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PITCH-ANGLE ANISOTROPY AND DIFFERENTIAL RIGIDITY SPECTRA OF COSMIC RAYS DURING GLE ON MAY 2 AND 6, 1998

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Abstract. Using data from the worldwide network of neutron monitors (39 stations) and the method of global spectrographic survey, we have studied pitch-angle anisotropy and differential rigidity spectra of cosmic rays during the ground level enhancements on May 2 and 6, 1998. We obtained differential rigidity spectra of solar cosmic rays in these events and determined the maximum rigidities to which protons accelerated. The maximum rigidities of accelerated protons during the ground level enhancements on May 2 was ~2.4; on May 6, ~1.8 GV. The revealed bidirectional pitch-angle anisotropy indicates that Earth was in the IMF loop structure during these events.

Keywords: cosmic rays, ground level enhancement, anisotropy, rigidity spectrum.

INTRODUCTION

Solar cosmic rays (SCRs) are charged particle fluxes accelerated to high energies in the Sun's upper atmosphere during solar flares. SCRs are recorded near Earth as sudden sharp increases in CR intensity. Increases in fluxes of solar proton events (SPEs) with energies above 500 MeV detected on Earth are called Ground Level Enhancements (GLE).

While the number of GLE events is only ~5 % of SPEs, many publications have been devoted to their study [Smart, Shea, 1991; Cliver, 2006]. GLE events began to be numbered on February 28, 1942 (GLE No. 1) once detected by ionization chambers [Smart, Shea, 1991]. By now, 73 events have been recorded [http://gle.oulu.fi; http://nmdb.eu/nest]. GLE events occur during local short-term sunspot maxima and are a manifestation of intense bursts of solar activity (SA) [Cliver, 2006; Belov et al., 2010]. GLE research is important for understanding the mechanisms of acceleration and propagation of charged particles on the Sun and in the interplanetary medium, for ensuring radiation safety during spacecraft flights, preventing major accidents at power plants, etc.

The most significant sporadic variations in CR intensity are associated with flares and coronal mass ejections (CMEs) [Reames, 1999; Miroshnichenko, Perez-Peraza, 2008], followed by changes in interplanetary magnetic field (IMF) and solar wind (SW) parameters. GLE events occur most often during SA maximum and decay phases [Shea, Smart, 1990]. According to [Bazilevskaya et al., 2004; Belov et al., 2005], accelerated particles are most often related to >M5 X-ray flares, but not every large flare is accompanied by a relativistic proton flux.

According to the international GLE database [http://gle.oulu.fi], there were 16 GLE events in solar cycle 23.

May 1998 is related with the ascending phase of solar cycle 23 during which a number of CR events took place. During the month, several active regions were observed on the Sun, but the most significant events are associated with the active region (AR) 8210, in which over the period April–May 1998 four X-class flares, five M-class flares, and 22 C-class flares were recorded. At that time, 16 Forbush effects (FE) [http://spaceweather.izmiran.ru/rus/fds1998.html] and 2 GLE events [http://gle.oulu.fi; http://nmdb.eu/nest; Usoskin et al., 2015] occurred.

Various aspects of the May 2 and 6 CR events have been explored in [Danilova et al., 1999; Belov et al., 2000; Richardson et al., 2000; Petukhov et al., 2003; Logachev et al., 2015; Thakur et al., 2016; Kocharov et al., 2017]. In this work, from ground-based measurements made at the worldwide network of CR stations using the method of global spectrographic survey (GSS) we have obtained differential rigidity spectra and pitch-angle anisotropy of CRs, originated from the same AR, for May 2 and 6 GLE events. The novelty of this work lies in the fact that when studying the May 2 and 6 GLE events by the GSS method we have determined the maximum rigidities to which particles accelerated and have found out that on May 6 Earth was in the IMF loop structure.

CONDITIONS IN INTERPLANETARY SPACE IN MAY 1998

A source of solar flares associated with the May 2 and 6 GLE events (GLE56 and GLE57) was AR 8210: on May 2, an X1.1/3B flare appeared in this region (coordinates S15W15, beginning at 13:31, maximum at 13:42, ending at 13:51 UT, the maximum proton flux (IMP, GOES) >10 MeV is 150 pfu; >100 MeV, 9.2 pfu). CME occurred at 14:06 UT, its velocity V=938 km/s [https://www.

solarmonitor.org; http://omniweb.gsfc.nasa.gov; http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/1998_05/univ1998_05.html].

In the same AR 8210 on May 6, an X2.7/1N flare was observed (coordinates S11W65, beginning at 07:58, maximum at 08:09, ending at 08:20 UT, the maximum proton flux (IMP, GOES) >10 MeV is 210 pfu; >100 MeV, 5.4 pfu). CME was recorded at 08:29 UT, V=1099 km/s [https://www.solarmonitor.org; http://omniweb.gsfc.nasa.gov; http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/1998_05/univ1998_05.html].

During the May 2 GLE event there were the following IMF parameters: IMF modulus ~14 nT, SW velocity ~600 km/s, SW proton temperature ~$0.1\cdot10^6$ K, density ~5 particles/cm^3. At 09:00 UT on May 6, the following SW parameters were recorded: IMF modulus ~8 nT, SW velocity ~500 km/s, temperature ~$0.1\cdot10^6$ K, and SW proton density ~0.5 particles/cm^3.

The *Kp* index increased to 7 on May 2 and did not exceed 5 on May 6 [https://www.spaceweatherlive.com/ru/arhiv/1998/05/02/kp.html].

Petukhov et al. [2003] have indicated that during the May 2 event the large-scale magnetic clouds from previous disturbances that crossed Earth's orbit caused local variations in the intensity of low-energy SCRs. Belov et al. [2000] observed a significant IMF deviation from the helical direction, bidirectional pitch-angle anisotropy in CR distribution, and a complex GLE pattern as a result of Earth entering CME caused by preceding solar activity.

GLE56 was observed against the background of the FE that began on May 1 at 21:56 UT. The FE was associated with the arrival of a magnetic cloud at Earth, in which it was until the arrival of the disturbance from the May 2 flare, which became a source of relativistic solar protons (RSPs) [Belov et al., 2000]. A maximum increase was recorded at Oulu CR station at 14:05–14:10 UT and was as large as ~7 % in five-minute data [Belov et al., 2010].

GLE57 occurred against the background of the interplanetary disturbances that began on May 1. A maximum increase was seen on neutron monitors at Oulu CR station on May 6 at 09:30–09:35 UT and, according to five-minute observations, was ~4 % [Belov et al., 2010]. Logachev et al. [2015] have indicated that on May 6 there was a minimum proton flux >1000 MeV of all GLE events in solar cycle 23. During the May 6 GLE event, GOES did not record an increase in the >700 MeV proton flux (~1.3 GV rigidity) [Kühl et al., 2017]. Thakur et al. [2016] have established that there is a relationship between GLE in SA cycles 23–24 and an intensity increase according to GOES observations. The absence of an increase in the >700 MeV proton flux according to GOES-08, 09 data during GLE57 is an exception among all GLE events of SA cycles 23 and 24 [Thakur et al., 2016].

In [Danilova et al., 1999; Danilova et al., 2002] it was noted that GLE56 saw bidirectional pitch-angle anisotropy of solar protons, as a consequence of Earth entering CME. IMF inside CME often has a loop structure with bidirectional pitch-angle anisotropy.

Belov et al. [2000] have indicated that on May 2 Earth was inside CME in the form of a loop structure with both footpoints on the Sun. When Earth enters this structure, we can see bidirectional pitch-angle anisotropy.

Stoker [2002] has found that there were no accelerated protons with rigidity above 4 GV in the May 2 event.

DATA AND METHOD

The GLE56 and GLE57 events were analyzed using the GSS method [Dvornikov and Sdobnov, 1998] based on data from the worldwide network of neutron monitors (39 neutron monitors) [ftp://cr0.irmiran.rssi.ru], corrected for pressure and averaged over hourly intervals. The GOES-9 proton measurements in Earth's orbit were taken from [http://satdat.ngdc.noaa.gov./sem/goes].

The GSS method can identify CR variations of interplanetary and magnetospheric origin. For the calculations, a ground-based recording equipment system (the worldwide network of neutron monitors located at different levels in Earth's atmosphere) is used as a single multichannel device that scans the celestial sphere and collects information from each station in a certain asymptotic cone. Compared to individual CR stations, the multichannel system ensures reliability and continuity of measurements, high statistical accuracy, and minimizes instrumental variations. This makes it possible to calculate phases of the first and second pitch-angle anisotropy harmonics, to determine variations in rigidity spectra of isotropic component and anisotropy, and to obtain information about IMF orientation from the pitch-angle anisotropy phase. Moreover, using CR intensity observations at mid- and low-latitude stations and the GSS method, we can identify changes in the planetary system of geomagnetic cutoff rigidities per observation hour. The root-mean-square solution errors, taking into account statistical errors in observation data from CR stations of the worldwide network and errors introduced by the model, average ~0.4–0.5 %; when determining by the GSS method, amplitudes of rigidity spectrum variations and amplitudes of CR pitch-angle anisotropy are ~1–2 %, changes in the planetary system of geomagnetic cutoff rigidities, ~0.05–0.07 GV [Kravtsova and Sdobnov, 2019].

The CR modulation amplitudes were measured from the background level on April 30, 1998.

RESULTS AND DISCUSSION

Figure 1 *a*, *b* presents estimated amplitudes of the first A_1 and second A_2 spherical harmonics of CR pitch-angle anisotropy for particles with R=4 GV from May 1 to 6. Also shown are variations in the geomagnetic cutoff rigidity ΔR at a point with threshold rigidity R=4 GV together with the *Dst* index (panel *c*). On May 2, an increase in the first pitch-angle anisotropy harmonic to ~35 % was observed; on May 6, to ~25 % (panel *a*). On May 2 at 14:00 and on May 6 at 09:00 UT, an increase was found in the amplitude of the second pitch-angle anisotropy harmonic to ~11 and 6 % respectively (panel *b*).

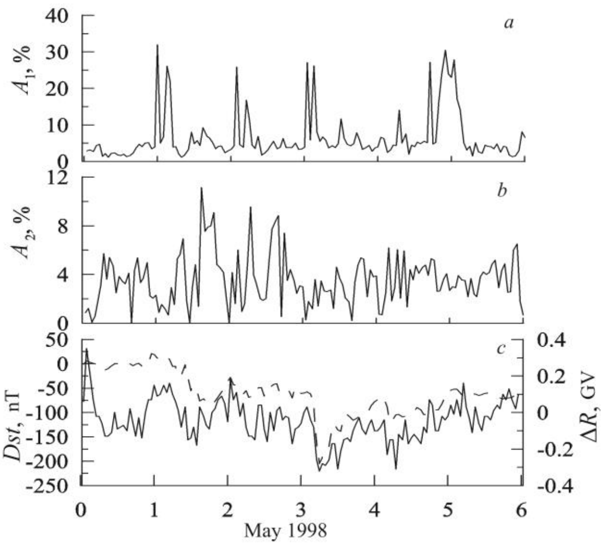

Figure 1. Amplitudes of the first A_1 and second A_2 harmonics of pitch-angle distribution of CRs with a rigidity of 4 GV (*a*, *b*); *Dst* index (solid line, left scale) and variations in geomagnetic cutoff rigidity Δ*R* for *R*=4 GV (dashed line, right scale) (*c*)

The May 2 event occurred during the FE that began on May 1 at 21:56 UT against the background of a geomagnetic disturbance (*Dst*~–80 nT). Geomagnetic cutoff rigidities in Irkutsk varied from ~–0.16 to ~0.20 GV (panel *c*). The May 6 event took place during the recovery phase of FE, which began on May 4 at 02:15 UT, and a geomagnetic storm (*Dst*~–70 nT). During this period, geomagnetic cutoff rigidities in Irkutsk varied from ~–0.17 to ~0.20 GV (panel *c*).

Isolines in Figure 2 show the relative variations in CR intensity (without division into GCR and SCR) with a rigidity *R*=4 GV in the solar-ecliptic geocentric coordinate system for the moments of maximum ground level enhancement on May 2 and 6.

One can see a complex angular distribution of CR intensity with a rigidity of 4 GV along the directions of particle arrival. For example, an increased particle flux with a rigidity of 4 GV was observed on May 2 at 14:00 UT from the directions of ~20°, ~–30° and ~180°, ~30° (panel *a*). The results on CR pitch-angle anisotropy agree with those obtained in [Belov et al., 2000].

Bidirectional pitch-angle anisotropy with increased intensity was observed on May 6 at 09:00 UT from the directions of ~70°, ~15° and ~265°, ~0° (panel *b*).

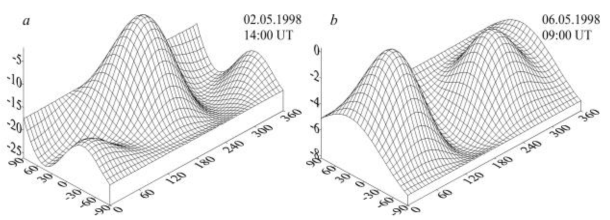

Figure 2. Relative variations in CR intensity with *R*=4 GV in the solar-ecliptic geocentric coordinate system on May 2 at 14:00 (*a*) and on May 6 at 09:00 UT (*b*). The X-axis is the longitudinal angle ψ; the Y-axis is the latitudinal angle λ, the Z-axis is the amplitude of particle intensity variations as a percentage of the background level

The increase in the amplitude of the second pitch-angle anisotropy harmonic A_2 suggests that during the events described Earth was inside the IMF loop structure [Richardson et al., 2000].

In [Danilova et al., 1999; Belov et al., 2000; Danilova et al., 2002], devoted to the study of GLE56, bidirectional pitch-angle anisotropy was also found and a conclusion was drawn that there was an IMF loop structure which Earth entered during that period.

Figure 3 presents differential rigidity spectra of CRs for May 2 and 6 together with GOES-9 data: before the event (curves 1) and during the event (curves 2). The spectra were calculated using the model of CR modulation by regular heliospheric fields [Dvornikov, Sdobnov, 2002] from GOES-9 data (up to 1 GV) and from results of our calculations with data from the worldwide network of CR stations in a high-energy region.

The differential CR spectra at the moments of ground level increases in the count rate of detectors of the worldwide network of stations on May 2 and 6 include both GCRs and SCRs, i.e. particles accelerated in the vicinity of the Sun. Since these events occurred during the FE period at the recovery phase, to obtain differential spectra of only May 2 and 6 SCRs we subtracted the differential CR spectra before GLE from the differential CR spectra at the moments of maximum GLE amplitudes. We assumed that the GCR spectra did not change significantly by the time of GLE, and particles accelerated to values at which the difference between the spectra during the GLE maximum and before it became zero (negative).

Figure 4 illustrates SCR differential rigidity spectra at the moments of maximum (curve 1) and GLE57 (curve 2).

The calculation results show that protons accelerated during GLE56 to rigidity of ~2.4 GV; and during GLE57, to rigidity of ~1.8 GV. The results do not contradict the conclusion made in [Stoker, 2002] that there were no accelerated protons with rigidity above 4 GV during GLE56.

While the same AR was the source of both May 2 and 6 GLE events, there are differences between them. X-ray flares of different intensity caused different maximum ground level enhancements: on May 2, according to Oulu CR station data, the amplitude of the increase in 5-min values was ~1.8 times greater than that on May 6.

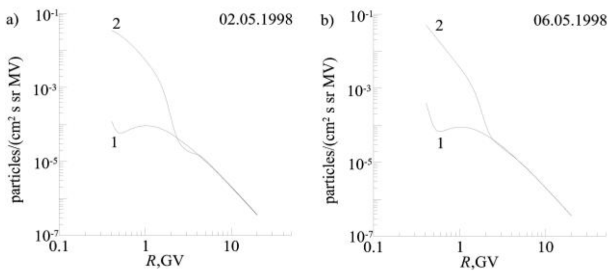

Figure 3. Differential rigidity spectra of primary CRs at some moments of GLE on May 2 and 6 (*a*, *b*). Curves 1 — before the event, red circles (<1 GV) — GOES-9 data, blue circles (>1 GV) —GSS calculation results; curves 2 — during the event, purple triangles (<1 GV) — GOES-9 data, green triangles (>1 GV) — GSS calculation results

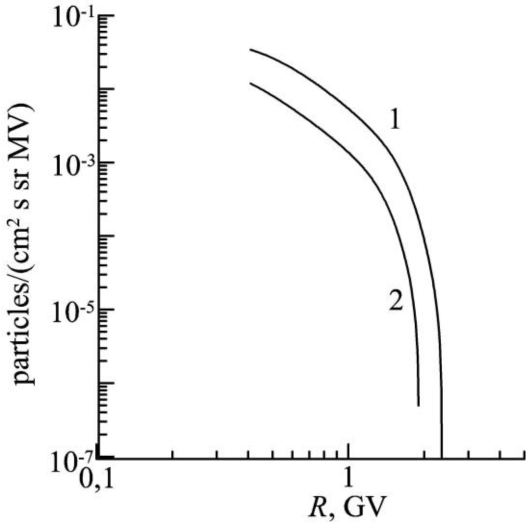

Figure 4. Differential rigidity spectra of SCRs at the boundary of Earth's atmosphere during GLE56 (curve 1) and GLE57 (curve 2)

Particles in the former event of interest accelerated to higher rigidities (~2.4 GV) than in the latter (~1.8 GV).

The presence of bidirectional pitch-angle anisotropy (amplitude of the second pitch-angle anisotropy harmonic A_2) suggests that in both events Earth at those moments was in the IMF loop structure of the magnetic trap type.

CONCLUSIONS

This study has shown the following results.

1. We have obtained SCR differential rigidity spectra during the May 2 and 6, 1998 GLE events.

2. The maximum rigidities to which particles accelerated in these events have been determined. The maximum rigidity of accelerated protons during the May 2 GLE was ~2.4 GV; and during the May 6 GLE, ~1.8 GV.

3. During GLE56 and GLE57, bidirectional pitch-angle anisotropy was found in the directions of ~20°, –30° and ~180°, ~30° at 14:00 UT on May 2 and in the directions of ~70°, ~15° and ~260°, ~0° at 09:00 UT on May 6, which suggests that Earth was in the IMF loop structure during these periods.

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