Relativistic SPE events of the 19th solar cycle: modeling study

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***Abstract* — GLE modeling technique developed during the last decades allows to obtain the characteristics of relativistic solar cosmic rays from the data of ground based cosmic ray detectors. The worldwide network of neutron monitors can be used as multidirectional cosmic ray spectrometer. With the modeling technique employing the optimization methods and modern magnetosphere models the rigidity (energy) spectra, anisotropy axes and pitch angle distributions in the primary solar proton flux can be obtained. Up to the present time with the help of modeling technique the majority of large GLEs of solar cycles 20-23 were investigated. However, some events of the 19th solar cycle remained unexplored. After enough data were assembled, the work on modeling of these GLEs has been completed. This paper describes the results of the modeling analysis of 3 large GLE events of 1960: May 4 (GLE 8), November 12 and 15 (GLEs 10 and 11). The characteristics of relativistic solar protons were derived and their dynamics studied. This allowed to judge about the processes of generation at the sun and also about the subsequent propagation in the IMF, in absence of spacecraft data.**

1. Introduction

19th solar cycle was marked by a number of large GLE (Ground Level Enhancement) events. The paper is devoted to the analysis of three GLEs, which have taken place within 1960: May 4, November 12 and 15. At this time there already existed a network of neutron monitor stations created for the IGY. With data obtained by this network, and modeling technique, the characteristics of relativistic solar protons (RSP) during the GLE events in 1960 were obtained and their dynamics studied. The GLE modeling technique is based on the solving of a reciprocal task (least square problem or optimization task) of obtaining the characteristics of relativistic solar protons (RSP) by comparison of the modeled responses of neutron monitors with observed ones [Shea and Smart, 1982 [1], Cramp et al., 1997 [2]. Asymptotic cones of view of ground based detectors were calculated with magnetosphere model T89 (Tsyganenko, 1989 [3]). We did not use here the more recent magnetosphere model T02 (Tsyganenko, 2002 [4]), because it requires for its definition parameters of IMF and solar wind which were absent in 1960. At the same time, the model T89 requires only the index Kp as a parameter.

By the modeling analysis the characteristics of RSP: rigidity spectra, symmetry (anisotropy) axis direction and pitch-angular distributions were obtained at various moments of time, that has allowed to investigate dynamics of relativistic SCR in all three events. The spectra, obtained from ground based data, well agree with direct measurements on balloons simultaneously carried out, in particularly, by the group of A.N. Charakhchyan from the Lebedev Physical Institute (Charakhch'yan et al., 1962 [5]. For the first time GLE events of 1960 on the data of neutron monitors were described in (Steljes et al., 1961 [6], McCracken, 1962 [7]), and also in (Dorman, 1963 [8]). This paper gives a quantitative study with derived relativistic solar protons parameters and their variations. Together with modeling study of the super GLE 23.02.1956 (Vashenyuk et al., 2007 [9]) the paper finishes the analysis of the largest solar cosmic ray events of 19th solar cycle. As the main source of data concerning the GLE effect on the neutron monitors of the worldwide network in 1960 we used the GLE database [10] of the Australian Antarctic data center (http://data.aad.gov.au/aadc/gle/index.cfm). It is a pity among the available neutron monitor data there are a lot of files with only the hourly time resolution. Thus, a few increase profiles with high time resolution (from 5 to 15 min) were scanned from figures published in (Steljes et al., 1961 [11], McCracken , 1962 [7] and Dorman, 1963 [8].

2. Modeling technique of the ground level events

Using the data of ground based neutron monitor network the parameters of primary solar protons outside magnetosphere can be obtained by a modeling [Shea and Smart, 1982 [1], Cramp et al., 1997 [2]). Our recent modeling technique, in general, is similar to that of [2], as it takes into account the contribution into the neutron monitor response not only vertical, but also oblique incident particles. This kind of analysis requires the data of no less than 20-25 ground-based cosmic ray stations, and consists of a few steps:

1. Definition of asymptotic viewing cones (taking into account not only vertical but also oblique incident on detector particles) of the NM stations under study by the particle trajectory computations in a model magnetosphere [3] with a step in rigidity $\Delta R = 0.001$ GV;
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, rigidity (energy)

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spectrum, anisotropy axis direction, pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations.

Detailed description of the GLE modeling technique is given in [11].

3. The GLE of May 4, 1960

The GLE8 on 4.05.1960 was connected to a flare of importance 3+ and heliocoordinates N13 W90 in the active region McMath 5642. The onsets in H-alpha, radio 9.4 GHz and 536 MHz were detected respectively at 10.00, 10.13 and 10.10 UT (Svestka and Simon ed., 1975 [12]). The increase on neutron monitors started at 10.30±1 UT (Cliver et al., 1982 [13]). In the modeling analysis we used data of 21 neutron monitor stations (Table 1). A few stations has not registered an increase effect, however their data are included in the least square analysis. Fig. 1 shows a number of increase profiles at selected neutron monitor stations. Points show the modeled responses.

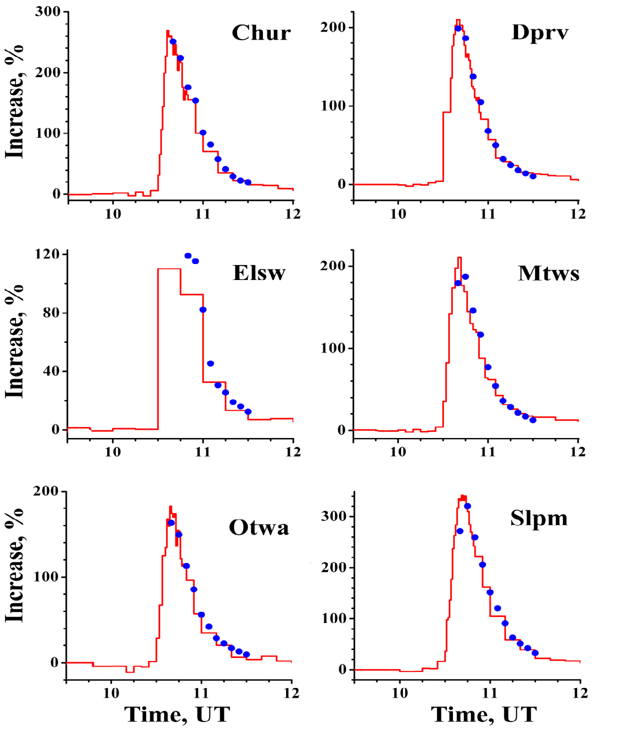

Fig.1. Increase profiles at a number of neutron monitor stations during the 4.05.1960 GLE. Points are the modeled responses. The station titles are: Churchill, Deep River, Elsworth, Mt. Washington, Ottawa, Sulphur Mountain

Increase profiles in Fig. 3.1 are not adjusted to 1000 mB pressure level.

Fig. 2 shows calculated asymptotic cones with the derived axis of symmetry and a pitch angle grid of equal pitch angles. Dynamics of relativistic solar protons in the GLE 4.05.1960 are demonstrated in Fig. 3, where on the data of least square analysis RSP characteristics at the various moments of time are constructed.

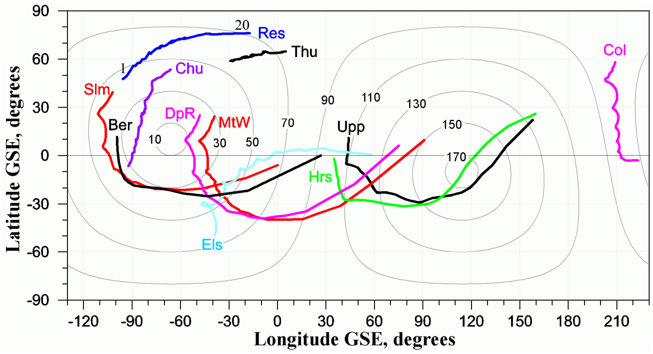

Fig.2. The derived anisotropy axis and pitch angle grid lines for solar proton flux at 10.40 UT, 4.05.1960. The asymptotic cones for vertically incident particles (1-20 GV), the title is placed at the 20 GV end, are shown for the following NM stations: Slm- Sulphur Mountain, Ber-Berkely, Chu-Churchill, DpR –Deep River, MtW- Mount Washington, Els-Elsworth, Res-Resolute, Thu-Thule, Hrs-Herstmonceux, Upp-Uppsala, Col-College.

The GLE 4.05.1960 was characterized by a short duration and very strong anisotropy. In Fig. 3a the characteristic increase profiles at high latitude neutron monitors Ft Churchill and Resolute are shown. Note that Ft. Churchill was collecting radiation with pitch angles in a range of 20-30 degrees and Resolute 40-60 ones (Fig.2). Drastically different profiles at these stations testify an extreme anisotropy during all the event. It can be seen quantitatively in Fig. 3b, where dynamics of modeled pitch-angle distributions are shown. During the most part of event the RSP flux represented strongly focused bunch of particles propagating away from the Sun along the Archimedian spiral direction. Only during the late decrease the small flux (~ 10 % of maximal) from a direction, perpendicular to a symmetry axis of a bunch has appeared. Similar PAD was observed in (Bieber et al., 1980 [14]) on a late phase of a short-lived solar particle event at the weak scattering propagation conditions. In Fig. 3 **c** and **d** the energy spectra derived from the neutron monitors data at the consecutive moments of time, accordingly in double logarithmic (c) and semi-logarithmic (d) scales are shown.

One can see, that during the time interval from 10.40 to 11.15 UT the spectrum has the close to exponential form in a range of energies from 2 to 9 GeV (straight line in the semi log scale). After 11.25 UT the form of a spectrum essentially differs from exponential. This period of time coincides with occurrence of particles with pitch angles 90^{o} (Fig. 3b). In Fig. 3 **c** and **d** the data of direct solar protons measurements with balloons in Murmansk are shown as well. The group of A.N. Charakhchyan from the Lebedev Physical Institute (LPI) [5] carried out the balloon measurements. The good consent of direct solar proton intensity with spectra derived from the ground based neutron monitor can be seen.

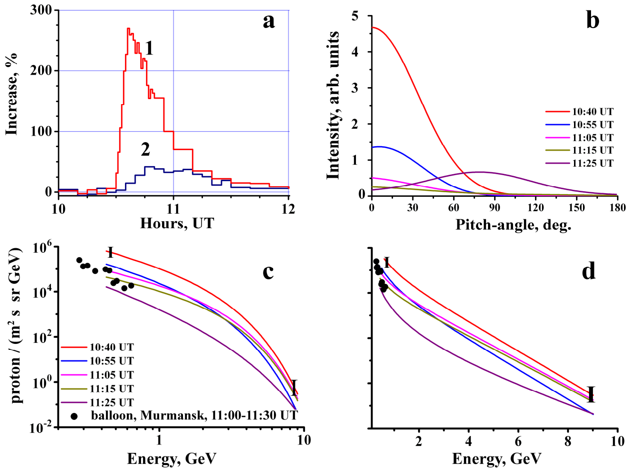

Fig. 3. **a**. Increase profiles during the GLE on May 4, 1960 at the neutron monitor stations: Ft Churchill (1) and Resolute (2). **b.** Dynamics of derived pitch angle distributions, **c,d.** Dynamics of derived energetic spectra in the double logarithmic scale (**c**) and semi logarithmic one (**d**). Black points are the direct solar proton data obtained from the balloon measurements.

4. THE GLE OF NOVEMBER 12, 1960

Three GLEs: 10,11,12, that occurred on November 12, 15, and 20, 1960 were connected to the same active region, McMath 5925, crossing the solar disk from 5 to 18 November [12], [7]. We consider here only GLEs 10 and 11. The event 12.11.1960 (GLE 10), was caused by a flare of importance 3+, heliocoordinates N 27 W 04. The start and maximum of the flare in H-alpha were reported at 13.15 and 13.30 UT, respectively [12]. The increase at neutron monitors began at 13.35±5 UT (Cliver et al., 1982 [13]). At our modeling analysis we used the data of 44 neutron monitors.

Fig. 4 shows a number of increase profiles at selected stations. Points show the modeled responses. By features of the GLE 12.11.1960 was that the arrival of two shock waves from the previous flares in the active region has coincided with it. First SC (the shock from the importance 3, N28 E28 flare on November 10, 10.29 UT) was fixed at 13.48 UT, through 13 min after a GLE onset. The second shock arrived at 18.44 UT (the source was a 2+, N28 E 12 flare on November 11, 03.05 UT) [6],[7]. Together with it the high energy solar protons arrived, which could not reach the Earth earlier and were kept inside a flare ejecta containing a magnetic bottle from the solar flare on 11 November [6],[7]. These protons eventually were transported to Earth inside the magnetic bottle and formed the second maximum at the increase profiles in Fig. 4.

In Fig. 5 the asymptotic view cones of neutron monitor stations are shown together with equal pitch angle grid drawn around the derived anisotropy axis for the moment close to the first maximum. Note, that the anisotropy (symmetry) axis (W 68°, S 14°) during the first maximum (15.39 UT) is close

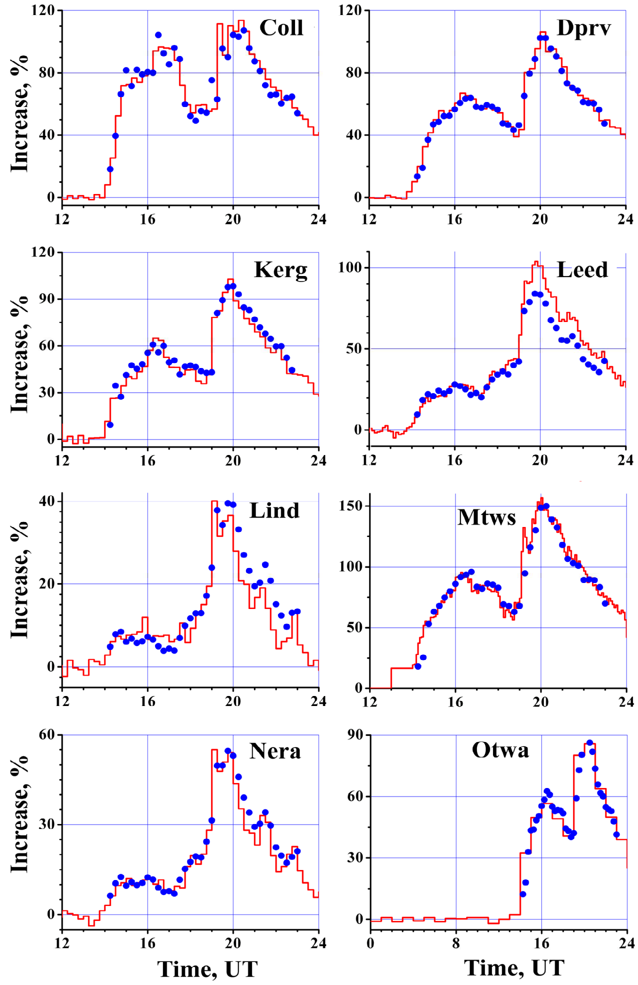

Fig. 4. Increase profiles at a number of neutron monitor stations during the 12.11.1960 GLE. Points are the modeled responses. The titles of stations are: College, Deep River, Kerguelen, Leeds, Lindau, Mt Washington, Nederhorst**,** Ottawa

to the classical Parker spiral IMF direction (W 60^{o}). During the second increase pitch-angular distribution becomes almost isotropic and the derived symmetry axis direction show large variations.

In Fig.6. **a,b** the enhancement profiles at two pairs of neutron monitors: Deep River, Leeds (a) and Munchen, Jungfrau (b) are shown together with energetic spectra and pitch angle distribution dynamics obtained by the modeling from the neutron monitors data.

At the moment of the GLE onset there were two shock waves between the Sun and Earth.. Probably, for this reason a prompt component of relativistic solar protons (RSP) could not reach the Earth. Instead of it the smooth delayed rise of intensity of RSP with a power law energetic spectrum was observed. After arrival of the second shock wave the sharp increase on neutron monitors was observed which has reached a maximum at about 20 hr UT (Figs. 4, 6). Simultaneously with the second increase at neutron monitors, muon telescopes registered the Forbush-effect started at 19.30 UT [6]. The spectrum of RSP during a maximum of the second increase

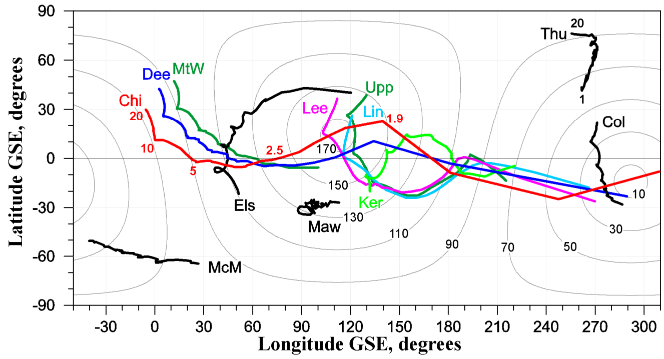

Fig. 5. The derived anisotropy axis and pitch angle grid lines for solar proton flux during the first increase at 15.30 UT, 12.11.1960. Asymptotic cones for vertically incident particles (1-20 GV), the title is placed at the 20 GV end, are shown for the following NM stations: Chi-Chicago, Dee-Deep River, MtW-Mt Washington, McM-McMurdo, Els-Elsworth, Maw-Mawson, Lee-Leeds, Upp-Uppsala, Lin-Lindau, Ker-Kerguelen, Th-Thule, Col-College.

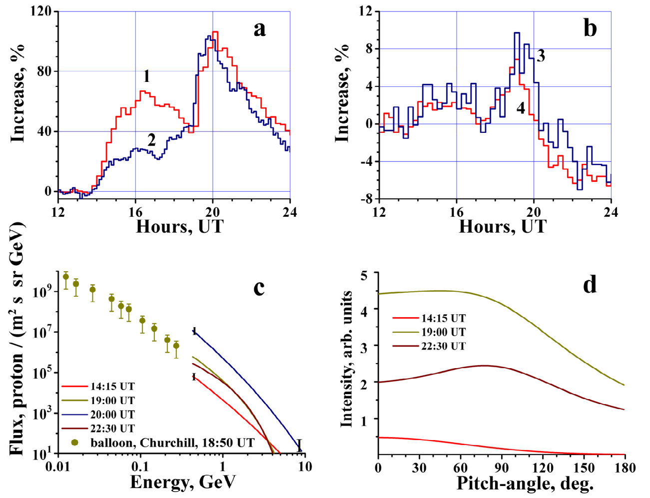

Fig.6. **a:** Increase profiles during the GLE November 12, 1960 at the neutron monitor stations, Deep River(1) and Leeds (2)**, b:** Munchen (3) and Jungfrau (4), **c:** Dynamics of derived energetic spectra**, d:** Dynamics of derived pitch angle distributions. Points in Fig.6 **c** are the direct solar proton data obtained by rocket & balloon measurements [15].

had the pure power law form with a slope close to 6 (Fig. 6c).

It is necessary to note the good consent of a spectrum of solar protons derived from the neutron monitors data with direct measurements of solar protons by rockets and balloons over Ft Churchill **(**Ogilvie et al., 1962 [15]). During the first increase the RSP flux was directed away from the Sun and along the classical direction to the west of the Sun-Earth line. With arrival of the second shock and particles of the second increase the pitch-angular distribution has widened.

5. The GLE of November 15, 1960

The event of 15.11.1960 (GLE 11), was related to a flare of importance 3, heliocoordinates N 27 W 04. The start and maximum in the H-alpha emission were reported at 02.07 and 02.21 UT, respectively [12], the type II radio onset at 02.28 UT and the GLE onset at 02.30 ±5 UT [13]. At our modeling analysis we used data of 49 neutron monitors.

Fig. 7. shows increase profiles at a number of neutron monitor stations during the 15.11.1960 GLE. Not for each of these stations there were data with high (5 or 15 min) time resolution. Nevertheless, responses were calculated for all of them. Example is the Hobart station for which there were only hourly data (Fig. 7). Nevertheless, the good consent between observed and modeled increase values is seen.

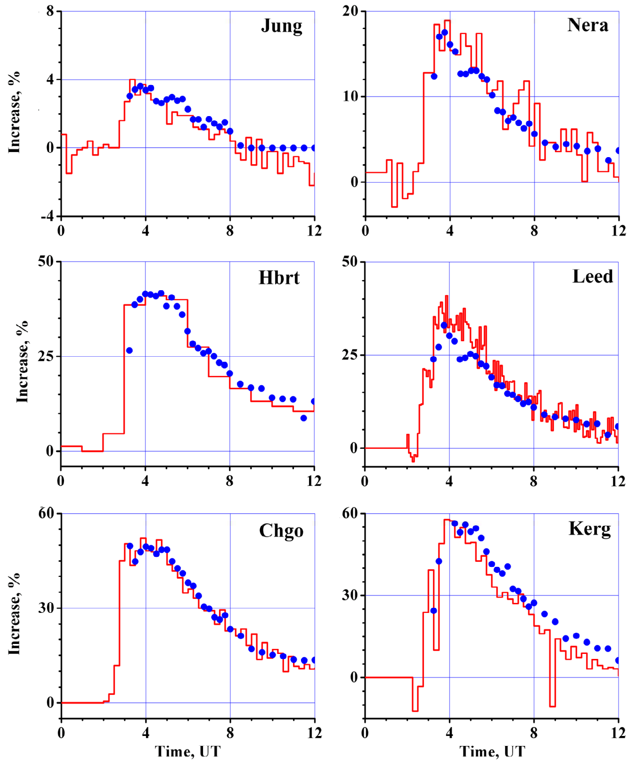

Fig. 7. Increase profiles at a number neutron monitor stations during the 15.11.1960 GLE. Points are modeled responses. The titles of stations are: Jungfrau, Nederhorst**,** Hobart, Leeds, Chicago, Kerguelen.

In Fig. 8 an asymptotic directions map for vertically incident particles is shown for a number of neutron monitor stations. The derived symmetry axis during the increase phase of event was to the West of the classical Parker spiral direction (S11 W83). Fig. 9 demonstrate dynamics of relativistic solar protons based on their modeled parameters derived for different moments of time. Significant anisotropy existed during the GLE onset phase. We can see it on a difference in the initial parts of increase profiles at Uppsala and College stations (Fig.9 a), as well as on the derived pitch-angle distribution (PAD) for the moment 03.15 UT (Fig. 9 b). However already at 4.00 UT the pitch-angle distribution became almost isotropic. At the decline phase of event the maximum in pitch angle distribution has appeared at 90^o. The GLE 15.11.1960 has taken place during a late recovery phase of a Forbush-decrease. Pitch angle distribution with a maximum at 90^o can appear inside a closed loop like IMF structures, which often accompany Forbush - effects.

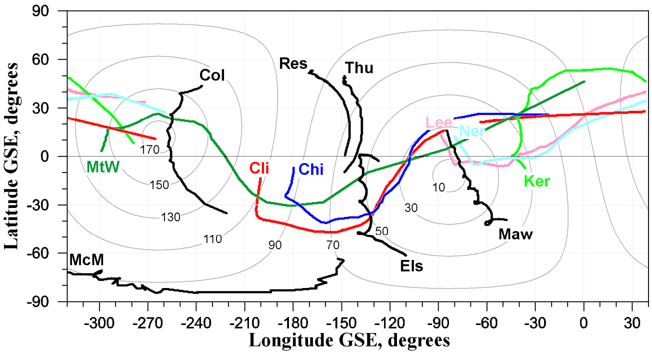

Fig. 8. The derived anisotropy axis and pitch angle grid lines for solar proton flux at 03.30 UT, 15.11.1960. The asymptotic cones for vertically incident particles (1-20 GV), the title is placed at the 20 GV end, are shown for the following NM stations: McM-McMurdo, MtW-Mount Washington, Col-College, Cli–Climax, Res-Resolute, Chi-Chicago, Thu-Thule, Els-Elsworth, Lee-Leeds, Maw-Mawson, Ner-Nederhorst, Ker-Kerguelen.

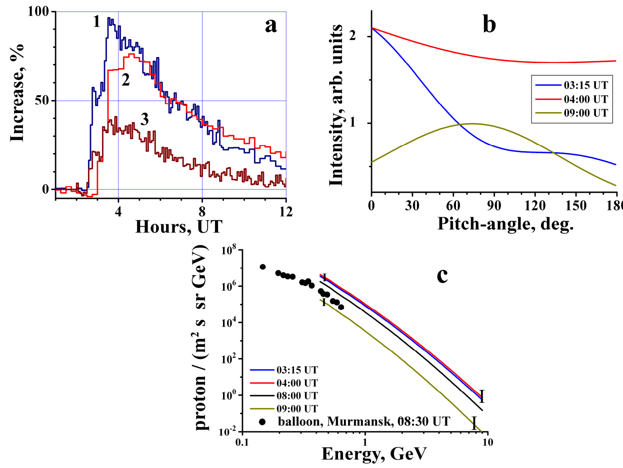

Fig.9. **a**. Increase profiles during the GLE November 15, 1960 at the neutron monitor stations: Uppsala (1), College (2), and Leeds (3). **b** Dynamics of derived pitch angle distributions, **c.** Dynamics of derived energetic spectra, points are direct solar proton data obtained by balloon measurements over Murmansk.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project 07_02_01405) and by the Presidium of the Russian Academy of Sciences (program 6 “Neutrino Physics”).

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