GLE events in 24th solar cycle

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Abstract. Started in 2009, the 24th solar cycle is going to end. In 2015, the solar activity was at its maximum, turning down. According to many indices, this cycle turned out to be abnormal. For instance, in the previous, the 23rd cycle, the index such as the number of solar spots was as high as 175, compared with that of the 24th cycle, not exceeding 100.According to the number of GLE-events (ground level enhancement of solar cosmic rays, observed on neutron monitors), the current cycle also differs greatly from the previous ones. In the 23rd cycle, the number of great GLE-events was as high as four, and that of small and moderate being five. In the 24th cycle, only two GLE-events were recorded: GLE 71 (17.05.2012) и GLE 72 (10.09.2017), with the last event being of small amplitude (5%). The presence of the neutron monitors network data enables calculation of the energy spectrum and other parameters of solar cosmic rays. The GLE-events are processed by special technique developed at PGI. It is aimed at solving the inverse problem: based on the data from the world neutron monitors network, to obtain the parameters of solar cosmic rays energy spectra. Like the previous ones, GLE-events 71 and 72 were processed by this technique. The energetic spectra obtained were compared with those in other events of the previous cycles

1 Introduction

Powerful solar flares are accompanied by coronal mass ejections which are full of a hot plasma with magnetic field. Sometimes, during the solar flares occurrence, energetic particles, mainly protons, are generated, with the energy being of up to 20-30 GeV, though a typical upper limit of energy is 5-10 GeV. These highly energetic particles generated on the Sun, are referred to as solar cosmic rays (SCR). If the SCR-flux reaches the Earth, neutron monitors recording the cosmic rays level, show an enhancement referred to as Ground Level Enhancement (GLE). In some events, the enhancement amplitude was as high as 5000 % (events on 23.02.1956 and 20.01.2005). The amplitude is counted from the base level produced by galaxy cosmic rays continuously coming to the Earth. Compared to an almost isotropic galaxy cosmic rays flux, the solar cosmic rays are highly anisotropic.
Due to it, valuable observations over SCR are possible only through a wide net of neutron monitors (NM) located all over the world. The NM data are used in special techniques to calculate the parameters of the SCR in the interplanetary space. The paper presents the techniques developed at the Laboratory of cosmic rays, PGI. The techniques are based on the solution of the inverse problem: using the least square method, one can determine such

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parameters of the SCR flux that the disagreement between the modeled enhancements in the NM net and the observed ones is minimum [1-3]. The derived SCR-spectra are compared with those obtained by direct measurements on spacecraft and in the stratosphere in the neighboring energy spectrum.

2 GLE 71 and GLE 72 events

Presented below is the analysis of two GLE events which were recorded in the current 24th solar cycle. In the period of the cycle from 2009 to 2018, only these two events were recorded. The average frequency of GLE-events during the previous cycles in the period of 1950-2006 is one event per year. The 24th cycle is poor in GLE events.

2.1 The event on May 17, 2012 (GLE 71)

The event recorded on May 17, 2012, was the first GLE-event in the current 24th cycle of the solar activity, having attracted attention [4]. The solar flare that has generated GLE71, took place in the active zone when it was very close to the western limb. The helio-coordinates of the solar flare are N11W76. The flare was rather weak: 1F/M5.1. It was accompanied by radio emission of the II/3 type (onset 01:31-01:41 UT) and of the IV/2 type (onset 01:32-02:52 UT). The event was unusual in that it was generated by a weak, on many parameters, active region: type is beta, area is 230, the X-rays flare is as small as M5.1. The event took place at calm geomagnetic setting. The event started at 01:54 UT (by Oulu MN data, 1-minute data), having reached the greatest amplitude 18% at 02:08 UT at the same station. Apatity station has recorded the enhancement in maximum, which was of the same amplitude. The South Pole station, in reducing to the sea level, has recorded the enhancement amplitude being equal to 8%. This value is the third one in GLE. According to the greatest enhancement values recorded by the stations, the event lasted about one hour.

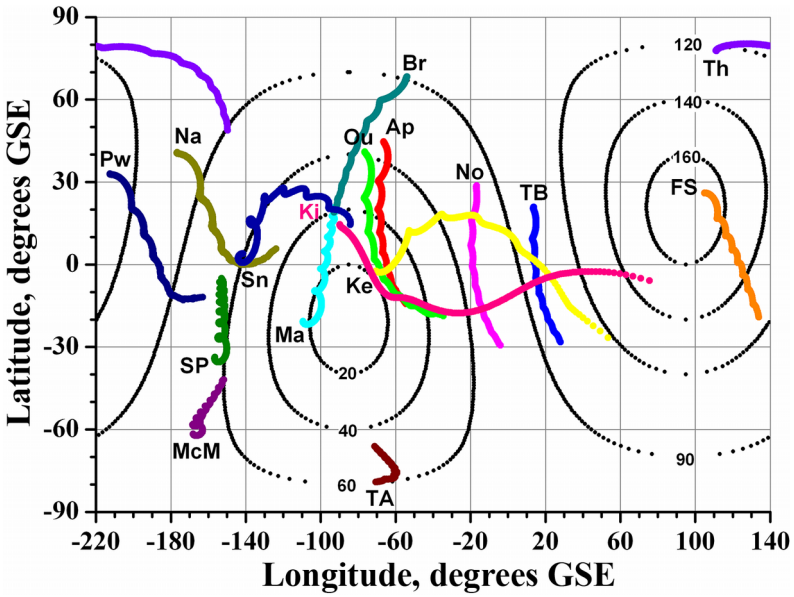

Fig.1. Asymptotic cones recorded by the NM at a number of stations. The lines of the equal pitch-angles, relative to the direction of the interplanetary magnetic field, are in dots. It was used Tsyganenko-01 model [5].

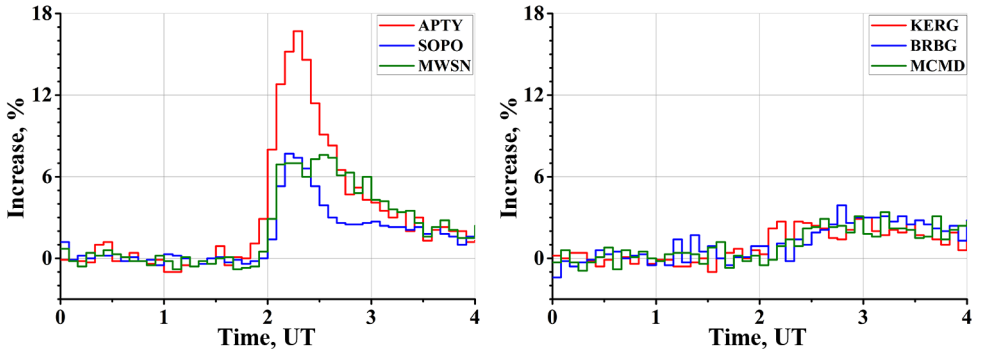

Fig.2. The enhancement profiles at the stations.

The absence of enhancement at the stations with cutoff rigidity over 4 GeV points to the fact that the SCR spectrum was soft. Due to the technique of the inverse problem solution the basic SCR characteristics were determined by the NM-stations data: the spectrum, the width of the pitch-angle distribution and the anisotropy axis position. The data from 27 NM were analyzed in total. The asymptotic cones were calculated with the Tsyganenko-01 model. The solutions have been made with a 5-minute interval for an hour since 02:10 UT. The results are shown in Figures below. During the event the SCR energy spectrum is exponential (the direct line is on a semi-logarithmic scale) with the characteristic energy of E0 ~ 0.4 GeV. The anisotropy axis position is determined as $\theta = -23°$, $\varphi = -95°$, which is quite good with the direction of the interplanetary magnetic field. The pitch-angle distribution shows that at the initial phase (02:10 UT), the event was highly anisotropic, but at the intermediate phase there appeared particles moving in the opposite direction. The peculiarity (gap) is observed at pitch-angles of about 90°. Such a gap is explained by the fact that the particles at 90 pitch-angle drift along the magnetic field lines at a velocity which is several times less than their intrinsic velocity. For instance, at pitch-angle equal to 60°, the particle drift is a half of intrinsic velocity.

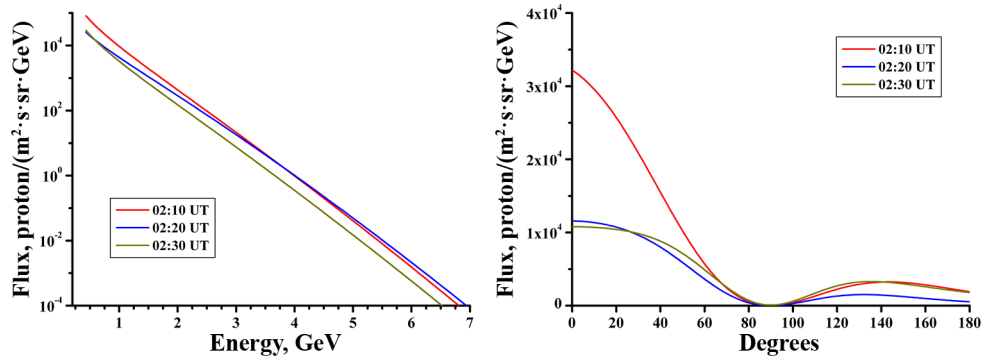

Fig.3. The SCR energy differential spectra in the event on 17.05.2012 and the pitch-angle distribution of the flux.

2.2 The event on 10.09.2017 (GLE 72)

In 2017, there was recorded a new GLE event. It is the second event in the current cycle. The event was generated by an active region of the type "Beta-Gamma-Delta", which has produced a series of great solar flares in September 2017. The X-flare which generated the

event, was of X8.2 class (the flare coordinates - S08W83), started at 15:35 UT, with its maximum being reached at 16:06 UT. The enhancement amplitude on NM did not exceed 6% by five-minute data, but it is clearly observed by dozens of stations attached to the world NM network.

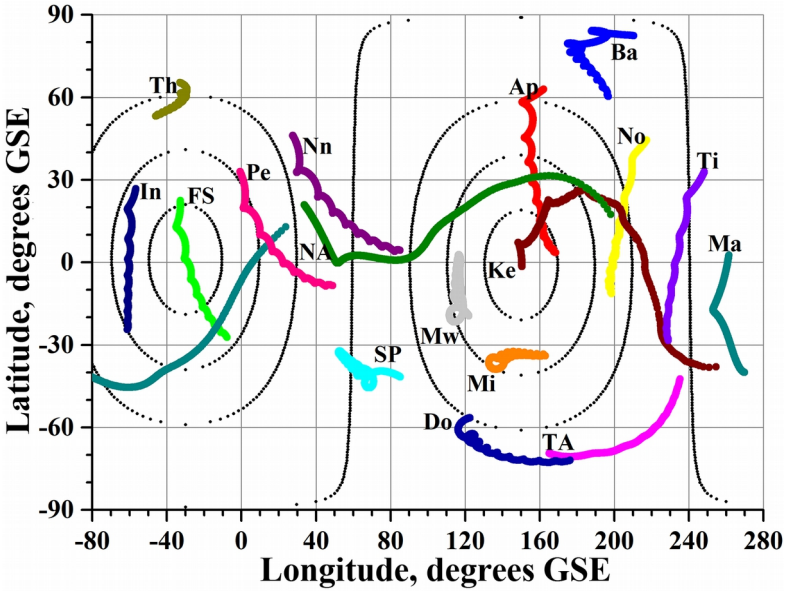

Fig.4. Asymptotic cones calculated at a number of NM stations. In – Inuvik, Th – Thule, FS – Fort Smith, Pe – Pewanuk, Nn – Nain, NA – New Ark, SP – South Pole, Mw – Mawson, Do – Domc, Mi – Mirny, Ke – Kerguelen, Ap – Apatity, TA – Terre Adelie, Ba – Barentsburg, No – Norilsk, Ti – Tixie, Ma – Magadan. It was used Tsyganenko-01 model. It should be noted that the difference in the position of the stations Inuvik and Fort Smith cones are as low as 40-50 grades. Black dots are the lines of equal pitch-angles relative the anisotropy axis determined.

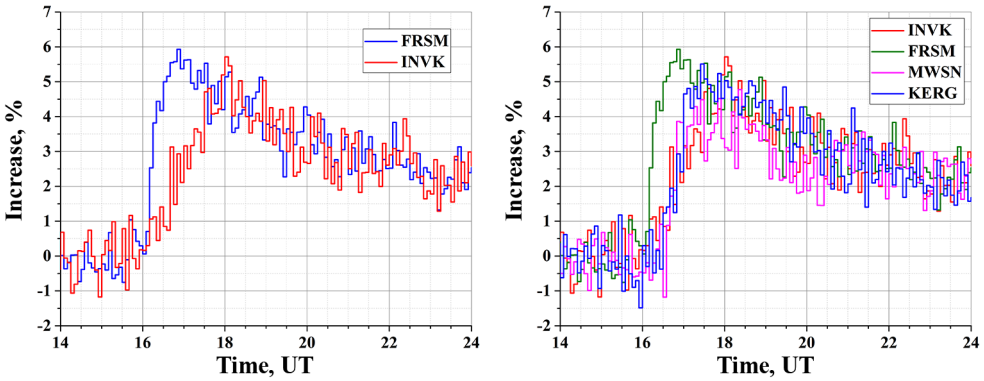

Fig.5. The enhancement profiles at a number of stations. Left – Inuvik and Fort Smith, two next stations, whose cones are rather close. Right – the profiles of the stations remote or closely located to the Fort Smith station.

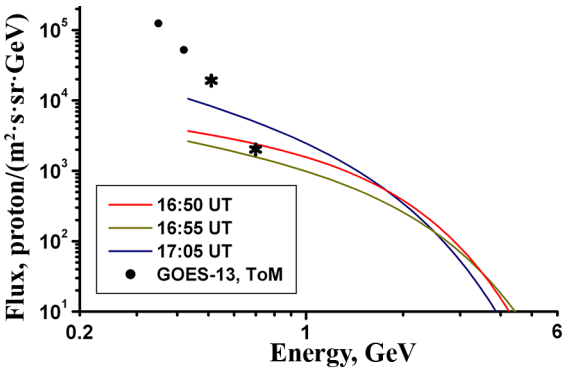

Fig.6, The SCR spectrum obtained as a result of the inverse problem solution. Asterisks show the data of GOES-13 corresponding to the measurements at 16:50-17:15 UT. ToM (Time of Maximum) - the techniques used to determine the SCR energy spectrum by the time of delay of the protons of different energy arrival to the Earth.

The difference in the profiles at the initial GLE phase (Fig.5, left) means that the solar relativistic proton flux (>500 MeV, the threshold of atmospheric cutof) was narrow, and only in 30-40 minutes it has become close to an isotropic one (all the stations have simultaneously shown an increase, Fig.5, right). The maximum amplitude of the event did not exceed 6 %. The spectrum is between the exponential and power law forms at $\gamma \approx$ -3.8....-4. For the SCR, such index means a rigid spectrum.

3 Discussion

The current 24th solar cycle is characterized by a very small quantity of great surface SCR events, though in terms of the number of SCR events of lower energy recorded in the interplanetary space, the current cycle little differs from the previous ones [6]. Since the beginning of the cycle in 2009, two events were recorded: on 17.05.2012 and 10.09.2017. Both events occurred at a relatively calm interplanetary currency. At the initial phase (before maximum), the events were highly anisotropic, and at the phase of decrease the events changed for isotropic ones. The events greatly differ here in the SCR flux spectrum. In the first event, the spectrum was exponential through all the enhancement phase, in the second event, the spectrum was a mixture that lies somewhere between an exponential and a power law form. The difference between the exponential and power law form spectra is in that in the case of high energies, the depression in the exponential spectrum is faster and this spectrum contains relatively less highly energetic particles which penetrate much deeper layers of the atmosphere.

The derived spectra were used in other studies dealing with calculations of air ionization at different altitudes in the atmosphere, from 80 km to the Earth surface level. The spectra can also be used in radiation dose calculations.

4 Conclusion

The current 24th solar cycle is poor in the events of the solar cosmic rays recorded by the ground neutron monitors network. Since 2009, the beginning of the current cycle, there were only two events (17.05.2012 and 10.09.2017), when the average frequency of GLE event is one per year. Both events are of moderate amplitude. The method of the inverse problem solution by the ground observations has derived the parameters of the SCR-spectra

in the interplanetary space. The calculations were made with a five-minute interval. The events spectra differ significantly: an exponential form in the first event, and a close to the power law one in the second event.

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