The energy spectrum of solar cosmic rays during periods of their ground level enhancements

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Abstract. By data of the neutron monitor worldwide station network the events of ground level enhancements of solar cosmic rays are studied. The absolute flow $J$ and the energy spectral index $\gamma$ of solar cosmic rays during the isotropic phase for 14 GLE events observed for 1977-2006 have been estimated using the method of effective energy by [1]. It is shown that in these events the changes of the power spectral index in the range from 3 to 7 are observed. It is noted that for the individual events the index about 5 is observed for a long time.

1. Introduction

In the paper [1] a new original method allowing to estimate an absolute flux $J$ and index of energy spectrum $\gamma$ of solar cosmic rays (SCR) during periods of events of their ground level enhancements (GLE) is presented. Unlike a complex numerical calculation method of spectra proposed in [2, 3], this method is simple and applicable only for calculations of the isotropic part of GLE events. The essence of the proposed method consists in the determination of effective impulse $P_{\text{eff}}$ (or effective energy $E_{\text{eff}}$) for each CR station which have registered GLE. At this energy the calculated absolute flux of SCR $J$ does not change at small changes of energy spectral index $\gamma$.

For example, in Fig.1 the SCR energy spectrum for the event on December 13, 2006 is shown [1]. Fig.1 presents the data of direct measurements of SCR fluxes aboard the GOES-11 satellite, and also calculation results of SCR fluxes by data of the neutron monitor worldwide network [3] and according to the method [1]. It is seen from Fig.1 that the data of direct measurements are in satisfactory agreement with calculation results [3] and our calculations. It means that the method suggested in [1] describes the observable SCR spectrum correctly. Note, that, in general, the SCR spectrum in a wide energy range is nonmonotonic but in the relativistic energy range in the most cases the spectrum can be described by a power function of $J(E) \sim E^{-\gamma}$ form [4].

Below the results of analysis of SCR spectra dynamics for 14 events observed for the 1977 to 2006 period obtained with the help of the method described in [1] are presented.

2. Experimental data and results

For the calculation of GLE spectral index $\gamma$ we have used the data of measurement at 28 neutron monitor stations. The data of high-mountainous stations have been excluded from our analysis. For each event a set of stations (from 8 to 17) with various thresholds of the geomagnetic cut-off rigidity has been selected. For the exclusion of influence of anisotropy effects during the growth phase of event, the calculations have been carried out only in 60 minutes after the beginning of GLE. The calculations of spectral index $\gamma$
Figure 1. Energy spectrum of SCRs on December 13, 2006 at 03 : 25 UT according to the direct measurements by the GOES-11 satellite (closed blue circles) and the data by the worldwide neutron monitor network (solid line: calculations [3]; opened red circles: the results derived by calculations based on the proposed method).

have been carried out in the range of 3 to 7 with a step of 0.1. Table 1 shows the values of index $\gamma$ for all selected 14 GLE events in every 15 minutes from 2-nd to 4-th hour of measurements after the beginning of enhancement. In the first column the event number is shown, in the second one the starting time of calculation of $t_1$ is depicted, in the rest of 12 columns the estimations of value of SCR spectral index $\gamma$ are given. The symbols at index $\gamma$ mean the ordinal number of calculation. The error of estimation of the spectral index $\gamma$ does not exceed 0.1.

Table 1. Values of the SCR spectral index $\gamma$ for the selected 14 GLE events.

| GLE | $t_1$     | $\gamma_1$ | $\gamma_2$ | $\gamma_3$ | $\gamma_4$ | $\gamma_5$ | $\gamma_6$ | $\gamma_7$ | $\gamma_8$ | $\gamma_9$ | $\gamma_10$ | $\gamma_11$ | $\gamma_12$ |
|-----|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 30  | 1977-11-12 11:00 UT | 4.7 | 4.8 | 4.9 | 5.0 | 5.1 | 5.3 | 5.6 | 5.6 | 5.6 | 5.9 | 6.1 | 6.4 |
| 42  | 1989-09-29 12:45 UT | 3.5 | 3.5 | 3.5 | 3.6 | 3.6 | 3.6 | 3.7 | 3.9 | 4.0 | 4.1 | 4.1 | 4.2 |
| 43  | 1989-10-19 15:00 UT | 4.8 | 5.0 | 5.2 | 5.3 | 5.3 | 5.5 | 5.7 | 5.7 | 5.7 | 5.8 | 5.8 | 5.8 |
| 44  | 1989-10-22 19:00 UT | 5.9 | 5.9 | 5.6 | 5.6 | 5.6 | 5.6 | 5.6 | 5.7 | 5.7 | 5.8 | 5.8 | 5.8 |
| 45  | 1989-10-24 19:30 UT | 4.6 | 4.7 | 4.9 | 5.0 | 5.0 | 5.1 | 5.2 | 5.3 | 5.3 | 5.4 | 5.4 | 5.4 |
| 47  | 1990-05-21 23:30 UT | 3.3 | 3.4 | 3.3 | 3.9 | 4.6 | 4.6 | 4.7 | 4.9 | 4.9 | 4.9 | 5.2 | 5.2 |
| 48  | 1990-05-24 22:00 UT | 4.8 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.1 | 5.4 | 5.5 | 5.5 | 5.5 | 5.7 |
| 52  | 1991-06-15 09:45 UT | 4.9 | 5.0 | 5.0 | 5.1 | 5.1 | 5.1 | 5.2 | 5.2 | 5.2 | 5.3 | 5.3 | 5.3 |
| 55  | 1997-11-06 13:30 UT | 3.9 | 4.0 | 4.2 | 4.4 | 4.6 | 4.9 | 4.9 | 5.1 | 5.1 | 5.2 | 5.2 | 5.2 |
| 59  | 2000-07-14 11:30 UT | 6.3 | 6.3 | 6.5 | 6.6 | 6.6 | 6.6 | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 | 6.8 |
| 60  | 2001-04-15 15:00 UT | 5.6 | 5.6 | 5.7 | 5.7 | 5.7 | 5.8 | 5.8 | 5.8 | 5.8 | 5.8 | 5.8 | 5.9 |
| 65  | 2003-10-28 12:15 UT | 4.7 | 4.7 | 4.8 | 4.8 | 4.8 | 4.9 | 4.9 | 5.0 | 5.0 | 4.9 | 4.9 | 4.8 |
| 69  | 2005-01-20 07:45 UT | 5.2 | 5.2 | 5.2 | 5.2 | 5.3 | 5.4 | 5.5 | 5.5 | 5.5 | 5.6 | 5.6 | 5.6 |
| 70  | 2006-12-13 03:45 UT | 4.9 | 5.2 | 5.2 | 5.2 | 5.3 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.5 |

As follows from Table 1, in the most cases the SCR spectra undergo the specific dynamic changes. In some events the spectra become considerably are softened, and the values of index $\gamma$ in a general case changes from 3.5 up to 6.8. Herewith, for the separate events these changes reach great values up to 1.7. However, in some cases (for example, for GLE44 and GLE52 events) the spectral index changes very weakly and practically keeps the constant value for a long time.

For example, Table 2 presents the effective energies $E_{eff}$ and particle fluxes $J$ for the GLE45 event.
registered by the worldwide neutron monitor network on October 24, 1989 and calculated by data of various stations. Fig. 2 shows the picture of dynamic changes of the expected and calculated SCR spectra corresponding to Table 2. The analysis testifies that in this event the SCR spectrum undergoes softening in the course of time from $\gamma = 4.6$ to $\gamma = 5.4$. It, apparently, reflects propagation conditions of SCRs in the interplanetary medium from the Sun to the Earth and perhaps the nature of particle injection at the Sun.

### Table 2.

| Station | $E_{\text{eff}}$ | $J$ | $E_{\text{eff}}$ | $J$ | $E_{\text{eff}}$ | $J$ | $E_{\text{eff}}$ | $J$ |
|---------|-----------------|----|-----------------|----|-----------------|----|-----------------|----|
| TERA    | 2.30            | 2587 | 1.98            | 6802 | 1.85            | 9133 | 1.74            | 10653 |
| APTY    | 2.30            | 2128 | 1.98            | 5183 | 1.85            | 7049 | 1.74            | 8237  |
| OULU    | 2.33            | 1941 | 2.02            | 4773 | 1.90            | 6298 | 1.79            | 7332  |
| SANA    | 2.45            | 1528 | 2.15            | 3555 | 2.04            | 4493 | 1.94            | 5504  |
| KERG    | 2.53            | 1446 | 2.24            | 3055 | 2.12            | 4165 | 2.03            | 4992  |
| YKTK    | 3.17            | 523  | 2.88            | 1064 | 2.77            | 1187 | 2.67            | 1277  |
| NEWK    | 3.42            | 313  | 3.12            | 494  | 3.01            | 527  | 2.91            | 512   |
| MGDN    | 3.68            | 358  | 3.38            | 559  | 3.26            | 557  | 3.16            | 580   |
| KIEL    | 3.81            | 240  | 3.51            | 376  | 3.39            | 372  | 3.29            | 358   |
| MOSC    | 4.08            | 224  | 3.77            | 352  | 3.65            | 359  | 3.55            | 332   |
| NVBK    | 4.80            | 101  | 4.47            | 136  | 4.34            | 121  | 4.23            | 116   |
| IRKT    | 5.40            | 40   | 5.05            | 50   | 4.91            | 39   | 4.79            | 34    |
| HERM    | 7.41            | 7    | 6.99            | 7    | 6.82            | 6    | 6.67            | 5     |

### Figure 2.

The dynamics of SCR spectra for the GLE 45 event are shown. At the top of pictures the number of event, values of the spectral index slope, and also the time corresponding to the above SCR spectrum are shown. The values of SCR fluxes calculated by neutron monitor data by means of the method [1] are shown by blue crosses; the expected theoretical SCR spectra are shown by the red line.

The event of GLE71 taken place on May 17, 2012 has been registered only at several CR stations (http://www.nmdb.eu). It is of short duration (less than 2.5 hours) and has a major anisotropy. The preliminary analysis of this event carried out by us by data of the SOPO, APTY, OULU and YKTK
stations by means of the method [1], shows that the flare’s spectrum is very soft. The spectral index $\gamma$ during the decay phase of the GLE71 event from 02:15 UT up to 03:00 UT is of value from 6.9 to 7.2.

3. Conclusion
Thus, on the basis of investigation conducted by us one can make the following conclusions:

1. The dynamics of the SCR energy spectra for the 14 selected GLEs have been calculated.
2. It is shown that in the investigated events the change of spectral index $\gamma$ within the 3.5 to 6.8 interval is observed. In this case, for the separate events the interval of changes of index $\gamma$ accounts for the value from 0.3 to 1.7.
3. It is noted that for the individual events the spectral index $\gamma$ changes very weakly and practically keeps a constant value for a long time.

Acknowledgments
We wish to thank the World Data Center for Solar-Terrestrial Physics (Moscow, Russia, http://www.wdc.ru), the Australian Antarctic Data Centre (http://data.aad.gov.au) and the NMDB database (http://www.nmdb.eu), founded under the European Union’s FP7 programme (contract no. 213007), for providing data. This work was supported by the Russian Foundation for Basic Research (projects Nos. 10-02-00877-a, 12-07-00227-a and 12-02-98507-r_a), Program No. 10 of the Presidium of the Russian Academy of Sciences, and grant No. NSH-1741.2012.2 from the President of Russia for support of leading scientic schools.

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