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COSMIC-RAY VARIATIONS DURING THE TWO GREATEST BURSTS OF SOLAR ACTIVITY IN THE 23RD SOLAR CYCLE

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Abstract. During two extreme bursts of solar activity in March–April 2001 and October–November 2003, the ground-based neutron monitor network recorded a series of outstanding events distinguished by their magnitude and unusual peculiarities. The important changes that lead to increased activity initiated not with the sunspot appearance, but with the large-scale solar magnetic field reconfiguration. A series of strong and moderate magnetic storms and powerful proton events (including ground-level enhancements, GLE) were registered during these periods. The largest and most productive in the 23rd solar cycle, active region 486, generated a significant series of solar flares among which the 4 November 2003 flare (X28/3B) was the most powerful X-ray solar event ever observed. The fastest arrival of the interplanetary disturbance from the Sun (after August 1972) and the highest solar wind velocity and IMF intensity were recorded during these events. Within 1 week, three GLEs of solar cosmic rays were registered by the neutron monitor network (28 and 29 October and 2 November 2003). In this work, we perform a tentative analysis of a number of the effects seen in cosmic rays during these two periods, using the neutron monitor network and other relevant data.

1. Introduction

Solar activity always reveals cyclical and random variations within a rather wide range of amplitude, duration and other characteristics. The enhanced activity periods are known to be most common near the maximum of the 11-year solar cycle, when the flare and eruptive activity of the Sun increases abruptly. During these periods, two or three powerful and fast evolving active regions (AR) produce many flares and coronal mass ejections (CMEs) and provide the most powerful energy release in the cycle. Often these periods occur in the first years of the descending phase of the solar cycle. Examples are provided by such events as November 1960 (cycle 19), August 1972 (cycle 20), June–July 1982 (cycle 21), August 1991 (cycle 22), and March–April 2001 (cycle 23). The existence of a complex solar magnetic structure during the maximum phase of the 11-year solar cycle was recognized by Gnevyshev (1963, 1967, 1977), who suggested that the 11-year cycle does not contain one but two waves of activity with different physical properties. Such

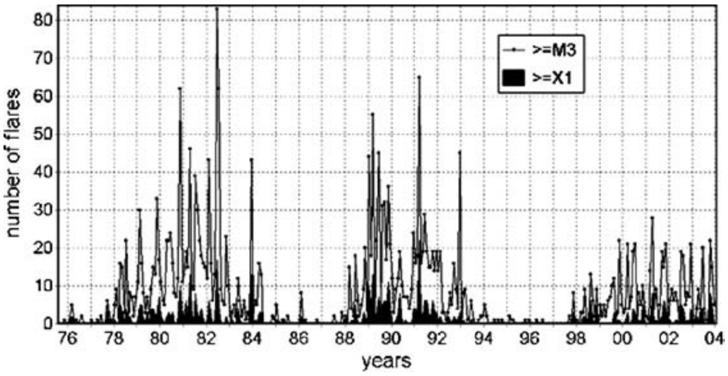

Figure 1. Solar flare monthly numbers of ≥M3 importance during last three cycles (21–23). Dark areas mean the periods with flares of ≥X1 importance.

a structured maximum (Feminella and Storini, 1997; Bazilevskaya *et al.*, 2000) was revealed also in the behavior of solar (Nagashima, Sakakibara, and Morishita, 1991; Bazilevskaya *et al.*, 1999) and galactic cosmic rays as well (Storini, 1995; Storini *et al.*, 1997; Storini, Laurenza, and Fujii, 2003; Krainev, Bazilevskaya, and Makhmutov, 1999). The periods of reduced solar activity between the two peak waves during the solar maximum phase were named Gnevyshev Gaps (GG) and even now the nature of the complicated double-peak structure of the solar cycle maximum is still obscure (Storini *et al.*, 2003a). In Figure 1 we have plotted the monthly number of solar flares of ≥M3 importance during the last three solar cycles. As one can see, the current cycle (23) is not characterized by high activity. Nevertheless, the high-energy release periods are well pronounced during this cycle, clearly seen in Figure 1 from the behavior of the flares of greater than or equal to X1 importance (dark areas). The most significant in the current cycle are the periods in March–April 2001 and in October–November 2003.

In the first period, 66 flares of ≥M1 importance and 9 of ≥X1 were recorded during the month, whereas only 18 flares of ≥M1 and none of ≥X1 were generated during three previous months (IZMIRAN database created from internet sources). Two regions – located at almost complete solar antipodes (9393 and 9415) – proved to be the most active during this period. A beta–gamma–delta magnetic configuration in these regions persisted throughout their disk passage. The most powerful solar flare (X20) occurred on April 2 and was largest seen until November 2003. Two strong ground-level enhancements (GLEs) of solar relativistic particles were recorded on 15 and 18 April 2001 and event on 15 April turned out to be the largest one of cycle 23. A severe magnetic storm (daily $Ap = 192$), persisting for more than 24 h, occurred on 31 March 2001. An impressive series of Forbush decreases in cosmic rays (CRs) was a result of a sequence of interplanetary disturbances.

Despite this activity, the 23rd cycle did not seem to be an above-average solar cycle. Then an extremely high burst of solar, geomagnetic and CR activity in October–November 2003 – during the descending phase of the current cycle – proved to be unexpectedly strong. Throughout this period (about 1 month) many outstanding events occurred: the fastest (since 1972) arrival of the interplanetary disturbance at Earth, the highest solar wind velocity (2100 km s^{-1}), the biggest intensity of the interplanetary magnetic field (IMF) (57.2 nT) near Earth, all directly resulting in significant changes in the cosmic ray intensity.

In this paper we analyze cosmic ray phenomena as a result of the solar activity burst in October–November 2003 and compare them with the other outstanding events within the 23rd cycle.

2. Data and Methods

Data from about 40 neutron monitors (NMs) have been used for analysis together with solar, IMF, solar wind and geomagnetic data from different internet sources: (ACE/SWEPAM [*http://helios.gsfc.nasa.gov/ace/swepam.html*], ACE/SWICS [*http://www.srl.caltech.edu/ACE/ASC/SWICS.html*]), (ACE/MAG [*http://www.sec.noaa.gov/ace/*]), [*http://swdcdb.kugi.kyoto-u.ac.jp/dstdir/*], and [*ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/*]. All results on cosmic ray variations are obtained for the first time after complicated calculations and analysis based on the original sophisticated methods and a database developed in IZMIRAN. The global survey method (GSM) (e.g. Belov, Dorman, and Yanke, 1985) was applied to derive CR density variations and a 3D-vector of the cosmic ray anisotropy for every hour throughout the period under consideration. Data on the cosmic ray anisotropy together with the solar wind measurements have been used to calculate the CR space gradients by the method described by Belov *et al.* (1987).

3. Results and Discussion

The 23rd cycle bears out the point of view that flares, GLEs, Forbush effects (FEs) and geomagnetic storms occur most commonly during the descending phase than during the rising or even during maximum solar activity.

The most significant events in the 23rd cycle occurred during the descending phase: just after the GG in March–April 2001 and in October–November 2003 – also after a number of quiescent months. The basic information on the cosmic ray events within the last period is shown in Figure 2, wherein the CR density and anisotropy calculated by GSM for 10 GV particles are presented. GLEs and FEs are named and numbered chronologically. The beginning of this period (FE1) coincides with the appearance on the solar disk of the sunspot group 484, and the end (FE10) corresponds to group 486 returning on the next solar rotation. Over a period of less than 1 month, the longest series of GLEs (65, 66 and 67) and an impressive series of FEs, exceeding the famous series in July 2000 and March–April 2001, were observed.

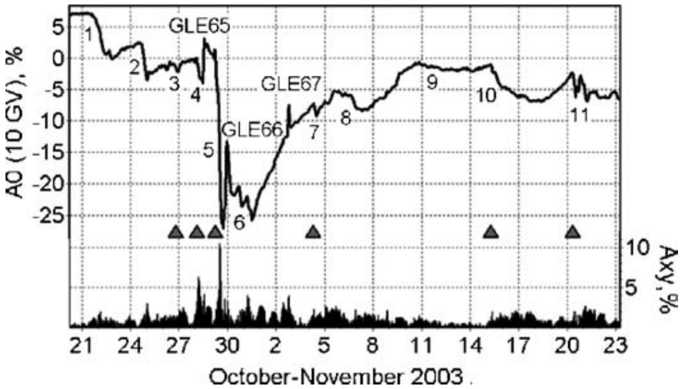

Figure 2. Cosmic-ray density (A0) and equatorial component of the first-order anisotropy (A_{xy}) derived from the NM network data by GSM for 10 GV particles. *Triangles* mark SSC (or the shock arrival). Numbers show FEs in chronological order.

3.1. GROUND-LEVEL ENHANCEMENTS OF THE SOLAR COSMIC RAYS

After the solar activity burst in March–April 2001 the 23rd cycle still seemed to be lacking in GLEs, as compared with the previous cycles. But in October–November 2003 neutron monitors (NMs) recorded three additional GLEs marked in Figure 2 as GLEs 65, 66 and 67. Thus, during 1 week, three events supplemented the list of GLEs in 23rd cycle. It should be recalled that over cycle 20, 12 GLEs were recorded, in the 21-13, in the 22 cycle – 15 (Shea and Smart, 1990). The event on 2 November (GLE67) occurred exactly 11 years after the 2 November 1992 event, when the last GLE of the 22nd cycle was recorded. The 23rd cycle evidently may be characterized now as a typical one, and the GLE rate changes little from cycle to cycle.

In Figure 3 the profiles of the solar CR recorded by a number of sub-polar NMs are plotted together with a measure of the N–S anisotropy for GLEs 65 and 66. All GLEs in this series have some common features. They are a result of the sporadic phenomena in the same AR 486 and were observed after extremely powerful X-ray flares X17.4/4B and X10.0/2B on 28 and 29 October and X8.3/2B on 2 November. All three enhancements turned out to be quite large, although smaller than the event on 14 July 2000 (the "Bastille day" event). All three cases demonstrate a large and long-lasting N–S anisotropy of the solar particle fluxes. In doing so, the fluxes in southern hemisphere recorded are far in excess of those observed by the northern stations (see Figure 3). This is in complete agreement both with the proton flare locations in the southern portion of the solar disk (from S16 to S14) and with the Earth's southern hemisphere turned towards the Sun. It is noteworthy that the same sign anisotropy in the solar particles of lower energy was found during flights of the CORONAS-F above the polar caps (Kuznetsov *et al*., 2004, private communication). More detailed analysis of this information may be used in understanding particle propagation in the heliospheric medium.

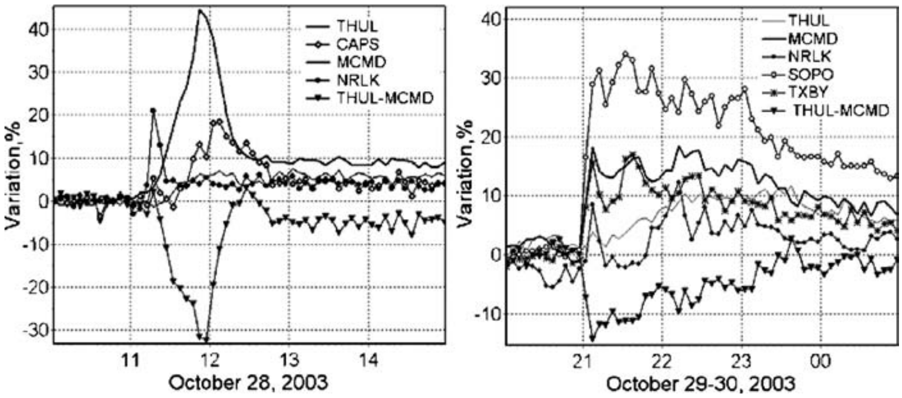

Figure 3. GLE 65 and 66 as recorded at some sub-polar stations (THUL: Thule, CAPS: Cape Shmidt, MCMD: McMurdo, NRLK: Norilsk, SOPO: South Pole, and TXBY: Tixie Bay) and N–S anisotropy of the solar cosmic rays (THUL–MCMD).

The last three GLEs also reveal essential differences (see Figure 3). Time profiles for the first two of them are very complicated. It is sufficient to examine data from the Norilsk station showing a 10-min peak at the very beginning of GLEs 65 and 66. These peaks far exceed the solar CR effect at this time at some other stations with similar characteristics. Some stations give CR profiles with two well-separated maxima in the first and second events, which implies the existence of similar conditions for solar particle propagation during at least 2 days.

The third event (GLE 67, is not plotted here) seems to be simple and has a classical profile, but it is surprising in that there is no increase seen by the northern sub-polar station Thule. This enhancement is essentially isotropic because of the rather ineffective interplanetary scattering of the solar relativistic particles on 2 November. Differences in the observed GLEs can be explained by the location of solar sources and different interplanetary and magnetosphere conditions. In Table I we have listed the maximum GLE amplitude, solar flare heliolongitudes, maximum values of the solar wind velocity, the IMF intensity near Earth, maximum *Kp* and minimum *Dst* indices at the time of the solar CR observations by neutron monitors. These indices characterize a certain level of the heliosphere disturbance in the

TABLE I

Difference in the conditions for GLE 65–67 (see the text for details).

GLE	Date	Hours (VT)	$A_{\max}$ (%)	Longitude	Latitude	U_{SW} (km s^{-1})	IMF (nT)	*Kp*	*Dst* (nT)
65	28 October	11–13	45	E08	S16	790	11.0	5_-	−37
66	29 October	21–24	35	W02	S15	1100	29.3	9_-	−345
67	2 November	17–20	36	W56	S14	536	5.2	4_+	−23

Earth's vicinity, but indirect data indicate the conditions to be strongly disturbed also in the whole heliosphere during these periods, due to extremely high eruptive activity of the Sun. Nevertheless, data in Table I illustrate GLE 67 to be associated with the flare better located in longitude and with a relatively quiescent solar wind and magnetosphere. GLE 65 was observed during a period of disturbed solar wind, a large Forbush decrease and an evolving magnetic storm. Especially complicated conditions followed GLE 66 where a strong interplanetary disturbance, severe magnetic storm and giant Forbush decrease were in progress. The analysis of this event is certain to be very complicated.

3.1.1. *Solar Neutrons*

Solar neutrons appear to be observed during GLE 65. In Figure 4, data from the Tsumeb and Norilsk neutron monitors are plotted together with data on neutron >20 MeV measurements onboard CORONAS-F, kindly presented by Kuznetsov *et al.* (2004, private communication). During the flare on 28 October 2003 the South African station Tsumeb was located close to the sub-solar point and had the greatest probability, compared with other stations, to record solar relativistic neutrons. Due to its high threshold of geomagnetic cutoff (9–10 GV) Tsumeb could not get proton enhancement, and a small but well-pronounced counting rate increase (∼3%) at 11:05–11:10 UT, just before the earliest observation of the proton event onset (Norilsk NM) may be considered as being caused by solar neutrons. A similar but smaller increase (∼2%) was observed at the other South African station Potchefstroom. At this time, protons had not yet arrived at Earth but in the CORONAS-F data the increase recorded from 11:04 to 11:12 UT provides a time for neutron generation at the Sun. Solar neutron observation at Earth is a very rare phenomenon, and only in history have ground-level detectors recorded solar neutron increases of greater magnitude than this one: 3 July 1982 and 24 May 1990 (Belov and Livshits, 1995, and references therein).

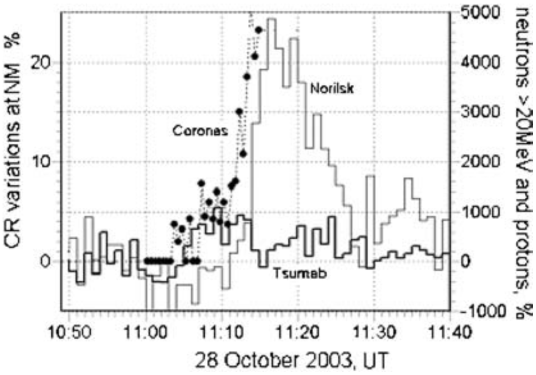

Figure 4. Cosmic ray variations recorded at Norilsk (Rc = 0.65 GV) and Tsumeb (Rc = 9.3 GV) NMs. *Dark circles* indicate data on neutrons measured onboard CORONAS-F by the SONG instrument (Kuznetsov *et al.*, 2004, private communication).

3.2. FORBUSH DECREASES

The extremely large interplanetary disturbances caused by the solar activity burst affected galactic cosmic rays and produced in an impressive series of 11 FEs in October–November 2003 which turned out to be the most significant series throughout the cycle. In Figure 2 the separate FEs are numbered chronologically. The two first FEs are a result of eastern hemisphere CMEs, associated with AR 484. FE3 is the smallest event in this series, but this is the first manifestation of group 486 activity: a near-limb eastern flare (S21 E80 of X5.4/1B importance) was followed by a large fast CME (full halo), so that the interplanetary shock from this remote source was able to reach Earth. FEs 4 – 8 are due to activity in the same sunspot group. The last one (FE8) occurred after the near-west-limb giant flare (S19 W83) X28/4B on 4 November. Again, the remote source location did not block the full halo observation and shock arrival. So the events in AR 486 were geoeffective over a span of 13 days. Among the later events FE11 is more interesting because of the great geomagnetic effect in CR (discussed in Section 3.3).

The FE that occurred on 29 October 2003 (FE5, Figure 2) is worthy to be considered separately. There was an extremely fast CME (2125 km s^{-1} by SOHO/LASCO [*http://lasco-www.nrl.navy.mil/*] observations) after the central X17.4/3B flare, which also produced GLE 65. It took about 19 h to get to Earth, so this disturbance was the fastest since August 1972. From the ACE/SWICS data, the solar wind velocity increased to 1910 km s^{-1} in the first hours after the shock arrival, and the IMF intensity (ACE/MAG) reached 47.2 nT. According to an empirical correlation derived by Belov *et al.* (2001) from analysis of several thousands FEs, an interplanetary disturbance of such characteristics is expected to create a Forbush decrease of 17.5% magnitude in the CR of 10 GV rigidity. However, the effect under consideration turned out to be 1.5 times greater than this.

This event seems to be the largest Forbush effect in history, and exceeds all FEs in the current cycle by more than a factor of 2 (see Table II).

In Table II are entered the main characteristics of some of the largest FEs, wherein the A_{FD} is the maximum Forbush decrease magnitude, $\Delta A_{0\max}$ means

TABLE II

Characteristics of the greatest FEs in 23rd solar cycle and the FE in August 1972.

Date	A_{FD} (%)	$A_{0\max}$ (%)	$A_{xy\max}$ (%)	G_{r0} (%/au)
4 August 1972	25.0	7.0	9.8	>145
15 July 2000	11.7	2.4	2.6	~100
11 April 2001	11.9	3.2	2.8	180
6 November 2001	12.4	2.4	4.0	>80
24 November 2001	9.2	2.8	3.2	90–140
29 October 2003	28.0	7.3	10.4	200

hourly maximal CR density variation, $A_{\mathrm{xy\,max}}$ is the maximum equatorial component of the first-order CR anisotropy, G_{r0} is the CR radial gradient estimated on the basis of $\Delta A_{0\mathrm{max}}$ and solar wind velocity near Earth. All results in Table II are obtained by means of the GSM and do not represent cosmic ray variations at some separate stations, but characteristics of 10 GV CR beyond the Earth's atmosphere and magnetosphere that allows a justified comparison between different events and disturbances in the heliosphere.

This approach was also realized to derive some parameters (density and anisotropy for 10 GV cosmic rays away from the Earth) for the two biggest FEs in the 23rd cycle and for the event in August 1972, which are plotted in Figure 5. These parameters can be used for interplanetary space diagnosis (Belov *et al.*, 2003a,b): any changes in CR density and anisotropy, in their magnitude and direction correspond to changes in the interplanetary medium. Turning to the largest FE5 in October 2003 we can say that the main fall of CR intensity (~22%) occurred on 29 October during 6 h, herewith in 1 h a decrease was about 7%. This implies a very large CR gradient in the leading part of the disturbance. Such a gradient (~200%/a.u.) will create a large CR anisotropy, and this is confirmed in Figure 5: the anisotropy vector rises in the first hours of the main phase of the FE, and in the 29 October event it was enhanced unusually strongly even compared with other giant FEs. The radial gradient estimations performed by the data on CR anisotropy show the values of G_{r0} in Table II to be considered as the lowest limit for the maximum increase of CR gradient in the great FEs.

The analysis of this event is basically very complicated because of the two GLEs and the severe magnetic storm overlapped with the Forbush effect.

3.3. GEOMAGNETIC EFFECTS IN COSMIC RAYS

Three severe magnetic storms, the largest in the current solar cycle, occurred in October–November 2003. The *Kp* index several times reached a maximum value of 9_0, and the *Dst* variation dropped to -363, -401 and -473 nT in these three storms. Usually, such a great magnetospheric perturbation affects the neutron monitor measurements by a change in the effective cutoff rigidity at the point of CR observation (Debrunner *et al.*, 1979; Flueckiger, Smart, and Shea, 1981; Kudela and Storini, 2002; Miyasaka *et al.*, 2003). The geomagnetic effect in cosmic rays distinguishes CR variations at mid-latitude stations from those at high latitudes; this is observed during every sufficiently large geomagnetic storm including the three mentioned earlier.

The greatest geomagnetic effect was observed on 20 November 2003 during a severe magnetic storm, which caused even the red aurora at low latitudes (for example, in Athens [*http://www.perseus.gr/Astro-Aurorae-20031120-001.htm*]). High-latitude NMs recorded a moderate Forbush decrease of ~5% that time, although a larger effect might be expected bearing in mind a record growth of the IMF intensity (up to 55.7 nT). Low-latitude stations (Athens, Potchefstroom, Rome and

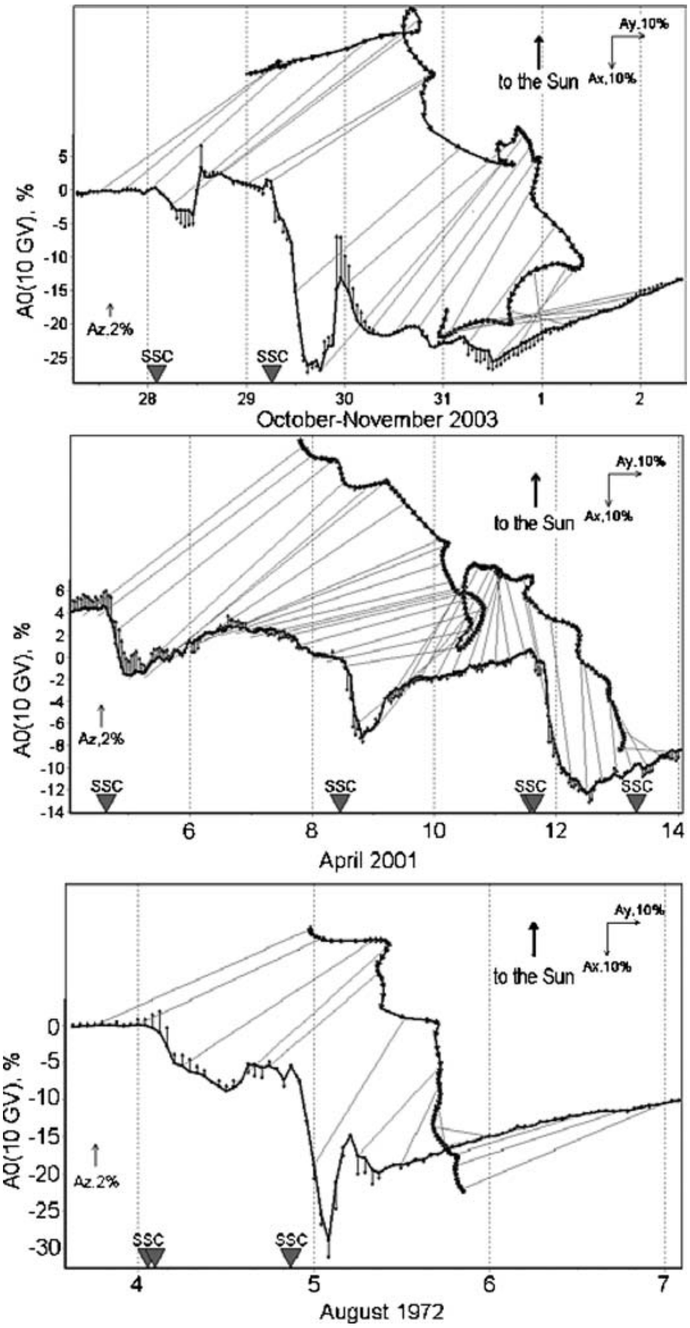

Figure 5. CR density (A0) for 10 GV and vector diagram for equatorial component of the CR first-order anisotropy are plotted for two giant FEs in solar cycle 23 and in August 1972. *Thin lines* connect equal time intervals every 6 h on the density curve and vector diagram.

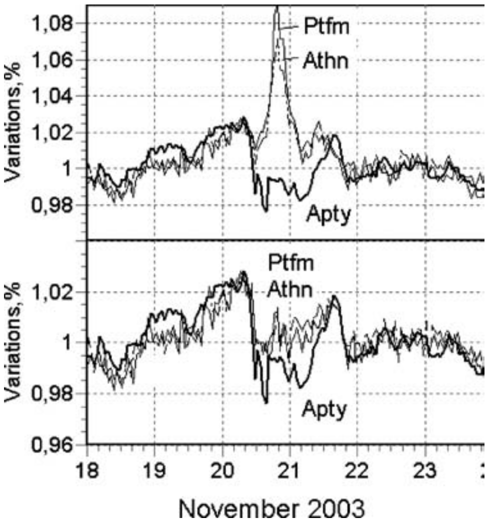

Figure 6. CR variation on the high (APTY) and mid latitude NMs (ATHN, PTFM) during the severe magnetic storm in November 2003 without correction (*upper panel*) and after correction for geomagnetic effect at low latitude stations (*bottom panel*).

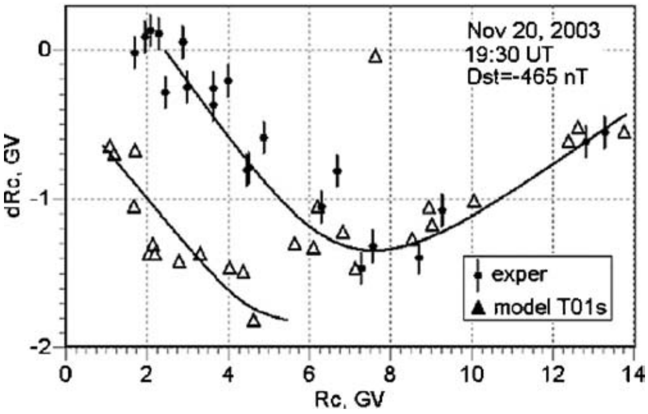

Figure 7. A distribution of dRc variations in the maximum of geomagnetic storm on 20 November 2003. *Points* are derived from the experimental data with GSM approach, and *triangles* are calculated by means of the Tsyganenko "storm" model T01s.

some others) recorded a big increase of the counting rate instead of a decrease (see Figure 6 upper portion). The CR variations at the same NMs corrected for geomagnetic effect by the method described by Baisultanova *et al.* (1987) are also plotted in Figure 6. The maximum geomagnetic effect on 20 November was observed as at high as 7–8 GV (usually at 3–5 GV during great storms). Latitudinal dependences of the cutoff rigidity variations (dRc) were found for each hour starting from the moment of shock arrival, and this dependence during the maximum evolution of the magnetic storm is plotted in Figure 7 as points. Figure 7 shows a comparison between this experimental dRc and that calculated by means of the last Tsyganenko model of the magnetosphere (Tsyganenko, Singer, and Kasper, 2003), wherein a disturbed magnetosphere up to *Dst* of -140 nT is included ("storm" model T01s). The method of calculations is described by Pchelkin and Vashenuyk (2001). Good agreement between experimental and calculated values is clearly seen for rigidities >6 GV. The model is possibly not adequate for the largest magnetospheric disturbances in that there is a discrepancy for lower rigidities. In favor of our "experimental" method note that performing the same analysis for other magnetic storms (Baisultanova, Belov, and Yanke, 1995) we found that the classical latitudinal dependence of Rc changes, with a maximum at 3–5 GV. As was mentioned, the specific feature of this event is that a maximal magnetosphere effect was recorded at more low latitude stations than usual. In this case a maximum in the latitudinal distribution of the cutoff rigidity variations is shifted significantly to larger cutoffs, and is found at $\sim$7–9 GV (that is confirmed also by the red aurora observations). Thus, the ring current which, according to the simplest model (Treiman, 1953) is distributed in proportion to cosine of the latitude and flows in the western direction, is very close to Earth in this case (located at 3 *Re* from the Earth's center). In magnetic storms when the maximum in the latitudinal distribution of the cutoff rigidity variations is nearly 4-5 GV, the ring current system is found at about 5 Earth radii.

3.4. LONG-TERM VARIATIONS OF THE GALACTIC COSMIC RAY

The counting rate of the neutron monitors during the FEs on 29–31 October fell to the lowest level since June 1991, both in hourly and daily data. Such deep modulation is thus expected to be seen also in long-term CR variations. It should be borne in mind that after the AR 484, 486 and 488 rotated off the visible disk at the beginning of November 2003, solar activity did not disappear but continued on the back side of the Sun. Great CMEs recorded from the back side by SOHO/LASCO coronographs on 4, 6, 10–12 November, created interplanetary disturbances and modulated CR. In Figure 8 the monthly mean sunspot numbers and the CR data are plotted. One can see two minima in the cosmic ray intensity in each of the last solar cycles (except perhaps the 20th cycle, which was relatively weak): the first one occurred after sunspot maximum, the deeper second one, about 2 years later. In solar cycle 21, a well-pronounced second minimum was recorded in July 1982, in cycle 22 it was found in June–July 1991. In the current cycle, the first minimum was observed in July 2000, but the second one occurred 3 years and 4 months later (far later than in previous cycles) in November 2003. It turned out to be not as deep as in 1991, but again, much deeper than the first one. The CR modulation in cycle 23 is essentially higher than in cycle 21, and CR intensity remained near this low level for more than 4 years (since the end of 1999). It can be noted that the minimum of the CR intensity has a longer duration in the odd than in the even numbered cycles.

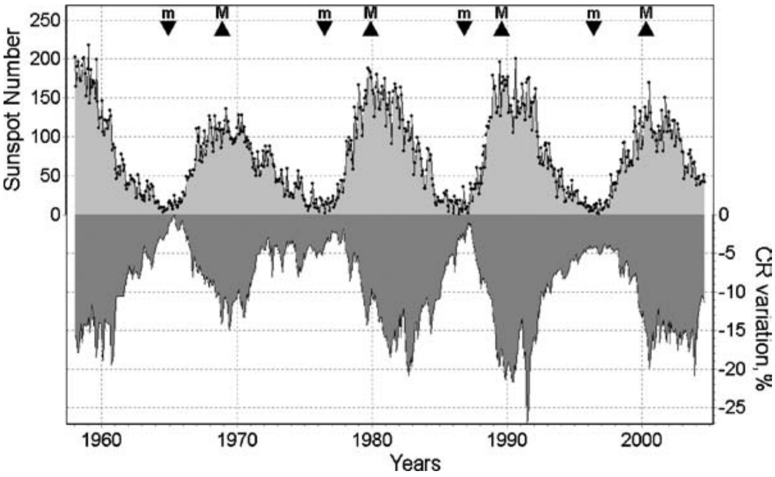

Figure 8. Long-term variations of the sunspot number and CR variations on Moscow NM recorded during last four solar cycles. M corresponds to maximum, m to minimum in the sunspot behavior.

This was shown by Krainev, Bazilevskaya, and Makhmutov (2001) and Storini *et al.* (2003b), and its explanation is likely to be connected with the 22-year cycle in the global solar magnetic field and with magnetic drift of cosmic rays in the heliosphere. The October–November 2003 period indicated the end of this minimum and just after this period the recovery phase in CR intensity started.

4. Summary

Two distinguished periods characterized by a great increase of all solar activity parameters, were recorded in cycle 23: one after the GG in March–April 2001, and another in October–November 2003, also after several months of a quiescent Sun. In both these cases, the main part of the space weather changes (heliosphere, magnetosphere, cosmic rays) was caused by very productive activity in two sunspot groups: 9393 and 9415 (NOAA catalogue numbers) in 2001, and 10 484 and 10 486 in 2003, which provided the most significant series of flares, the largest in the history of solar X-ray event observations (X28.4 on 4 November 2003), and the fastest arrival of a disturbance from the Sun, except for the August 1972 shock. These vigorous bursts of solar activity are strongly revealed in different kinds of cosmic ray variations: in ground-level enhancements of solar protons and neutrons, in series of FEs, in dramatic changes of CR anisotropy, in geomagnetic effects and in long-term CR variations as well.

During one week, two times in April 2001 and three times in October–November 2003, charged particles were accelerated up to such high energy as to be registered at Earth's surface by neutron monitors. These events increased the total number of GLEs in cycle 23 and made it comparable with preceding solar cycles. GLEs 65 and 66 (28–29 October 2003) have very complicated profiles as a result of a combination of perturbed interplanetary and geomagnetic conditions; GLE 66 is the most complicated of all ground-level events. Moreover, solar neutrons appeared to be recorded on 28 October 2003.

An impressive and long series of FEs occurred during 10 and 13 days in these two periods and accounted for 7 and 11 Forbush decreases, respectively. Herewith, the FE on 29 October 2003 (28% for 10 GV particles) is the largest one ever seen (among about 4000 FEs in our database); it exceeds even the FE on 5 August 1972. Comparative analysis of all large FEs revealed the biggest anisotropy (10.4%) and one of the biggest CR gradient (about 200%/a.u.) for this event.

An unusually large geomagnetic effect in CR (up to 7%) was observed on 20 November 2003 with an unusual latitudinal distribution: the maximum effect was recorded at low latitudes, under 7–9 GV cutoff rigidity; this effect is also the largest one ever seen. Its distribution is confirmed also by the red aurora observation at such latitudes, but this measurement differs from the calculations performed on the basis of the last "storm" model of magnetosphere (Tsyganenko, Singer, and Kasper, 2003).

Solar activity at the end of 2003 created the second minimum in the global behavior of galactic CR in the 23rd cycle, which appeared to be deeper than the first. The recovery phase started just after these events. Thus, the duration of the galactic CR minimum level proved to be longer in cycle 23 than in the previous (even) cycle 22.

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