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Variations of the heliospheric modulation strength during the neutron monitor era

I.G. Usoskin[1], K. Alanko[2], K. Mursula[2], K. Kudela[3], and G.A. Kovaltsov[4]

[1]Sodankylä Geophysical Observatory (Oulu unit), FIN-90014 University of Oulu, Finland
[2]Department of Physical Sciences, FIN-90014 University of Oulu, Finland
[3]Institute of Experimental Physics, 04353 Kosice, Slovakia
[4]Ioffe Physical-Technical Institute, 194021 St.Petersburg, Russia

Abstract. Using a simple stochastic $1D$ simulation model of the heliosphere we calculate galactic cosmic ray spectra at the Earth's orbit for different values of the heliospheric modulation strength Φ. Convoluting these spectra with the specific yield function of a neutron monitor, we obtain the expected neutron monitor count rates for different values of Φ. We present here a normalization method which allows to easily estimate the value of Φ on the basis of actually recorded neutron monitor count rates. By means of this approach we estimate the heliospheric modulation strength for the neutron monitor era using long-term records of count rates from the high-latitude Oulu and mid-latitude Hermanus neutron monitors.

1 Introduction

The global network of neutron monitors consists of many stations located around the globe at various latitudes, longitudes and altitudes. Neutron monitors (NMs) are in routine operation since mid-1950 which determines the era of continuous measurements of cosmic ray (CR) intensity. NM count rates vary in time with the 11-year solar cycle due to changes in the heliospheric modulation of galactic cosmic rays (GCR). Therefore, the NM count rates are unambiguously related to the modulation strength, and an inverse relation can be found (O'Brien and Burke, 1973). In this paper we calculate the relation between NM count rates and the modulation strength and estimate the level of modulation during the neutron monitor era. This work is related to our recent suggestion to normalize the NM count rates by the unmodulated GCR spectrum (Usoskin et al., 1999, 2001).

2 Heliospheric modulation of GCR

A neutron monitor can effectively register neutrons from atmospheric nucleon cascade initiated by CR particles with rigidity above some GV on the top of the atmosphere, (see, e.g., Nagashima et al. (1989) and references therein). NM count rates can be obtained as follows:

$$N(P,x,t) = \int_{P_c}^{\infty} G(P,t)\cdot Y(P,x)\cdot dP \tag{1}$$

where x and P_c are the atmospheric depth and the geomagnetic rigidity cutoff of the NM location, $G(P,t)$ is the rigidity spectrum of the CR particle in the Earth's vicinity (i.e. after modulation) at time t and $Y(P,x)$ is the specific yield function which accounts for the propagation of GCR particles in the Earth's atmosphere and the detection of secondary nucleons (Nagashima et al., 1989; Clem and Dorman, 2000). The modulated CR spectrum is

$$G(P,t) = \int_{P}^{\infty} G_{LIS}(P_o)\cdot M(P_o,P,t)\cdot dP_o \tag{2}$$

where $G_{LIS}(P_o)$ is the local interstellar spectrum (LIS) outside the heliosphere, i.e., before modulation, and $M(P_o,P,t)$ is the modulation function which gives the probability of a CR particle with initial rigidity P_o to be found in the Earth's vicinity with rigidity P at time t. The modulation function is calculated by solving numerically the transport equation of GCR in the heliosphere (see, e.g., Labrador and Mewaldt (1997); Gervasi et al. (1999a)). We require $\int M(P_o,P,t)dP \leq 1$ (particles cannot be created or multiplied in the heliosphere) and $P < P_o$ (particles lose energy due to modulation but do not gain energy inside the heliosphere). Here we consider only modulation of GCR. Anomalous and solar CR are beyond the scope of this study.

One can see from Eqs. 1-2 that the only time-dependent part is the modulation function, $M(P_o,P,t)$. A commonly used parameter of heliospheric modulation is the modulation strength Φ (Gleeson and Axford, 1968) which can be expressed in a spherically symmetric and steady-state case for the Earth's orbit as

$$\Phi = \frac{(D-r_E)V}{3\kappa}, \tag{3}$$

Correspondence to: I. Usoskin (Ilya.Usoskin@oulu.fi)

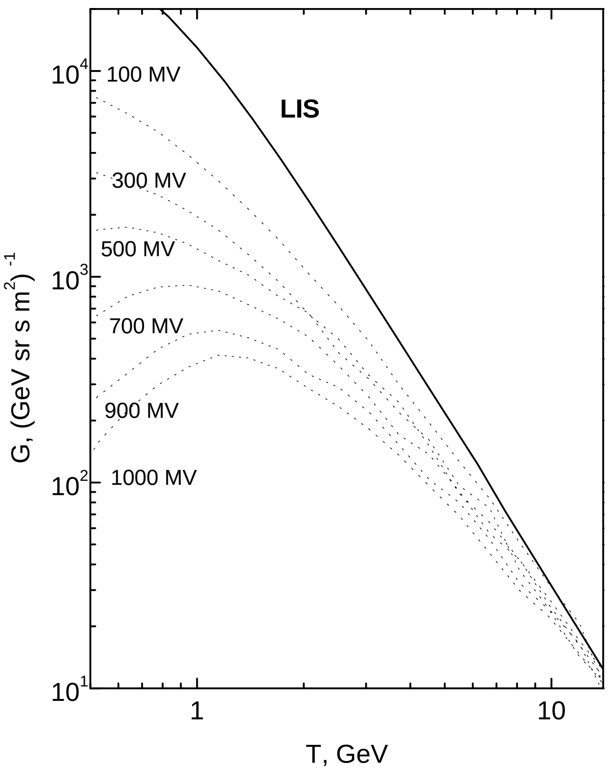

Fig. 1. Spectra of GCR at the Earth's orbit (dotted curves) for different modulation strength Φ (as denoted near the dotted curves). The solid curve (marked as LIS) denotes LIS of GCR ($\Phi = 0$).

where D is the heliospheric boundary, r_E is 1 AU, V and κ are the solar wind velocity and the diffusion coefficient. Although very useful for theoretical considerations, the modulation strength is not easy to estimate in practice. In order to calculate the value of Φ one needs satellite data of solar wind speed, and estimates of the diffusion tensor. On the other hand, one can calculate the modulated spectra $G(P, \Phi)$ for a set of fixed values of Φ within the framework of the employed heliospheric model. Then, using Eq. 1 one can estimate $\Phi(t)$ directly from NM count rates $N(P_c, x, t)$. We note that the modulation strength Φ only takes into account the diffusion-convection terms of CR modulation in the heliosphere. Other effects, e.g., particle drift and the heliospheric current sheet (see Belov (2000) and references therein) also play a role in the variation of NM count rates. However, a rough estimate of the heliospheric state from NM count rates can be done under the above assumptions (see, e.g., O'Brien and Burke (1973)).

3 Calculation results

3.1 Modulated spectra at the Earth's orbit

We have calculated the modulated CR spectra at the Earth's orbit by solving numerically the spherically symmetric Parker's equation of GCR transport in the heliosphere (Parker, 1965)

$$\frac{\partial f}{\partial t} = -V\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial f}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2V)\frac{P}{3}\frac{\partial f}{\partial P} \quad (4)$$

where $f(r, P, t)$ is the omnidirectional distribution function of GCRs. We use the stochastic simulation (Monte-Carlo) approach described in detail elsewhere (Gervasi et al., 1999a,b).

The local interstellar spectrum of GCR was taken as a function of rigidity according to Burger et al. (2000):

$$G_{LIS}(P) = 1.9 \cdot 10^4 P^{-2.78} \qquad , P \geq 7GV$$
$$G_{LIS}(P) = exp(9.472 - 1.999 \cdot lnP - 0.6938(lnP)^2 + 0.2988(lnP)^3 - 0.04714(lnP)^4) \, , P < 7GV \quad (5)$$

where P is expressed in GV, and G_{LIS} in (GeV sr m^2 s)$^{-1}$. Note that there is an error in formula (2) of (Burger et al., 2000) which is corrected in Eq. 5 (Burger and Potgieter, personal communication). The resulting modulated energy spectra are shown in Fig. 1 for different values of Φ, together with LIS ($\Phi = 0$ MV). For each spectrum we calculated one million particle trajectories.

3.2 Neutron monitor response

Using the GCR spectra, $G(P, \Phi)$, and the specific yield function of a NM, we calculated the expected differential response function of a standard NM to GCR

$$R(P, \Phi) = G(P, \Phi) \cdot Y(P) \quad (6)$$

(As the standard NM, we consider a 1-NM-64 neutron monitor at the sea-level.) Here we used the specific yield function, $Y(P)$, as given by Debrunner et al. (1982) and modified in the high rigidity part according to (Nagashima et al., 1989). The response function is shown in Fig. 2 for different values of Φ. One can see that the differential response has a sharp peak-like structure due to the convolution of the growing specific yield function and the sharply declining rigidity spectrum. The peak of the response function lies in the several GV rigidity range and moves slowly to higher rigidities with increasing modulation strength. The most effective rigidity range is 3 - 10 GV.

The standard NM count rate can be calculated by integrating the differential response function above the geomagnetic rigidity cutoff:

$$N_{st}(\Phi, P_c) = \int_{P_c}^{\infty} R(P, \Phi) \cdot dP \quad (7)$$

The resulting standard NM count rates are shown in Fig. 3 as a function of the modulation strength Φ and the local geomagnetic rigidity cutoff P_c. Note that the profile of N_{st} at a fixed Φ is similar as given by the geomagnetic latitude survey of cosmic ray intensity (e.g., Moraal et al. (1989)). The count rate of a given NM can be easily calculated from N_{st} as

$$N(\Phi, P_c, x) = N_{st}(\Phi, P_c) \cdot S \cdot h(x) \quad (8)$$

where S is the number of (NM-64) counters, $h(x)$ accounts for the atmospheric depth of the NM site if different from the sea-level.

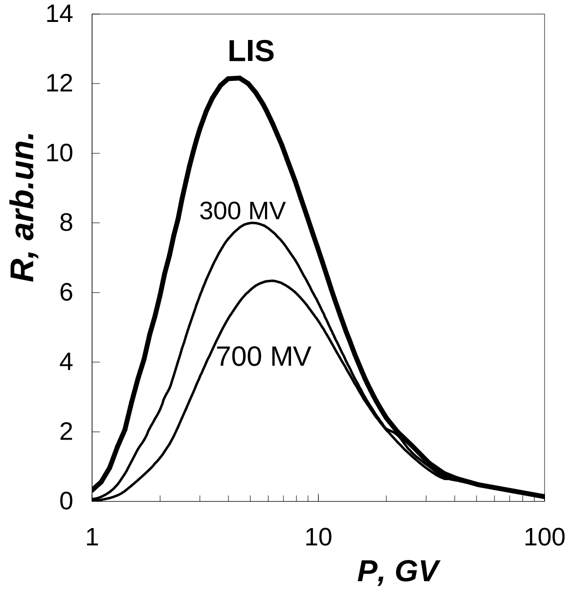

Fig. 2. Differential response function, R (in arbitrary units), of the standard NM to CR for different modulation strengths Φ.

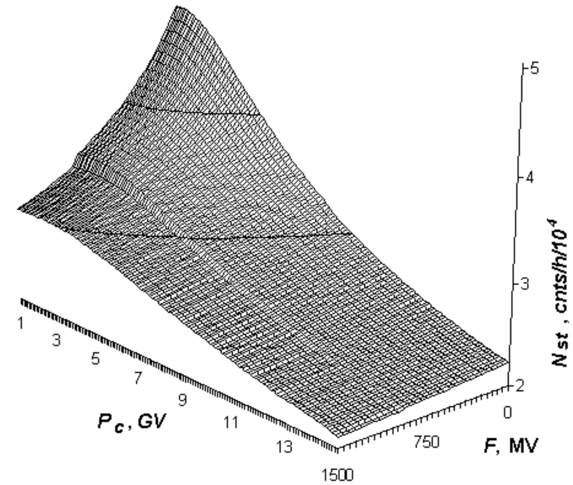

Fig. 3. Differential response function, R (in arbitrary units), of the standard NM to CR for different modulation strengths Φ.

4 Reconstruction of modulation strength

Equation 7 can be numerically inverted so that one can estimate the value of modulation strength Φ on the basis of the measured NM count rates. For a fixed P_c, there is a single-valued functional relation between N_{st} and Φ (see Fig. 3). Using the results of calculations presented above, we fitted a third-order polynomial approximation for the modulation strength as a function of the NM count rate for different values of the geomagnetic rigidity cutoff. E.g., the relation for the high latitude Oulu NM ($P_c \approx 0.8\ GV$) is, within the range of Φ from 0 to 1500 MV:

$$\Phi = -65.23N^3 + 106.3N^2 - 60.99N + 12.08 \qquad (9)$$

where Φ is expressed in GV, and N - in 10^5counts/(h counter). Using the long-term record of Oulu NM count rates, we estimated the time profile of the modulation strength over the last decades (see Fig. 4). Similarly we estimated the time profile of Φ for the mid-latitude Hermanus NM ($P_c \approx 4.7\ GV$), also shown in Fig. 4. One can see that the two estimates of the modulation strength as reconstructed from Oulu and Hermanus count rates are quite close to each other. Similar results for the modulation strength are not so consistent for equatorial stations with the rigidity cutoff above 10 GV, since their count rates are determined by the very tail of the differential response function (Fig. 2), and have only a small variation over the 11-year cycle.

5 Concluding remarks

The reconstructed annual modulation strengths Φ shown in Fig. 4 depict a clear 11-year cycle which varies from the minimum of about 280 (260) MV in 1965 to the maximum of 880 (960) MV in 1990-1991, according to Oulu (Hermanus) records. We note that our reconstruction is in a good agreement with the values of Φ reported for some years in literature: $\Phi \approx 350$ MV and ≈ 750 MV for 1977 and 1992, respectively (see, e.g., Labrador and Mewaldt (1997)). Although the employed model of the heliosphere is very simple (spherically symmetric, quasi-steady state), it suits well for the long-term studies, even for low-energy cosmic rays, and the reconstructed profiles of the modulation strengths are similar for different NMs. Some difference exists because of the simplicity of the model and uncertainties related to the yield function (Pyle, 1997; Belov and Struminsky, 1997), geomagnetic cutoff (Cooke et al., 1991), impact of obliquely incident particles (Clem et al., 1997), heavier species of GCR, etc. We still note that, since the modulation strength parameter is defined for a diffusion-convection driven heliospheric modulation, our calculations do not include drifts or transient phenomena.

Concluding, we have presented and used a method to estimate the modulation strength from the NM count rates. We have reconstructed the annual values of the modulation strengths for the neutron monitor era using data from the high-latitude Oulu and mid-latitude Hermanus NMs. We have shown that the reconstructed modulation strengths Φ are close to the earlier estimates reported in the literature for some years. The new method allows to obtain a rough but quick-and-easy estimate of the modulation strength without employing complicated additional computations or an extensive analysis of satellite data.

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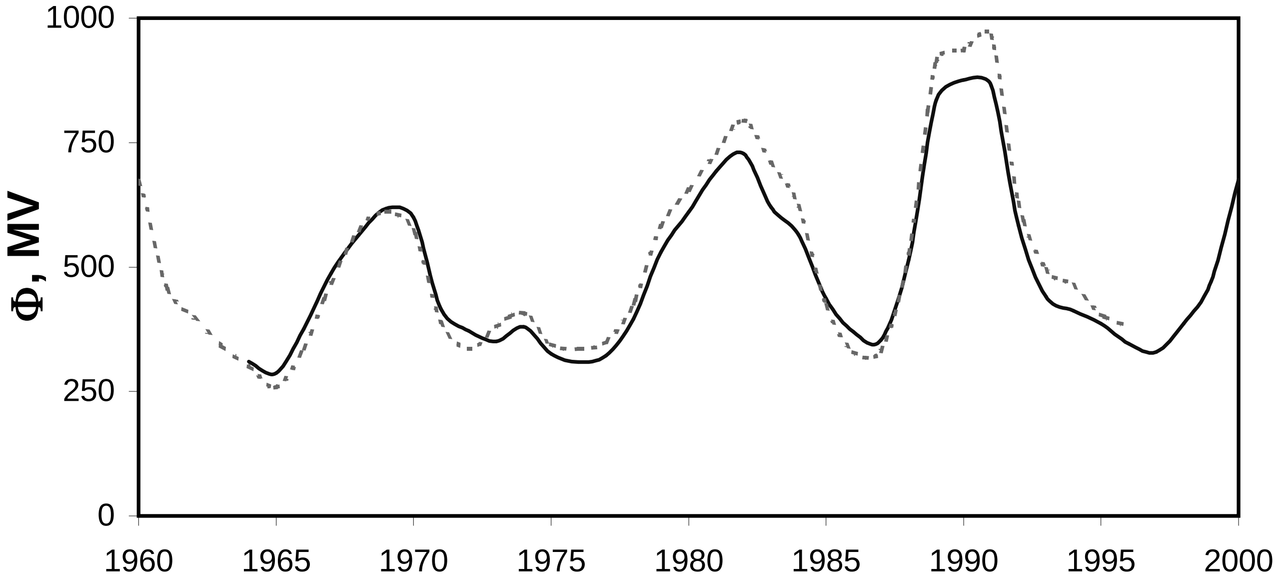

Fig. 4. The level of modulation strengths Φ reconstructed from Oulu (solid curve) and Hermanus (dotted curve) NM data.

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