On the current phase of the solar cycle in the solar and heliospheric parameters and GCR intensity

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***Abstract*. The present-day phase of the solar cycle in the parameters important for the GCR modulation (the sunspot activity in the royal zones, the high-latitude magnetic fields, the tilt of the heliospheric current sheet) is compared with the behavior of the GCR intensity both in the inner and outer heliosphere. We discuss the usual and strange features in the time profiles of the listed characteristics and try to make some prediction of the GCR behavior in the heliosheath in the near future. The special attention is paid to the manifestations of the magnetic (or 22-year) cycle in the GCR intensity and its causes.**

***Keywords*: solar cycle, minimum phase, galactic cosmic rays**

I. INTRODUCTION

The present-day phase in the development of the 11-year cycle in the solar, heliospheric and cosmic ray characteristics in the inner heliosphere is intriguing in many aspects. In short it is rather difficult to find its counterparts in the solar and geophysical archives.

As to the GCR intensity in the outer heliosphere its time history is also puzzling. Here we are mostly interested in the GCR intensity levels in the successive minima of solar cycle. It was Webber and Lockwood, [15], who about 10 years ago constructed the radial profiles of the GCR intensity in the equatorial region of the heliosphere during the successive minima and put forward the hypothesis that the magnetic cycle in the heliosheath beyond the termination shock is much greater than in the inner heliosphere. In the last decade we repeatedly studied this effect (see references in [8]). Our interest in this subject is related to our hope that it can be due to the influence of the quasi-radial electric fields in the heliosheath (see [5], [9] and references therein).

In this paper in Section II we consider the current phase of the 11-year cycle in the solar characteristics and in the GCR intensity near the Earth. To understand the unusual features of the current solar cycle both in the solar and GCR characteristics it is compared with the preceding cycles. In Section III we deal with the GCR behavior in the outer heliosphere to check the above hypothesis and try to predict the GCR intensity for next few years. Then, in Section IV, the possible causes of the magnetic cycle in the GCR intensity in the heliosheath are discussed.

II. MINIMUM OF SOLAR CYCLE 24 AND GCR NEAR THE EARTH

In Fig. 1 the time profiles of some solar and heliospheric characteristics and GCR intensity are shown, the thin lines being for the detailed data (the Carrington rotation or monthly averaged) while the thicker lines being for the detailed data smoothed with about one year period.

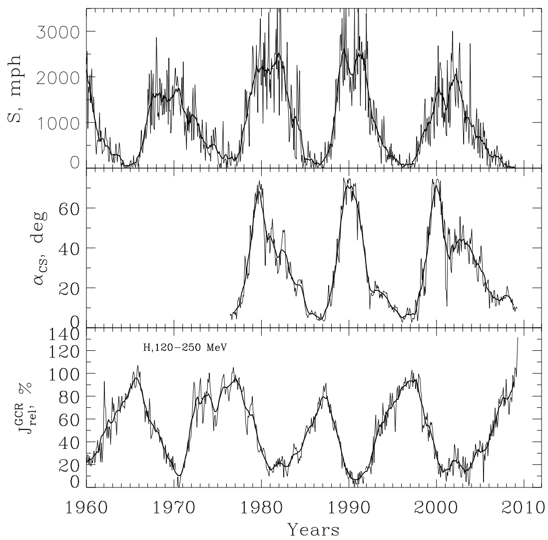

Fig. 1: The sunspot area (upper panel), the tilt of the heliospheric current sheet (middle panel) and the medium energy GCR intensity (lower panel) near the Earth in 1960-2009.

The upper panel shows the total area of the sunspots, [17]. It can be seen that the smoothed sunspot area decreased almost monotonically during the last few years and up to now (May 2009) there is no sign of the global minimum. However, the sunspots of new cycle appeared about 1.5 or even 2.5 years ago and for the last year the major part of sunspots were high-latitude ones.

The tilt to the equator of the heliospheric current sheet, α^{cs} ([18], the radial boundary condition) is shown in the middle panel. One can see that the most important difference between the current solar cycle and previous ones is too great residual tilt. It is about three times as great as it was before. And it is the most important parameter for the galactic cosmic ray modulation in the current ($A < 0$)-period. Probably, the weak concentration of the current sheet to the solar equator is mainly due to the exceptionally week high-latitude solar magnetic fields (see [14], [7]). However, the tilt is decreasing up to the present time and now it is less than 10°.

For the relative GCR intensity shown in the lower panel of Fig. 1 we use our stratospheric proxy for proton intensity of about 200 MeV (see [11]). It can be seen that after the local maximum of the GCR intensity smoothed with a one year period (July 2007) the intensity is strongly increasing; now the monthly intensity is about 30% higher than it was during the last 52 years and there is no signs of the forthcoming maximum.

The question arises if the prolonged period of low solar activity (both middle- and high-latitude) is the exceptional one. In the upper panel of Fig. 2 the length of SC 1-22 (the plus signs) and of the period after its maximum (the asterisks) are compared with those of the current cycle (respectively, the dashed and dotted horizontal lines) with provisional SC24 minimum in May 2009. Note that we have chosen only those cycles for which there are quantitative data on the position and area of sunspots (Greenwich/USAF series since 1874, [17], shown by the vertical dashed line in the upper panel of Fig. 2). The cycles similar to SC 23 are indicated by their numbers and big squares. It was shown in [6] that these cycles are similar to SC 23 in some other respects as well. However, the present-day level of the high-latitude photospheric field is the lowest one for the last ≈ 110 years, [14].

As to the unprecedented growth of the GCR intensity during the last half a year it may have a bearing on the prolonged period of the low solar activity because of the heliosheath memorizing and integrating the previous solar activity due to very slow solar wind velocity there (see [10], [13]). In the lower panel of Fig. 2 the sunspot area around solar minima is shown for SC 19-24 as function of time elapsed since solar cycle beginning. Again the provisional SC 24 minimum in May 2009 is used. One can see that when compared with four previous cycles the sunspot area in SC 23 is really at a lowest level for the last 5 years before next solar minimum. Note that May 2009 is the lower boundary of the time of SC 24 minimum, so in all likelihood the curve for SC 23 will be shifted to the left in the lower panel of Fig. 2 (and up in the upper panel). In any case the present-day growth of the GCR intensity reminds of the very high level of the intensity during the prolonged periods of low solar activity suggested in [3].

III. GCR IN THE OUTER HELIOSPHERE

In Fig.3 the time profiles are shown of the medium energy GCR intensity measured aboard the spacecraft moving out from the Sun.

To separate the time changes from those due to moving in the space it is very useful to normalize the intensity and to bring it to the same radial distance using the radial profiles of the intensity for the extreme phases: the alternating minima, $J_{m,+}(r)$ and $J_{m,+}(r)$, and maximu, $J_M(r)$, of the solar cycle. These composite profiles were first compiled by Webber and Lockwood, [15], about 10 years ago and naturally, they used only data for one $A < 0$ minimum twenty years ago (SC 22), using the spacecraft Pioneer 10 at the $r = 42$ AU, so that the extrapolation to the outer heliosphere was made for $\triangle r \approx 60$ AU. From this extrapolation they inferred that the amplitude of the magnetic cycle in the heliosheath beyond the termination shock could be much more than near the Earth.

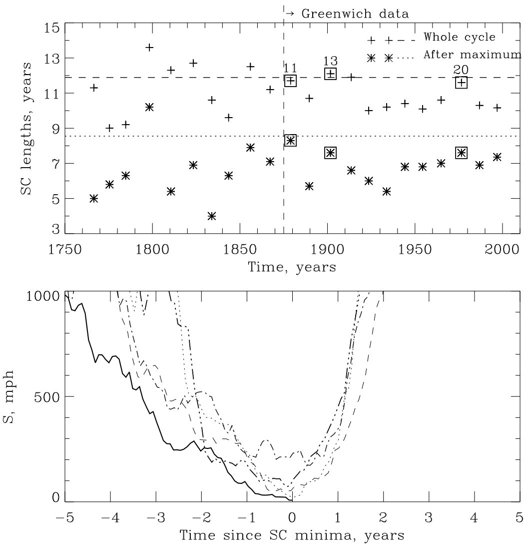

Fig. 2: The comparison of the SC 23 with the previous cycles. The upper panel: the characteristic lengths of solar cycles for SC 1-23. The lower panel: The total sunspot area around solar minima as function of time elapsed since solar cycle beginning for SC 19-24. The solid curve is for the current solar cycle.

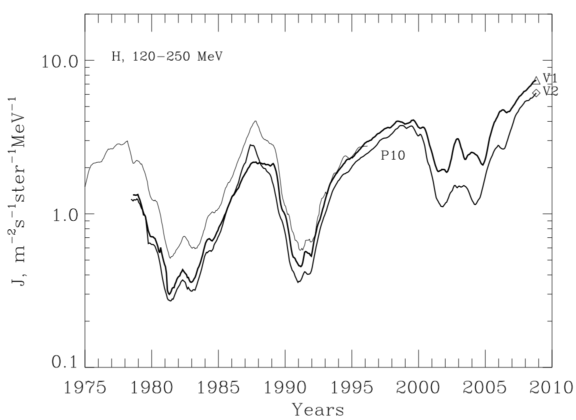

Fig. 3: The GCR intensity on board the spacecraft in 1975-2009.

In [16], [12] we suggested to normalize the GCR intensity to $r = 1$ AU using the radial profiles for the related extreme phases as boundaries between which the intensity changes during the solar cycle, $J_{norm} =$

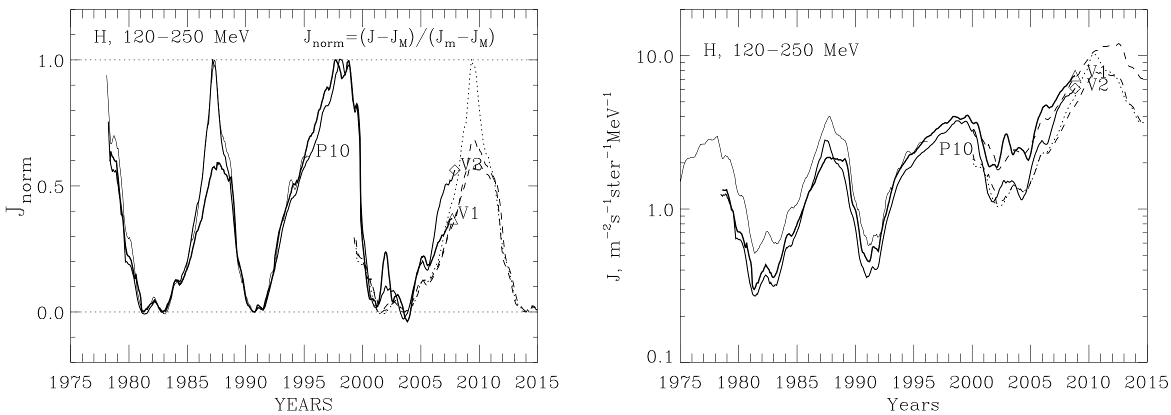

Fig. 4: The normalized to $r = 1$ AU (left panel) and real (right panel) GCR intensity time profiles aboard V1,2 with those expected for 2000-2015 for the case of the great negative latitude gradient of the intensity (dashed curves) and with zero latitude gradient (dotted curves).

$(J(r,t) - J_M(r))/(J_m(r) - J_M(r))$. In the left panel of Fig. 4 the normalized GCR intensity is shown corresponding to that measured aboard the spacecraft which real time behavior is shown in Fig.3. One can see the clear synchronous 11-year cycle in the GCR intensity for all spacecraft being at different heliocentric distances. Then in [8] we suggested that the behavior of the normalized intensity aboard Voyager 1 spacecraft in the current decade should be about the same as it was in 1980-s (the period with the same HMF polarity). The dashed lines in the left panel of Fig. 4 show the normalized GCR intensity in the 1980-s, shifted and stretched to bring the length of SC21 to that of SC 23 (see [8] for details). However, the dashed line in Fig. 4 is a little different from that in Fig. 3 in [8] because of a small mistake we made in constructing this line in the latter paper. Two dashed curves in Fig. 4 correspond to V1 and V2 and the curve for V2 takes into account the same strong negative gradient which affected V1 in the 1980s and the lower latitude of V2 in the 2000s. However, the last polar pass of Ulysses showed no latitude gradient in 2007. In this case the normalized intensity in the 2000s for both V1 and V2 will be the same as it was in the 1980s for the equatorial spacecraft (P10, V2), but shifted and stretched. This normalized intensity is shown by the dotted line in the left panel of Fig. 4.

Then we transform the expected normalized intensity to the real one (not normalized). The expected time behavior of the intensity measured aboard V1, V2 is shown by the dashed and dotted lines in right panel of Fig. 4. It can be seen that up to now the growth of the GCR intensity at V1 and V2 approximately follow the expected time profile.

So the observed behavior of the GCR intensity at the heliospheric distances up to $r = 105$ AU indicates that during the current solar minimum with $A < 0$ the GCR intensity in the equatorial region just beyond the termination shock is about three times as great as that observed during previous solar minimum with $A > 0$ at $r = 70$ AU and extrapolated with constant radial gradient to $r = 105$. In other words, the current time behavior of the GCR intensity aboard Voyager 1 does not contradict the hypothesis that beyond the TS the amplitude of the magnetic cycle in this intensity is great (a factor of 3).

IV. ON THE CAUSES OF THE MAGNETIC CYCLE IN THE HELIOSHEATH

The mechanism causing this strong variation in the GCR intensity shock should work somewhere in the heliosheath nearer to the heliopause. There are a few candidates for this mechanism and we briefly consider them.

The magnetic drifts in the inhomogenious magnetic fields in the outer heliosheath are hardly probable to produce such a strong variation in the intensity on two reasons. First, the drift velocity should be small for the 200 MeV/n particles because of their small rigidity. Second, according the Baranov-Malama model of the heliospheric-interstellar interface [1], as one approaches the heliopause, the solar wind velocity, supersonic in the inner heliosphere, becomes progressively smaller and it is only about 20 km/s in the layer near the heliopause. Consequently, the time which solar plasma needs to get there is very large, at least several 11-year periods. If the magnetic field is transported there by such a slow solar wind, it looks like "a patched blanket" with rather small "patches" of different polarity, so that on large scale the regular magnetic field in the outer heliosheath is weak (see [4]). So the magnetic drifts are also weak there.

The diffusion's dependence on the HMF polarity. The long-term efforts to fit the observed GCR intensity (e.g., [2]) lead to the conclusion that it was necessary to account for rather strong dependence of the diffusion coefficients K on the HMF polarity because of the interplay between the regular field and its helicity.

However, it looks that the dependence of K on A needed to explain the magnetic cycle in the radial dependence of the GCR intensity even in the inner and intermediate heliosphere ($r \leq 70$ AE) is too great (a factor of 5) and it can hardly be used to explain the magnetic cycle beyond the termination shock, taking into account what was said in the previous paragraph on the regular magnetic fields in the outer heliosheath.

The external electric fields. Because of the solar wind moving through the perpendicular to its direction regular heliospheric magnetic field there should be a regular heliospheric electric field, longitudinal inside the termination shock but quasi-radial in the outer heliosheath. In several papers (see [5], [9] and references therein) we studied the possible effects of these ("external") electric fields in the outer heliosheath on the GCR intensity, postulating the acceleration/deceleration of the GCRs by the related potential difference before exposing to the usual modulation inside the modulation region. It was shown ([5], [9]) that using this additional modulation the magnetic cycle in the radial dependence of the GCR intensity in the inner and intermediate heliosphere can be easily explained without a factor of five change in K.

However, there is a general belief that according to the well-known transport equation governing the GCR modulation, the rate of the energy change is due only to the term including the divergence of the solar wind velocity. Our position in [5] was that then the boundary of the modulation region should comprise all space regions where any influence of the heliosphere magnetic and electric fields on GCR took place, while the commonly used GCR modulation with this boundary well inside the region where the distribution of regular magnetic fields conserves its quasi-dipole character during periods of low solar activity obviously does not meet the latter condition.

Here we want to add another possibility to justify the direct acceleration/deceleration of the GCRs by the electric fields in the outer heliosheath. Our point is that in the presence of the electric field the divergence of the plasma velocity is the only channel to change the energy of the charged particles only in case if there is the substantial regular magnetic field, hindering the direct acceleration/deceleration of the particle and forcing it to drift normally to both fields. As we discussed above there could be a situation in the outer heliosheath when the regular magnetic field is very weak there while there is a substantial electric field due the distribution of the electric charges well nearer to the Sun. Probably, in such a case the direct acceleration/deceleration of the particles is possible.

To emphasize what behavior of the GCR intensity aboard Voyagers 1, 2 we expect in the next 3-5 years the dashed and dotted lines in Fig. 4 are shown up to 2015. The expected decrease of the GCR intensity is due to the decrease of the potential difference after the minimum of solar cycle. Then the GCR intensity will progressively approach its value in the Galaxy.

V. Conclusions

1) The smoothed solar activity decreased almost monotonically during the last few years and up to now (May 2009) there is no sign of the global minimum. There are cycles similar to SC 23 though the high-latitude photospheric field is the lowest one ever observed. The unprecedental growth of the GCR intensity during the last half a year may have a bearing on the prolonged period of the low solar activity because of the heliosheath memorizing and integrating the previous solar activity.

2) The current time behavior of the GCR intensity aboard Voyager 1 does not contradict to the hypothesis that beyond the termination shock the amplitude of the magnetic cycle in this intensity is great.

3) It is rather difficult to explain a strong magnetic cycle in the GCR intensity in the inner heliosheath using the present-day modulation theory. There is a possibility that it could be connected with the unusual properties of the electromagnetic fields in the outer heliosheath that make the direct influence of the electric field on the energy of the charged particles possible.

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References

[1] Baranov, V.B., Malama, Yu.G., Journ. Geophys. Res., **98**, 15157-15163, (1993)
[2] Burger R.A., Potgieter M.S., Heber B., Journ. Geophys. Res., **105**, 27447-27455, (2000)
[3] McCracken K.G., McDonald F.B., Proc. 27th Int. Conf. Cosmic Rays, P.3753-3756, 2001
[4] Kalinin M.S., Krainev M.B., Adv. Space Res., **19**, No. 6, 969-972,(1997)
[5] Kalinin M.S., Krainev M.B., Intern. J. Geomagn. Aeron., **4**, No. 1, 83-90,(2003)
[6] Krainev M.B., Proc. conf. "Solar and Solar-terrestrial Physics-2008", Pulkovo, St.-Peterburg, Russia, p. 181-182,2008
[7] Krainev M.B., Makarova V.V., Proc. conf. "Solar and Solar-terrestrial Physics-2008", Pulkovo, St.-Peterburg, Russia, p. 183-186, 2008
[8] Krainev M.B., Kalinin M.S., Webber W.R., Proc. 30th Intern. Cosmic Ray Conf., Merida, Mexico, **1**, 417, (2007)
[9] Krainev M.B., Kalinin M.S., Bull. RAS, ser. fiz., **67**, N 10, 1439-1442, (2003)
[10] Krainev M.B., Webber W.R., in Multi-Wavelength Investigations of Solar Activity, Proc. IAU Symp. No. 223, A.V. Stepanov, E.E. Benevolenskaya, A.G. Kosovichev, eds., Cambridge University Press, p. 81-84, doi: 10.1017/S1743921304005150, 2004
[11] Krainev M.B., Webber W.R., Preprint Lebedev Physical Institute RAS, No. 11, Moscow: FIAN, 18 p., (2005)
[12] Krainev M.B., Webber W.R., Bulletin of the Russian Academy of Sciences, Physics, Allerton Press Inc., **69**, No. 6, 838-841, (2005)
[13] Krainev M.B., Webber W.R., Geomagnetism and Aeronomy, **45**, N 4, p. 453-458, (2005)
[14] Sheeley N.R., Ap. J., **680**, N 2, pt.1, p. 1553-1559, (2008)
[15] Webber W. R., and Lockwood J. A., J. Geophys. Res., **106**, A12, 29323-29331,(2001)
[16] Webber W.R., Krainev M.B., Intern. J. Geomagn. Aeron., **5**, No. 2, GI2003, doi:10.1029/2004GI000066, (2004)
[17] http://solarscience.msfc.nasa.gov/greenwch.shtml
[18] http://wso.stanford.edu/Tilts.html