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Galactic Cosmic Ray Fluctuation Parameter as an Indicator of the Degree of Magnetic Field Inhomogeneity

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Abstract—The parameter of cosmic ray fluctuations, which indicates the degree of IMF inhomogeneity, was introduced in order to quantitatively describe the dynamics of the galactic cosmic ray (GCR) intensity fluctuations during the geoeffective phases of the 11-year cycle. The 5-min data of the high-latitude neutron monitor at Oulu station (Finland) during cycles 20–23 was used in the calculations. The nonrandom non-Gaussian character of the GCR fluctuation parameter is caused by the nonstationary semiannual variation reflecting the transient nonstationary oscillatory process of sign reversal of the general solar magnetic field. This transient oscillatory process is responsible for the maximal geoeffectiveness and duration of the phase of polarity reversal, which manifests itself in a sharp and deep GCR intensity minimum during the final stage of the field sign reversal. The invariant of the 11-year "amplitude–duration" cycle was confirmed on a new basis: the LF drift of the "low" cycle period was detected, which was observed in an increase in the duration of cycle 23 we anticipated.

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1. INTRODUCTION

The nonstationary transient oscillatory process of sign reversal of the general solar magnetic field was previously detected in the work [Kozlov and Markov, 2007] devoted to studying GCR intensity fluctuations. Considering the importance of such a conclusion and its consequences, we verified the results achieved previously. This is the aim of the present work. To quantitatively describe the GCR fluctuation dynamics during the geoeffective phases of the 11-year cycle, we introduced a new parameter of cosmic ray fluctuations, which indicates the degree of magnetic field inhomogeneity. We used the data of the Oulu (Finland) high-latitude neutron monitor with a high (5 min) resolution for almost the entire period of their registration. This was done to confirm (or deny) our conclusion on the detection of the nonstationary transient oscillatory process of sign reversal of the general solar magnetic field drawn based on studying cosmic ray fluctuations.

We can anticipate that the Forbush effects are distributed as groups or series rather than randomly during the solar cycle geoeffective phase. After averaging of the 5-min data on the GCR intensity for each solar rotation, the series of Forbush decreases will be observed as a sharp and deep minimum in the GCR intensity, as is registered at the beginning of the 11-year cycle decline phase. After a similar averaging of the cosmic ray scintillation index, the characteristics dynamics of GCR fluctuations are also revealed on this larger scale [Kozlov and Kozlov, 2008], which indicates that these dynamics have a scaling, self-similar, or fractal character. This is confirmed by the small and finite ($d \sim 2.5$) value of the process correlation dimension [Kozlov, 1999], which means that GCR fluctuations are theoretically nonrandom (nonGaussian) during the solar cycle geoeffective phases.

It is customary to consider that the time series in terms of a unit variable gives rather limited information. Nevertheless, the time series has information content: it bears traces of all other variables participating in the description of the system dynamics. The procedure of reducing the initial nonstationary (in the sense of average values) series to the nonstationary form by eliminating a trend in data is a weak but necessary link of the spectral–time approach in analyzing time series. However, the eliminated trend can also bear useful information "accumulated" during the latent phase of activity source formation. From this it follows that a usual (frequency or integral) histogram of initial data bears the most complete information. We should only extract a potentially possible regular signal from a noise-like signal.

In the second methodical section of the work, we briefly justify the necessity of applying the method that forms the basis for a new approach to extraction of a potentially possible regular signal from the noise-like process, i.e., the time series of 5-min values of the cosmic ray intensity. In the second section, we present the results of calculations (performed using the proposed algorithm) of the annual, 27-day, and daily values of the cosmic ray fluctuation parameter, which are subjected to the known methods for analyzing time series: linear regression, wavelet transform, epoch superposi-

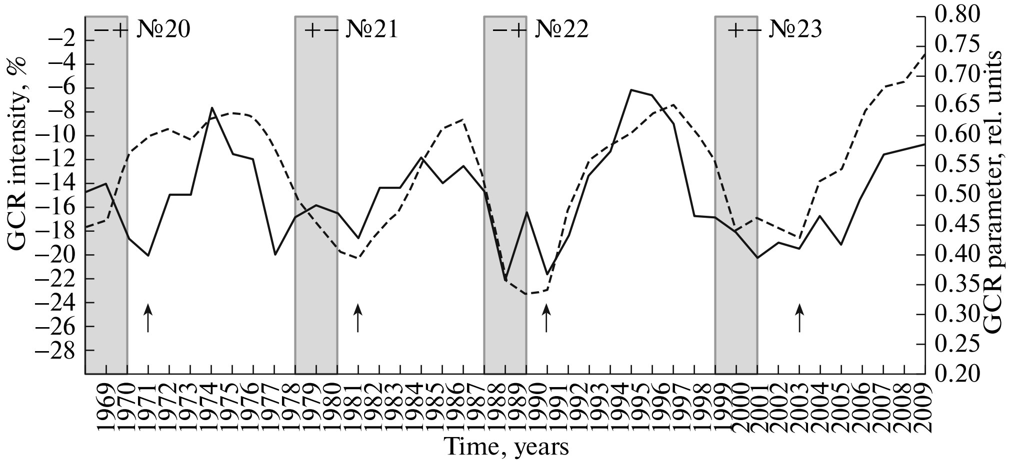

Fig. 1. Calculated annual values of the GCR fluctuation parameter in relative units for solar cycles 20–23 (the solid curve, the right-hand scale. The GCR intensity at Oulu station (Finland) in percent (the dashed curve, the left-hand scale). The cycle numbers and the periods of field sign reversal are indicated.

tion, and cross correlation analysis. The achieved results are discussed in the fourth section. As a result, we established that the introduced GCR fluctuation parameter is an inverse factor relative to the degree of magnetic field regularity. In other words, this means that the fluctuation parameter indicates the degree of magnetic field inhomogeneity in the vicinity of interplanetary waves and during geoeffective phases of the 11-year cycle.

2. METHOD

The second and the following moments of the GCR intensity distribution function can naturally include a potentially possible useful signal. This is confirmed by the estimated asymmetry coefficient. In this case it is desirable to separate changes in the histogram shape from scale variations. In such a case it is better to use the Weibull two-parametric distribution function instead of the asymmetry coefficient [Aivazyan et al., 1983]. This is confirmed by testing statistical hypotheses. The GCR intensity normal distribution hypothesis is rejected at a significance level of 99%. The Weibull distribution hypothesis indicates that it can be accepted at a significance level of 90%. According to the continuum destruction probabilistic theory and the theory of reliability, the Weibull generalized distribution function describes how the system starts operating in the limiting critical mode, which can be the transient mode of transition to the 11-year cycle geoeffective phase in our case.

In terms of the continuum destruction probabilistic theory (and the theory of reliability), studying the transient mode is reduced to determining the failure rate function for a system that exhausted its resources. In essence, the maximum of the failure rate (or risk) function is the probability of reaching the critical value of an analyzed variable: cosmic ray intensity in this case. We determine this probability as a parameter of cosmic ray fluctuations [Kozlov, 2008]. To calculate the risk function, it is necessary to estimate the shape parameter of the Weibull empirical distribution, which is responsible for the degree of deviation of the approximating function shape from the normal distribution. We use the least squares method in order to find the approximating function of the empirical (integral) intensity histogram. The average intensity values for each bin interval of the integral histogram empirical distribution function will be grouped in the vicinity of the matched straight line but in a new coordinate grid (after the procedure of taking the log–log logarithm and transformation of variables). In this case the slope of the curve that is selected using the least squares method and the constant term give the relationships necessary for estimating the required shape and scale parameters.

3. RESULTS

The calculation of the fluctuation parameter values for the last four 11-year solar cycles (cycles 20–23) is presented in Fig. 1 (solid curve, right-hand scale). We used the 5-min data of the Oulu (Finland) high-latitude neutron monitor for each year from 1969 to 2009 (factually, for the entire period of cosmic ray registration with high (5 min) resolution). The cosmic ray intensity values (in percent) are presented on the same plot by a dashed curve (left-hand scale). On the whole, the average annual values of the calculated parameter rather pronouncedly correspond to the GCR intensity: the 11-year variation is observed in both cases. The quantitative estimation that was performed using the linear regression model indicates that the correlation between the average annual values of the com-

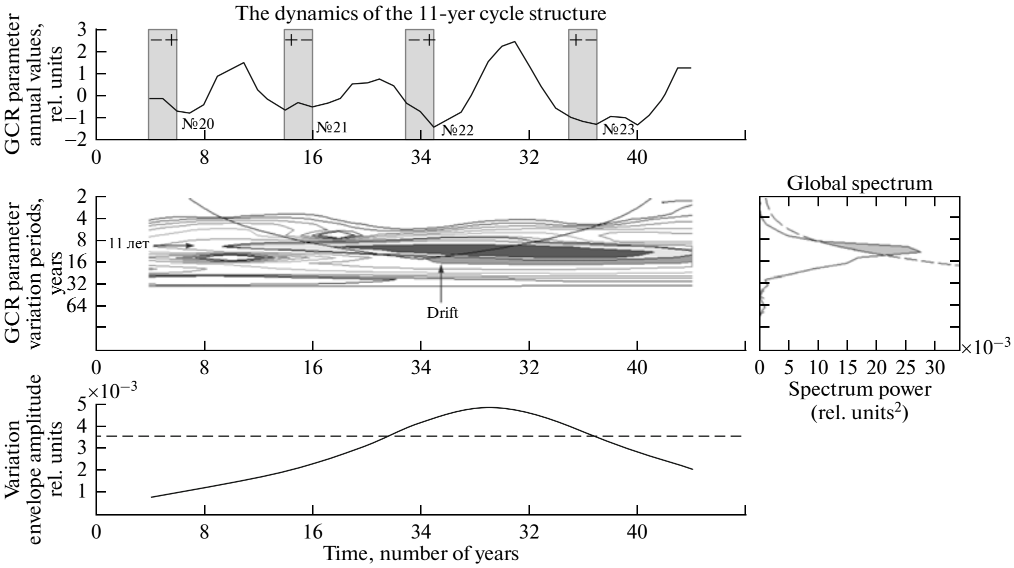

Fig. 2. The dynamics of the 11-year cycle structure according to a wavelet analysis. The time variations in the average annual values of the GCR fluctuation parameter are shown at the top. The periods of field sign reversal are indicated conditionally. The measured values of the time variations in the 11-year period are shown below on the diagram. The location of the 11-year variation is marked by a horizontal arrow on the left. The region of LF drift is shown by a vertical arrow. The averaged or global spectrum for the entire period analyzed is given in the right part of the figure.

pared series is high ($R = 0.71$). This correlation is evidently caused by the 11-year variation. This is confirmed by the results of a wavelet analysis: the 11-year variation in the GCR fluctuation parameter is revealed rather distinctly (Fig. 2). The LF drift of the 11-year variation period into the region of low frequencies (i.e., toward periods longer than the period of the 11-year cycle) attracts attention.

The HF component of the 27-day values of the calculated parameter (Fig. 3), which remained after the elimination of the 11-year variation, is determined as a GCR fluctuation parameter (the data are smoothed over three points). The envelope of the variations in the 27-day values of the cosmic ray fluctuation parameter in all four cycles (cycles 20–23) reaches its maximum during the final stage of polarity reversal of the general solar magnetic field, i.e., at the beginning of the solar activity decline branch. Below, we analyze the fine structure of the fluctuation parameter for three complete 11-year cycles (cycles 21–23), using wavelet analysis. The presented results (Figs. 4, 6) indicate that the annual variation is clearly defined at a minimum of the odd cycles (cycles 21 and 23), when the general solar magnetic field was negative, which agrees with the 11-year cycle model developed in [Krymsky et al., 2001].

The nonstationary semiannual variation predominates during the polarity reversal phase, i.e., at a maximum and at the beginning of the 11-year cycle decline (Figs. 4–6). The completion of the polarity reversal phase is determined based on a sharp and deep decrease in the GCR intensity in 1972, 1982, 1991, and 2003 (these years are marked by an arrow in Fig. 1). The higher the cycle (maximum), the shorter the polarity reversal phase, which is followed by the beginning of the GCR intensity recovery, i.e., the solar cycle decline branch. In contrast, the lower cycle is, the longer the polarity reversal phase is, which was observed in cycles 20 and 23. Indeed, in cycle 23 the intensity started recovering only at the end of 2003 after the termination of polarity reversal that lasted more than 3 years. Thus, the nonstationary semiannual variation that was detected based on cosmic ray fluctuations is essentially a transient nonstationary oscillatory processes of sign reversal of the general solar magnetic field [Kozlov et al., 2003]. This transient oscillatory process is most probably responsible for the maximal geoeffectiveness and duration of the polarity reversal phase. The duration of polarity reversal for "low" cycles (20 and 23) is actually twice as long as such a duration for higher cycles (21 and 22).

We indicated above that the fluctuation parameter and intensity are in good agreement on large scales, i.e., on the scale of the 11-year variation with yearly averaging. It is equally important to know the relationship between the time variations in the fluctuation parameter and GCR intensity on smaller scales, specifically, the 27-day averaging. Therefore, it is interesting that the GCR fluctuation parameter maximum is registered one–two rotations before the beginning of a sharp and deep minimum in the GCR intensity: in 1972, 1982, 1991, 2000, 2001, and 2003 (see Fig. 3).

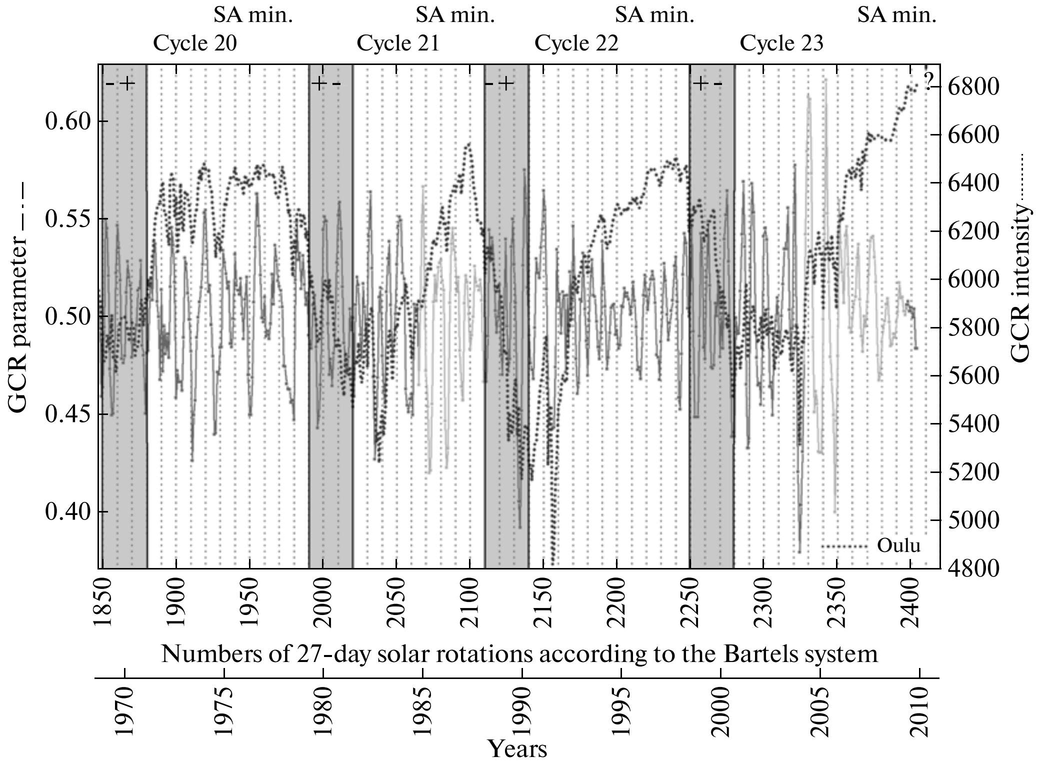

Fig. 3. The HF component of the GCR fluctuation parameter (a solid curve, the right-hand scale) for cycles 20–23 obtained by eliminating the 11-year variation from the calculated 27-day values. The GCR intensity in pulses (a dotted curve, the right-hand scale). The time (the Bartels rotation numbers and years) is plotted on the abscissa. The cycle numbers and (conditionally) the periods of field sign reversal are indicated.

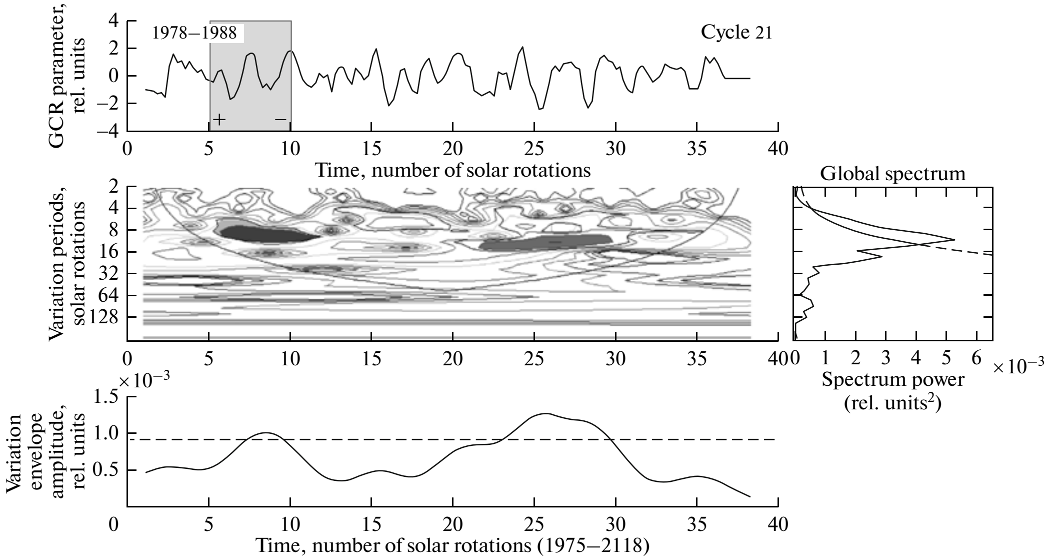

Fig. 4. Top: the time variations in the GCR fluctuation parameter in cycle 21. Below and on the diagram on the left: the nonstationary semiannual variation registered during field sign reversal. The annual variation typical of odd cycles with a negative sign of the general solar magnetic field is shown on the right. The averaged or global spectrum during the entire analyzed period is indicated on the right. The variation envelope amplitude is shown on the lower panel. The time (the number of Bartels rotations) is plotted on the abscissa.

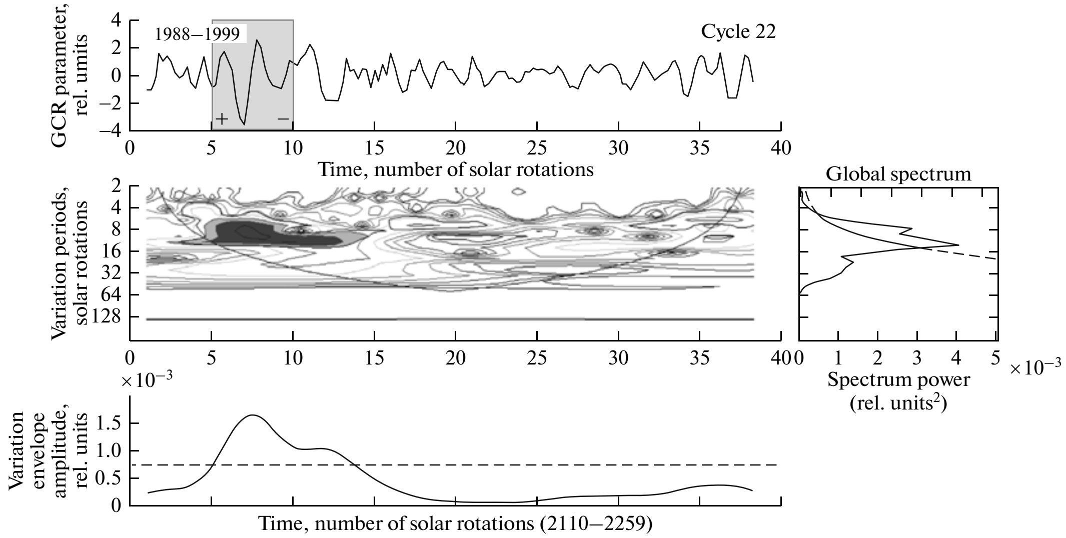

Fig. 5. The same as in Fig. 4 but for cycle 22.

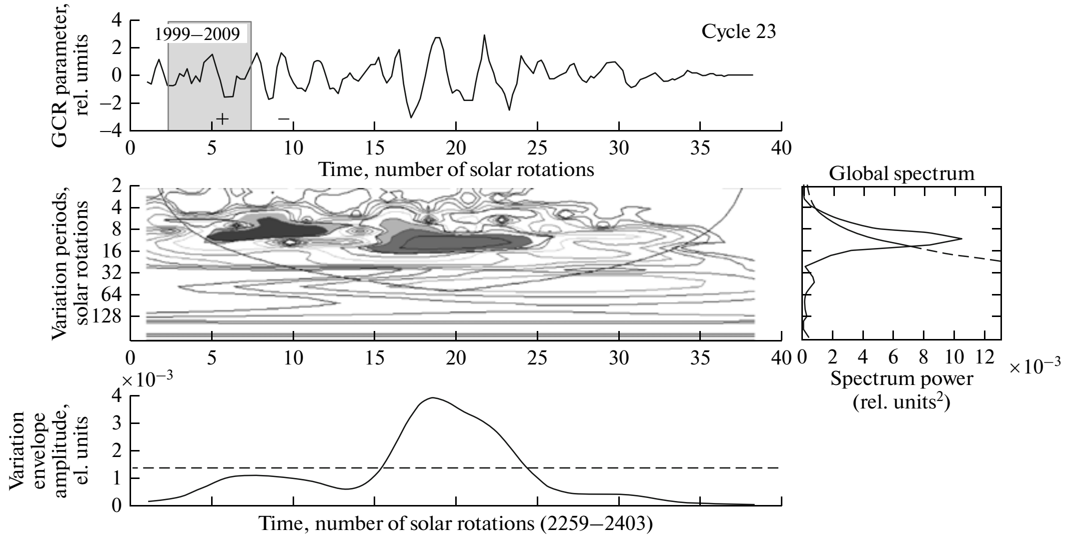

Fig. 6. The same as in Figs. 4 and 5 but for cycle 23.

To verify this effect, we used the epoch superposition method. The majority (ten) of the periods of sharp and deep minimums in the GCR intensity that were registered in the current cycle (23) were considered to be a "zero" event.

First, good agreement between the fluctuation parameter and GCR intensity was obtained. The coefficient of their linear regression relation is $R = 0.9$. Second, it is confirmed that a significant maximum in the fluctuation parameter exists on average one–two solar rotations before the beginning of a deep minimum in the GCR intensity (Fig. 7). This points to the prognostic possibilities of the fluctuation parameter. However, it is necessary to additionally use the quantitative criterion for making decision concerning the prediction of the geoeffective period in order to perform a medium-term prediction for the period about one solar rotation. According to the epoch superposition method, we deal with a conditional average "event"; therefore, our quantitative criterion is averaged. Proceeding from the probabilistic interpretation of the fluctuation parameter, we can select a probability level of $P \geq 0.5$ as a limiting level above which the occurrence probability of the solar cycle geoeffective phase can be considered significant (see http://www.forshock.ru).

The test calculation of the occurrence probability of the cycle geoeffective phase during the period

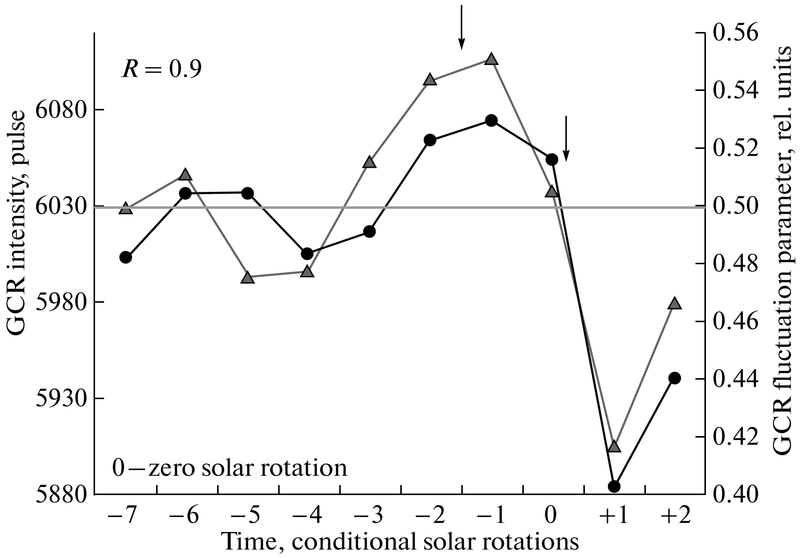

Fig. 7. The average values of the GCR intensity in pulses (the left-hand scale) and the fluctuation parameter in relative units (the right-hand scale), obtained using the epoch superposition method for ten cases of sharp and deep GCR intensity minimums during cycle 23. The cross-correlation coefficient of the series ($R = 0.9$) is presented in the upper left corner. The numbers of rotations relative to the conditional zero rotation are plotted on the abscissa. The $P \geq 0.5$ level is the level of making decision concerning the beginning of the geoeffective period.

before the known events in October–November 2003 (rotations 2323–2324) indicated that the proposed method is effective (Fig. 8a). The precursor registration lead time (τ) equal to one solar rotation is also confirmed by the quantitative estimation based on the calculation of the cross-correlation function $R(\tau)$ between the 27-day values of the fluctuation parameter and GCR intensity (Fig. 8b). The results of the calculation and their cross-correlation function, calculated using the data for all four 11-year cycles (20–23), indicate that the fluctuation parameter is systematically one solar rotation (on average) ahead of the GCR intensity (Fig. 9). This means that the GCR fluctuation parameter includes prognostic information in addition to the significant correlation between the introduced parameter and intensity, which is of prime importance in making a medium-term prediction of geoeffective periods of the 11-year cycle with a lead time of one solar rotation.

The fact that the introduced parameter is also rather effective on smaller averaging scales is of the same importance. Figure 10 illustrates the real-time prediction possibilities, using the known extreme events in October–November 2003 as an example. The possibilities of making a medium-term prediction of the geoeffective period in 2003 were shown above (see Fig. 8). It is clear that geoeffective rotations 2323–2324 follow the significant maximum with $P \geq 0.5$ registered on rotations 2320 and 2321. For the real-time prediction version, we calculated the fluctuation parameter for each day during rotations 2323 and 2324 from September 5 to November 10, 2003. The GCR intensity in percent is presented on the left-hand scale. The calculated fluctuation parameter is divided by the two-level band of “significance levels” in the $P = 0.55 \pm 0.01$ interval of values (the empirically determined levels for making decisions on the prediction with a probability of $P \geq 0.5$). The upper level corresponds to the present-day period of the 11-year cycle minimum (see http://www.forshock.ru). The lower decision-making level operates during the remaining periods. Significant daily average values of the fluctuation parameter were registered on October 23 and 27, 2003, i.e., a day before the beginning of a decrease in the GCR intensity (October 24–25 and 28–30, 2003). A significant precursor was also registered on November 3, 2003. It is known that the most powerful X ray flare was registered on November 4, and only the flare’s position on the western edge of the solar disk did not allow this flare to adequately manifest itself in the Earth’s orbit.

4. DISCUSSION

We now discuss the relationship between the introduced shape parameter and the traditional indices of solar and geomagnetic activities. High correlation with the Wolf numbers ($R \geq 0.74$) and the number of large geomagnetic storms with $Dst < -150$ nT ($R \geq 0.65$) was obtained for yearly averaging. It is important to compare the GCR fluctuation parameter with the key parameter of modulation ($k = \omega\tau$) introduced in [Krymsky et al., 2007] in order to characterize the degree of field regularity. Here ω is the particle gyrof-

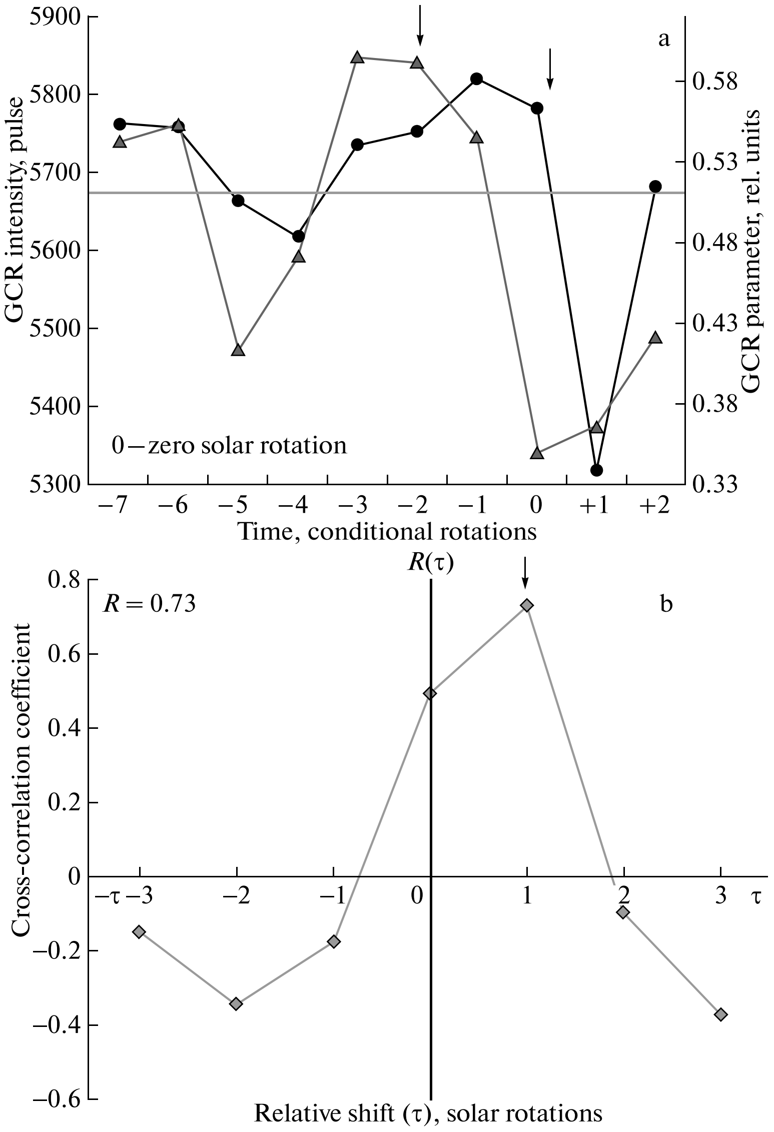

Fig. 8. (a) The GCR intensity in pulses (the left-hand scale and the fluctuation parameter in relative units (the right-hand scale) for the geoeffective period in October–November 2003. The number of rotations relative to the conditional zero rotation 2323 are plotted on the abscissa. The $P \geq 0.5$ level is the level of making decision concerning the beginning of the geoeffective period. (b) A cross-correlation analysis of the 27-day values of the GCR intensity and fluctuation parameter during rotations 2316–2325. The cross-correlation coefficient of the series ($R = 0.73$) is given in the upper left corner. The relative shift by one solar rotation is marked by an arrow. The relative shift (τ) of analyzed series in terms of solar rotations is plotted on the abscissa.

requency in a regular magnetic field, and τ is the average time between particle scattering acts. It is assumed that the modulation parameter is constant for the entire heliosphere and independent of particle energy, although it will vary in different solar cycles. It is assumed that the modulation parameter value reflects the relationship between the strengths of regular and turbulent fields (the former field is much smaller than the latter one during the maximum period). In contrast, the turbulent field strength reaches its maximum when the field sign reversal is finished. This strength first linearly increases in the course of time, reaches its maximum during polarity reversal, and then linearly decreases.

Being an indicator of the degree of IMF inhomogeneity, the GCR fluctuation parameter is in this sense an inverse factor with respect to the degree of magnetic field regularity k, which is the key parameter of modulation in the 11-year cycle model. This is confirmed by the behavior of the envelope of variations in the fluctuation parameter in each 11-year cycle: as for the IMF turbulent component, the envelope of variations in the GCR fluctuation parameter reaches its maxi-

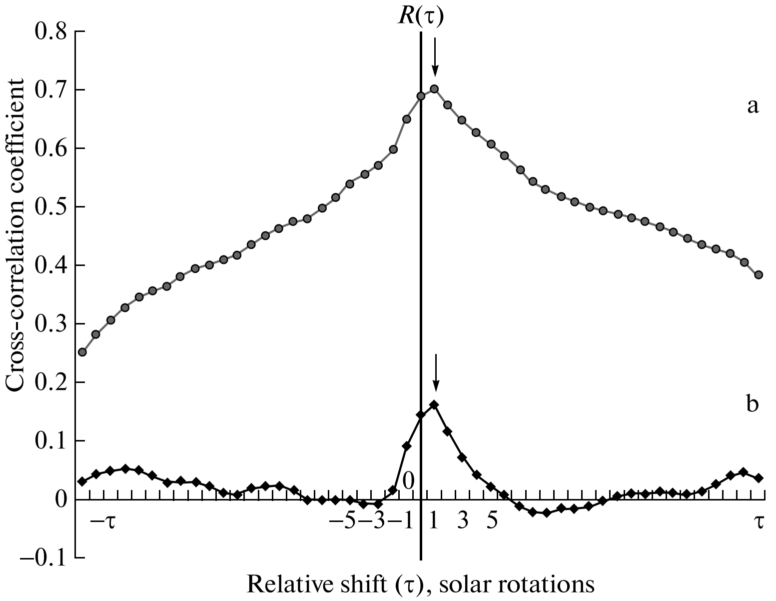

Fig. 9. (a) A cross-correlation analysis of the 27-day values of the GCR intensity and fluctuation parameter during cycles 20–23. The relative shift (τ) of the analyzed series in terms of solar rotations is plotted on the abscissa. The relative shift by one solar rotation is marked by arrows. (b) the same as in panel (a) but with an eliminated 11-year variation.

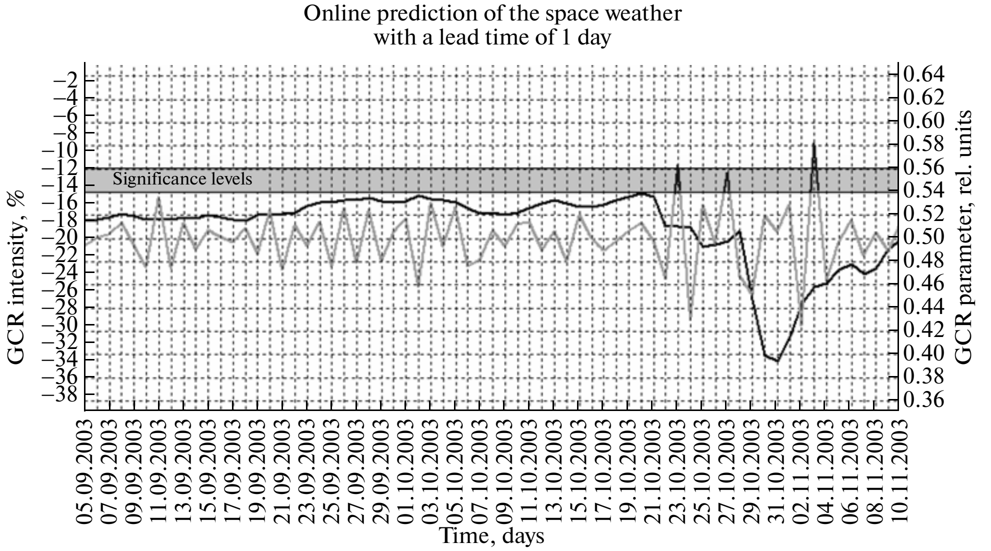

Fig. 10. The possibility of online prediction illustrated based on the known extreme events in October–November 2003. The fluctuations were calculated for each day from September 5 to November 10, 2003. The GCR intensity is given in percent (the left-hand scale). The GCR fluctuation parameter values (the right-hand scale) are separated by the two-level band of significance levels in the $P = 0.55 \pm 0.01$ interval (empirically determined levels of making decision concerning the prediction with a probability of $P > 0.5$). The upper significance level corresponds to the period of the 11-year cycle minimum.

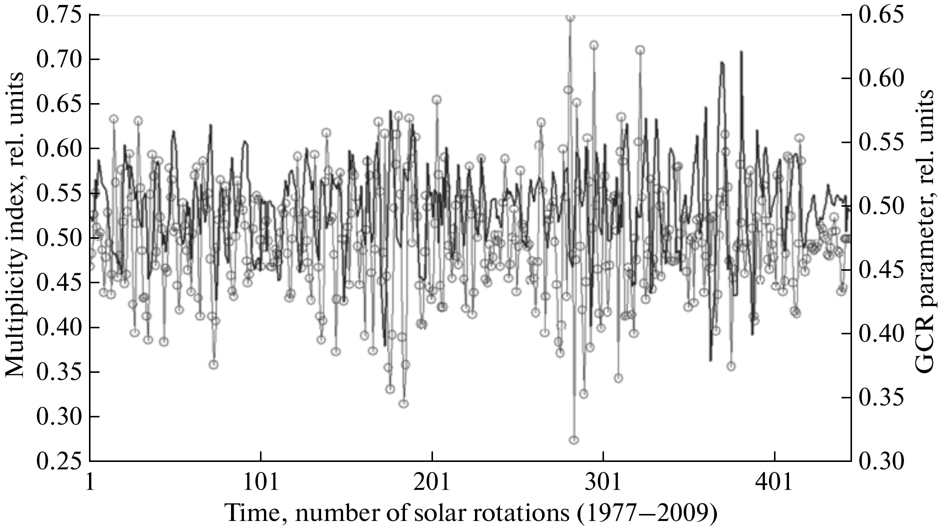

Fig. 11. A comparison of the HF component (the variations with periods longer than 1 year are eliminated) of the global solar magnetic field multiplicity index in relative units (open circles, the left-hand scale) and the GCR fluctuation parameter (the solid curve, the right-hand scale) for the last four 11-year cycles 20–23 (1977–2009). The time (the number of solar rotations) from 1977 to 2009 is plotted on the abscissa.

mum when sign reversal of the general solar magnetic field is finished (see Fig. 3). The relation of the GCR fluctuation parameter to magnetic field turbulence also follows from a comparison of the GCR parameter with the "indicator of the solar multiplicity effectiveness" (Fig. 11). This indicator was introduced in [Ivanov et al., 1997; Ivanov and Obridko, 2001].

The established relationship between the GCR fluctuation parameter and the degree of magnetic field inhomogeneity is the decisive factor in deciphering the GCR fluctuation dynamics. The nonrandom non-Gaussian character of the GCR fluctuation parameter is caused by nonstationary semiannual variation that reflects the transient nonstationary oscillatory process of sign reversal of the general solar magnetic field. Precisely this transient oscillatory process is responsible for the maximal geoeffectiveness and duration of the polarity reversal phase, which manifests itself in a sharp and deep minimum in the GCR intensity during the final stage of field sign reversal. The following pattern of the detected dynamics is important for understanding the phenomenon as a whole: it has been established that the polarity reversal duration inversely depends on the 11-year cycle amplitude at its maximum. The smaller the cycle amplitude is, the longer the transient oscillatory process of field sign reversal is, and vice versa. This allowed us to put forward a hypothesis that an invariant of the 11-year "amplitude–duration" cycle exists. The presence of a similar invariant means that the area "swept out" below the 11-year cycle curve is constant [Kozlov and Markov, 2007].

As is known, a similar invariant in physics takes place for solitons: the width of the envelope of a group soliton is inversely proportional to the square root of its amplitude at a maximum. A similar relationship between the width and amplitude of the 11-year cycle was obtained relatively recently [Kononovich, 2005]: "the time for reaching the 11-year cycle maximum is inversely proportional to the square root of its amplitude." In our case the envelope of the fluctuation parameter variations, upon reaching its maximum at the end of the polarity reversal stage (see Figs. 3, 11), is identified with the group soliton envelope. It is also known that the soliton mechanism is most effective as compared with other convective mechanisms by which excess energy is "bled," and this bleeding is performed in discrete portions, which is typical of energy regulation self-oscillation regimes. This indicates the nature of the 11-year cyclicity: the 11-year cyclicity is the most effective (i.e., soliton) regulation mechanism responsible for the constant solar temperature. From this standpoint, the failure of the 11-year cyclicity corresponds to a regime of chaotic self-oscillations!

The presence of the amplitude–duration invariant naturally results in an increase in the duration of low cycles with respect to the amplitude. Indeed, a wavelet analysis of the data for 1969–2005 indicated a LF drift toward periods longer than the 11-year variation period appeared from the end of the previous (22) solar cycle [Kozlov and Markov, 2007]. At present, 4 years later, the conclusion on the LF drift has been confirmed on a new basis, using the GCR fluctuation parameter. It is important that the detection of the LF drift is an independent argument for the existence of the 11-year cycle invariant and is its verifiable consequence.

Why is the fact of detection of a similar drift so important? The point is that the appearance of an LF substrate (LF drift according to our terminology) can precede a prolonged failure of the 11-year cyclicity [Frik, 2003]. The record high present-day GCR intensity is possibly related to weakening of the global solar dipole field; such data has already appeared. Obridko and Shelting [2009] indicated that in 2008 the solar dipole magnetic moment decreased to values typical of the beginning of the 20th century. Local fields are also anomalously low [Below and Gaidash, 2009]. Such a prolonged period with the complete disappearance of sunspots was observed only at the beginning of the last century.

Now, we can already state that we are at least in a stage of an extraordinary decrease in solar activity and, as a maximum, during the initial phase of a prolonged failure of the 11-year solar cyclicity with all its consequences. First of all we mean an anomalously high level of the GCR intensity radiation background (Fig. 3). As is known, an increase in GCR intensity promotes the process of cloud formation and, as a consequence, in a temperature decrease on the planetary scale. This is an alternative to the process of global warming [Kozlov and Markov, 2007]. This will evidently be substantial only in the case of a prolonged failure of the 11-year cyclicity, viz., breaking of the regular convection (self-oscillation) regime in the solar convection zone and transition in the regime of chaotic self-oscillations (strange attractor regime). The occurrence of a prolonged failure of the 11-year cycle in the nearest 10 years could mean that nonlinear regimes of the general solar magnetic field evolution are real. The scenario of failure of the 11-year cyclicity we proposed differs from the widely accepted scenario of “linear superposition” of periodic waves (11 years, 200 years, etc.). According to the linear superposition principle, a prolonged failure of the 11-year cyclicity will begin in the middle of the 21st century.

5. CONCLUSIONS

(1) We introduced the cosmic ray fluctuation parameter, which is an indicator of the magnetic field inhomogeneity degree in the vicinity of shocks and during 11-year cycle geoeffective phases.

(2) The nonrandom nonGaussian character of the GCR fluctuation parameter is related to nonstationary semiannual variation reflecting the transient nonstationary oscillatory process of sign reversal of the general solar magnetic field. This transient oscillatory process is responsible for the maximal geoeffectiveness and duration of the polarity reversal phase, which manifests itself in a sharp and deep minimum of the GCR intensity during the final stage of the field sign reversal.

(3) On a new basis we confirmed the invariant of the amplitude–duration 11-year cycle: we detected LF drift of the period of small-amplitude cycles at a maximum, which is observed in the anticipated increase in the cycle 23 duration.

(4) At present, we are at least during a stage of an extraordinary decrease in solar activity and, as a maximum, during the initial phase of a prolonged failure of the 11-year cyclicity.

(5) The introduced parameter of cosmic ray fluctuations is a theoretically prognostic factor, which is very important for a medium-term prediction of geoeffective 11-year cycle periods with a lead time of ~1 solar rotation and for an online prediction of shocks with a lead time of ~1 day.

(6) The 11-year cyclicity is the most effective (i.e., soliton) mechanism by which excess energy is bled, which is responsible for the regulation of a constant solar temperature.

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