On the current and maximum phases of solar cycle 24 in the galactic cosmic ray intensity

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Abstract. We compare the current characteristics of the sunspot activity and cosmic ray intensity with those expected in the future maximum of the current solar cycle. The values for maximum phase are estimated from the correlation between characteristics in the maximum and in the inflection points (few years before maximum) for the previous solar cycles. The expected galactic cosmic ray phenomena typical for the maximum phase of solar cycle (Gnevyshev Gap effect, quasi-biannual oscillations and energetic hysteresis) are discussed.

1. Introduction
The solar cycle (SC) 24 is under way for about 4 years now and it is instructive to compare its development in some solar and cosmic ray characteristics with that for previous solar cycles. As in [1] we assume that any cyclic characteristic \( F(t) \) (i.e. changing between its minimum \( F^m \) and maximum \( F^M \) values and back) should have two inflection points \( t^{inf}_{1,2} \) where \( \ddot{F}(t^{inf}_{1,2}) = 0, \dot{F}(t^{inf}_{1,2}) > 0, \dot{F}(t^{inf}_{2,1}) < 0, \) and \( F(t^{inf}_{1,2}) \) correlates with \( F^M \). In [1] we checked this assumption for the sunspot area and galactic cosmic ray (GCR) intensity and searched for the inflection points in SC24 by 11.2011. In this paper we prolong this search for the next year and also discuss some GCR phenomena typical for the maximum phase of solar cycle (Gnevyshev Gap effect, quasi-biannual oscillations and energetic hysteresis) are discussed.

2. Sunspot area and GCR intensity: the inflection points and maxima
In Fig. 1 the time profiles of the sunspot area \( S_{ss} \) and GCR intensity \( J \) and their first and second time derivatives are shown for SC 22. The derivatives were determined using the 1y smoothed data and then they were approximated by the 3–rd order polynomial to find the inflection points. For SC 22 the inflection points are clearly seen about 2 years before maximum. The same it true for a total of 9 previous solar cycles out of 12 for \( S_{ss} \) and for all 4 cycles for \( J \).

In Fig. 2 the same characteristics are shown for SC 24. In [1] we concluded that up to 11.2011 there were no clear indications of the first inflection points both for \( S_{ss} \) and \( J \). However, one can see from the left panels of Fig. 2 that the strong drop in \( S_{ss} \) in the beginning of 2012 resulted in
Figure 1. The inflection points in SC 22 in the sunspot area and GCR intensity time profiles. Left panels: The sunspot area (upper panel) and its first (middle) and second (lower panel) time derivatives. Right panels: The same three panels for the GCR intensity. The thin lines in the upper panels show the monthly data, while the thick lines are for the data smoothed with 1y period. The dotted curves in the middle and lower panels show the 3–rd order polynomial fitting the derivatives. The inflection points are shown by the stars and the squares stand for the maxima or minima.

Figure 2. The same as in Fig. 1, but for SC 24.

formation of this point in $S_{ss}$, although in $J$ it is absent as before (usually GCR intensity lags behind solar activity by $\approx 0.5$–1 year).

In [1] the regressions between the maximum values of $S_{ss}$, $S_{ss}^M$, and its values in the inflection point and between $J^M$ and its values in the inflection points were found for the previous solar cycles with the correlation coefficients $\rho = 0.83$ and $\rho = 0.94$, respectively. Using this regressions we can find the estimate for $S_{ss}^{M24}$ and the upper estimate for $J^{M24}$ using the last smoothed values of the characteristics. In Fig. 3 we compare $S_{ss}(t)$ and $J(t)$ in SC 24 with their behavior in the previous cycles SC 20–23 for GCR and for $S_{ss}$ with the average sunspot area for the groups of cycles of high and low activity, see [6, 1]). Also shown are our estimates of $S_{ss}^{M24}$ and
Figure 3. SC 24 in comparison with the previous solar cycles. The left panels: The solid curve is for the total sunspot area and the dotted and dashed lines are for the doubled sunspot area in the N– and S– hemispheres, respectively. The bands of different hatching show the development of the sunspot area averaged over the groups of the global minima and maxima of solar activity in the past and shifted to the time of the beginning of SC 24. The right panels: The solid curve is for the 1y-smoothed GCR intensity and the lines of different styles show the time behavior of the same intensity for SC 20–23, shifted to the time of the beginning of SC 24. The stars with the arrows show our upper or lower estimates of the characteristics in the maximum of SC 24.

J$^{M24}$. Beside the total sunspot area the doubled sunspot areas in the N– and S–hemispheres are shown. Our estimate $S_{as}^{M24}$ indicates that in SC 24 the maximum sunspot area can be even greater than during Glaisberg minimum (SC 14–16) but as we stressed in [1] a lot depends on the N–S asymmetry of the solar activity in the nearest future: up to now the development of SC 24 in the N–hemisphere is like in the ”modern maximum” (SC 17–23), while that in the S–hemisphere more closely resembles the Dalton minimum (SC 5–7). As to the GCR intensity, our upper estimate of J$^{M24}$ indicates that in SC24 the minimum GCR intensity can be on the same level as in SC 20, 21, 23 or slightly higher.

3. The GCR effects: Gnevyshev Gap, QBO, and energy hysteresis

So we are on the threshold of the SC 24 maximum phase and it is instructive to recall the effects in the GCR intensity characteristic for such periods in the past. In Fig. 1 one can easily see for SC 22 the double-peak structure of the sunspot maximum phase and corresponding double-gap signature in the GCR intensity (or the double-peak in its modulation). This phenomenon was called Gnevyshev Gap in [7] and was extensively studied (see [8] and references therein). In [8] we came to the conclusion that the double peak structures during solar maxima are due to the superposition of the 11-year cycle and quasi-biennial oscillations (QBO). The latter oscillations are inherent in the whole solar cycle, not only its maximum phase, and probably are due to the shallow dynamo on the Sun. Note that in the GCR intensity the same phenomena are sometimes called step-like changes and they are attributed to the global barriers in the heliospheric magnetic field [9] or to the waves in the solar magnetic field [10].

Another GCR effect specific for the maximum phase of solar cycle is the energy hysteresis, i. e. somewhat different behavior of the intensities of different energies (see [11]). Both effects are illustrated in Fig. 4. Note that QBO are not seen in the total sunspot area because the N– and S–hemispheres do not change in unison. Beside note that the hysteresis loop in the regression
Figure 4. The development of the QBO in the sunspot area and GCR intensity and the energy hysteresis between high and low GCR energies. The left panels: The curves in the upper panel show the $2\gamma$-smoothed (solid) and $0.5\gamma$-smoothed (dotted) sunspot area, while the panel under it is for the relative difference between these characteristics. The two bottom panels show the behavior of the similar smoothed time series and QBO but for the GCR intensity. The right panels: The regression between the normalized to 1987 $1\gamma$-smoothed high–energy GCR intensity and low–energy intensity during the SC 21, 23 when the polarity of the heliospheric magnetic field $A$ reverses from positive to negative (upper panel) and the SC 20, 22, 24 when $A$ reverses from negative to positive (lower panel).

between the high and low energy particle intensities clearly demonstrates the magnetic cycle: the area of the loop is much greater for the even solar cycle, so it should be significant for the current SC 24. This fact is important as the magnetic drift is sometimes considered insignificant in the periods around solar maximum [12]. In any case as the current solar cycle can be quite different from the previous 5 or 6 cycles for which the main features in Gnevyshev Gap, QBO in the sunspot activity and GCR (and also energy hysteresis in the latter) were studied, we are looking for new traits in these phenomena in the next few years.

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