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Cyclic variations of the heliospheric tilt angle and cosmic ray modulation

K. Alanko-Huotari [a], I.G. Usoskin [b,*], K. Mursula [a], G.A. Kovaltsov [c]

[a] *Department of Physical Sciences, University of Oulu, POB 3000, FIN-90014, Oulu, Finland*
[b] *Sodankylä Geophysical Observatory (Oulu unit), University of Oulu, POB 3000, FIN-90014, Oulu, Finland*
[c] *Ioffe Physical-Technical Institute, Politekhnicheskaya 26, RU-194021 St. Petersburg, Russia*

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Abstract

Using data on cosmic ray modulation parameter since 1951, we have estimated the evolution of the heliospheric current sheet tilt angle for the period 1951–1975, i.e., 25 years before regular observations of the tilt angle. This estimate is based on our recent empirical model relating cosmic ray intensity with global heliospheric parameters. We propose a simple model to describe the cyclic evolution of the tilt angle with the solar cycle. This model agrees with available observational data. Using this model, we have estimated the cosmic ray intensity since 1710. This estimate is consistent with the results based on cosmogenic isotopes (^{14}C and ^{10}Be).

Keywords: Galactic cosmic rays; Heliosphere; Heliospheric current sheet tilt angle

1. Introduction

One of the most important parameters characterizing the structure of the heliospheric magnetic field is the tilt angle of the heliospheric current sheet (HCS), which corresponds to the heliomagnetic equator. HCS is a thin interface between the opposite polarities of the heliospheric magnetic field (HMF) emerging from the Sun. The magnetic axis of the Sun is tilted with respect to rotational axis, and, together with the Sun's rotation and radially expanding solar wind, the sheet forms a complicated 3D-structure, resembling a ballerina's skirt. In a longitudinally and hemispherically symmetric approximation the waviness of HCS is defined by the tilt angle. The tilt angle has been observed at the Wilcox solar observatory since 1976. However, for many purposes it would be interesting to know its value for earlier times. The tilt angle is important for the large scale magnetic field and the solar dynamo, being related to the inclination of the Sun's magnetic dipole axis.

The HCS tilt angle is also a key parameter of galactic cosmic ray modulation in the heliosphere. The relation between the HCS tilt angle and variations of the cosmic ray intensity has been intensively studied both theoretically (e.g., Fisk et al., 1998; Potgieter and Ferreira, 2001) and empirically (see, e.g., Belov, 2000, and references therein). Cosmic ray intensity variations have been measured since 1951, when the worldwide network of neutron monitors (NM) was created. Using this data, Cliver (1993) made an attempt to reconstruct the HCS tilt angle before 1976 by extrapolating an empirical relation between the Deep River NM count rate and the observed tilt angle after 1976. Such an approach, based on the linear regression between the tilt angle and NM count rate, is promising but contains some shortcomings. First, the relation between the cosmic ray intensity and solar/heliospheric parameters is essentially non-linear (Mursula et al., 2003). Moreover, such a regression explicitly assumes that the cosmic ray intensity is only affected by the HCS tilt (or at least that all heliospheric parameters vary synchronously), which is not correct. Cosmic ray modulation is rather determined by a combined action of many heliospheric

* Corresponding author. Tel.: +358 8 553 1377; fax: +358 8 553 1287.
E-mail address: ilya.usoskin@oulu.fi (I.G. Usoskin).

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factors (in particular the magnetic field strength, solar wind velocity, HMF polarity) which can have different phases. In this paper we develop this approach and estimate the HCS tilt angle for the period 1951–1976, in a way which overcomes the above shortcomings. We use a non-linear relation (Alanko-Huotari et al., 2006) between cosmic ray variations and the major heliospheric parameters. Here we make use not of data from a single NM, which is an energy integrating local device (e.g., Alanko et al., 2003), but rather of the heliospheric modulation potential, which describes the shape of the differential energy spectrum of cosmic rays at the Earth's orbit (Usoskin et al., 2005).

It has been noticed that the tilt angle varies in phase with the sunspot cycle (e.g. Suess et al., 1993; Cliver and Ling, 2001), and a simple empirical model of cyclic evolution of the tilt angle was recently suggested (Alanko-Huotari et al., 2006). Here we also study a possibility to use this cyclic model to describe the tilt angle evolution and apply it to studies of the cosmic ray modulation in the past.

2. Empirical model for cosmic ray modulation

Recently, we have developed an empirical model describing the relation between global heliospheric parameters and cosmic ray modulation via the so-called modulation potential ϕ for the last 30 years (Alanko-Huotari et al., 2006). It has been shown that variations of ϕ can be described by a simple model employing only three variables – the open solar magnetic flux F, the HCS tilt angle α and the global magnetic field polarity p:

$$\phi = \phi_0 + \phi_1 \left(\frac{F}{F_0}\right)^{1+\alpha/\alpha_0} (1 + \beta p), \tag{1}$$

where F is the open solar flux, α is the HCS tilt angle and p is the magnetic field polarity. $\phi_0 = 150$ MV, $\phi_1 = 86$ MV, $F_0 = 2.5 \times 10^{14}$ Wb, $\alpha_0 = 91°$, and $\beta = -0.03$ are the best-fit parameters of the model. This set of parameters yields best fitting of the observed ϕ values for the period 1976–2005 (the correlation coefficient is 0.9 - see details in Alanko-Huotari et al., 2006). The model (Eq. 1) was constructed using monthly ϕ values in 1976–2005 (Usoskin et al., 2005), the modelled open magnetic flux F_0 (Solanki et al., 2000) and the tilt angle α measured at the Wilcox Solar Observatory since 1976 (radial boundary conditions). The open solar magnetic flux F_0 is a better index of the interplanetary magnetic field than the local values measured in the ecliptic plane. The HMF polarity was parameterized by the variable p: $p = 1$ (-1) for positive (negative) polarity periods. Reversal periods were taken as mid-1959, mid-1970, mid-1980, mid-1991, and late 2001.

The modulation potential ϕ describes the shape of the modulated cosmic ray spectrum in the framework of force-field approximation (Caballero-Lopez and Moraal, 2004; Usoskin et al., 2005). The modulated energy spectrum of i-th GCR species at the Earth's orbit, J_i, is related to the unmodulated local interstellar spectrum (LIS) via the modulation potential ϕ:

$$J_i(T, \phi) = J_{\mathrm{LIS},i}(T + \Phi_i) \frac{(T)(T + 2T_r)}{(T + \Phi_i)(T + \Phi_i + 2T_r)}, \tag{2}$$

where T is the particle's kinetic energy per nucleon, $\Phi_i = (eZ_i/A_i)\phi$, Z_i is the charge number and A_i the mass number. $T_r = 0.938$ GeV/nucleon is the proton's rest mass energy. The only temporally changing variable in the force-field approximation is the modulation potential ϕ, which is thus a useful tool to parameterize the shape of the modulated spectrum. On the other hand, Eq. (2) also includes the local interstellar spectrum (J_{LIS}) whose exact shape is not known. Therefore, the exact value of the modulation potential ϕ makes sense only for a fixed J_{LIS} (see details in Usoskin et al., 2005). Here we use the local interstellar spectrum according to Burger et al. (2000) for both protons and heavier species, in the form:

$$J_{\mathrm{LIS}}(T) = \frac{1.9 \times 10^4 \cdot P(T)^{-2.78}}{1 + 0.4866 P(T)^{-2.51}}, \tag{3}$$

where $P(T) = \sqrt{T(T + 2T_r)}$. J and T are expressed in units of particles/(m^2 sr s GeV/nucleon) and in GeV/nucleon, respectively.

3. Tilt angle estimate: 1951–1975

The empirical model (Eq. 1) was constructed for the reference period of 1976–2005, when the tilt angle has been measured. On the other hand, all other parameters of the relation (1) are known for longer periods: the modulation potential has been reconstructed since 1951 (Usoskin et al., 2005), the modelled open flux can be estimated from sunspot numbers (Solanki et al., 2000), and the HMF polarity can be estimated from the phase of a solar cycle. Therefore, the relation (1) allows a rough estimate of the tilt angle for the period 1951–1975. We have depicted the estimated tilt angle for the entire period 1951–2005 in Fig. 1 together with the observed tilt angle. For the period of overlap (1976–2005) the two curves follow fairly closely each other (correlation between annual values is 0.91). The estimated tilt angle yields some (-3 to $-5°$) negative values during some minimum years, but they are consistent with zero. We have plotted the annual values of the estimated tilt angle for 1951–1975 in Table 1.

4. Cyclic tilt angle model

The HCS tilt angle is known to vary cyclically over the solar cycle. E.g., Cliver and Ling (2001) studied variations of the tilt angle for solar cycles 21 and 22 and noted that the tilt angle evolution is very similar for the ascending phase of each solar cycle but somewhat noisy in the descending phase. We show in Fig. 2a the tilt angle variations for solar cycles 21–23 as a function of the cycle phase x, which takes values from 0 to 1 between two successive

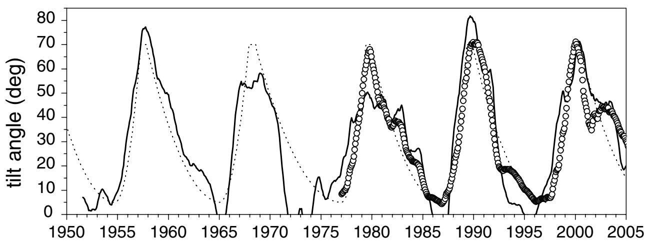

Fig. 1. Tilt angle variations (all data are 12-month running means). Observed and estimated (Section 3) series of tilt angle are depicted by circles and solid curve, respectively. Dotted curve corresponds to the cyclic tilt angle model (Eq. (4)).

cycle minima. Similar to Alanko-Huotari et al. (2006) we have defined the tilt angle minima as being seven month delayed with respect to sunspot minima. We have superposed tilt angles in these three cycles, and found the following simple cyclic shape to describe the tilt angle variation:

$$\alpha = \begin{cases} 5^{\circ} + 1100 \cdot x^2, & \text{for } x \leqslant 0.24, \\ 70^{\circ}, & \text{for } 0.24 < x \leqslant 0.30, \\ 5^{\circ} + 130 \cdot (1-x)^2, & \text{for } x > 0.30. \end{cases} \tag{4}$$

We note that due to the observation limitations the measured tilt angles are practically limited to 70°. The cyclic model fits almost perfectly in the ascending phase. Dispersion of individual points is larger in the descending phase but the cyclic model gives a reasonable fit to the data. Correlation between the measured and modelled monthly tilt angles is 0.91.

Some fragmentary estimates of the tilt angle have recently been presented by Pishkalo, 2006 who analyzed historical images of solar eclipses for the last 130 years. Each individual estimate has large uncertainties, since it is a momentary (snapshot) 2D-projection of an essentially 3D feature. The distribution of these data as a function of cycle phase is depicted in Fig. 2b and shows reasonable agreement with the cyclic model introduced here.

The time evolution of the cyclic model tilt angle is shown by the dotted line in Fig. 1. One can see that the cyclic model agrees well with the direct observations in 1976–2005. Interestingly, the cyclic model also agrees with the tilt angle estimated from ϕ data, except for the period 1972–1974, when the famous ‘mini-cycle’ in cosmic ray modulation appeared due to a very unusual heliospheric structure (Usoskin et al., 1998; Wibberenz et al., 2001).

We note that such a cyclic model of the tilt angle would remain a mathematical exercise unless confirmed by independent methods. In the following Section we will test if this model produce reasonable results on time scales longer than the last few solar cycles.

5. Cosmic ray modulation in the past

Here we apply the nonlinear model of Eq. (1) to study very early solar modulation, using the cyclic model of the tilt angle (Eq. (4)), the HMF polarity and the open flux computed from the group sunspot number (Hoyt and Schatten, 1998) after 1750. The modulation parameter ϕ computed in this way is shown in Fig. 3a together with the directly obtained ϕ. One can see a long-term trend in the modulation potential. E.g., the level of modulation was higher during the last 50 years than during the period before 1940. In particular, the maximum modulation during the Dalton minimum (1800–1830) was weaker than the minimum modulation for the modern cycles. Using the method developed by Usoskin et al., 2005, we have also calculated the count rates of a polar neutron monitor (NM) using these ϕ values. The polar NM has been chosen to avoid influence of the long-term changes of the geomagnetic field (see, e.g., Kudela and Bobik, 2004; Shea and Smart, 2004). These count rates are shown in Fig. 3b together with the actual count rate of the Oulu NM since 1964 (all data have been normalized to the highest observed count rate in 1965). Two important facts can be observed here. First, there is an overall decrease of cosmic ray intensity (in the NM energy range) by about 10% between the Dalton minimum and the present. Second, the cosmic ray intensity at solar minima during the Dalton minimum was about 7% higher than nowadays, implying for the existence of effective residual modulation during sunspot minima (McCracken et al., 2004). These results are consistent with earlier reconstructions of the cosmic ray flux from sunspot numbers (Usoskin et al., 2002) and with a recent regression model (Belov et al., 2006) based on geomagnetic activity since 1868. On the other hand, a regression model (Belov et al., 2006) based on sunspot numbers is in disagreement with these results, not showing any change in the level of cosmic ray intensity between the modern solar minima and, e.g., the Maunder minimum in 1645–1700. This disagreement is probably caused by the invalid linear regression used by Belov et al. (2006). The present model does not apply for the Maunder minimum, when the normal cyclic sunspot activity was almost absent and the cosmic ray modulation is known to vary with the dominant 22-year periodicity (e.g., Usoskin et al., 2001).

Table 1
Estimated values of the annual tilt angle α (deg) before 1976

Year	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
α	–	7	2	10	5	18	49	77	66	52
Year	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
α	41	25	21	16	5	0	37	54	55	52
Year	1970	1971	1972	1973	1974	1975				
α	42	7	0	0	12	6				

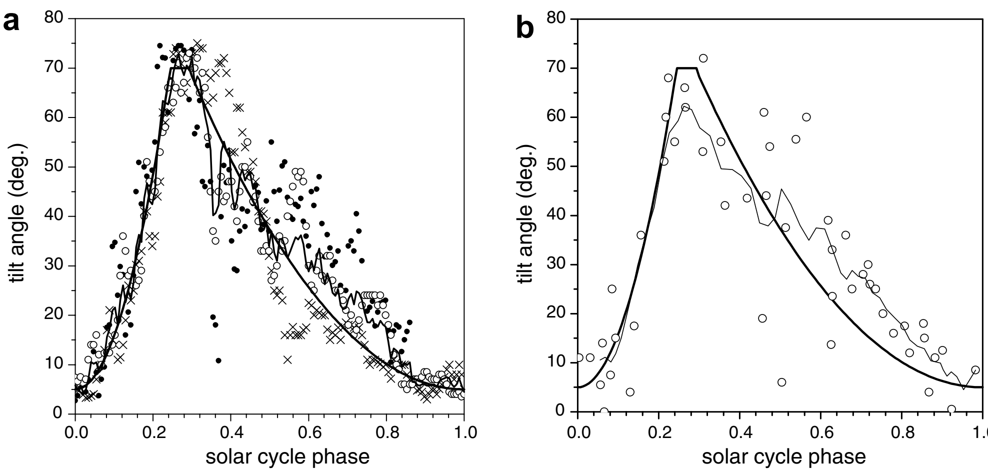

Fig. 2. Tilt angle as function of the solar cycle phase. (a) Directly measured tilt angles (WSO data): crosses, filled circles and open circles correspond to cycles 21 through 23, respectively. Thin line depicts the average over cycles 21–23, and the thick line represents the cyclic model (Eq. (4)). (b) Tilt angle (dots and thin line) reconstructed from observations of solar eclipses since 1870 (Pishkalo, 2006). The thick line represents the cyclic model (Eq. (4)).

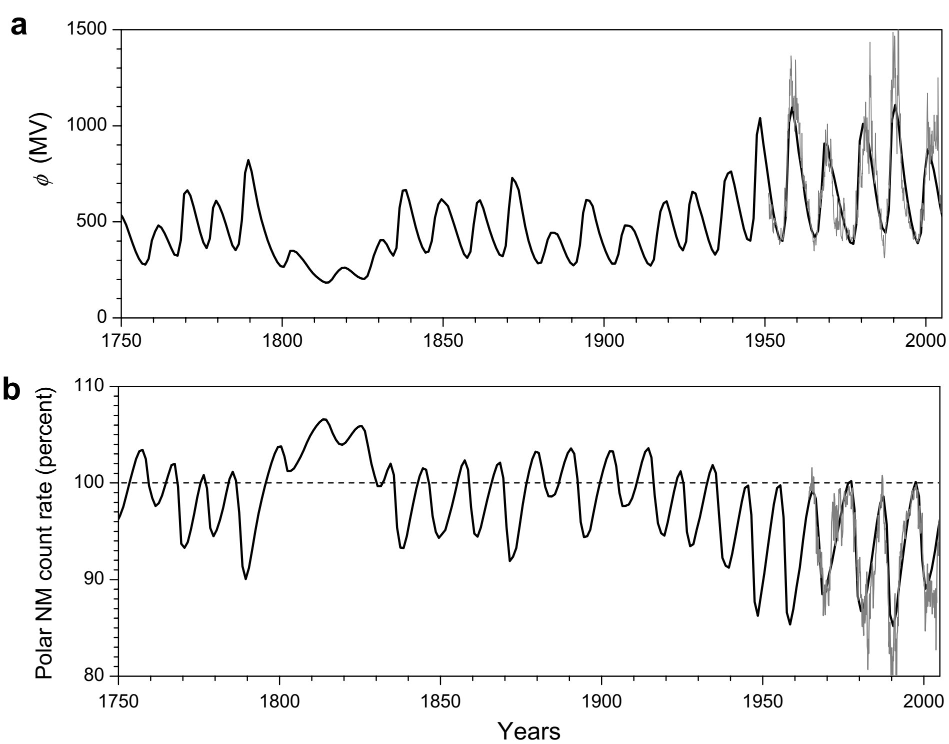

Fig. 3. Time variations of the cosmic ray modulation for 1750–2005. (a) The modulation potential ϕ estimated in this paper (solid line) and directly obtained from observations (grey line – Usoskin et al., 2005). (b) Count rates of a polar NM computed from ϕ shown in panel (a). Grey line depicts the actual count rate of Oulu NM. All data are normalized to the level (shown as the dashed line) corresponding to 1965.

Next we compare the modelled modulation potential ϕ with reconstructions based on cosmogenic isotopes. Decadal averaged values of ϕ evaluated here are shown as the thick curve in Fig. 4. It depicts remarkable agreement with the ϕ-series reconstructed using a physical model and data of ^{14}C in tree-rings (Solanki et al., 2004), tabulated in (Usoskin et al., 2006) for the entire period of overlap (1700–1900). Agreement with the ϕ-series obtained by (McCracken et al., 2004) from the ^{10}Be data in Antarctic ice is also rather good, particularly after 1750. The reason for the high modulation obtained from ^{10}Be for the period 1700-1750 is not known and is a topic of intense debate (see, e.g., Usoskin et al., 2002; McCracken et al., 2004). We conclude that the results of our simple empirical model are consistent with the results of independent evaluations based on measurements of cosmogenic isotopes in

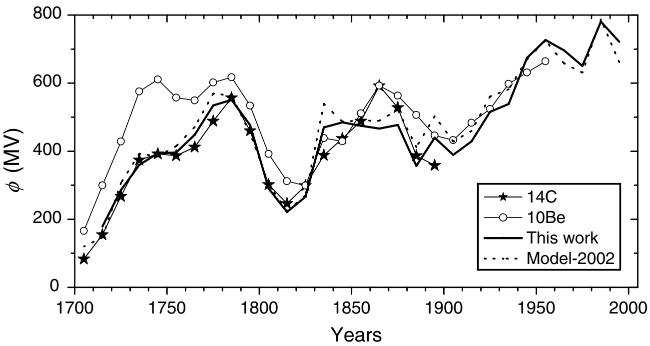

Fig. 4. Reconstruction of the modulation potential after the Maunder minimum (all data are 10-year averaged and reduced to the force-field model according to Usoskin et al., 2005). The present model estimate is shown by the thick black curve, while the dotted curve corresponds to the model by Usoskin et al., 2002. Curves marked by circles and stars correspond to the ^{10}Be- (McCracken et al., 2004) and ^{14}C-based (Solanki et al., 2004) reconstructions, respectively.

terrestrial archives. This gives additional support for the cyclic model of the HCS tilt angle. The result is also in close agreement with a physics-based reconstruction of the cosmic ray modulation from sunspot numbers by Usoskin et al., 2002 – see Fig. 4. It is interesting that the 10-year averaged modulation potential shows a dramatic increase (from 400 MV to about 700 MV) during the period between 1900 and 1950, which is consistent with the doubling of the solar magnetic flux since 1900 (Lockwood et al., 1999; Solanki et al., 2000; Lockwood, 2003). We note that this feature is apparent in both the model results (which explicitly include the increasing open magnetic flux) and in the modulation based on measured data, confirming their mutual consistency.

6. Conclusions

Using a recent empirical model (Alanko-Huotari et al., 2006, – see Eq. 1) relating the modulation potential ϕ to the HCS tilt angle, and a recent series of monthly ϕ values (Usoskin et al., 2005), we have estimated the HCS tilt angle for the period 1951–1975 (see Table 1), i.e., 25 years before direct observations. We have presented a simple cyclic model describing the evolution of the HCS tilt angle during a solar cycle (Eq. (4)). In this model the tilt angle depends only on the phase of the solar cycle but is not related to its amplitude. The tilt angle produced by this cyclic model is in good agreement with the direct observations since 1976, with fragmentary estimates from eclipse images after 1870 (Pishkalo, 2006) as well as with the values obtained from the modulation potential since 1951. The cyclic model can also be used for cosmic ray and heliospheric studies when no direct information on the HCS tilt is available.

Using this cyclic model, we have modelled the cosmic ray modulation potential after the Maunder minimum and found a good agreement with the results based on measurements of cosmogenic isotopes ^{14}C and ^{10}Be in terrestrial archives.

Therefore, we conclude that the presented cyclic model provides a rough estimate for the HCS tilt angle, consistent with other direct and indirect results on different time scales.

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