# On the magnetic cycle in the GCR intensity in the inner and outer heliosphere

M.B. Krainev[1], M.S. Kalinin[1]

*Abstract*— **The present-day phase, the minimum between the solar cycles 23 and 24, in the solar activity and GCR intensity both in the inner and outer heliosphere is considered. We concentrate on the manifestations of the magnetic (or 22-year) cycle in the GCR intensity and its radial dependence. Our conclusion is that there should be a strong source of the magnetic cycle in the outer heliosheath. The different candidates for this source are considered.**

## I. INTRODUCTION

The main manifestations of the magnetic (or 22-year) cycle on the Sun are 1) in the polarity of the toroidal (or azimuthal) component of the magnetic field in the active regions (the polarity of the leading sunspot in the bipolar group changes every 11 year around the solar minima) and 2) in the polarity of the poloidal component of the magnetic field (the polarity of the large-scale high-latitude magnetic fields changes every 11 years around the solar maxima). Due to relatively small scale of the active regions the first process scarcely affects the heliospheric magnetic fields and it is the second process that mainly gives rise to the magnetic cycle in the heliosphere, changing the sign of the related parameters during the reversal of the high-latitude solar magnetic fields around the solar maxima and reaching the maximum amplitude around the solar minima (see references in [1]).

The specific heliospheric characteristics in which the magnetic cycle manifests itself are 1) the dominant polarity of the regular HMF $\mathbf{B}$, opposite in different ”magnetic hemispheres”, divided by the thin global heliospheric wavy current sheet (WCS); and 2) the polarity of the regular heliospheric electric field, $\mathbf{E} = -\frac{\mathbf{V^{SW}} \times \mathbf{B}}{\mathbf{c}}$, where $\mathbf{V}^{SW}$ is the solar wind velocity. The corresponding well-known effects, important for the modulation of the GCR intensity are 1) the magnetic drifts of the GCRs, both regular and the current sheet ones; 2) the dependence of the GCR diffusion coefficients on the polarity of the regular HMF because of the interplay between the regular HMF and helicity. As to the influence on the GCR intensity of the regular electric fields, latitudinal in the inner heliosphere and radial near the heliopause, there is a general belief that it does not influence the charged particles directly but only through the change of their energy in the divergent (or convergent) solar wind.

The observed manifestations of the magnetic cycle in the GCR intensity are well-known. Here we are mostly interested in the radial dependence of the GCR intensity in the successive minima of solar cycle. It was Webber and Lockwood [2] 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 they put forward the hypothesis that the magnetic cycle in the heliosheath (the region of interaction between the solar and interstellar winds) beyond the termination shock is much greater than in the inner heliosphere. In the last decade we repeatedly studied this effect (see references in [3]). 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 [4], [5] and references therein).

In this paper we consider the current phase of the 11-year cycle in the solar characteristics and in the GCR intensity near the Earth (Section II), then deal with the situation in the outer heliosphere (Section III), then discuss the possible causes of the magnetic cycle in the GCR intensity in the heliosheath (Section IV).

## II. SOLAR CYCLE 23 AND GCR NEAR THE EARTH

In Fig. 1 the time profiles of some solar heliospheric and GCR characteristics are illustrated, the thin lines being for the detailed data (the Carrington rotation or monthly) while the thicker lines being for the detailed data smoothed with about one year period. The upper panel shows the total area of the sunspots, http://solarscience.msfc.nasa.gov/greenwch.shtml. It can be seen that the smoothed sunspot area decreased monotonically during the last few years and its first minimum (maybe the local one, however) occurred in 2008.3. So there is

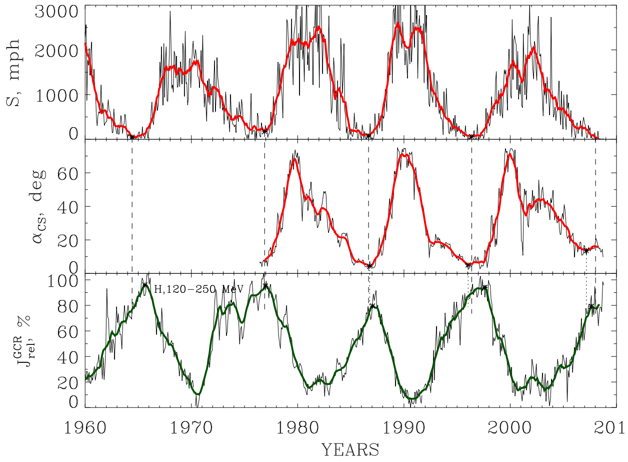

Fig. 1. The solar, heliospheric and GCR behavior in 1960-2008.

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[1] Lebedev Physical Institute, Russian Academy of Sciences, Leninsky Prospect, 53, Moscow, 119991, Russia, krainev@fian.fiandns.mipt.ru

a chance that it was the end of SC 23, and since then we live in the SC 24. The stars and the vertical dashed lines indicate the time of minima of this and four previous solar cycles.

The tilt to the equator of the heliospheric WCS ($\alpha_{CS}$; estimated as the half latitude width of the sector-zone on the source surface of the HMFs, http://wso.stanford.edu/Tilts.html) 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. Again the stars and the vertical dotted lines indicate the time of the $\alpha_{CS}$'s minima for this and three previous solar cycles.

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 [6]). It can be seen that the last maximum of the GCR intensity smoothed with a one year period occurred in 2007.6, however the intensity strongly fluctuates since then and it is clear that this maximum was a local one. For the subject of the present paper the main feature seen in the lower panel of Fig. 1 is that there is about 20% difference between the maximum GCR intensity for successive solar cycle, that is there is the magnetic cycle of rather small amplitude in the inner heliosphere.

## III. GCR IN THE OUTER HELIOSPHERE

Now we turn to the outer heliosphere. In Fig.2 the time profiles are shown of the GCR intensity in the same energy range as in the lower panel of Fig.1. measured aboard the spacecraft moving out from the Sun.

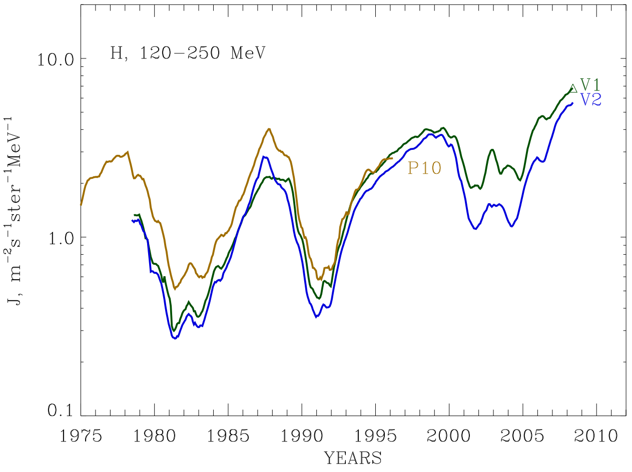

Fig. 2. The GCR intensity on board the spacecraft in 1975-2009.

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 (minima and maxima) of the solar cycle, shown in Fig.3.

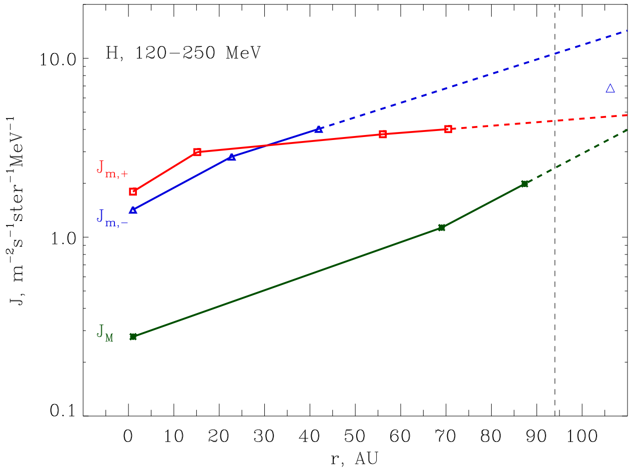

Fig. 3. The radial profiles of the GCR intensity for the extreme phases of the solar cycle.

In this figure the radial profile for the last solar maximum ($J_M(r)$) is shown along with the composite profiles for two alternating minima, $J_{m,+}(r)$ and $J_{m,+}(r)$. The solid lines show the radial dependence for the ranges where the interpolation of the intensity can be made while the dashed lines show the extrapolated radial profiles. In both cases the the relative radial gradient of the intensity was supposed to be constant.

These composite profiles were first compiled by Webber and Lockwood, [2], 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 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.

In [7], [8] 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:

$$J_{norm} = \frac{J(r,t) - J_M(r)}{J_m(r) - J_M(r)}$$

In Fig.4 the normalized GCR intensity is shown corresponding to that measured aboard the spacecraft which real time behavior is shown in Fig.2. The normalization used the composite radial profiles for solar minima 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. In [3] we normalized the GCR intensity in the above mentioned manner and then 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 line in Fig.4 shows the normalized GCR intensity in the 1980-s (see [3] for details). However, the dashed line in Fig.4 is a little different from that in Fig.3 in [3] because of a small mistake we made in constructing this line in the latter paper.

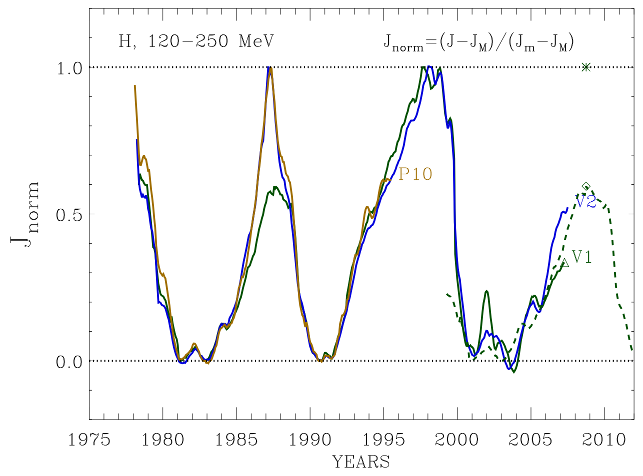

Fig. 4. The GCR intensity normalized to $r = 1$ AU using the radial profiles of the intensity for the extreme phases.

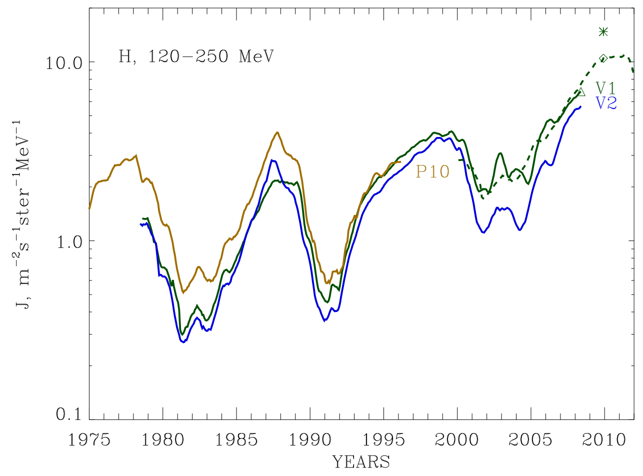

Fig. 5. The same as in Fig.2, but with the expected the GCR intensity aboard Voyager 1.

Then we transform the expected normalized intensity to the real (not normalized). The expected time behavior of the intensity measured aboard Voyager 1 is shown by the dashed line in Fig.5. It can be seen that up to now the growth of the GCR intensity at Voyager 1 approximately follows 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 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

So it looks that there is a strong magnetic cycle in the GCR intensity in the region not far beyond the termination shock and the mechanism causing this strong variation in the GCR intensity shock should work somewhere in the heliosheath, the region between the termination shock and the heliopause, nearer to the heliopause. There are a few candidates for this mechanism and we briefly consider them.

### *A. Magnetic drifts*

The drifts in the inhomogenious magnetic fields in the outer heliosheath are hardly probable to produce such a strong variation in the intensity on two counts. 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 [9], 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 [10]). So the magnetic drifts ar also weak there.

### *B. The dependence of the diffusion coefficient on the HMF polarity*

The long-term efforts to fit the observed GCR intensity (e.g., [11]) lead to the conclusion that it was necessary to account for rather strong dependence of the diffusion coefficients $K_{diff}$ on the HMF polarity because of the interplay between the regular field and its helicity ([12], [13], [14], [15]). However, it looks that the dependence of $K_{diff}$ 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, [16]) 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.

### *C. 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 (HEF). In the period of low solar activity due to small tilt of the wavy current sheet, this electric field is longitudinal inside the termination shock but quasi-radial in the outer heliosheath. These electric fields can be considered as due to the volume electric charges formed by the Lorentz forces and the related potential difference is of the order a few hundreds of MV, [17], [18], [10].

In several papers ([17], [18], [19], [20], [4], [5]) 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 (using the Liouville theorem) before exposing to the usual modulation inside the modulation region. We called this additional step the "external" modulation of the GCR intensity. It was shown ([4], [5]) 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 $K_{diff}$ needed without it [16].

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 by the term including the divergence of the solar wind velocity. So postulating some additional change of the GCR energy due to the direct acceleration/deceleration of the GCRs by the electric fields is unlegitimate. Our position in [4] was that it was true but then the boundary of the modulation region should has comprised 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 in 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.

## V. CONCLUSIONS

1) Probably, the solar cycle 23 ended around April, 2008, and since then we live in the next solar cycle. The GCR intensity strongly fluctuated during the last year, although it is clear the smoothed intensity is still increasing.

2) The current 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 such 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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