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The development of the maximum phase of solar cycle 23 in the galactic cosmic ray intensity

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[1] The overall features of the solar cycle maximum phase in the galactic cosmic ray intensity near the Earth and the solar and heliospheric factors responsible for them are discussed. The development of the solar cycle in the galactic cosmic ray intensity near the Earth and in the outer heliosphere is compared, both for the absolute intensity and for that normalized allowing for the changing radial position of the spacecraft and the 22-year wave. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2114 Interplanetary Physics: Energetic particles; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle; *KEYWORDS:* Galactic cosmic ray; Solar cycle 23; Voyager 1, 2 and IMP 8 observations.

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1. Introduction

[2] There are some indications that the current (23rd) solar cycle at the century boundary could be unusual when compared with the previous cycles in the second half of the 20th century when the galactic cosmic ray (GCR) intensity has been monitored near the Earth. Besides, during the last five solar cycles the spacecraft have been exploring the heliosphere at progressively greater heliocentric distances and now they send the data from the heliocentric distances $r = 75 - 93$ AU. In our previous work [*Krainev and Bazilevskaya*, 2004; *Krainev and Webber*, 2003; *Krainev et al.*, 1999a, 2001, 2002] we studied the development of the current solar cycle in the GCR intensity, especially its maximum phase, from the inside of this phase. Now when the current cycle maximum phase in the GCR intensity terminated in the inner heliosphere and it is close to the end in the outer heliosphere we can discuss the overall features of this phase and the solar and heliospheric factors responsible for them, both near the Earth, where it can be compared to the previous cycles, and in the outer heliosphere, where the influence of the termination shock can be searched for. In this paper we consider the structure of the maximum phase in the solar cycle variation of the GCR intensity using the data smoothed with a 0.5-year period. In what follows by the maximum phase we mean the time period between two main gaps in the intensity (corresponding to two peaks in the intensity modulation with the so-called Gnevyshev gap between them [see *Krainev et al.*, 1999a, and references therein]).

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2. Development of Solar Cycle 23 on the Sun and Near the Earth

[3] Figure 1 shows for 1995–2004 the time history of some solar, heliospheric and cosmic ray characteristics near the Earth: the strength of the interplanetary magnetic field (IMF) $B_{\rm IMF}$ (from http://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/omni_27_av.dat, the solid line) and the sunspot area S (from http://science.nasa.gov/ssl/PAD/SOLAR/greenwch.htm, the dotted line) in Figure 1a; the line-of-sight component of the polar photospheric magnetic field as seen from the Earth, $B_{is}^{\rm N,S}$, and the latitude boundary of the IMF sector structure zone, $\lambda_t^{\rm N,S}$ (Figures 1b and 1c, respectively) for the north (the dotted lines) and south (the dashed lines) solar hemispheres, (both from http://sun.stanford.edu/∼wso/wso.html); and the GCR intensity (the relative count rates of the Huancayo and Climax neutron monitors (ftp:// ulysses.sr.unh.edu/ NeutronMonitor/ DailyAverages.

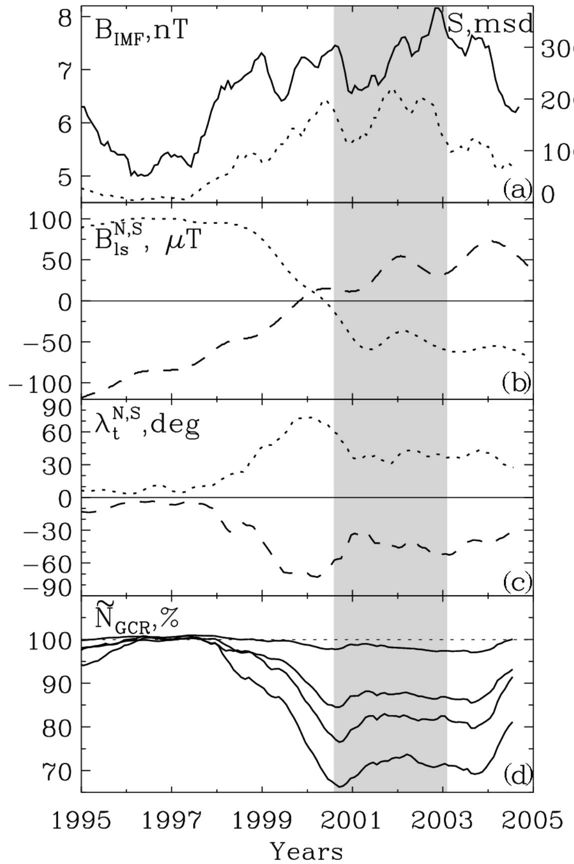

Figure 1. Solar cycle 23 in the different solar, heliospheric, and cosmic ray characteristics near the Earth.

1951-.txt) and of the omnidirectional Geiger counter in the Pfotzer maximum in the stratosphere at Moscow and Murmansk, listing from top to bottom in Figure 1d). All the initial monthly, Carrington rotation or 27-day averaged data were smoothed with a 0.5-year period. The cosmic ray data were additionally normalized to 100% for February 1997. For the current solar cycle the maximum phase in the GCR intensity, that is, the period $\Delta^{23}_{\rm Max} = t^{23}_{g2} - t^{23}_{g1}$ between two main gaps (t^{23}_{g1} and t^{23}_{g2}), lasted for 3 years, from 2000.7 to 2003.7, and it is shown by the shaded band in Figure 1.

[4] One can see from Figure 1 that the IMF strength was rather high during almost 5 years, from 1999.0 to 2004.0, while the period of maximum sunspot area is somewhat shorter, from 2000.4 to 2002.8. The long period of high $B_{\rm IMF}$ may have a bearing on the long maximum phase in the GCR intensity variation, although note that the IMF strength started decreasing a few months after the end of the maximum phase in the GCR intensity, t^{23}_{g2}. The polar magnetic fields in both hemispheres changed sign approximately simultaneously around 2000.0, but soon stopped increasing in strength and were rather small (less than a half of their maximum value) during next 3 years. This weak polar magnetic field is also reflected in rather large ($\approx \pm 40°$) and constant for 3 years latitude boundaries of the IMF sector structure zone. So the long maximum phase in the GCR intensity variation in solar cycle 23 can be related in general (but not in details) both to the behavior of the IMF strength (which reflects the toroidal or sunspot branch of solar activity [see *Krainev and Webber*, 2004]) and to the prolonged period of the weak high-latitude poloidal solar magnetic field.

[5] In order to facilitate a search of the factors responsible for the length and modulation depth of the solar cycle maximum phase in the GCR intensity we superposed in Figure 2 for solar cycles 20–23 the time histories of the solar, heliospheric and cosmic ray characteristics, already discussed for the current solar cycle, as functions of the time $t' = t - t^i_{\rm min}$ elapsed since the beginning $t^i_{\rm min}$ of the ith solar cycle. Note that we chose the stratospheric relative count rate at Murmansk, $\tilde{N}_{\rm Mu}$, as a GCR intensity index (the maximum phases shown by the thicker parts of the lines in Figure 2e) and instead of the polar magnetic field and latitude boundary of the IMF sector structure zone in each hemisphere we show the average characteristics: $B^{pol}_{ls} = \sqrt{({B^{\rm N}_{ls}}^2 + {B^{\rm S}_{ls}}^2)/2}$ (Figure 2c) and $\alpha_t = (\lambda^{\rm N}_t - \lambda^{\rm S}_t)/2$ (Figure 2d, the pseudotilt of the IMF current sheet) for solar cycles 21–23, when we have the systematic data on the solar magnetic fields. Besides, in Figure 2b we show (also for the cycles 21–23) one more solar factor, $B2$, the energy density of the solar magnetic field averaged over the photosphere [see *Krainev et al.*, 1999b, and references therein]. Naturally, as the solar cycles considered are different both in their height and duration, the modulation depth and position of the solar cycle maximum phase in the GCR intensity are also different for different solar cycles. However, one can notice some regularities.

[6] First, there is a concentration of the GCR maximum phases in the time period $t' = 4-6$, years since solar minima, and the corresponding concentration of the IMF strength and the solar magnetic field energy factor $B2$ in the ranges $t' = 4.5 - 6.5$ and $t' = 2.5 - 5$, respectively. Besides, the factor $B2$ clearly demonstrates the Gnevyshev gap effect, i.e., the pronounced double-peak structure with Gnevyshev gap between the peaks, also characteristic for the GCR intensity modulation (see [*Krainev et al.*, 1999a]). In addition, the depth of the GCR intensity modulation corresponds (at least qualitatively) to the maximum level of both $B_{\rm IMF}$ and $B2$. These facts make us suggest that the average energy density $B2$ of the photospheric magnetic fields, along with $B_{\rm IMF}$, is one of the important factors responsible for the characteristics of the solar cycle maximum phase in the GCR intensity. Another important feature also seen in Figures 2c and 2d is the behavior of the poloidal solar magnetic field characteristics. After the deep gap in the strength of the polar magnetic field and the corresponding peak in the pseudotilt (due to the reversal of the high-latitude photospheric magnetic fields) there is a period of relatively weak polar field (and the large latitude range of the IMF sector structure zone) for solar cycle 21 and, especially, 23. It can be seen that for these cycles the length of the solar cycle maximum phase in the GCR intensity is significantly longer than for cycles 20 and 22. It strengthens our opinion that the behav-

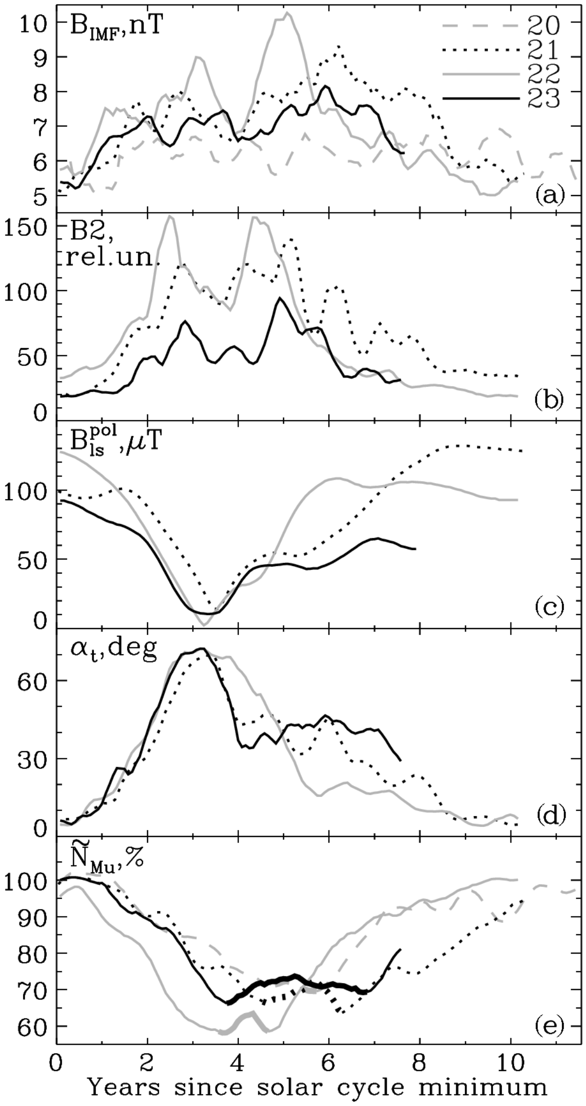

Figure 2. Comparison of the variations in some solar, heliospheric, and cosmic ray characteristics near the Earth for solar cycles 20–23 as functions of the time elapsed since solar cycle beginning.

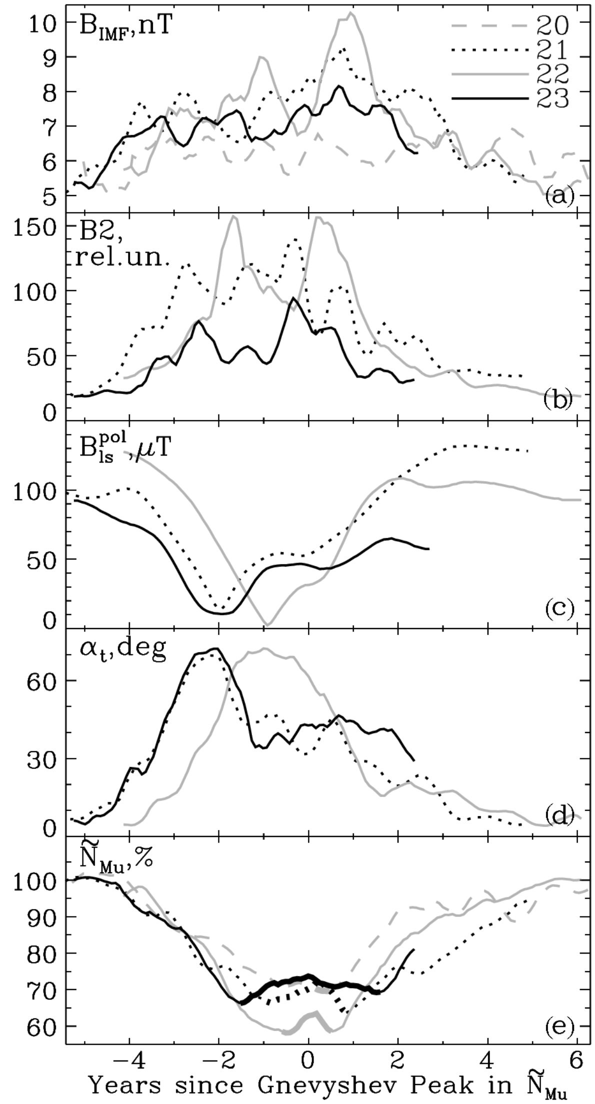

Figure 3. Same as in Figure 2, but with the characteristics plotted as functions of the time elapsed since the middle of the solar cycle maximum phase (the Gnevyshev peak) in the GCR intensity.

ior of the poloidal solar magnetic fields is another important factor for the characteristics of the solar cycle maximum phase in the GCR intensity.

[7] There is a fact that casts some doubt upon the use of $B2$ as a factor important for the features of the maximum phase in the GCR intensity. As one can see from Figure 2 the position of this phase is different for the different cycles while in solar cycles 21–23 the reversal of the high latitude solar magnetic field (and hence the gap in $B2$ and the peak in the pseudotilt) occurs approximately at the same time after the beginning of the solar cycle. In order to clarify the situation we made in Figure 3 the same superposition for solar cycles 20–23 of the time histories of the solar, heliospheric and cosmic ray characteristics as in Figure 2, but plotted them as functions of the time $t'' = t - t^i_{\rm GP}$ elapsed since the middle of the solar cycle maximum phase in the GCR intensity (or since the Gnevyshev peak, $t^i_{\rm GP} = t^i_{g1} + t^i_{g2}$, in the GCR intensity corresponding to the Gnevyshev gap in its modulation). We see that three solar cycles 21–23 are divided into two groups: (1) solar cycle 22 for which there is a small time advance (less than 1 year) of the Gnevyshev gap in $B2$ factor with respect to the Gnevyshev peak in the GCR intensity and (2) solar cycles 21 and 23 characterized by the greater time advance ($\sim$ 2 years) of the Gnevyshev gap in $B2$ and by the subsequent period of the weak poloidal solar magnetic field (and the large IMF sector structure zone). Probably, this division reflects one more aspect of the 22-year wave in the GCR intensity modulation.

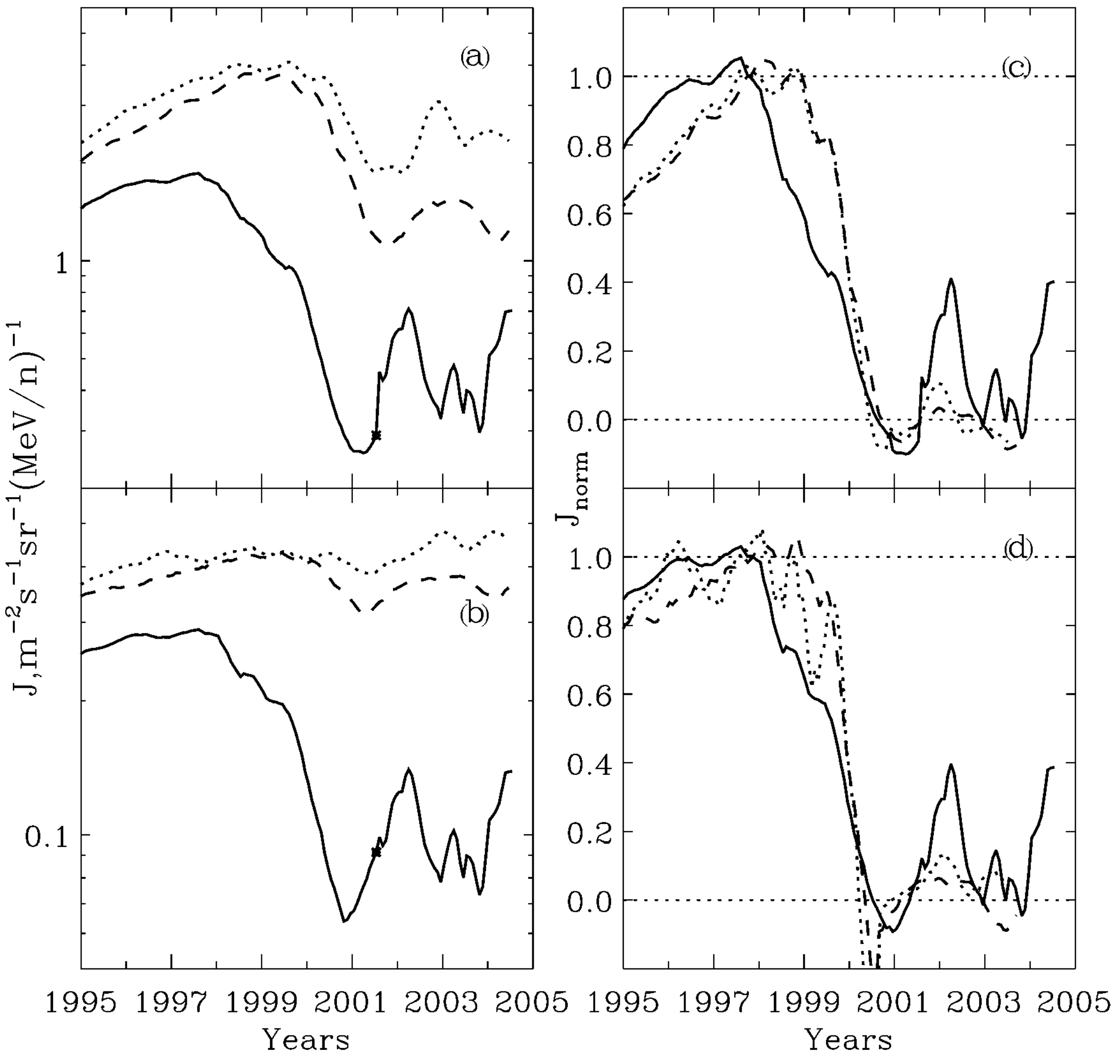

Figure 4. Time behavior for 1995–2004 of (a and b) the absolute and (c and d) the normalized according to (1) GCR intensity for the hydrogen (Figures 4a and 4c) and helium nuclei (Figures 4b and 4d) measured aboard IMP 8 (the solid lines), Voyager 1 (the dotted lines), and Voyager 2 (the dashed lines). The beginning of the IMP 8 data estimated since October 2001 is shown by the asterisks in Figures 4a and 4b.

3. Development of Solar Cycle 23 in the Outer Heliosphere

[8] In general, in the part of the heliosphere where the solar wind structure does not change with distance, the GCR intensity variations at different heliocentric distances also should be similar. In this connection it is interesting to compare the development of the solar cycle variation in the GCR intensity of the same species and energy T near the Earth and in the distant heliosphere. It would be possible for the present solar cycle using the GCR intensities JH for the hydrogen, averaged in the range $T = 120 - 240$ MeV, and $J_{\rm He}$ for the helium, $T_n = 180 - 450$ MeV n^{-1}, measured aboard the IMP 8, Voyager 1 and Voyager 2 spacecraft, but unfortunately, the data from the near the Earth IMP 8 stopped being detected systematically in October 2001 (see http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A).

[9] However it is possible to estimate what the detectors aboard IMP 8 would measure after 10.2001 using the cosmic ray data from other experiments. Of course, it would be better if the GCR data in the energy ranges in question could be inferred from the direct measurements aboard some spacecraft still in operation. For the time being as an alternative we use the stratospheric data. *Krainev and Webber* [2003] used the count rate of the omnidirectional Geiger counter in the Pfotzer maximum at Murmansk (the cutoff rigidity $R_c = 0.6$ GV, the medium rigidity during solar cycle maxima $R_m \approx 9$ GV [*Svirzhevsky*, 2003]) for this purpose. However, the effective rigidities of the GCR particles contributing to $N1^{\rm max}_{\rm Mu}$ and $J_{\rm H}$, $J_{\rm He}$, are too different, and *Krainev and Web-*

ber [2005] suggested for the purpose of estimating the IMP 8 intensities using the difference between the count rates of the Geiger counter in the Pfotzer maximum at Murmansk and Moscow, $N1^{\max}_{\mathrm{MM}} = N1^{\max}_{\mathrm{Mu}} - N1^{\max}_{\mathrm{Mo}}$ (the effective rigidity $R_e < 1$ GV). *Krainev and Webber* [2005] studied in the first approximation the test time series J_{H}, J_{He}, and $N1^{\max}_{\mathrm{MM}}$, their possible trends and regression relationship and made the estimation for the time period from October 2001 to November 2004 of the IMP 8 26-day averaged intensities, smoothed with the periods 0.5 and 2 years. Below we use the results of this estimation for the 0.5-year smoothed time series.

[10] In Figures 4a and 4b the 26-day averaged and smoothed with a 0.5-year period intensities measured aboard the Voyagers 1 and 2 (http :// voycrs.gsfc.nasa.gov / heliopause / heliopause.html) and IMP 8 spacecraft are shown for 1995–2004. The data in Figures 4a and 4b are for the GCR protons and helium nuclei, respectively, in the energy ranges very close to those listed above for IMP 8. The first fact one can notice is that the GCR intensity modulation in the minimum epoch of the current solar cycle began near the Earth much earlier than in the outer heliosphere (the maxima in the 2-year smoothed intensity-time profiles are $t^{23}_{\mathrm{m}} = 1997.1$ and 1998.9 [see *Krainev and Webber,* 2005]). The difference in the corresponding times of the first gap (t^{23}_{g1}) in the double-gap structure of the 0.5-year smoothed intensity-time profiles is not so significant (approximately 2001.0 and 2001.7 for IMP 8 and for Voyagers 1 and 2, respectively). *Krainev and Webber* [2005] suggested that this fact reflects the magnetic drift effects for $qA > 0$ phase of the solar magnetic cycle. As to the maximum phase in the GCR intensity, the main feature that one can see in Figures 4a and 4b is that although there is a double-gap structure with the Gnevyshev peak between the gaps in each intensity time profile, this structure for the intensity measured in the outer heliosphere looks rather strange, especially for the higher energy helium nuclei. Suffice it to note that the helium intensity around the Gnevyshev peak at the Voyager 1 is in excess of the maximum intensity in 1998! *Krainev and Webber* [2003] even suggested that the GCR intensity peaks at Voyager 1 have something in common with the very high fluxes of the low energy particles measured there in 2002–2003 and connected by some investigators [*Krimigis et al.*, 2003; *McDonald et al.*, 2003; *Zeldovich et al.*, 2003] with the effects of the termination shock.

[11] *Krainev and Webber* [2005] suggested that the "strangeness" of the double-gap structure of the GCR intensity-time profiles in the outer heliosphere and its difference from the corresponding double-gap structure near the Earth could be due to the strong 22 wave in the GCR intensity, observed in the outer heliosphere. In order to allow for both the changing heliocentric distance $r(t)$ of the spacecraft and the 22 wave we suggested normalizing the absolute GCR intensity, $J(r, t)$, using the GCR intensity radial profiles during the minimum ($J^i_{\mathrm{m}}(r)$), and maximum ($J^i_{\mathrm{M}}(r)$) of the ith solar cycle, in the following way:

$$J_{\mathrm{norm}}(t) = \frac{J(r,t) - J_{\mathrm{M}}(r)}{J_{\mathrm{m}}(r) - J_{\mathrm{M}}(r)} \quad (1)$$

The radial profiles of the GCR intensity in the extreme phases for solar cycles 21–23 were determined by *Krainev and Webber* [2005] using the intensity time series smoothed with a 2-year period. Besides, as the radial profile for the next minimum of solar activity is still unknown, we suggested that $J^{24}_{\mathrm{m}}(r) = J^{22}_{\mathrm{m}}(r)$, that is, that the GCR intensity radial profile in the minimum of solar cycle depends only on the IMF polarity. Note that using (1) one should take into account the change with time of the current radial profiles of the GCR intensity in the extreme phases of solar cycle. Namely, if and are the moments when the 2-year smoothed intensity attains its maximum (J^i_{m}) and minimum (J^i_{M}) values in the ith solar cycle, the radial profiles ($J^i_{\mathrm{m}}(r)$) and ($J^i_{\mathrm{M}}(r)$) should be used in (1) for $t^{i-1}_{\mathrm{M}} < t < t^i_{\mathrm{M}}$ and $t^i_{\mathrm{m}} < t < t^{i+1}_{\mathrm{m}}$, respectively (for the sake of simplicity, we suggested that the reversal of the high-latitude solar and heliospheric magnetic field in the ith solar cycle occurs in the moment t^i_{M}).

[12] In Figures 4c and 4d the same GCR intensities are shown as in Figures 4a and 4b; however, they are normalized according to (1). Besides, we allowed for the trivial effect of the difference $\Delta r = r - 1$, AU, in the radial distance of the spacecraft with respect to 1 AU, plotting $J_{\mathrm{norm}}(t - \Delta r/V_{\mathrm{sw}})$, with $V_{\mathrm{sw}} = 450$ km s^{-1}. One can see that the double-gap structure of the GCR intensity in the outer heliosphere took its usual form, even the positions of the first gap and Gnevyshev peak near the Earth and in the outer heliosphere being approximately the same. So probably the peak in the GCR intensity observed at Voyager 1 in 2002 does not have relation to the effects of the termination shock. The second gap in the outer heliosphere has not been completed by the 2004.7, but we expect it to be formed in the next half a year. Now we cannot state if the main cause of the significant difference in the magnitude of the Gnevyshev peak in the GCR intensity between the inner and outer heliosphere is due to smoothing of the double-gap structure with the radial distance, or just to the defects either of the method of the estimation of the IMP 8 GCR intensity since October 2001 or of the method of the GCR intensity normalization used by us. We are working on the improvement of these methods.

4. Conclusions

[13] 1. The maximum phase of solar cycle 23 in the GCR intensity terminated in 2003.7 in the inner heliosphere and is close to the end in the outer heliosphere.

[14] 2. For solar cycles 21–23 the depth in the GCR intensity modulation during the solar cycle maximum phase qualitatively corresponds to the maximum levels of the strength of the interplanetary magnetic field and of the average magnetic field energy density on the photosphere. For the length and position of this phase the behavior of the high-latitude solar magnetic fields and of the latitude range of the interplanetary magnetic field sector structure zone is also important. By the length of the maximum phase in the GCR intensity and its position with respect to the time of the solar magnetic field reversal the current solar cycle resembles

solar cycle 21 and differs from cycle 22, probably reflecting one more aspect of the 22-year wave in the GCR intensity modulation.

[15] 3. After the normalization of the GCR intensity allowing for the position of the spacecraft and the 22 wave in the heliosphere the structure of the maximum phase in the GCR intensity in the current solar cycle in the outer heliosphere looks similar to that near the Earth, manifesting usual double-gap structure corresponding to the well-known double-peak structure (the Gnevyshev gap effect) in the intensity modulation. So the high bump in GCR intensity observed at Voyager 1 in 2002 probably does not have relation to the effects of the termination shock. At the same time the normalized GCR intensity in this bump at both Voyagers 1 and 2 is much less than that near the Earth. The reasons for this difference are still unclear.

[16] **Acknowledgments.** The authors thank the principal investigators who placed their data on the Internet. We are also grateful to the Russian Foundation for Basic Research for helping the stratospheric cosmic ray experiment (grants 04-02-17380 and 04-02-31007).

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