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Wavelet Image of the Fine Structure of the 11-Year Cycle Based on Studying Cosmic Ray Fluctuations during Cycles 20–23

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Abstract—A non-stationary transient oscillating process of the solar magnetic field polarity reversal of ≈3 years in duration has been established: a U-shaped dynamics in the wavelet representation of variations in the scintillation index of galactic cosmic rays (GCRs) (≈7, 13–14, and ≈7 solar rotations). The transient oscillating process of the field reversal is concluded with a sharp and deep decrease in the GCR intensity at the branch of 11-year cycle decline (1972, 1982, 1991, and 2003). The duration of the transient process inversely depends on the 11-year cycle amplitude. Retardation of relaxation oscillations during "weak" cycles (20 and 23) explains "anomalous" solar activity in 1972 and 2003. A decrease in the amplitude of the current cycle 23 is accompanied by an increase in its duration, which can mean that the 11-year cyclicity has become anomalous. The constancy of the energy released in a single cycle indicates that the 11-year cycle is the mechanism of energy regulation preventing the Sun from "overheating" at the critical temperature.

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1. INTRODUCTION

The origin of sharp and deep decreases in the GCR intensity at the declining branch of the 11-year cycle is still a debatable problem. In the first works that considered this problem, it was assumed that similar decreases are caused by the presence of large-scale "magnetic barriers" in the interplanetary medium [Burlaga et al., 1993; Le Roux and Potgieter, 1993]. The authors of the recent publications [Svirzhevskaya et al., 2001; Belov et al., 2002] have the same viewpoint. Nevertheless, there are all reasons to believe that sharp and deep decreases in the GCR intensity in 1972, 1982, 1991, and 2003 are related to the decay of the large-scale magnetic field at the final stage of the sign reversal of the global solar magnetic field [Kozlov, 1996; Kozlov and Markov, 1997]. The sign of the global solar magnetic field is responsible for the structure of the 11-year cycle as a whole, which manifests itself in the difference in the structures of even and odd cycles [Krymsky et al., 2001]. The process of sign reversal is evidently responsible for the fine structure of the cycle. This work is dedicated to analyzing the fine structure dynamics during the 11-year cycle based on the GCR intensity fluctuations studied for the last four cycles (20–23).

2. FLUCTUATION ANALYSIS METHOD

The spectral–temporal index of GCR scintillations [Kozlov et al., 1984] was introduced in order to formalize the characteristic dynamics of the power spectra of GCR fluctuations found near interplanetary shock waves [Kozlov et al., 1973]. The dimensionality of the three-dimensional dynamic spectrum of the process is as a rule reduced to the usual (two-dimensional) numerical sequence of the scintillation index as a result of a similar formalization. This makes it possible to apply all known methods of quantitative analysis [Kozlov, 1999] to the scintillation index. The scintillation index is calculated based on the data of the global network of polar cosmic-ray stations with a high resolution (5 min) for the last four cycles (20–23), i.e., factually for the entire history of index registration with a similar resolution. For this purpose, the RECORD interactive database of the results of ground-based cosmic ray monitoring was created at the Institute of Cosmophysical Research and Aeronomy [Kozlov et al., 2003].

3. RESULTS OF ANALYSIS

Using the 5-min data of three high-latitude neutron monitors (Tixie; Apatity; and Oulu, Finland), we calculated the GCR scintillation index at an interval of 5 min for the last four 11-year cycles. The obtained values of the scintillation index and GCR intensity were averaged, first, for 27 days and, then, for three solar rotations. Figures 1, 3, and 5 present the results of calculation of the 27-day values of the GCR scintillation index in relative units and GCR intensities in percent for 1968–2005 (in pairs for cycles 20–21, 21–22, and 22–23). The results of a wavelet analysis of the correspond-

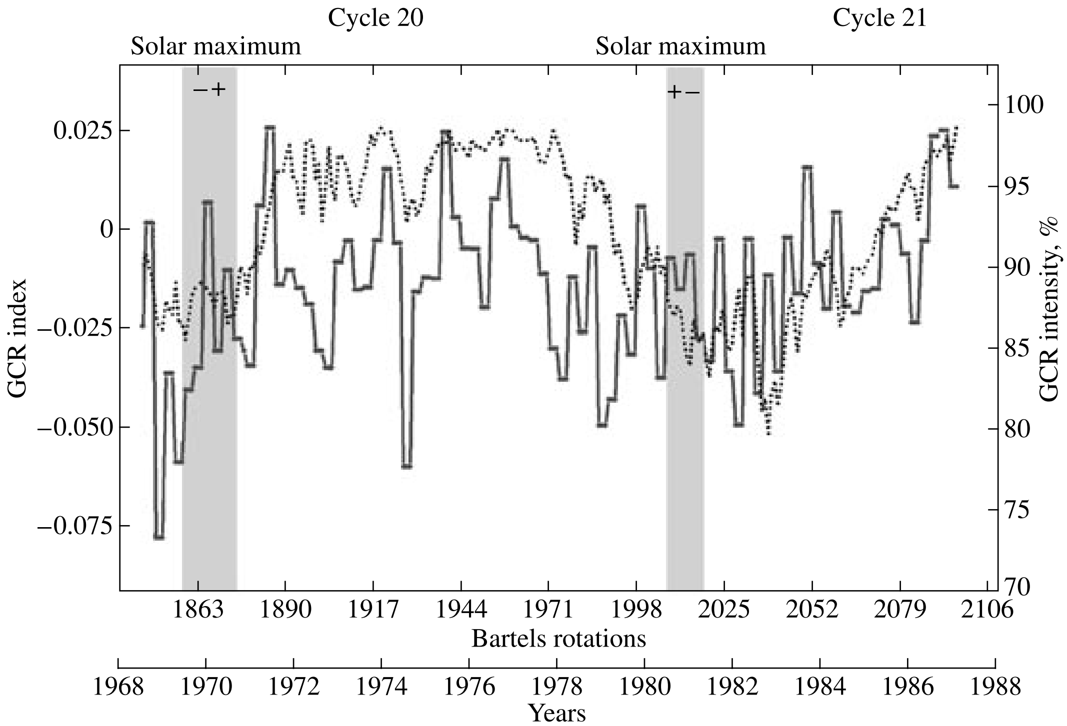

Fig. 1. Scintillation index (solid curve, scale on the left) and intensity (dashed line, scale on the right) according to the data of Oulu station (Finland) for two solar cycles 1968–1986. Horizontal axis: years and Bartels solar rotation numbers. The intervals of the sign reversal of the global solar magnetic field are indicated.

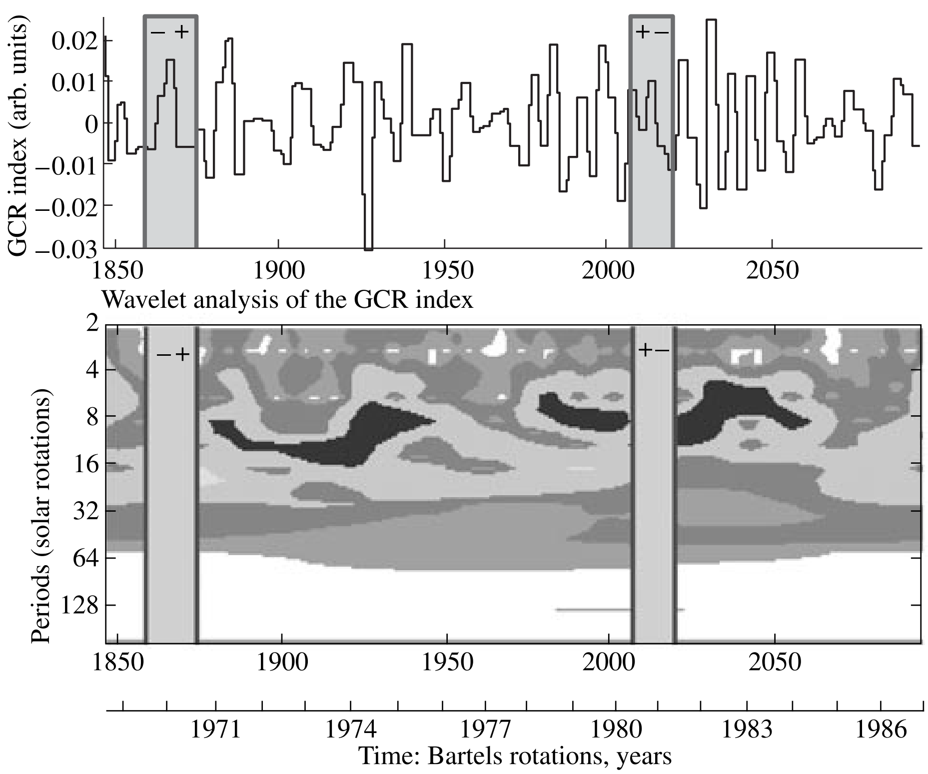

Fig. 2. Wavelet analysis of the dynamics of the variations in the GCR scintillation index for two solar cycles from 1968 to 1986. The trend caused by the 11-year cycle is eliminated from initial data. Bottom, vertical axis: periods of variations in solar rotations. The years and numbers of solar rotations are plotted on the abscissa.

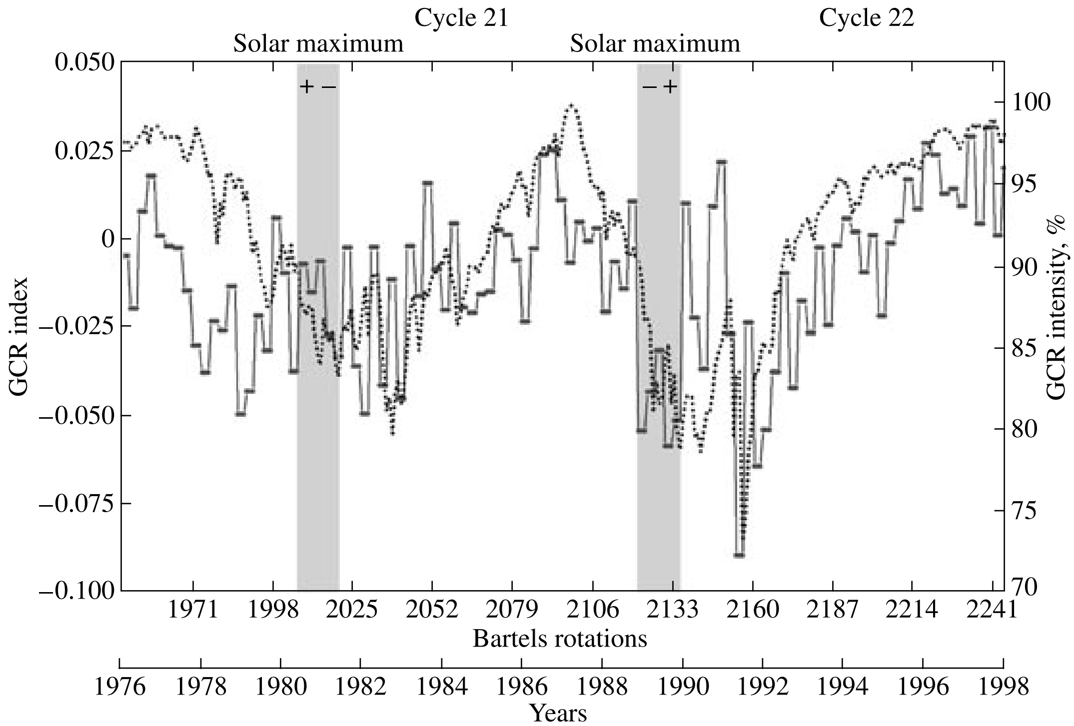

Fig. 3. The same as in Fig. 1 but for 1976–1997.

ing variations in the GCR scintillation index are shown in Figs. 2, 4, and 6. In Fig. 7 the amplitude–frequency dynamics of the 11-year variation for all four solar cycles (20–23) is analyzed. Figures 8 and 9 present the results of a joint analysis of variations in the GCR scintillation index and in the variance of the interplanetary magnetic field and the flux of protons with an energy of ~1 MeV.

4. DISCUSSION OF RESULTS

The results of our calculations indicate that the annual variation dominates in the GCR scintillation index in the years of the minimum of the odd (21) 11-year cycle (1985–1987). In the years of the minimum of the even (22) cycle, the annual variation has not been detected. The conclusion that the annual variation predominates at a minimum of the odd cycle, i.e., at the negative polarity of the global solar magnetic field, is consistent with the results obtained by Krymsky et al. [2001]. In the years of the maximum and decline of the 11-year cycle, the semi-annual variation in the scintillation index is predominant. On the whole, a similar non-stationary modulation is most evident in the results of a wavelet analysis of the GCR scintillation index variations (Figs. 2, 4, 6). The duration of the non-stationary oscillating transient process in the GCR scintillation index inversely depends on the 11-year cycle amplitude.

The establishment of the inverse relationship between the duration of the oscillating transient process and the cycle amplitude points to the presence of an "amplitude–duration" invariant for the solar cycle. The presence of an invariant means that the area "swept" under the curve of the 11-year cycle is constant. In this case a decrease in the cycle amplitude should be accompanied by an increase in the cycle duration and vice versa. The retardation of relaxation oscillations in the cycles with small amplitude (20 and 23) also explains the "anomalous" solar activity in 1972 and 2003. The existence of an inverse relationship between the time of reaching the maximum of the 11-year cycle and its amplitude was referred to earlier by Waldmeier [Vitinsky et al., 1986]. The inverse relationship between the time of reaching the cycle maximum and the square root of the cycle peak amplitude was also revealed in the recent work [Kononovich, 2005]. A similar dependence is typical of the envelope soliton (the soliton width is inversely proportional to the squared root of the soliton amplitude), which indicates that the 11-year cycle has a soliton-like origin.

The conclusion that the area "swept" under the curve of the 11-year cycle or the energy released in a single cycle are constant points to the possible origin of cyclicity of the global solar magnetic field: the 11-year (on the average) recurrence is the mechanism of energy regulation preventing the Sun from "overheating" at the critical temperature. Naturally, when the temperature of the Sun decreases below the critical value, it becomes unnecessary to bleed excess energy; i.e., cyclicity disappears (as during the "Maunder minimum").

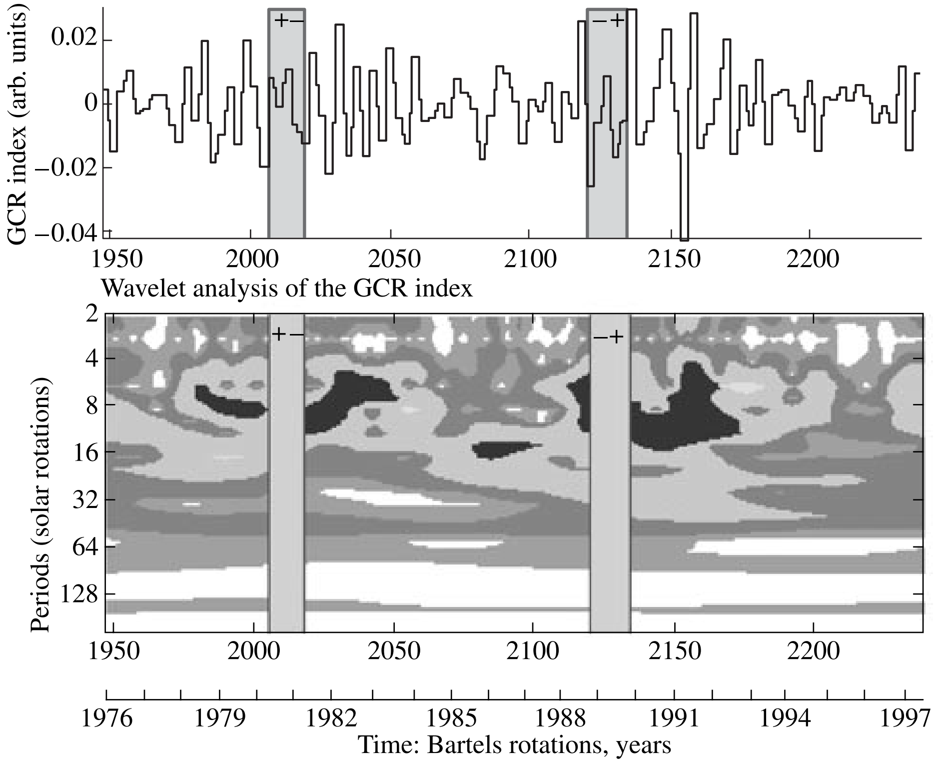

Fig. 4. The same as in Fig. 2 but for 1976–1997.

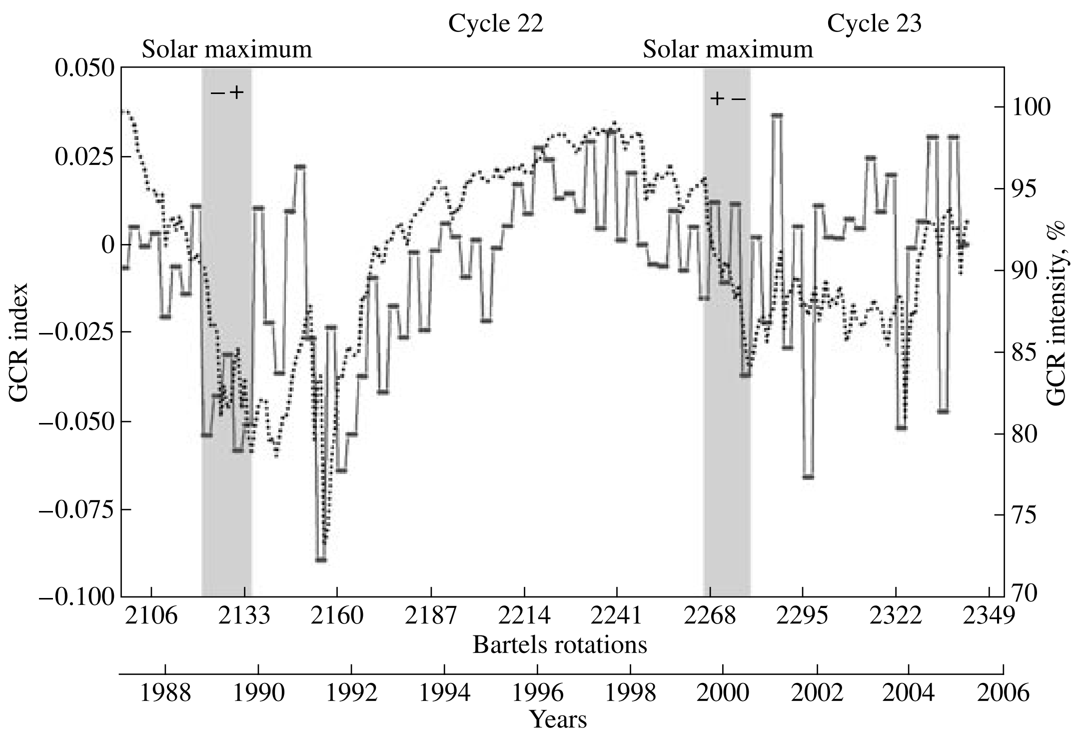

Fig. 5. The same as in Fig. 1 but for 1987–2005.

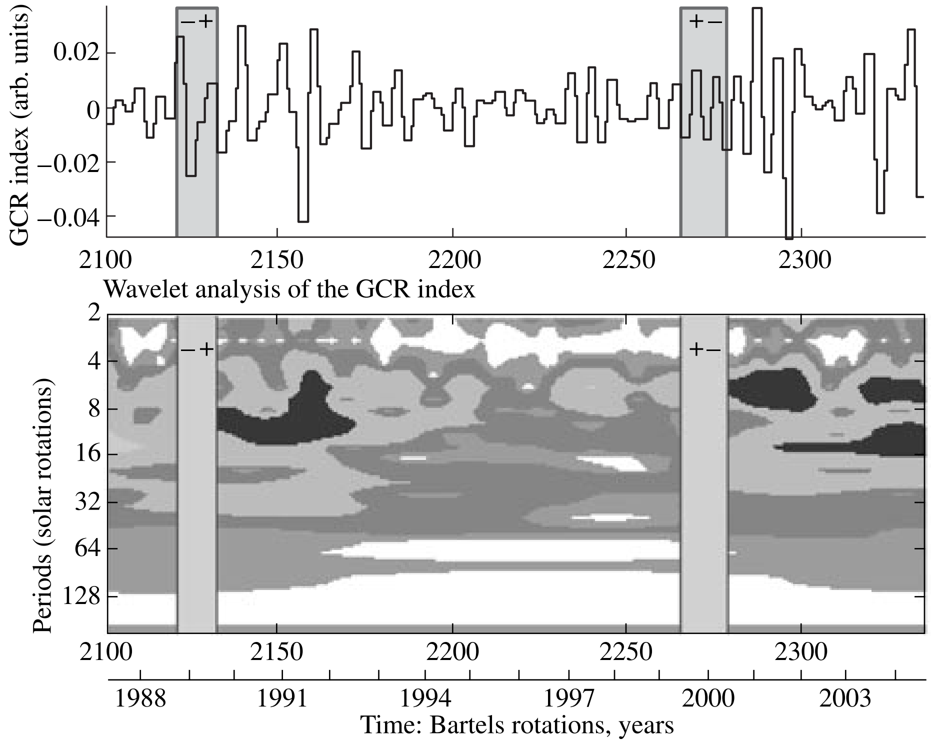

Fig. 6. The same as in Fig. 2 but for 1987–2005.

A similar possibility still exists. A decrease in the amplitude of the current cycle 23 in full conformity with the "amplitude–duration" invariant manifests itself in an increase in the cycle duration. This is confirmed by a drift of the maximum of the 11-year cycle variation into the LF region (Fig. 7). The wavelet representation makes it possible to determine the time of the beginning of the first harmonic drift into the LF region. This moment is marked in Fig. 7 with a vertical arrow. The anomalous behavior of the 11-year cyclicity appeared at the end of cycle 22 and beginning of cycle 23.

This can become important from the viewpoint of a long-term forecasting of the development of events in the forthcoming cycle 24, and in other respects. As a rule, an increase in the solar cycle duration is observed before the long-term distortion of the 11-year cyclicity, e.g., before the "Maunder minimum" [Frik, 2005]. In this connection, we should also indicate that the Gnevyshev–Ohl rule is distorted during cycle 23. Contrary to this rule, the amplitude of the odd cycle 23 turned out to be smaller then the amplitude of the previous even cycle. This happens rarely and only before long-term distortions of the 11-year cycle [Komitov and Kaftan, 2003]. By the way, the failed forecasts of the expected large amplitude of cycle 23 were based on this rule. As is known, such distortions were accompanied by a decrease in the mean temperature on the Earth. Indeed, a decrease in solar activity results in an increase in the GCR intensity. In turn, an increase in the GCR intensity is accompanied by an increase in cloudiness, e.g., by means of the mechanism proposed by Krymsky [2002]. If the anomalous behavior of the 11-year cyclicity predicted by for the next decade is confirmed, we will face global cooling instead of expected disastrous global warming.

Since 1998, we have got an opportunity to easily obtain the data of direct measurements of solar wind parameters in real-time mode via the Internet. Together with the scintillation index and GCR intensity, Figure 8 presents the data of direct measurements of the variance of the interplanetary magnetic field (IMF) and the flux of low-energy (~1 MeV) protons. It is clear that the variations in the GCR scintillation index lead the variations in the analyzed parameters by three solar rotations. An increase in the amplitude of the variations in the scintillation index, IMF variance, and flux of low-energy protons is observed near the maximum and at the declining phase of cycle 23. This is especially obvious in the results of the wavelet analysis. The wavelet images are almost identical (Figs. 9a–9c). The semi-annual variation is prominent in all three cases. At the same time, the semi-annual variation in the scintillation index leads the semi-annual variation in the IMF variance and proton flux. We used this result as the basis for the medium-term (with a lead time of ≈3 solar rotations) forecast of heliospheric storms [Kozlov, 1996].

Recently, semi-annual harmonics were detected in the variations in the frequency of coronal mass ejec-

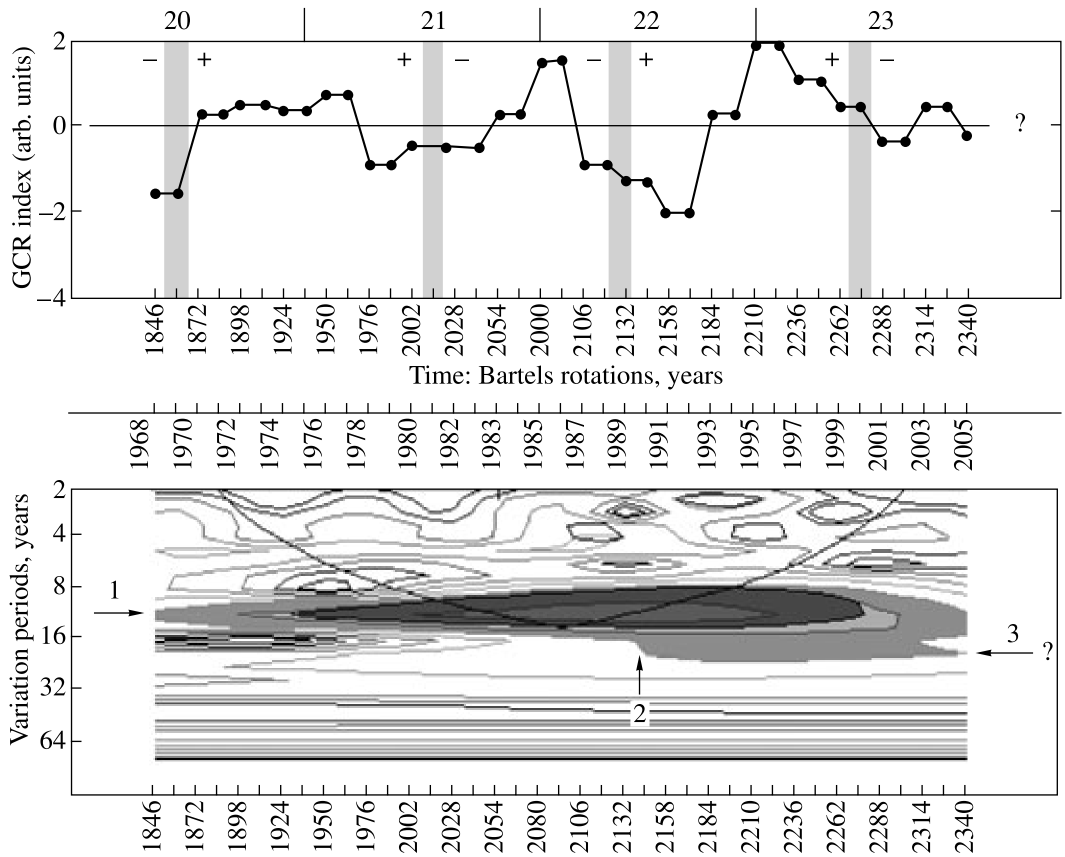

Fig. 7. Results of a wavelet analysis of the dynamics of the 11-year variation in the GCR scintillation index for four cycles (20–23). Bottom, left: scale of periods of variations in years (the 11-year variation is shown by a horizontal arrow on the left). Horizontal axis: time (Bartels solar rotation numbers and years).

tions (CMEs) during the current cycle 23 [Yu Oing Lou et al., 2003]. It should be noted that the semi-annual (and annual) variations were detected for the first time at the declining stages of cycles 21–22 based on studying the variations in the GCR scintillation index [Kozlov and Markov, 1997; Kozlov, 1999; Kozlov et al., 2003]. At the same time we drew the conclusion that the detected variations are related to the decomposition of the large-scale magnetic field at the final stage of sign reversal of the global solar magnetic field. In this connection it is expedient to quote Professor I.S. Veselovsky: "…it is possible to distinguish a number of regular processes against this (chaotic) background even at the highest (solar) activity, and this possibility is always of interest from the viewpoint of determining the horizons of forecast, which are now uncertain and require a careful analysis" [Veselovsky, 2001].

We relate the non-stationary U-shaped dynamics of variations in the GCR scintillation index and in the analyzed solar wind parameters to the transient process of sign reversal of the global solar magnetic field. The field sign reverses due to destruction of the large-scale solar dipole: a quadrupole component of the field appears. It follows, in particular, from the observational data on polarity of the solar magnetic field for the studied interval [Sanderson et al., 2003]. The variations in the ratio of the quadrupole components to the dipole ones continue for several years, at least until 2002 inclusive. We relate the occurrence of powerful and, as a rule, multiple "sporadic" events at the declining stages of the 11-year cycle to the prevalence of quadrupole components at that time. A systematic insufficient recovery of the GCR intensity during multiple Forbush effects (by analogy with the known Lockwood's hypothesis about the origin of the 11-year cycle in the GCR intensity) should result in sharp and deep decreases in the GCR intensity at the final stage of the sign reversal of the solar magnetic field, i.e., at the declining stage of the 11-year cycle.

A pronounced intensity of the semi-annual variation in the GCR scintillation index in cycle 23 is evidently related to a shallow depth of modulation of the current 11-year cycle. On the contrary, in the cycles with deeper modulation (21–22), the semi-annual variation is least pronounced. This variation is most modulated on steep decline branches of the cycle. Near the maximum of the 11-year cycle, i.e., in the region of a comparative "plateau", the semi-annual variation is rather distinct and is observed in different parameters. Precisely this is apparently the well-known Gnevyshev

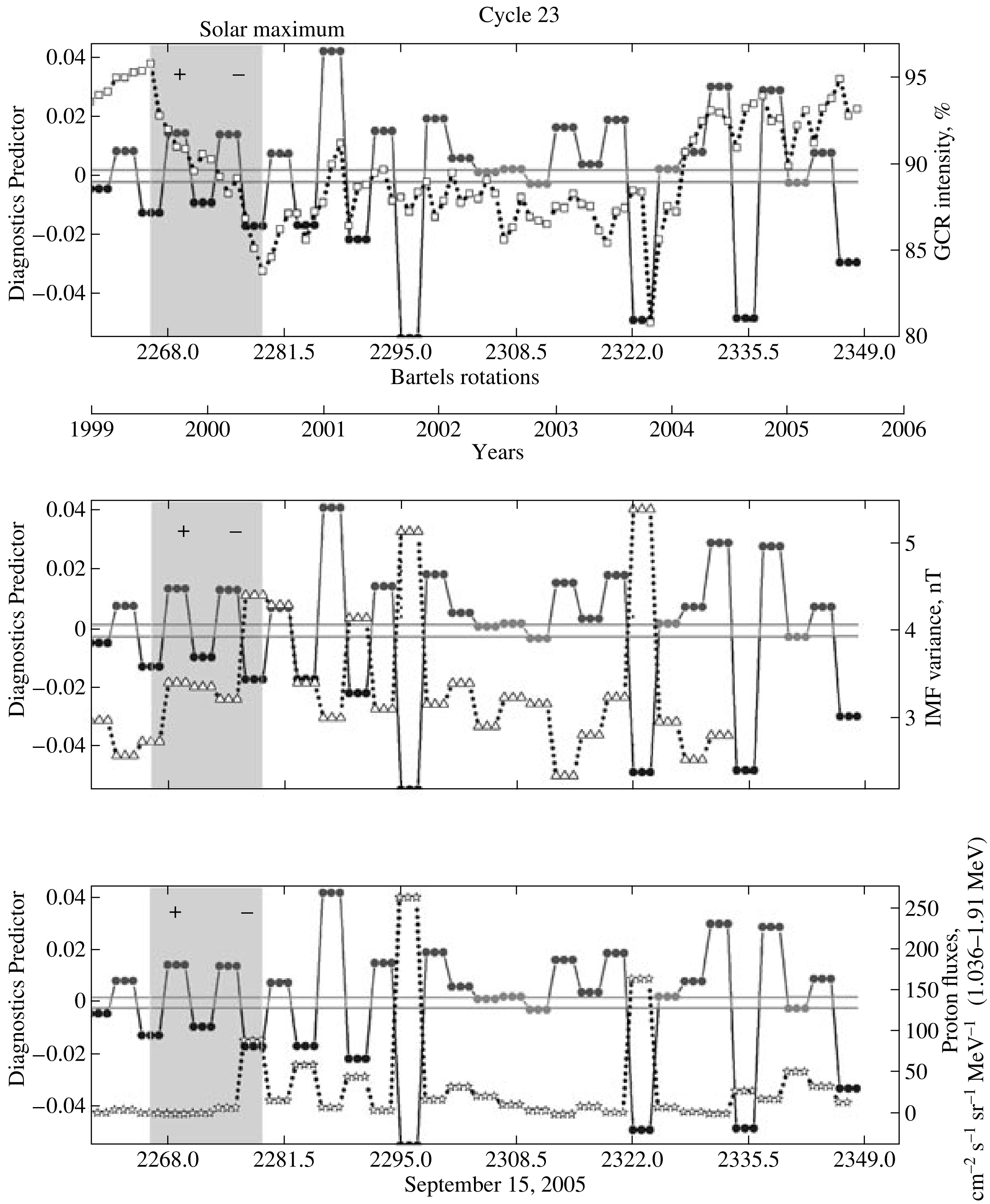

Fig. 8. The 27-day values of the scintillation index (solid curve, left scale) and GCR intensity (dashed curve, left scale) averaged over three solar rotations; data from Oulu (Finland). Bottom: variations in the IMF variance and flux of low-energy protons with an energy of ~1 MeV. Horizontal axis: years and Bartels solar rotation numbers.

trough [Kozlov et al., 2003]. From this point of view, the Gnevyshev trough is nothing but the onset of a non-stationary oscillating transient process of sign reversal of the global solar magnetic field “visible” in the vicinity of the plateau of the 11-year cycle maximum. This allows us to explain in a unified manner the Gnevyshev trough and a sharp decrease in the GCR intensity at the declining stage of the 11-year cycle. Most likely, precisely the non-stationary character of the U-shaped dynamics of the oscillating transient process causes the appearance of the so-called quasi-biennial variations in the GCR intensity in the vicinity of the maximum of the

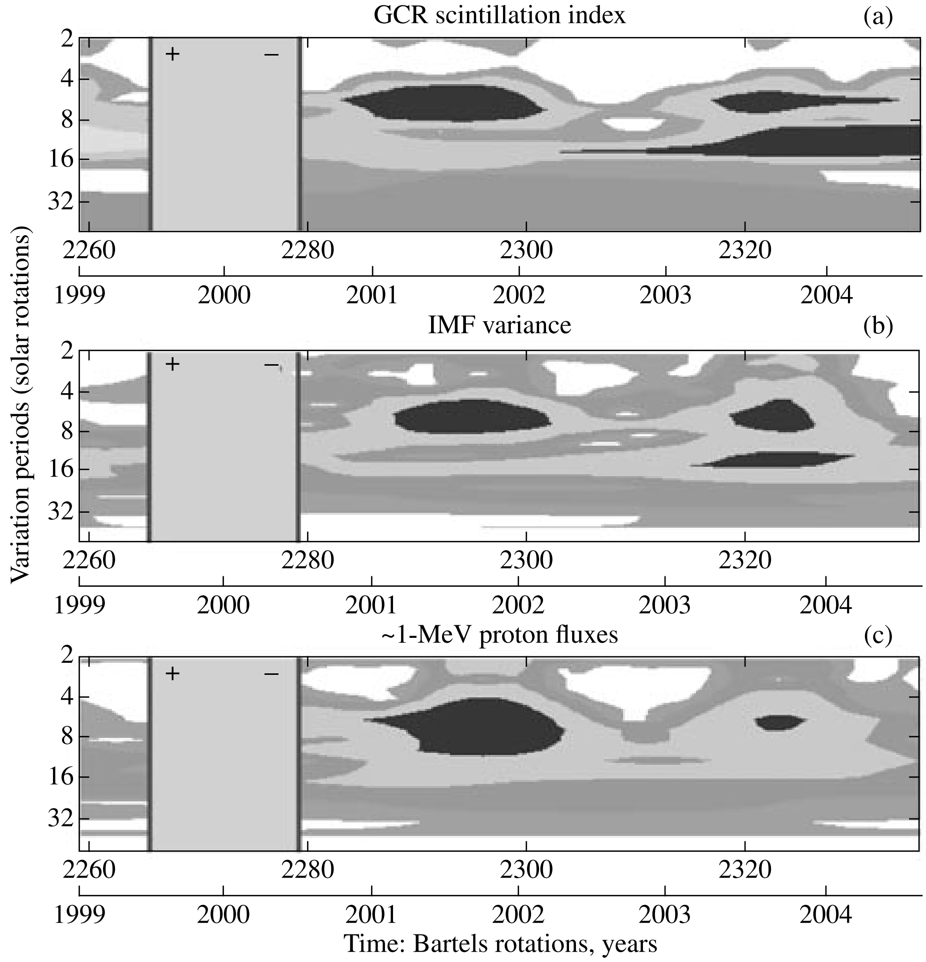

Fig. 9. Wavelet analysis of the 27-day values averaged over three rotations: (a) GCR scintillation index, (b) IMF variance, (c) flux of low-energy protons with an energy of ~1 MeV from 1999 to 2004. Vertical axis: variation periods in solar rotations.

11-year cycle if narrow-band filtering is applied, which, unfortunately, often takes place.

5. CONCLUSIONS

(i) We established the non-stationary oscillating transient process of sign reversal of the global solar magnetic field of ≈3 years in duration: a U-shaped dynamics in the wavelet representation of the variations in the GCR scintillation index (≈7, 13–14, and ≈7 rotations).

(ii) The non-stationary transient process of the field sign reversal is concluded with a sharp and deep decrease in the intensity of galactic cosmic rays at the declining stage of the 11-year cycle (1972, 1982, 1991, and 2003).

(iii) The duration of the oscillating transient process inversely depends on the 11-year cycle amplitude. Retardation of relaxation oscillations during "weak" cycles (20 and 23) also explains the "anomalous" solar activity in 1972 and 2003. A decrease in the amplitude of the current cycle 23 is accompanied by an increase in the cycle duration, which can point to the beginning of the anomalous behavior of the 11-year cyclicity.

(iv) The constancy of the energy released in a single cycle indicates that the 11-year cycle is the mechanism of energy regulation preventing the Sun from "overheating" at the critical temperature.

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