HELIOSPHERIC MODULATION STRENGTH DURING THE NEUTRON MONITOR ERA

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Abstract. Using a stochastic simulation of a one-dimensional 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. Finally, inverting this relation, we calculate the modulation strength using the actually recorded neutron monitor count rates. We present the reconstructed annual heliospheric modulation strengths for the neutron monitor era (1953–2000) using several neutron monitors from different latitudes, covering a large range of geomagnetic rigidity cutoffs from polar to equatorial regions. The estimated modulation strengths are shown to be in good agreement with the corresponding estimates reported earlier for some years.

1. Introduction

Neutron monitors (NMs) have been in routine operation since the early 1950s. The NM count rates vary in time with the 11-year solar cycle due to changes in the heliospheric modulation of galactic cosmic rays (CR). 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 using a 1-D model.

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

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

where x and P_c are the atmospheric depth and the geomagnetic rigidity cutoff of the NM location, $G(P, t)$ is the CR rigidity spectrum in the Earth's vicinity (i.e., after modulation) at time t, and $Y(P, x)$ is the specific yield function which accounts

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for the propagation of CR 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

$$G(P,t) = \int_{P}^{\infty} G_{\rm LIS}(P_0) M(P_0, P, t)\, \mathrm{d}P_0, \tag{2}$$

where $G_{\rm LIS}(P_0)$ is the local interstellar spectrum (LIS) outside the heliosphere, i.e., before heliospheric modulation, and $M(P_0, P, t)$ is the modulation function which gives the probability of a CR particle with initial rigidity P_0 to be found in the Earth's vicinity with rigidity P at time t. In our study, we require that $\int M(P_0, P, t)\, \mathrm{d}P \leq 1$ (particles cannot be created or multiplied in the heliosphere) and $P < P_0$ (particles lose energy due to modulation but do not gain energy inside the heliosphere). Here we consider only modulation of galactic CR. Anomalous and solar CR are beyond the scope of this study.

The only time-dependent part in Equations (1) and (2) is the modulation function $M(P_0, P, t)$. A commonly used parameter of heliospheric modulation is the modulation strength Φ (Gleeson and Axford, 1968) which is defined in a spherically symmetric and steady-state case for the Earth's orbit and constant V as follows:

$$\Phi = \int_{r_E}^{D} \frac{V}{3\kappa_0}\, \mathrm{d}r = \frac{(D - r_E)V}{3\kappa_0}, \tag{3}$$

where D is the heliospheric boundary, $r_E = 1$ AU, V and κ_0 are the solar wind velocity and the diffusion coefficient. Although very useful for theoretical considerations, the direct evaluation of the modulation strength is not easy in practice. However, indirectly, one can calculate the modulated spectra $G(P, \Phi)$ for a set of fixed values of Φ within the framework of a heliospheric model. Then, using Equation (1) one can estimate $\Phi(t)$ from the observed NM count rates $N(P_c, x, t)$. Finally, we note that the theory of 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, e.g., Belov, 2000, and references therein) also play a role in the variation of NM count rates. However, even neglecting the latter effects, a rough estimate of the overall heliospheric state and the effective modulation strength can be found from NM count rates under the above assumptions (see, e.g., O'Brien and Burke, 1973).

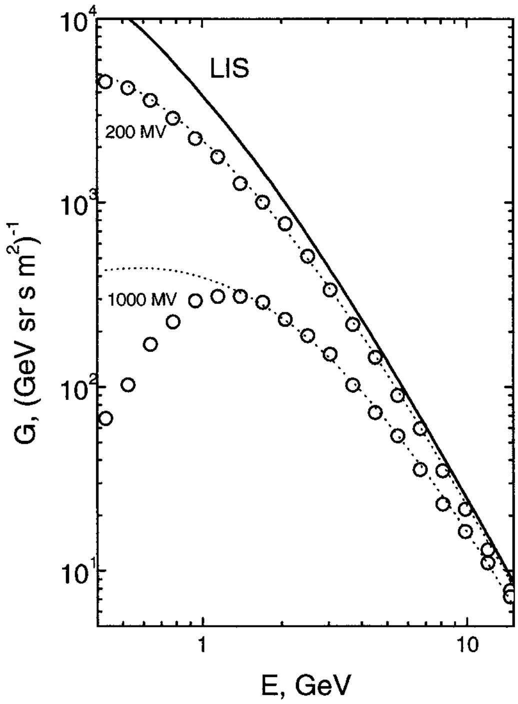

Figure 1. Differential energy spectra of galactic CR at the Earth's orbit for the modulation strength $\Phi = 200$ and 1000 MV (as denoted near the curves) calculated using the stochastic simulation method (*open circles*) and using the force-field approximation (*dashed lines*). The *solid curve* (marked as LIS) denotes LIS of GCR ($\Phi = 0$).

2. Heliospheric Modulation of Galactic CR

2.1. Stochastic simulation

Modulated CR spectra at the Earth's orbit can be calculated by solving numerically the Fokker–Plank equation of GCR transport in the heliosphere (Parker, 1965) which can be written in the spherically symmetric quasi-steady form as

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial U}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2VU) + \frac{1}{3}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2V)\right)\left(\frac{\partial}{\partial T}(\alpha TU)\right) = 0, \quad (4)$$

where $U(r, T, t)$ is the cosmic-ray number density per unit interval with kinetic energy T per nucleon, $\alpha = (T + 2 \cdot T_r)/(T + T_r)$, and T_r is proton's rest energy. In this study, we make use of the stochastic simulation method. This method has been introduced and described in detail by Gervasi *et al.* (1999) and Gervasi, Rancoita, and Usoskin (1999). The method is based on the equivalence between Fokker–Planck equations and stochastic differential equations (Gardiner, 1985; van Kampen, 1992). According to the stochastic simulation method, Equation (4) can be solved by tracing the test particle's orbit. At each small time step Δt, the corresponding changes in the particle's coordinate and energy are given as follows (Kocharov *et al.*, 1998):

$$\Delta T = -\frac{2}{3}\frac{V\alpha T}{r}\Delta t, \tag{5}$$

$$\Delta r = V\Delta t + \frac{1}{r^2}\frac{\mathrm{d}(\kappa r^2)}{\mathrm{d}r}\Delta t + G\sqrt{2\kappa\Delta t}, \tag{6}$$

where G is a Gaussian distributed random number with unit variance.

We have adopted the following model parameters: the size of heliosphere (termination shock) is 100 AU, and the solar wind is assumed to be radial with constant velocity of 400 km s^{-1}. The diffusion coefficient was taken in the form (see, e.g., Perko, 1987)

$$\kappa = \kappa_0\beta P, \quad P > P_c, \qquad \kappa = \kappa_0\beta P_c, \quad P < P_c, \tag{7}$$

and κ_0 was replaced by Φ according to Equation (3). The local interstellar spectrum of galactic CR as a function of rigidity is as follows (Burger, Potgieter, and Heber, 2000):

$$\begin{aligned} G_{\mathrm{LIS}}(P) = &\; 1.9\times 10^4 P^{-2.78}, \quad P \geq 7GV, \\ G_{\mathrm{LIS}}(P) = &\; \exp(9.472 - 1.999 \ln P - 0.6938(\ln P)^2 + \\ &\; + 0.2988(\ln P)^3 - 0.04714(\ln P)^4), \quad P < 7GV, \end{aligned} \tag{8}$$

where P is expressed in GV, and G_{LIS} in (GeV sr m^2 s)$^{-1}$. The resulting modulated energy spectra are shown in Figure 1 for different values of Φ, together with LIS ($\Phi = 0$ MV). For each spectrum we calculated one million test particles. (Note that there is an error in formula (2) of (Burger, Potgieter, and Heber, 2000) which is corrected in our Equation (8) (Burger and Potgieter, private communication).)

2.2. Force-field approximation

Under some simplifying assumptions, the basic transport Equation (4) can be reduced to the so-called force-field approximation form (Gleeson and Axford, 1968):

$$\frac{\partial U}{\partial r} + \frac{VP}{3\kappa}\frac{\partial U}{\partial P} = 0. \tag{9}$$

This approximation is valid (Fisk and Axford, 1969) if

$$\frac{r}{U}\frac{\partial U}{\partial r} \ll 1. \tag{10}$$

This partial differential Equation (9) can be solved analytically in the form of characteristic curves (see, e.g., Kamke, 1959; Boella *et al.*, 1998). Although the force-field approximation is good for weak heliospheric modulation and in the

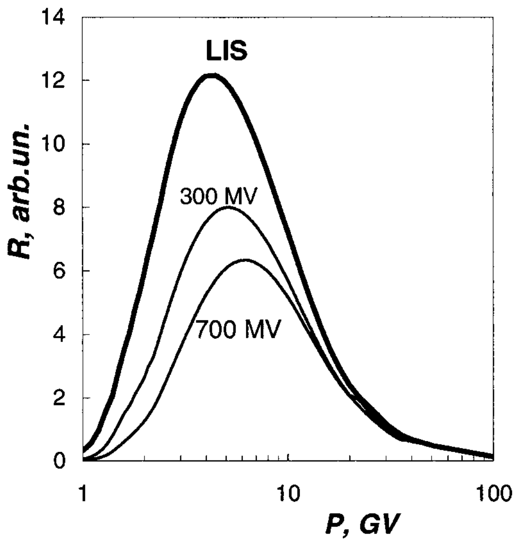

Figure 2. Differential response function R (in arbitrary units) of a standard NM for different modulation strengths Φ.

outer heliosphere, it overestimates the differential flux of low-energy cosmic rays at a strong modulation level because the validity condition (Equation (10)) breaks there. This is also seen in in Figure 1 as the difference between the force-field curve and the stochastic simulation curve for $\Phi = 1000$ MV at low rigidities.

3. Reconstruction of the Modulation Strength

Using the galactic CR spectra, $G(P, \Phi)$, and the specific yield function of a NM station, one can calculate the expected differential response function of a standard NM,

$$R(P, \Phi) = G(P, \Phi)Y(P). \tag{11}$$

(The standard NM is a 1-NM-64 neutron monitor at sea level.) Here we use the specific yield function $Y(P)$ as given by Debrunner, Flückiger, and Lockwood (1982) and modified in the high rigidity part by Nagashima *et al.* (1989). The response function is shown in Figure 2 for different values of Φ. Note that the response function at $\Phi = 0$ corresponds to the case of no heliosphere. One can see that the differential response function 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 rigidity range of several GV and moves slowly to higher rigidities with increasing modulation strength. The most effective rigidity range is 3–10 GV. We note that the calculated differential response function does not depict the 'cross-over' phenomenon in high

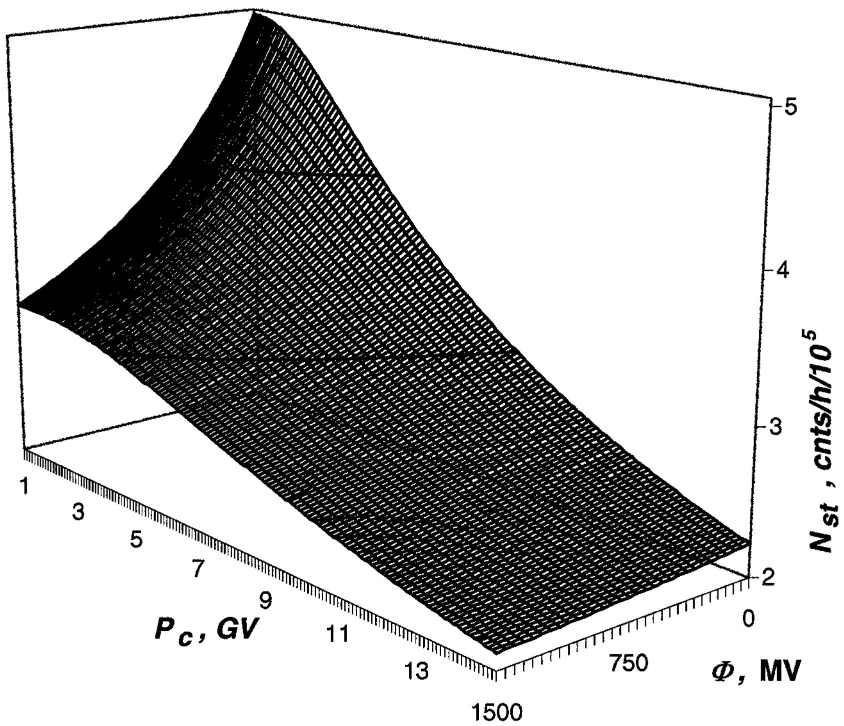

Figure 3. Calculated count rate of the standard NM as a function of modulation strength Φ and local geomagnetic rigidity cutoff P_c.

energies found in the latitudinal NM surveys (Moraal *et al.*, 1989; Popielawska and Simpson, 1990) since the latter is driven by the 22-year magnetic cycle and therefore cannot be reproduced in the frames of a spherically symmetric model.

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

$$N_{st}(\Phi, P_c) = \int_{P_c}^{\infty} R(P, \Phi)\, dP. \tag{12}$$

The resulting standard NM count rates are shown in Figure 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 to that given by the geomagnetic latitude survey of cosmic-ray intensity (see, e.g., Moraal *et al.*, 1989). The count rate of a given NM can then be easily calculated from N_{st} as follows:

$$N(\Phi, P_c, x) = N_{st}(\Phi, P_c) S_{\mathrm{NM64}} h(x), \tag{13}$$

where S is the number of NM-64 counters, and $h(x)$ accounts for the atmospheric depth of the NM site if different from the sea-level. If the NM is of IGY type, a special reduction factor should be applied (Usoskin *et al.*, 1997):

TABLE I

Location (geographical coordinates λ and ϕ and altitude h) and geomagnetic cutoff rigidity of neutron monitor stations as well as coefficients of Equation (15).

Name	ϕ	λ	h, m	P_c, GV	Type	A	B
Oulu	65.0	25.5	15	≈ 0.8	NM64	−933.6	2.324×10^4
Climax	39.4	253.8	3400	≈ 3	IGY	−1134	2.477×10^4
Rome	41.9	12.5	60	≈ 6.3	NM64	−2206	2.914×10^4
Huancayo	−12	284.7	3400	≈ 13	IGY	−8160	4.76×10^4

$$S_{\mathrm{NM64}} = S_{\mathrm{IGY}} R_{\mathrm{IGY}\rightarrow\mathrm{NM64}}. \tag{14}$$

Equations (12)–(14) can be numerically inverted so that one can estimate the value of modulation strength Φ on the basis of the measured NM count rate. For a fixed P_c, there is a single-valued functional relation between N_{st} and Φ (see Figure 3). Using the results of calculations presented above, we fitted the modulation strength for fixed P_c as a function of the NM count rate in the following approximate form:

$$\Phi = A + \frac{B}{N_{st}^2}, \tag{15}$$

where Φ is expressed in MV and N_{st} in 10^5 counts hr^{-1}. It gives an approximation of the Φ vs. N_{st} relation (Figure 3) within ± 10 MV for $P_c < 10$ GV and within $\pm$ 50 MV for $P_c > 10$ GV in the range of Φ from 100 to 1500 MV. Parameters A and B are shown for several selected NMs in Table I. These NMs cover a large cutoff rigidity range from polar to equatorial regions. Using the long-term records of selected NM count rates (Figure 4(a)), we have estimated the time profiles of the modulation strengths according to these stations over the last decades (see Figure 4(b)).

Using the results for the selected stations, we have calculated the weighted mean time profile of $\Phi(t)$ shown in Table II and in Figure 4(b). The values of Φ as calculated from the individual stations data are quite close to each other and to the mean value (within $\pm$ 50 MV) for all years except for 1989–1991. Only the values of Φ from the equatorial Huancayo station fluctuate sizably around the mean value. We note that the calculations are less reliable for this equatorial station ($P_c = 13$ GV) since its count rates are determined by the far tail of the differential response function (Figure 2), and have only a small variation of a few percent over the solar cycle (Figure 4(b)). This fact leads to larger uncertainties in the modulation strength reconstruction at Huancayo than all other stations. Note also that there is a clear rigidity cutoff dependence in 1989–1991. This period was characterized by a series of huge Forbush decreases which suppressed CR inten-

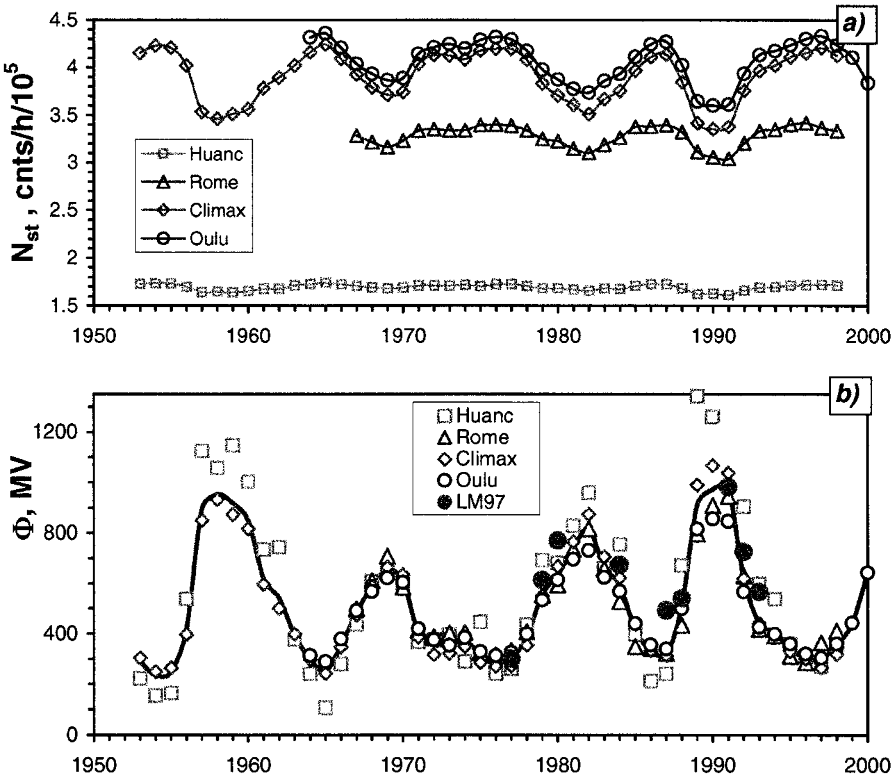

Figure 4. (a) NM count rates reduced to the standard observational conditions. (b) The modulation strength Φ as calculated from the NM data (*open symbols*) and as estimated by Labrador and Mewaldt (1997) (*filled circles*). The curve depicts the weight mean Φ (see Table II).

sity and distorted the 'normal' modulation evolution, leading to rigidity dependent modulation (Usoskin *et al.*, 1998).

4. Comparison with Other Results

There exist some earlier estimates of the modulation strength obtained for some years from directly observed cosmic ray spectra (see Labrador and Mewaldt, 1997, and references therein). These are shown as solid circles (LM97) in Figure 4(b). These estimates are fairly close to the values obtained here, supporting our way of reconstructing the modulation strength. Note in particular that the range of Φ between weak modulation in 1977 and strong modulation in 1991 is almost exactly the same for the two methods.

In order to further verify our method, we performed the following test. High-precision measurements of the CR energy spectrum have been performed by the *Alpha Magnetic Spectrometer* (AMS) experiment on board STS-91 Space Shuttle

TABLE II
The annually averaged modulation strength Φ in MV.

		1960	847	1970	610	1980	634	1990	971
		1961	619	1971	402	1981	739	1991	980
		1962	540	1972	357	1982	817	1992	623
1953	289	1963	394	1973	355	1983	663	1993	442
1954	233	1964	299	1974	369	1984	592	1994	405
1955	246	1965	251	1975	320	1985	417	1995	338
1956	420	1966	355	1976	292	1986	334	1996	305
1957	895	1967	482	1977	303	1987	319	1997	300
1958	953	1968	587	1978	387	1988	511	1998	356
1959	918	1969	656	1979	555	1989	911	1999	443
								2000	643

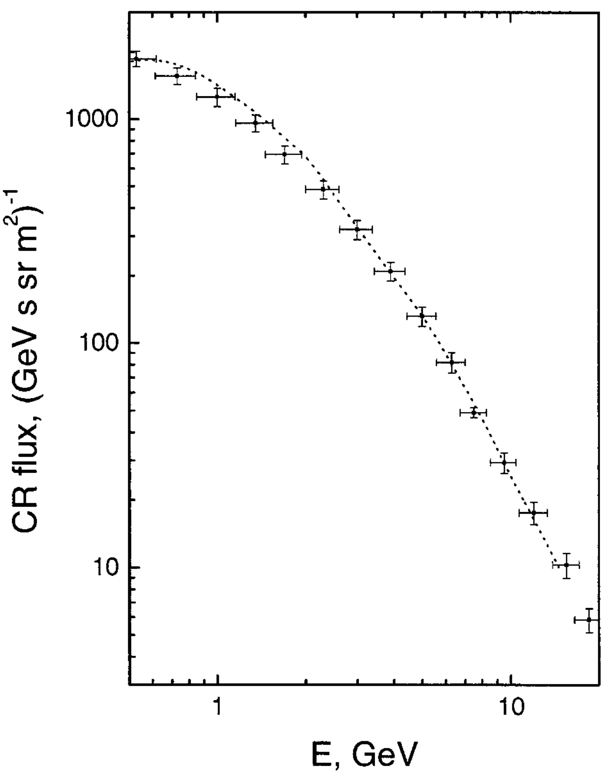

Figure 5. CR differential energy spectra in 1998. *Experimental points* correspond to measurements by AMS (Alcaraz *et al.*, 2000). *Dotted line* depicts our stochastic simulation model for $\Phi = 350$ MV.

'Discovery' flight in June 1998 (Alcaraz *et al.*, 2000). Our reconstruction predicts a value of $\Phi = 356$ MV for the year 1998. Figure 5 shows both the actual CR proton spectrum (as recorded by AMS) and the calculated CR spectrum according to our model for $\Phi = 350$ MV. The two spectra are in very good agreement, giving further support for the model.

We note that some earlier estimations of the modulation strength (see, e.g., Masarik and Beer, 1999) using the force-field approximation give systematically higher values of Φ during periods with strong modulation. This is due to the fact that the force-field approach overestimates CR flux in the lower energy range during medium to strong modulation strength as discussed in Section 2.2 and shown in Figure 1.

5. Conclusions

The reconstructed annual modulation strengths Φ shown in Figure 4 depict a clear 11-year cycle which varies from the minimum of about 230 MV in 1954 to the maximum of 980 MV in 1991. We estimate the uncertainties in the reconstructed annual values of Φ to be within $\pm$ 50 MV except for years 1989–1991 where the uncertainties are about ± 100 MV. We note that our reconstructions are in good agreement with the values of Φ obtained earlier for some years (Labrador and Mewaltd, 1997). We have also verified that the modeled CR spectrum agrees well with the actual cosmic proton spectrum measured in June 1998 by the AMS experiment (Alcaraz *et al.*, 2000). Although the employed model of the heliosphere is quite simple, it is well suited for long-term studies even at low-latitude cosmic ray stations. Moreover, the reconstructed profiles of modulation strengths are extremely similar for different NMs. Some uncertainty in the reconstruction strength may arise from the simplicity of the model, from uncertainties related to the yield function (Pyle, 1997; Belov and Struminsky, 1997) and to the geomagnetic rigidity cutoff (Cooke *et al.*, 1991), from the impact of obliquely incident particles (Clem *et al.*, 1997), and from heavier species of GCR, etc. We note that, since the modulation strength 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 several NMs covering a large range of geomagnetic rigidity cutoffs. We have shown that the reconstructed modulation strengths Φ are close to the experimental estimates reported earlier for some years.

Acknowledgements

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References

Alcaraz, J. *et al.* (AMS collaboration): 2000, *Phys. Lett.* **B490**, 27.

Belov, A. V.: 2000, *Space Sci. Rev.* **93,** 79.

Belov, A. V. and Struminsky, B.: 1997, *Proc. 25 Int. Cosmic Ray Conf.*, Durban **3**, 201.

Boella G., Gervasi, M., Potenza, M. A. C., Rancoita, P. G., and Usoskin, I.: 1998, *Astropart. Phys.* **9**, 261.

Burger, R. A., Potgieter, M. S., and Heber, B.: 2000, *J. Geophys. Res.* **105**, 27447.

Clem, J. M., Beiber, J. W., Evenson, P. *et al.*: 1997, *J. Geophys. Res.* **102**, 26919.

Clem, J. M. and Dorman, L. I.: 2000, *Space Sci. Rev.* **93,** 335.

Cooke D. J., Humble, J. E., Smart, M. A., Smart, D. F., and Lund, N.: 1991, *Nuovo Cimento*, **14C**, 213.

Debrunner, H., Flueckiger, E., and Lockwood, J. A.: 1982, *8th Europ. Cosmic Ray Symp., Rome* **13**, 1982.

Fisk, L. A. and Axford, W. I.: 1969, *J. Geophys. Res.* **74**, 4973.

Gardiner, G. W.: 1985, *Handbook of Stochastic Methods*, Springer-Verlag, Berlin.

Gervasi, M., Rancoita, P. G., and Usoskin, I. G.: 1999, *Proc. 26th Intern. Cosmic Ray Conf. Salt Lake City* **7**, 69.

Gervasi, M., Rancoita, P. G., Usoskin, I. G., and Kovaltsov, G. A.: 1999, *Nucl. Phys. B, Proc. Suppl.* **78**, 26.

Gleeson, L. J. and Axford, W. I.: 1968, *Astrophys. J.* **154**, 1011.

Kamke, E.: 1959, *Differentialgleichungen, Losungsmethoden und Losungen*, Akademische Verlag, Geest and Portig, Leipzig.

Kocharov, L., Vainio, R., Kovaltsov, G. A., and Torsti, J.: 1998, *Solar Phys.* **182**, 195.

Labrador, A. W. and Mewaldt, R. A.: 1997, *Astrophys. J.* **480**, 371.

Masarik, J. and Beer, J.: 1999, *J. Geophys. Res.* **104**, 12099.

Moraal, H., Potgieter, M. S., Stoker, P. H., and van der Walt, A.J.: 1989, *J. Geophys. Res.* **94**, 1459.

Nagashima, K., Sakakibara, S., Murakami, K., and Morishita, I.: 1989, *Nuovo Cimento* **12**, 173.

O'Brien, K. and de P. Burke, G.: 1973, *J. Geophys. Res.* **78**, 3013.

Parker, E. N.: 1965, *Planetary Space Sci.* **13**, 9.

Perko, J. S.: 1987, *Astron. Astrophys.* **184**, 119.

Popielawska, B. and Simpson, J. A.: 1990, in S. Grzeszielski and D. E. Page (eds.), *Physics of the Outer Heliosphere*, Pergamon Press, Oxford, p. 133.

Pyle, K. R.: 1997, *Proc. 25 Int. Cosmic Ray Conf., Durban* **2**, 197.

Usoskin, I. G., Kovaltsov, G. A., Kananen, H., and Tanskanen, P.: 1997, *Ann. Geophys.* **15**, 375.

Usoskin, I. G., Kananen, H., Kovaltsov, G. A., Mursula, K., and Tanskanen, P.: 1998, *J. Geophys. Res.* **103**, 9567.

van Kampen, N. G.: 1992, *Stochastic Processes in Physics and Chemistry*, 2nd ed., North-Holland, Amsterdam.