Correlation between diffusion-convection and drift parameters of cosmic ray modulation in the minima of solar activity

G A Bazilevskaya, M B Krainev, A K Svirzhevskaya and N S Svirzhevsky
Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky prospect, 53, 119991, Moscow, Russia
E-mail: gbaz@rambler.ru

Abstract. We consider the cosmic ray modulation parameter \( \propto \exp(-V/\lambda) \) including \( V \) as the solar wind velocity and \( \lambda \) as the cosmic ray diffusion path in the interplanetary space. On the other hand, in the minimum of solar activity, the tilt angle of heliospheric current sheet \( \alpha \) was used as possible characteristic of drift influence on cosmic ray intensity. We found that in the time periods around minima of solar activity the two parameters are in a rather strong anticorrelation, both facilitating the cosmic ray access into the inner heliosphere in the periods with the negative magnetic field in the northern hemisphere of the Sun.

1. Introduction
Cosmic rays (CRs) inside the heliosphere underwent modulation by solar activity (SA). In the periods of SA minima the galactic CRs have the easiest access into the heliosphere and reach the maximum intensity. During the last minimum of the 23/24 solar cycles an unusually high increase in the CR intensity was observed which was strongly dominated by the relatively low-energy CRs [1]. Trying to understand this effect we have analyzed the interplanetary conditions in the minima of SA in the cycles 21/22, 22/23, and 23/24 [2, 3]. Spatial diffusion of CRs in the turbulent heliospheric magnetic fields (HMF) and outward convection in the expanding solar wind was accounted for by the parameter \( P = \exp(-V/\lambda) \) where \( V \) is the solar wind velocity and \( \lambda \) is the cosmic ray diffusion mean free path in the interplanetary space. Increasing of \( P \) leads to easier CR access into the inner heliosphere, hence we consider it as a diffusion-convection parameter of CRs modulation. In [2, 3] the CR mean free path was expressed as \( \lambda \propto B^{5/3}/\delta B^2 \), where \( B \) is the HMF strength and \( \delta B \) is the rms variation in the vector magnetic field [4]. The tilt angle \( \alpha \) of the heliospheric current sheet (HCS) was used as possible characteristic of drift influence on cosmic ray intensity in the minimum of SA. Neither \( P \) nor \( \alpha \) demonstrated an extraordinary magnitude in the minimum of the cycle 23/24. Nevertheless, CRs of different energies responded similarly to variations of \( P \) and \( \alpha \) in the solar activity minima of the cycles 21/22 and 22/23, but their behavior was different in the cycle 23/24. The fluxes of lower energy CRs effectively recovered up to the second half of 2009 while the growth of the more energetic CRs was suppressed [2, 3]. This is a new challenge to understanding of energy dependence of the solar cycle CR modulation which remains to be elusive [e.g., 5-9]. This work aims at more detailed consideration of the interplanetary space indices around minima of SA.
2. Observations

As the CR data series we used the results of the long-term observations conducted by the Lebedev Physical Institute with balloon-borne detectors in the stratosphere at the Murmansk region (geomagnetic cutoff rigidity $R_c = 0.6$ GV) [10] and the data of the Moscow neutron monitor with $R_c = 2.4$ GV [11]. The median rigidities in the SA minimum are ~ 6 GV and ~ 17 GV for the first and the second data sets, respectively [12]. The CR time history is presented in figure 1a. The data are normalized at 100% to the annual averaged count rates in 1965. Period of the CR energy anomaly in the minimum of the cycles 23/24 is marked by the thick horizontal bar.

Figure 1. Time histories of different parameters during the 21 – 24 cycles of solar activity. a – monthly averaged fluxes of cosmic rays as measured by balloons (red curve) and by the Moscow neutron monitor (violet); b – parameter $P$; c – mean free path $\lambda$; d – solar wind velocity, e – HCS tilt angle. Monthly averaged and 11-point smoothed data are given on panels b – e.
Panels b – e of figure 1 display the interplanetary indices: the modulation parameter $P$ relevant to CR access into the heliosphere, the CR mean free path $\lambda \propto B^{5/3}/\delta B^2$, and the tilt angle of HCS $\alpha$. The data on $B$ and $\delta B$ are from [8], while the tilt angle, classical version, from [9]. The parameter $P$ to a first approximation reproduces the 11-year cycle in CRs (figure 1b) however it has a peculiarity that is even more pronounced in behavior of $\lambda$. It is seen in figure 1c that $\lambda$ is almost constant in periods of ~IX.1977 – IX.1984, ~IV.1988 – XII.1993, and ~II.1999 – II.2004, i.e. during rather high solar activity. These periods are overshadowed in figure 1. At approach to solar minima $\lambda$ increases and demonstrates the highest values around the solar minima in correlation with the CR fluxes during this time. It should be noted that the $\lambda$ behavior in the minimum of the cycles 23/24 differed from the previous cycles by the smooth growth beginning from ~ III.2004. It is seen in figure 1e that the not shadowed periods in the cycles 20, 21, and 22 coincide with the times of low values of $\alpha$ when the CR drift along the HCS may significantly contribute to the CR modulation [e.g., 10]. None of the interplanetary parameters shown in figures 1b – e has extraordinary magnitude in the minimum of the cycles 23/24. The striking difference of this minimum from the previous ones is its long duration. As it is indicated by horizontal bars in figure 1, in the middle of 2008 decreasing in the solar wind velocity and the HCS tilt angle suddenly became faster which was apparently accompanied by the growth of CR fluxes of relatively low energy (balloon data). However, the growth of the more energetic CRs (neutron monitor data) was suppressed which can be considered as an indication that the effects of the drift and convection may under certain conditions be weaker for the higher energy particles [16].

It can be noticed that during the time periods not shadowed in figure 1 the parameters $P$ and $\alpha$ show a negative correlation both facilitating the CR access into the inner heliosphere in the case of the negative magnetic field in the northern hemisphere of the Sun. Actually, during these periods the correlation coefficients between CR fluxes and interplanetary space indices are higher and more stable than in other periods as it follows from the 3 right columns of table 1 (red ones). Correlation coefficients are given only for the CR balloon data, but they are fully consistent with those for the neutron monitors. Again, the only peculiarity of the cycles 23/24 minimum is its long duration.

### Table 1. Coefficients of correlation between CR fluxes (balloon data) and interplanetary indices.

|               | IX.77-IX.84 | IV.88-XII.93 | II.99-II.04 | X.84-III.88 | I.94-I.99 | III.04-VI.11 |
|---------------|-------------|--------------|-------------|------------|-----------|-------------|
| CR & $B/\delta B$ | 0.43        | 0.16         | 0.51        | 0.76       | 0.74      | 0.72        |
| CR & $V$       | -0.34       | 0.20         | -0.17       | -0.87      | -0.64     | -0.75       |
| CR & $\alpha$  | -0.09       | -0.90        | 0.44        | -0.60      | -0.67     | -0.65       |

### 3. Discussion

Behavior of $\lambda$ is governed by ratio of $B$ to $\delta B$ which is plotted in figure 2 alongside with the HCS tilt angle $\alpha$. A negative correlation is seen in the not shadowed area (which is the same as in figure 1). This correlation exists only around minima of SA and when $B/\delta B \approx 1.3$. This level is indicated by the dotted horizontal line in figure 2. In the cycles 20-22 this occurred when $\alpha$ became small enough (less than ~30°). In the solar cycle 23 the ratio $B/\delta B$ became more than 1.3 in beginning of 2004, when the tilt angle was $\approx 60$°; the strong anticorrelation between $B/\delta B$ and $\alpha$ started at the same time, or probably even earlier. Since high $B/\delta B$ ratio means the small turbulence in the HMF one can suggest that inside the region of the IMF sector structure the magnetic field turbulence is higher. In the solar cycle 23 the magnetic field was probably more smooth and the ratio $B/\delta B$ reached a value close to 1.3 when $\alpha$ was still big. In general, it is not surprising that various indices of SA correlate with each other, but more work is needed to understand the underlying physics.
4. Conclusion
In the periods around the minima of solar activity cycles 21/22, 22/23, and 23/24 the interplanetary conditions stimulated the CR access into the inner heliosphere both via diffusion and drift mechanisms since the CR mean free path value and the HCS tilt angle showed a clear negative correlation. We have not found any features of interplanetary indices which could explain the unusual rigidity dependence of the CR modulation in the minimum of the cycles 23/24. However duration of this minimum was unusually long, and the CR energy anomaly occurred after abrupt strong decrease in solar wind velocity and HCS tilt angle.

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