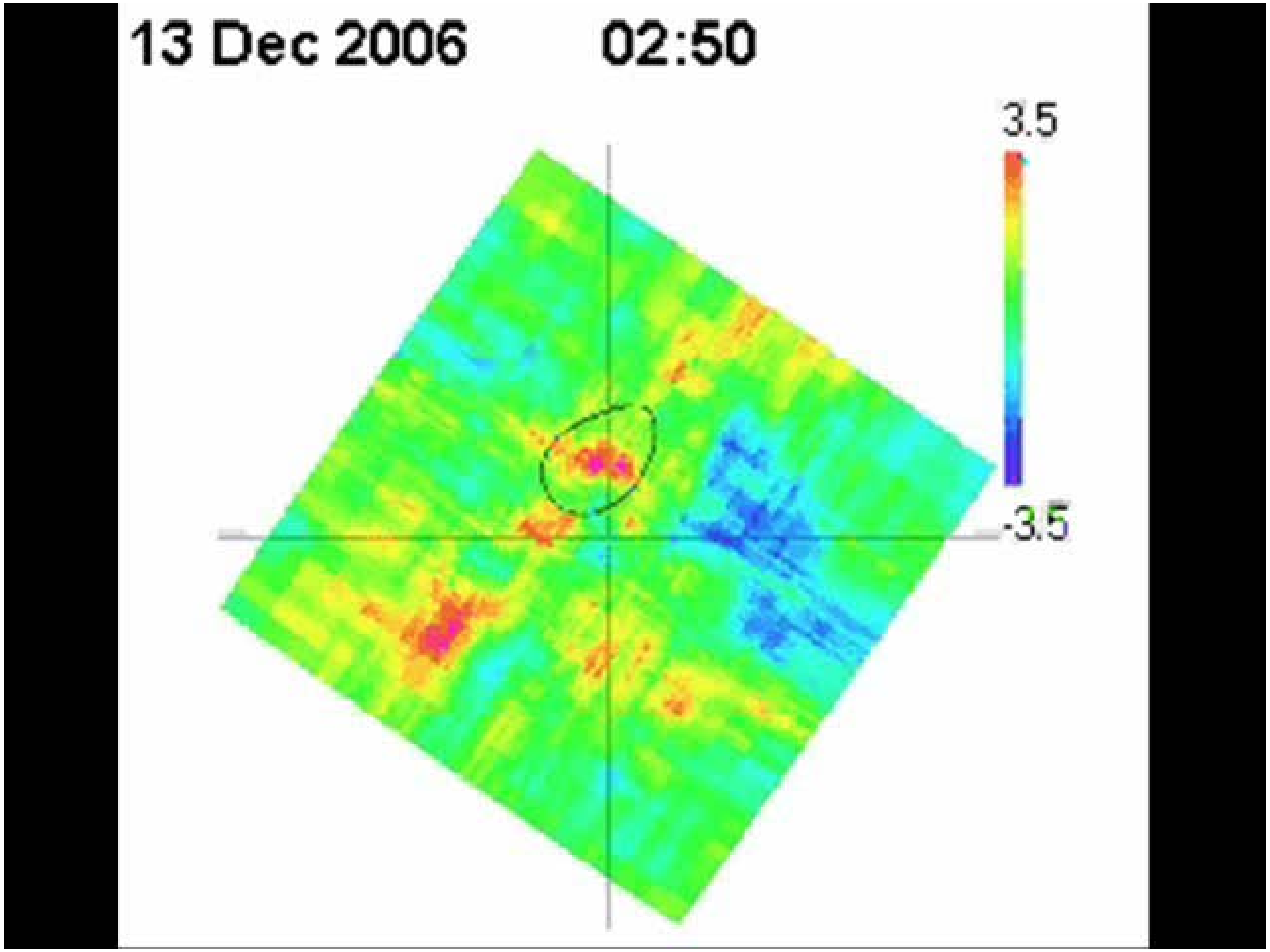
Neutron monitors



their asymptotic cones



Prompt peak



Reference:

D. A. Timashkov, Yu.V. Balabin, V. V. Borog, K. G. Kompaniets, A. A. Petrukhin, D. A. Room, E. V. Vashenyuk, V. V. Shutenko, I. I. Yashin
Ground-Level Enhancement of December 13, 2006 in muon hodoscopes data. **30 ICRC, Paper 0298**

Conclusions

The dynamics of relativistic solar cosmic rays on data of ground level observations during the GLE of 13.12.2006 have been studied. By least square (optimization) methods parameters of relativistic solar protons: rigidity (energetic) spectra, anisotropy directions and pitch-angular distributions were obtained and their dynamical changes studied. It is shown, that:

1. In the beginning of the event solar protons arrived at the Earth along the IMF as a narrow collimated beam. These particles caused short-lived peak increase on a number of neutron monitor stations.

2. On later phase a reverse flux (to the Sun) has appeared and the spectrum became appreciably softer.

3. On the data of ground based neutron monitors the rigidity (energetic) spectrum was dweived and its dynamics stugied. The rigidity spectral exponent changed from 4 to 6 in course of the event.