Long-Term Cosmic Ray Modulation by Heliospheric Parameters: Non-linear Relations

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Abstract

The heliospheric modulation strength is a good parameter for the long-term modulation of cosmic rays in the neutron monitor energy range. Here we study an empirical relation between the modulation strength and the global heliospheric parameters: the heliospheric current sheet tilt angle, the open solar magnetic flux and the global IMF polarity. The suggested relation closely reproduces the measured annual NM count rates. Using the measured IMF parameters and the modulation strength values computed since 1951, this relation allows us to reconstruct the annual tilt angle for about 25 years before the time of direct measurements of the tilt angle.

In addition to more sophisticated theoretical models of galactic cosmic ray (GCR) modulation it is also useful to study empirical regression models. Usually such models linearly relate various heliospheric parameters to the GCR intensity at a fixed energy (see, e.g., [2]). Here we try to generalize this approach.

A general parameter of the heliospheric modulation of GCR is the modulation strength Φ, which defines the shape of the modulated GCR spectrum for many practical purposes. E.g., for a given value of Φ one can calculate an approximate shape of GCR differential energy spectrum and the expected count rate of a cosmic ray detector [1], [11]. The modulation strength is measured in MV, has the physical meaning of the average rigidity loss of CR particles in the heliosphere and takes the following form [4] $\Phi = (D - r_E)V/(3\kappa_o)$, where D is the distance of heliospheric boundary (termination shock), $r_E = 1$ AU, V is the solar wind velocity and κ_o is the (rigidity independent part of the) GCR diffusion coefficient. Although defined only in 1D, Φ can also be used in the real conditions as a formal parameter that fits GCR spectra calculated in 1D model to the actual GCR spectrum measured at 1 AU. The values of Φ have been calculated for the last 50 years [11]. However, here we use an updated Φ series (Fig. 1.a) where heavier species of GCR ($\alpha-$particles) are also taken into account. The value of Φ depends on several global heliospheric parameters as discussed below. In con-

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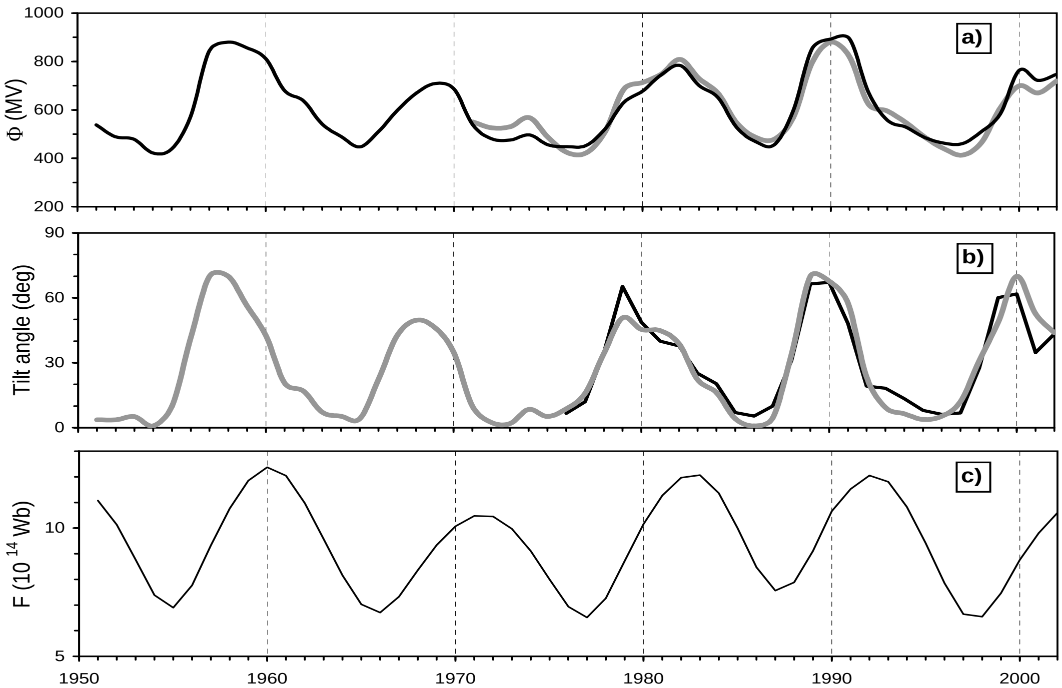

Fig. 1. Annual values of the heliospheric parameters. a) Actual (solid) and calculated (grey) heliospheric modulation strength Φ. b) Heliospheric current sheet tilt angle α (solid curve). Our reconstruction of α is shown as the grey curve. c) Open solar magnetic flux F.

trast to the earlier regression models of the GCR intensity evolution (e.g., [2]), here we study empirical relations between this modulation strength and various heliospheric parameters for the last 50 years.

The diffusion coefficient κ_o depends inversely on the interplanetary magnetic field (IMF) strength B [3],[7]. Accordingly, $\Phi \propto B/B_0$. However, the usual IMF strength as measured in the ecliptic plane at 1 AU gives a very local representation, while the modulation is affected by the global IMF. Recently, an index of the global magnetic field, the open solar magnetic flux through the source surface, was calculated [9]. This index is related to the global dipole component of the solar magnetic field [6]. Accordingly we use the open solar magnetic flux F as an index of the global IMF strength in our model. Then, $\Phi \propto F/F_0$, where F_0 is not a free parameter of our model but is needed only to reduce the model to dimensionless variables. Another heliospheric parameter affecting GCR modulation is the tilt of the heliospheric current sheet (HCS) (e.g., [5]). We use here the classical HCS tilt angle (obtained using a line-of-sight boundary condition) obtained from the Wilcox Solar Observatory since 1976 (http://quake.stanford.edu/∼wso/wso.html). We used also HCS tilt angle reconstruction for 1971-1974 [8]. Drifts of GCR particles along the HCS depend on the particle's charge and the global IMF polarity. Here we use a discrete parameter p corresponding to the global IMF polarity so that $p = -1$, 0 or 1 for the $A < 0$, polarity reversal or $A > 0$ periods, respectively. Although the solar wind speed is important for cosmic ray modulation, its direct correlation with CR variations is weak (see, e.g., [2]) because of its small variations during solar cycle in the ecliptic plane. Unlike the global IMF, data of the global solar wind speed do not exist. Accordingly we do not include ecliptic solar wind data into our regression model to reduce the number of free parameters.

Since the modulation strength Φ is defined only on the time scale of one year or longer [11], we average all used data to annual means (Fig. 1.). Because of the large size of the heliosphere, there is a time delay τ of up to one year between changes of the heliospheric parameters near the Sun and the corresponding response of GCR intensity [10]. Accordingly, Φ at the time t is related to the heliospheric parameters at the time $(t - \tau)$.

The modulation strength Φ is considered to depend on three heliospheric parameters: global IMF flux F, HCS tilt angle α, and the global IMF polarity p. In contrast to the linear additive regression model by [2], we use a multiplicative model taking into account that different effects are not completely independent: $\Phi = \Phi_0 + f(F) \cdot f(\alpha) \cdot f(p)$. Taking into account time delay τ we write the regression model as:

$$\Phi(t) = \Phi_0 + \Phi_1 \cdot \frac{F(t-\tau)}{F_0} \cdot \left(1 + \frac{\alpha(t-\tau)}{\alpha_0}\right) \cdot (1 + \beta p(t-\tau)). \qquad (1)$$

The model has five free parameters: Φ_0, Φ_1, α_0, β and τ (F_0 is fixed at $6 \cdot 10^{14}$ Wb). We have numerically searched for such a set of the parameter values that minimizes the log-discrepancy (relative error):

$$\epsilon = \sqrt{\frac{1}{n} \sum_n \left(\ln^2(\Phi_{actual}) - \ln^2(\Phi_{calc})\right)}. \qquad (2)$$

The best set of the formal parameter values ($\tau = 0.13$ year, $\alpha_0 = 36.5°$, $\beta = 0.09$, $\Phi_0 = 265$ MV and $\Phi_1 = 122$ MV) yields the discrepancy $\epsilon = 0.07$ and the cross-correlation coefficient $r = 0.96$ (Fig. 1.a).

In order to verify the model, we calculated the expected neutron monitor (NM) count rate from the reconstructed Φ similarly to [11] and compared it to the actual Oulu NM count rate (Fig. 2.). The NM count rate is well reproduced, within the accuracy of 0.15 Hz/counter ($r = 0.97$). Count rates of other NMs are reproduced equally well. The quality of CR reconstruction is similar to that obtained in [2] using a linear multi-parameter regression employing twelve free parameters. We also note that the model reproduces the so-called mini-cycle in 1971–1974 [12].

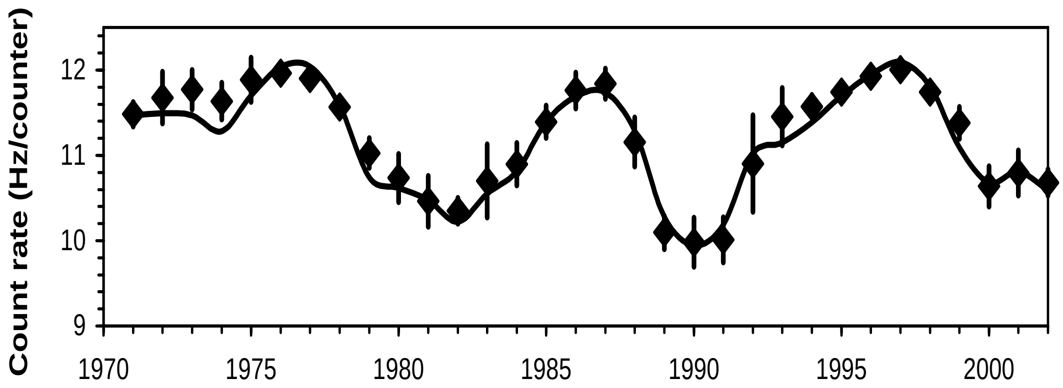

Fig. 2. Annual values of the Oulu NM count rate. Dots represent the actually recorded count rate with error bars corresponding to fluctuations of monthly values around the mean within the year. Line depicts the reconstructed NM count rate.

Generally speaking, the present model (Eq. 1) can be inverted so that, for a given values of Φ and F, one can estimate the value of α. The HCS tilt angle reconstructed in this way is shown in Fig. 1.b since 1951, i.e., 25 years before its measurements. The reconstruction is in a good agreement with the measured α after 1976 (accuracy 6.6°, $r = 0.95$).

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