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The general features of the galactic cosmic ray intensity in the maximum phase of solar cycles 19-23

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Abstract.

Recently the conclusion has been made that in the behaviour of the galactic cosmic rays some effects characteristic of the maximum phase of a solar cycle could be isolated: (1) the sudden decreases (the Gnevyshev Gaps) in the modulation and variability and (2) the change in the energy dependence of the cosmic ray modulation from that characteristic of the ascending phase of a solar cycle. In this paper we discuss the definition of the maximum phase in the solar and cosmic ray characteristics and consider the neutron monitor and balloon data during the last four full solar cycles in order to check the chronological order of the mentioned cosmic ray effects. Then the drawn conclusions are checked against the development of the current solar cycle 23.

1 Introduction

Considering the variations in the solar, heliospheric, cosmic ray or geomagnetic characteristics with the 11-year (or solar) cycle (SC) it is natural to refer to the phase of this quasi-periodical variation with respect to the moments of the extream values of the activity. However, because of the significant random component in solar activity, the moments of the formal maxima and minima of solar characteristics are often misleading and the division of the SC on the Sun into the main periods – minimum, ascending, maximum and descending phases – looks more promising.

In papers (Krainev et al., 1999a, 1999b; Bazilevskaya et al., 1999, 2000) we studied the behaviour of the solar activity and the galactic and solar cosmic rays in the periods of the maximum phase (MP) of a solar cycle using the solar cycle phase classification, suggested by Vitinsky et al. (1986), and the time boundaries of the maximum phase determined in (Ivanov et al., 1997). In the following we shall refer to this MP as the VKO MP. For the galactic cosmic rays (GCRs) two main effects during the MP were isolated: (1) the sudden decreases (called the Gnevyshev Gaps (GGs), see (Storini and Pase, 1995)) along with generally highest levels of both the modulation and the variability of the intensity and (2) the abrupt change in the energy dependence of the cosmic ray modulation from that characteristic of the ascending phase of solar cycle.

We feel some inconvenience in using the VKO MP as the only reference period for the solar cycle MP. The only change we made in getting the "heliospheric maximum phase" (HMP) when the specific for the solar cycle maximum phase GCR effects were looked for was to prolong the VKO MP by one year (to account for the possible delayed response of the GCRs to solar changes). However, the VKO MP on the Sun is a complex period when at least two different processes run, which could variously influence the GCRs (see below). On the other hand, such MP detailes as the positions of the peaks and gaps sometimes significantly differ from one solar activity index to another. That is why it could be useful (1) to divide (when it is possible) the periods correspponding to the VKO MP into more simple phases, and (2) to determine the solar cycle MP from the GCR data in themselves and then look for the solar index corresponding to the GCR behaviour.

As the discussion of the solar cycle MP rests on facts about the solar activity, considering in the next section the solar and GRC data during 1950–1996 on a global scale, we schematically outline the processes on the Sun and their impact on the heliosphere especially during the solar cycle maximum phase. Then each individual cycle will be considered in more details. To check some of the conclusions drawn from the SC19-22 the development of the current SC23 also will be discussed.

2 The Solar and GCR Solar Cycle Maximum Phases in 1950–1996

In Figure 1 the long-term history of some solar and GCR characteristics (monthly averaged and 7 month smoothed) is shown.

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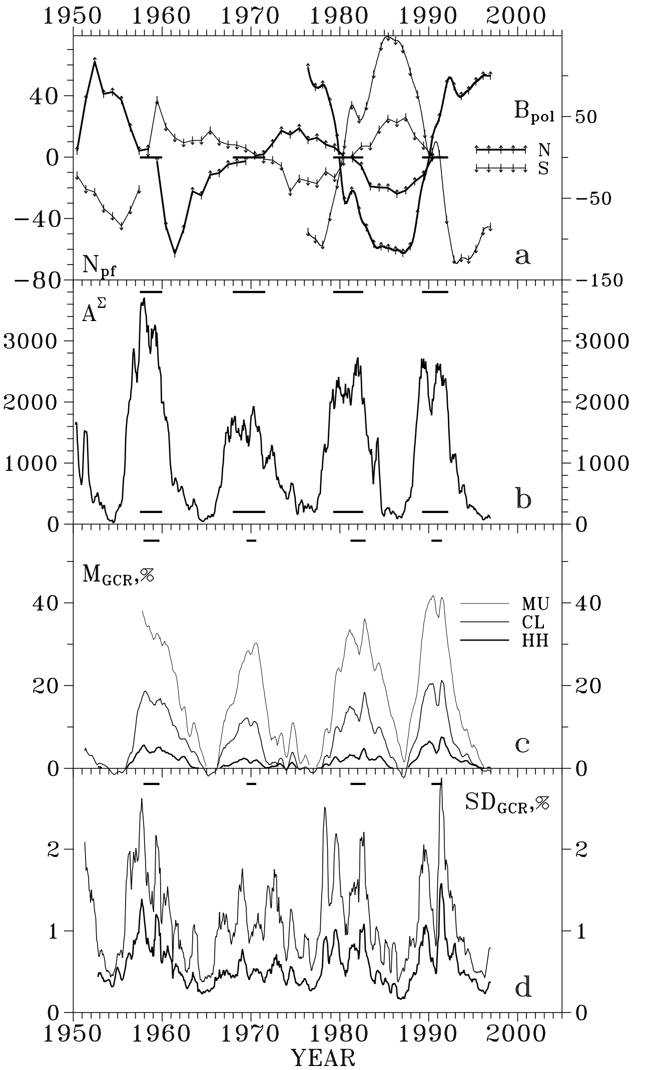

Fig. 1. The solar and GCR solar sycle maximum phases in 1950–1996. For the explanation see the text.

The solar cycle phase classification suggested in (Vitinsky et al., 1986) actually considers the two quasi-periodical types of solar activity (SA) developing approximately in counterphase which could be called toroidal (T) and poloidal (P) types of SA according to the main direction of their magnetic fields. The T-type SA is a sunspot-like activity (the number of the active regions, flares and coronal mass ejections, the intensity of the corona etc), while the P-type SA consists of the high-latitude magnetic fields, polar faculae, coronal holes etc. As a poloidal (or P-type) data we show in panel a the line-of-sight photospheric magnetic field in the polar zones (Stanford WSO) and the signed number of polar faculae (Sheeley, 1991). As a T-type solar activity data (panel b) the total sunspot area (http:/science.msfc.nasa.gov/ssl/pad/solar/greenwich.htm) is used. The thick horizontal lines in both upper panels show the solar cycle VKO MP (Ivanov et al., 1997) (except for SC 19, for which we estimated the MP ourselves). These periods incorporate both maximum level (with the double peak structure (DPS) and GG between the peaks), of the T-type solar characteristics and the minimum level and the reversal in sign of the P-type solar magnetic fields. In the following we shall sometimes refer to these subphases as MPT and MPP, respectively. One can see that in the SC 19, 21, 22 the high-latitude line-of-sight photospheric magnetic field revers sign in between the peaks of the T-type sunspot area, while for SC 20 the reversal occurs after the DPS in A^{Σ}. As the characteristic scale of the photospheric magnetic fields connected with T-type SA is much smaller than that for the P-type fields, it could be expected (in case of a simple current-free layer between the photosphere and the base of the heliosphere), that the strength and direction of the interplanetary magnetic field would display the P-type behaviour (Hoeksema, 1984). It is really true for the direction of the regular IMF. However, because of the influence of the energetic T-type solar activity on the Sun's atmosphere, the mentioned layer is not current-free and as a result the IMF strength and hence the GCR intensity modulation near the Earth display the distinct T-type time profiles, i. e., they vary in phase with the sunspot-like solar activity. The panel c of Figure 1 shows the modulation M of the GCR count rate N $(M \equiv (N(06.1977) - N(t))/N(06.1977) \cdot 100, \%)$ for Climax (effective vertical cutoff rigidity $R_c \cong 3GV$) and Huancayo/Haleakala (HH, $R_c \cong 13GV$) neutron monitors and the balloon data in the transition maximum in the stratosphere at Murmansk ($R_c \cong 0.6GV$) (Bazilevskaya et al., 1991, Bazilevskaya and Svirzhevskaya, 1998, and references therein). The DPS and GG for the periods of the maximum modulation are easily seen for all solar cycles and all GCR series considered, the positions of both peaks and gaps between them practically not changing with the GCR energy. So we consider the time interval between these peaks as the SC maximum phase (MPT-type) in the GCR modulation. These periods are shown by the thick horizontal lines in the upper part of Figure 1, c. The difference between the periods of the VKO MP for the Sun and MPT for the GCR modulation is clearly seen. Another very dinstinct feature seen in the GCR modulation is that the change in the energy dependence of the GCR modulation occurs well in advance of the DPS structure for all solar cycles. In the panel d the simplest measure of the GCR time variability – standard deviation (SD) of the daily intensities with respect to the monthly mean – is shown for the Climax and Huancayo/Haleakala neutron monitor data. One can also note the deep gaps in the SD-series near the MPT for the GCR modulation (repeated by thick lines in the panel d), but there are also many other peaks and gaps in the SD-series.

3 The Sructure of the Maximum Phase of the Individual SC 19–22

To illustrate the mentioned regularities in more details, we show all the related characteristics (monthly averaged and 7 point smoothed) for each SC 19–22 in separate panel in Figure 2.

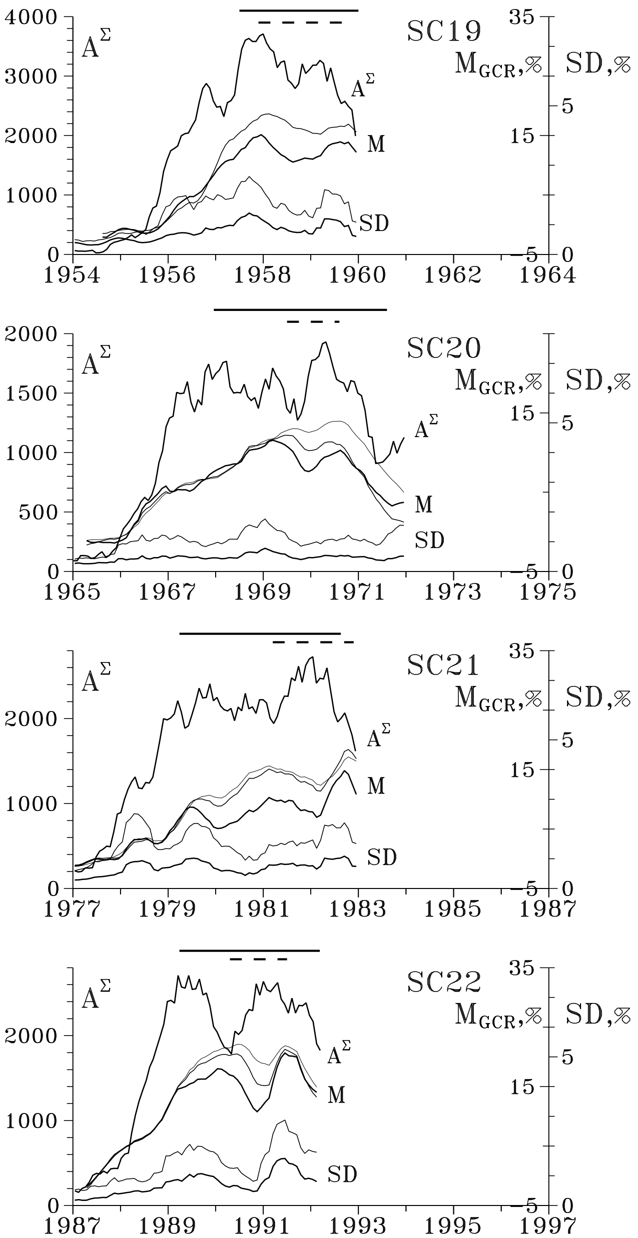

Fig. 2. The development of the solar cycles 19–22.

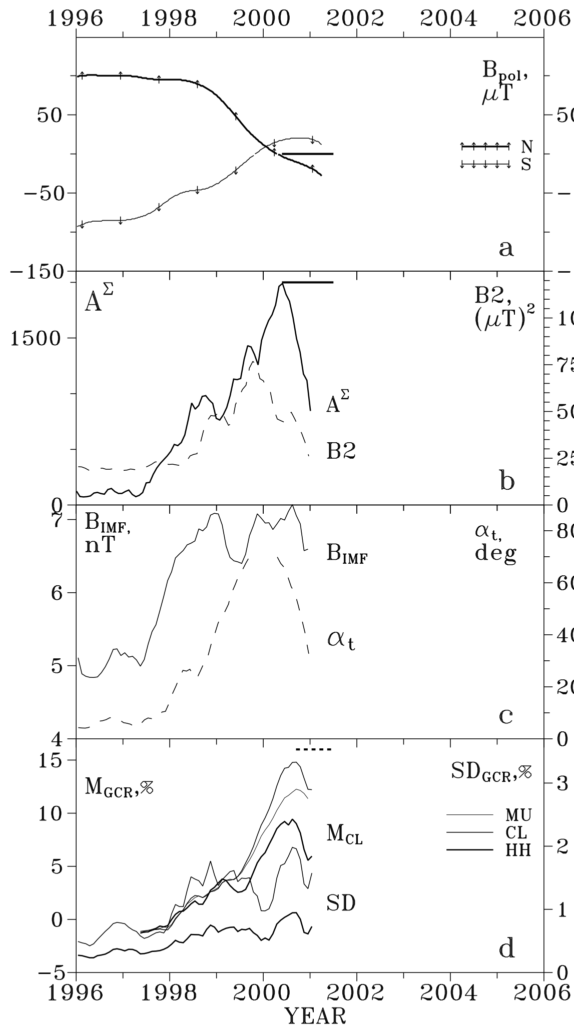

Fig. 3. The development of the solar sycle 23.

For each solar cycle the T-type SA characteristic are shown (the sum area of the sunspot for cycles 19-20 and the mean large-scale photospheric magnetic field energy density $B2$ (Obridko and Shelting, 1992), calculated using the WSO data for SC 21, 22). The upper horizontal thick lines again show the solar cycle VKO MP. To illustrate both the GCR modulation time profile and its energy dependence we, as in Figure 1, show for each SC the GCR modulation normalized by the power regression to that of Climax. The dashed thick lines just below the VKO MP bars correspond to the MPT in the GCR modulation. Below the GCR modulation lines the SD-series for the Climax and Huancayo/Haleakala neutron monitors are shown. The abrupt change in the energy dependence followed by the distinct DPS and GG structure in the GCR modulation is seen more clearly. Besides one can note that the main peaks and gaps in the GCR SD-series are sometimes (as in SC 20-21) considerably ahead of those for the GCR modulation.

4 The development of the solar cycle 23

Recently we concluded (Krainev et al., 2001) that the development of the current (23rd) solar cycle is rather unusual when correlated with that for the last two cycles, although in some respects it reminds of solar cycle 20. It is also highly probable that now we are already in the midst of the maximum phase of the current cycle and it looks worthwhile to check against even incomplete SC23 our conclusions found for four full previous cycles.

In Figure 3 we correlate for 1996-2001 the GCR modulation (normalized to the Climax series) and variability (panel d) with the line-of-sight high-latitude photospheric magnetic field B^{ls}_{pol} (a), the total area of the sunspot groups A^{Σ} and the photospheric magnetic field energy index $B2$ (b) and the IMF strength B_{IMF} and the current sheet pseudo-tilt α_t (c).

All the data were monthly averaged and 7 point smoothed. We purposely broke the curve for the IMF current sheet tilt to show the period when $\alpha_t > 70$ degrees and the heliospheric current sheet is practically absent as a unique global heliospheric structure.

First, one can see very pointed maximum in A^Σ at 2000.4 and the deep decrease till the end of the year. The maximum in the $B2$-index is also very distinct, but it occurred about a half year earlier. The start of decrease in A^Σ and $B2$ marks the beginning of the solar cycle MPT (shown by the horisontal bar in the panel b for A^Σ) in these T-indices. Second, the IMF strength varies simillar to the total sunspot area and the reversal of the high-latitude photospheric magnetic field occurred during a half year period centered at 2000 in both solar hemispheres, i. e., practically coinciding with the reversal of the B^{ls}_{pol} and well ahead of the MPT period in A^Σ. Third, the maximum in the GCR modulation occured in 2000.7 marking the beginning of the corresponding solar cycle MPT (shown by the dashed bar in panel c), while the change in the energy dependence of the GCR modulation started in the beginning of 1999, well ahead of the reversal of B^{ls}_{pol}. The main peak in the GCR variability occurred simultaneously with the peak in their modulation, but the distinct gap in the SD-series coincides with the period of the B^{ls}_{pol} reversal. Note that calling the moments of the peaks in the sunspot area and GCR modulation the beginnings of the corresponding MPTs, we presume that the second peaks will follow. We believe that the second solar activity maximum really occurred in the April 2001, although the unabated decrease in the IMF current sheet tilt looks enigmatic.

5 Discussion and Conclusions

1. During the periods of the high solar activity in all four last full solar cycles 19–22 there are well defined double-peak (or Gnevyshev Gap) structure in the GCR modulation, the change of its energy dependence of the modulation and the strong reductions in the time variability of the intensity. The energy change occurs some time ahead of the first peak in the modulation. As to the variability of the GCR intensity it has much more complex structure than the GCR modulation and the position of peaks and gaps for different solar cycles can both coinside with those for the modulation and strongly differ from them.

2. For the proper formulation of the boundaries of the solar cycle maximum phases in the heliospheric characteristics (including the GCR modulation and variability) and of the effects specific for this phase, the detalization of the corresponding phases on the Sun and in the heliosphere should be made to separate the effects due to the maximum phase of the sunspot-like solar activity from those due to the minimum phase of the poloidal activity of the Sun. The most suitable solar cycles for such an analysis are those for which the toroidal-type activity runs ahead of the poloidal-type one (as in SC 20) or lags behind it (as in SC 23).

3. The definition of the period of the solar cycle maximum phase for the GCR modulation exclusively from the position of the peaks in the double-peak structure of the time profile implies the highest importance of the toroidal-type solar activity (sunspots, IMF strength etc) in determination of the GCR intensity time profile. The development of the poloidal-type solar activity (the polar magnetic fields etc) can influence the minor detailes of the GCR modulation but not its general appearance.

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