Solar modulation of cosmic rays since 1936: Neutron monitors and balloon-borne data

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Abstract: We present a series of reconstructed monthly values of the so-called modulation potential, often used to parameterize the energy spectrum of galactic cosmic rays, for the period from July 1936 through December 2010. This work extends our earlier study by employing new data and improving the reconstruction method. The reconstructed series has been tested against long-term data of balloon-borne measurements of flux of cosmic ray ionizing radiation in the stratosphere performed by the Lebedev Physical Institute since 1957. The comparison shows good general agreement. Some minor discrepancies during solar minimum years with negative heliospheric magnetic field polarity may be related to possible deviations of the lowest energy part of the GCR spectrum from the force-field approximation.

Keywords: Cosmic Rays, heliosphere, neutron monitor

1 Introduction

Modulation of galactic cosmic rays (GCR) in the heliosphere is well understood in the framework of modern theory (see, e.g., reviews [1, 2]) but its time variability is only generally monitored, particularly on the long-term scale. Cosmic rays are monitored by the ground-based network of neutron monitors (NMs) since 1951 [3], and by ground-based ionization chambers (ICs) 1936 [4]. Here we present a reconstruction of variations of the GCR spectrum, parameterized via the force-field approximation, for the period of 1936–2010 using the data of ground-based NM and IC data [5]. This is un upgraded reconstruction comparing to the previous one [6]. We also compare our present reconstructions with the series of balloon-borne measurements of the flux of ionizing radiation performed by Lebedev Physical Institute since 1957 [7, 8].

2 Reconstruction of modulation potential

The differential energy spectrum of GCR, J, in the vicinity of Earth is often parameterized using the force-field approximation [9], via the modulation potential ϕ:

$$J_i(T,\phi) = J_{\mathrm{LIS},i}(T+\Phi_i)\frac{(T)(T+2T_{\mathrm{r}})}{(T+\Phi_i)(T+\Phi_i+2T_{\mathrm{r}})}, \quad (1)$$

where index i denotes the type of GCR particle (with charge Z_i and mass A_i numbers), T is the particle's kinetic energy per nucleon, $\Phi_i = (eZ_i/A_i)\phi$, $T_{\mathrm{r}} = 0.938$ GeV/nucleon, and $J_{\mathrm{LIS},i}$ is the unmodulated local interstellar spectrum (LIS). We note that all the temporal changes are included in the modulation potential ϕ, driven by solar activity. The prescribed function $J_{\mathrm{LIS}}(T)$ is not exactly known (e.g., [6, 10]) and the adopted model of LIS must be specified together with the values of ϕ. Here we use (see details in [6]) the proton LIS in the form [11]:

$$J_{\mathrm{LIS}}(T) = \frac{1.9\times 10^4 \cdot P(T)^{-2.78}}{1+0.4866\,P(T)^{-2.51}}, \quad (2)$$

where $P(T) = \sqrt{T(T+2\,T_r)}$, J and T are expressed in units of particles/(m^2 sr s GeV/nucleon) and in GeV/nucleon, respectively. LIS for heavier species, including $\alpha-$particles, is scaled correspondingly (see [5, 6] for details).

The monthly values of the modulation potential and its uncertainties have been evaluated using the same procedure as described in refs. [5, 6]. For the analysis we used data from the following NMs, as listed in Table 1. We employ three different calculations of the NM yield functions [12, 13, 14], the latter was not used in the previous reconstruction [6]. We also included here contribution from GCR species heavier than $\alpha-$particles, neglected in [6].

Before the period of regular NM observations (1951) we use the pseudo-Climax NM count rate reconstructed since 1936 by [4], who used records of ground-based ICs at several locations [15, 16], re-calibrated vs. a possible instrumental drift [16, 3]. However, a question on the long-term trend in ionization data may still contain systematic uncer-

Table 1: List of NMs analyzed here and their parameters: their type and geomagnetic rigidity cutoff P_c (GV) for the 1995 epoch and the period of data used here.

Name	type	P_c	Period
Goose Bay	NM64	0.74	01/1965–12/1998
Oulu	NM64	0.77	04/1964–12/2010
Kerguelen	NM64	1.15	04/1964–12/2009
Kiel	NM64	2.4	01/1965–12/2009
Hermanus	NM64	4.5	01/1973–10/2009
Rome	NM64	6.3	01/1967–12/2009
Climax	IGY	3	02/1951–03/2004
Mt.Washington	IGY	1.3	11/1955–03/1991

tainties, and therefore this reconstruction should be taken with caveats.

The reconstructed monthly series of the modulation potential ϕ is depicted in Fig. 1 together with the estimated uncertainties, which include the dispersion or measurement errors of the data, and the model's uncertainties. The digital data for the modulation potential are given in Table 3 of [5] until 2009. An electronic, continuously updated version of the Table is available at http://cosmicrays.oulu.fi/phi/phi.html.

3 Test vs. balloon-borne data

In order to test the reliability of the reconstructed modulation potential, we compare it with the long-term data series of balloon-borne measurements of the ionizing radiation in the stratosphere, obtained by the Lebedev Physical Institute [17, 7]. Technical details of the detector can be found elsewhere (e.g., [8]). Measurements are performed at high and middle latitudes onboard balloons launched several times a week, each flight lasting for several hours (80,000+ launches in total). Standard detectors of the identical design, calibrated in the laboratory, have been used throughout the entire period securing the homogeneity of the data series. We use here monthly averages of the integral flux of cosmic rays with energy above 180 MeV, F_{180}, for 1957–2009, as depicted in Fig. 2.

Form the reconstructed NM-based modulation potential (Fig. 1) we computed the GCR spectrum for each month using Eqs. 1 and 2. Then an integral of thus calculated spectrum $J(T,t)$ can be computed:

$$F^*_{180}(t) = \int_{T_o}^{\infty} \left(J_{\rm p}(T,\phi(t)) + J_\alpha(T,\phi(t))\right)\cdot dT, \quad (3)$$

where time t corresponds to the month under consideration and T_o corresponds to the kinetic energy of 180 MeV. This computed series F^*_{180} is shown in Fig. 2 as the solid curve with the grey shading denoting the uncertainty. The values of F^*_{180} computed from NM-based reconstructions generally agree well with the measured ones (correlation coefficient is 0.96), but there are periods of small but systematic discrepancies. They may be related, e.g., to the different sampling rates: balloons measure several hours a week, while NMs record is continuous. The yield function of a NM quickly grows with energy, making them sensitive to GCR with high energy (median energy is 10–15 GeV/nuc [18]. The balloon-borne Geiger counter is sensitive to the lower energy of GCR (median energy is ≈2 GeV/nuc). Therefore, one may expect some difference during periods of the distorted GCR spectrum, e.g., in the 1970s, 1989-1991 and 2001 when strong solar transient events were frequent. The systematic difference during solar quiet periods of 1965, 1987, 2008 may indicate that the calculated F^*_{180} can be overestimated at solar minima with the $A < 0$ heliospheric polarity. We can speculate that the low energy part of GCR spectrum (< 300 MeV) may deviate from the force-field approximation, implying that extrapolation of the GCR spectrum reconstructed from NM data into low-energy range may be quite uncertain (cf. [19]). Thus, we can conclude that the two data sets are consistent, within the uncertainties, with each other, confirming the validity of the reconstruction.

4 Discussion and Conclusions

In this paper we present a series of monthly averaged values for the cosmic ray modulation potential ϕ for the period from July 1936 through December 2010. The modulation potential provides a useful parametrization of the GCR energy spectrum in the vicinity of Earth. Although its accuracy is not very high, it is enough for many practical applications, including, e.g., radiation dosimetry, studies of cosmogenic isotopes, atmospheric effects of cosmic rays, etc. The presented series consists of three unequal parts in the sense of the data quality. The most reliable part is based on the data from the world-wide network of standard sea-level neutron monitors. It starts from April 1964 and has quite low uncertainty – the mean 1σ error is σ_ϕ ≈26 MV. For the period between February 1951 and March 1964 only a few NM data-sets are available, and these NMs are of IGY type (with less precisely known yield function) and at high mountain altitude (requiring additional altitude correction). As a result, the corresponding uncertainties of the ϕ reconstruction are larger (σ_ϕ ≈44 MV). The reconstruction before 1951 is based on data from the ground-based ionization chambers, re-calibrated by McCracken and Beer [4]. The uncertainties for this part are quite large, being about 140 MV. The reconstruction has been tested against the long-term series of balloon-borne measurements of the cosmic-ray induced ionizing radiation in the stratosphere performed by the Lebedev Physical Institute since 1957. The agreement between reconstructed and measured series is very good after 1964, with only a few short periods of noticeable discrepancy associated to the enhanced rate of solar transient events, and periods around minima of solar activity and the negative polarity of the heliospheric magnetic field.

Concluding, we have presented an extended series of the reconstructed modulation potential since 1936 and tested it with the directly measured flux of cosmic-ray induced ionizing radiation in the stratosphere.

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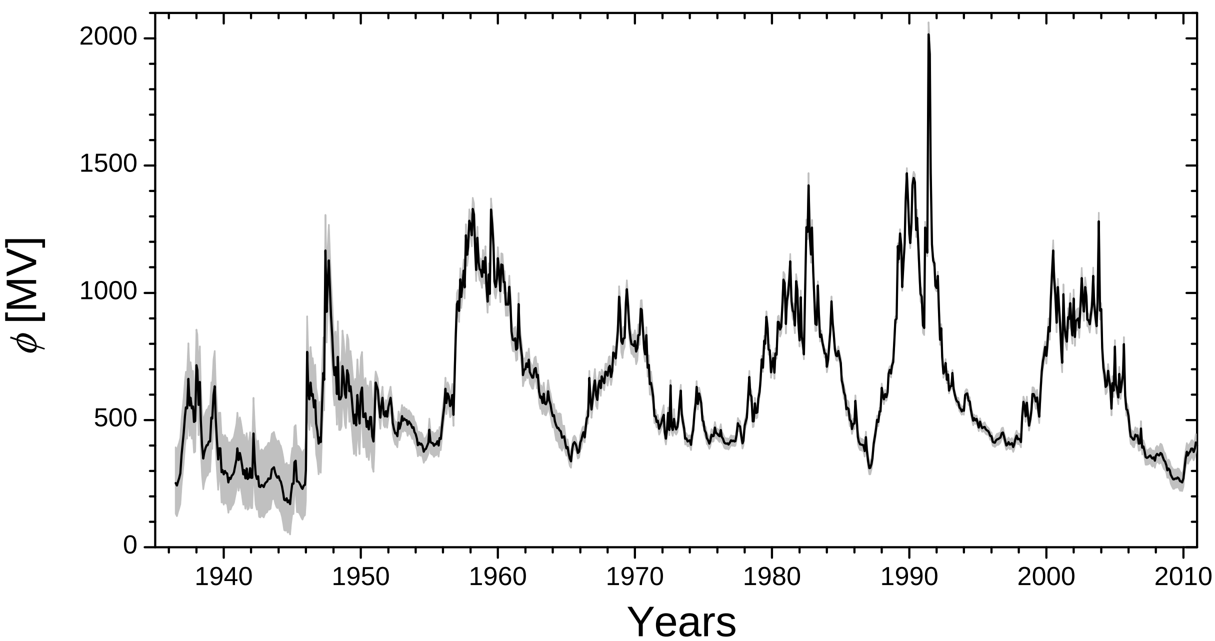

Figure 1: Modulation potential ϕ, reconstructed for the period 1936–2010, along with the 68% confidence interval (grey-filled). This plot is updated from Fig. 1 of [5].

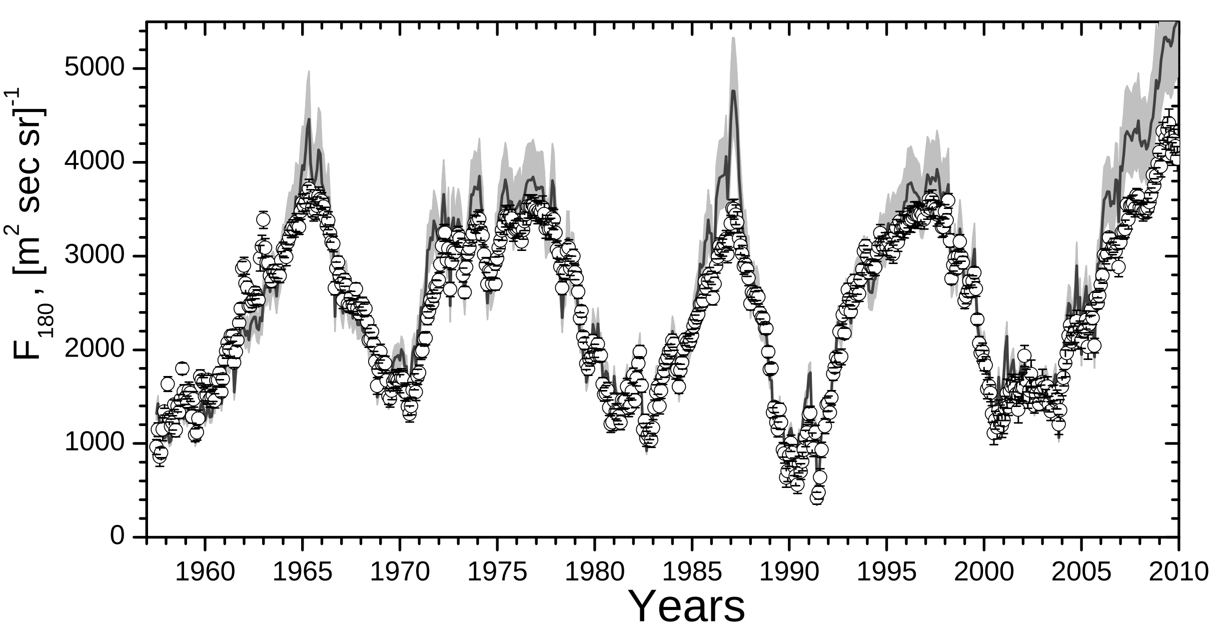

Figure 2: Time profile of the cosmic ray flux ($>$ 180 MeV/nuc) F_{180} as measured at the Lebedev Physical Institute balloons (open dots with error bars) and computed from NM-data (solid curve with grey shading denoting 1σ uncertainty).