Monitoring of GCR temporal and spatial variations in the inner heliosphere according to cosmogenic radionuclides in fresh-fallen meteorites

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Abstract. The meteorite data on monitoring of the GCR gradient variations at 2-4 AU from the Sun in 1957-2010 testify to the influence of the character of the solar magnetic field inversions during the maximum of the solar cycles on depth of the GCR modulation in the heliosphere.

1. Meteorite data
Cosmogenic radionuclides with different $T_{1/2}$, which are observed in meteorites, are natural detectors of cosmic rays along the meteorite orbits during $\sim$1.5 $T_{1/2}$ of the radionuclides before the meteorite fall onto the Earth. The investigation of radionuclides with different $T_{1/2}$ in the chondrites with various dates of fall, which have various extension and inclination of orbits, provides us with such long sequences of homogeneous data on variation of the GCR intensity and integral gradients ($E > 100$ MeV) in the 3D heliosphere [1]. The long sequences of homogeneous data on the GCR intensity in the stratosphere [2] are used for evaluation of the gradients. Nowadays, such a sequence of certain homogeneous data on the GCR intensity and gradients in the inner heliosphere covers $\sim$5 solar cycles (see figure 1) [3]. This smooths, to a considerable extent, both the temporal and spatial GCR variations revealing the most important general regularities (curve 1), namely: the dependence of the GCR gradients in the inner heliosphere (at 2–4 AU from the Sun) on the phase of the solar cycles and the constancy of the mechanism of the solar modulation of GCRs, at least over the last $\sim$1 Ma.

2. Correlative analysis
The existence of scaling in the power of the interplanetary magnetic field fluctuations [4] leads to necessity of separation of the stochastic effects and the effects caused by the solar activity (SA) in modulation of GCRs. In this connection, rigorous analyses of correlations between the distribution and variations of GCRs and various indexes of SA, as well as the strength of interplanetary magnetic fields...
(IMF) and the title of the heliospheric current sheet (HCS) in the three-dimensional heliosphere, turn out to be of paramount importance. Figure 2 shows variations in GCR radial gradients in comparison with variations in the SA [5], in the SMF strength [6] and in the HCS tilt angle [7]. One can see the positive correlation of GCR radial gradients at 2 - 4 AU with the SA, as well as with the strength of IMF and the HCS tilt angle up. However, the correlation differs for various solar cycles, as well as for growth and decay phases of solar cycles. Indeed, along with general positive correlations of the gradients with the level of SA (figure 3), there are time lags, $\Delta t$, of the gradient variations from $R_j$ variations (figure 4). It is apparently determined by the dynamic of accumulation and dissipation of a modulating layer of magnetic irregularities at 2-4 AU from the Sun in the different phases of SA [1]. It is seen in figure 4 that $\Delta t$ values vary in the range of ~ 1.27-2.38 years (with correlation coefficients $>0.9$) up to the maximum of the 22nd solar cycle, and then they drop rapidly down, even to negative values (perhaps, due to the SA decrease that started in the following years). It is also interesting that there exists a considerable north-south (N-S) asymmetry of GCR distributions in 3D-heliosphere at the different stages of SA, which follows from analysis of the data [5] on the green coronal lines [3], and which is confirmed, e.g., by values of the latitudinal GCR gradients ($E > 100$ MeV) in 1973–1976 (derived from the radionuclide contents in the Dhajala and Innisfree chondrites with known orbits): $G_\theta$ is ~ 3–5% per degree in S-latitudes and from –1.5 to 0.8% per degree in N-latitudes [8].

3. Effects of the total solar magnetic field (TSMF) inversions on depth of the GCR modulation
Violation of correlations of the GCR gradients with SA might be conditioned by the disturbance of the SA itself by stochastic processes, e.g.,, first of all, by the processes of inversion of TSMF during the maximum phases of the solar cycles [9]. Under the polarity replacement from − to + in the N-hemisphere, the positive phase ($A>0$) of the 22-year magnetic cycle begins. After passage of the negative phase ($A<0$), when + replaces − during the maximum of the next solar cycle, the beginning of the new magnetic cycle starts. The TSMF inversion periods differ in their character and duration in N- and S-hemisphere of the Sun for various solar and magnetic cycles [10, 11]. Indeed, according to [12], in the 20 solar cycle the inversion began developing in March 1968 at heliolatitudes of 40°–50° in the S-hemisphere, and propagated slowly towards the pole, which was reached in September 1969. In the N-hemisphere, the inversion started in the 40°–50° zone only in August 1970, but it was stronger and reached the pole within one year. No inversion occurred in the ±40° equatorial zone in 1969, so that charged particles could penetrate the heliosphere in S-latitudes along the magnetic field lines not only from the polar side but also in the near-equatorial zone at $\leq 40^o$ S [9]. In N-latitudes, charged particles had such an opportunity only starting from August 1970 and, especially, in 1971, when the polarity of the magnetic field changed at the N-pole. This means that since September 1969 both the poles were negative for about two years. Thus, owing to the TSMF inversion, the heliosphere proved to be open...
not only near the poles but also partly in the near-equatorial zone at ±40°. This additional possibility for the penetration of charged particles into the heliosphere through some kind of holes in the magnetosphere was probably responsible for the rapid increase in GCR intensity at the end of 1971 and for the general higher level of GCR intensity in solar cycle 20 as compared with cycle 19 [2]. In fact, TSMF can probably have such configurations when, instead of a single neutral current sheet, there is one neutral sheet and two neutral cones at heliolatitudes of ±40°, which may play a key role if the processes of drift are predominant [13].

Meanwhile, the character of TSMF inversion at the replacement of the magnetic cycle during the maximum of the 22 solar cycle essentially differed from that in the 20 cycle, and it was opposite to it in some details. The fact is that the inversions terminated earlier in the S-hemisphere, at the maxima of solar cycles 18, 19, and 20, and in the N-hemisphere they terminated at the maxima of solar cycles 21 and 22 [10]. This is related to the fact that during seven 11-year cycles, up to cycle 20 inclusively, the activity in the N-hemisphere was higher than in the S-hemisphere [14]; however, since 1981 the S-hemisphere became more active than the N-hemisphere [15]. At the maximum of the 21 solar cycle the TSMF inversion from + to – terminated earlier in N-hemisphere (02. – 11. 1979) vs. (09.1979 – 05. 1980) in S-hemisphere, and its duration, as a whole, was less than a year, so that such a short-term TSMF deviation from dipole was not especially displayed. However, at the maximum of cycle 22 the inversion from – to + in N-hemisphere covered the range of (01.1989 – 03.1990), which was considerably shorter than the inversion period of (08.1989 – 05.1991) from + to – in S-hemisphere. Hence, some period should exist when both the poles were positive. It means that the heliosphere was closed for positively charged particles, except for two neutral cones with high inclination. That resulted in the deepest minimum of the GCR intensity in stratosphere in 1990-1991 [2] and the highest GCR gradients for the 22nd solar cycle (see figure 1).

At last, the 23 solar cycle is considered to be unusual because of very low amplitude of SA and prolonged minimum before the development of the 24 solar cycle [16]. The TSMF inversion from + to – in N-hemisphere took place during about one year (11.1999 – 10.2000), whereas in S-hemisphere the inversion from – to + lasted for about 2 times longer (06.1999 – 06.2001), so that the period when both the poles turned out to be negative (as well as in the 20 cycle), was prolonged enough. With the decline of the IMF, observed since 2000 [6], the heliosphere turned out to be still more open for GCR penetration, which is confirmed by the decrease of their gradients (see figure 1). The weakness of the magnetic fields as well as the unusual duration of the SA decline before the 24 solar cycle testify to the transformation of the magnetic field generation in the convective zone of the Sun [16, 17, etc.], which becomes more and more evident with the development of the 24 solar cycle. In particular, in 2008-2009 the IMF were so weak that the fluxes of particles with energy being less than a few GeV were recorded in stratospheric measurements, which never occurred before [18].

### 4. Secular cycles and the solar dynamo

In contrast to the 11-year cycles connected with the frequency of SA phenomena, the secular cycles reflect mainly variations in their intensity, and thus they allow us to judge about the state in the convective zone of the Sun [14]. It is clearly seen in figure 5 that just with the 20 solar cycle the decrease of the current secular cycle has begun, and nowadays we are at – or approach to – its minimum, which may evidence the decrease of depth of the convective zone of the Sun. The turbulent convection of the solar plasma and its differential rotation underlie free-running operation of the solar dynamo [19]. When some conditions of generation of convection are disturbed, or interaction of the convection with the differential rotation is disturbed (e.g., due to viscosity), states of instability can arise, the ambiguity of going out from which leads to failure of the solar dynamo operation. Then the prolonged minima of SA, being similar to the Maunder minimum, are coming. Nowadays, there is, apparently, just such a trend of events. It will depend, to a large extent, on the character of the inversion in the 24 cycle, which is expected in ~2014 [17]. Cycle 24, being similar to cycle 22, must pass through the stage when both the poles will be positive, but it cannot last for a long time. For instance, at low SA the magnetic fields near the poles can be only neutralized, but the inversion will
not take place. The disappearance or extreme weakness and instability of the magnetic fields near the poles will open free penetration of GCRs into the heliosphere. The exit from such a state of instability can depend on its duration. In the protracted case, when toroidal, axisymmetric field will be developed near the equatorial zone, a prolonged minimum of SA can come as well as a cold period on the Earth, which is conditioned by it. According to many authors (see, e.g., [20]), SA together with the greenhouse effect are the possible causes of the observed global warming on the Earth. However, the superposition of the cycles of various duration and their disturbance demonstrate the complexity and ambiguity of this mechanism. As seen from figure 5, the replacement of every successive secular cycle occurs at the higher level of the solar activity (see the regression line). This means that the more prolonged cycle (perhaps, 400- or 600- year cycle) is on the rise, and just it may be one of the reasons of the observed global warming on the Earth. The future will show whether this tendency to warming will endure a competition with cooling through stochastic turning-off (or attenuation) of the SA cycles or not. It is interesting to know: can the cycles being longer than 11-year ones be turned off too?

Figure 5. Secular cycles of SA in 1700–2001 (solid curve is a variation of the maximum annual average Wolf number $R_j$ smoothed by the Gleisberg method; the maxima of the cycles are marked by arrows; the dotted line is a regression line $y = -203 + 0.166x$.

Acknowledgments
We are grateful to G A Bazilevskaia and all your colleagues for the permission to use their long sequences of homogeneous data on the GCR intensity in stratosphere. We thank Yu I Stozhkov for valuable comments and G A Bazilevskaia for stimulating questions. This work is supported in part by the Program No. 22 of Fundamental Research of Russian Academy of Sciences.

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