SENSITIVITY OF A NEUTRON MONITOR TO GALACTIC COSMIC RAYS

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ABSTRACT

We studied the sensitivity of a neutron monitor to Galactic cosmic rays depending on energy of cosmic ray particles in the interstellar medium. This is important for studying of the interstellar spectrum of cosmic rays and details of solar modulation by means of the world neutron monitor network. We calculated the expected response of a standard sea-level neutron monitor vs. energy of cosmic ray particles. First, we studied modulation of a monoenergetic flux of cosmic rays. Then the specific atmospheric yield function of a neutron monitor was applied to the calculated flux of cosmic rays at the Earth's orbit. The obtained response function, being convoluted with the model interstellar spectrum of cosmic rays, gives a maximum of neutron monitor sensitivity at around several GV of rigidity of cosmic ray particles. We performed calculations for weak ($\Phi = 350$ MV) and medium ($\Phi = 750$ MV) modulation strength. A normalisation of neutron monitor count rate is suggested which can give an experimental measure of the overall solar modulation of cosmic rays.

INTRODUCTION

The World Network of Neutron Monitor consists of many stations located around the Globe at various geographical locations and altitudes. Therefore, there is a problem of comparison of different neutron monitor (NM) count rates with each other. In order to compare different observational results, responses of a NM to cosmic rays (CR) should be normalized in the same way. Since it is difficult to compare absolute values of NM count rates, usually responses of NM to CR are given in percent to a certain reference level of the count rate. For the study of long-term CR variations it is common to use the monthly count rate of a NM during May 1965 as the 100% reference level. May 1965 was considered to be the month of minimum solar modulation of CR. This approach does not depend on the current level of solar activity and is seemingly time independent. However, there is a problem of the reference level definition for stations which were not in operation in May 1965. Moreover, characteristics (location, number and type of counters, readout electronics, etc.) of some stations have been changed through the years. Therefore, in order to study the parameters of CR modulation from NM count rates one should account for a set of correction factors accumulated for the NM during more than 30 years. This means that the usual normalization indirectly varies with time or, in other words, is only quasi time-independent.

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[1] deceased in March 2000

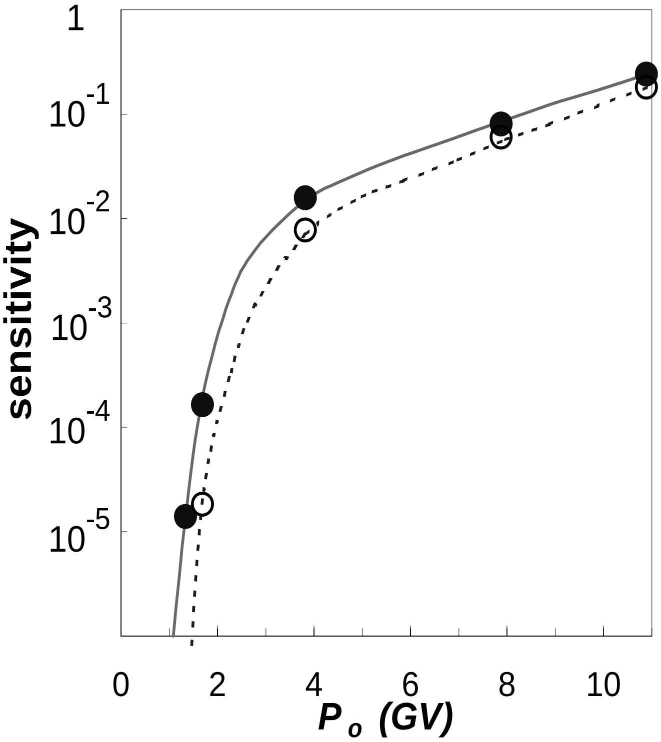

Fig. 1. Sensitivity of a sea-level NM to GCR for weak (dark circles and solid line) and medium (open circles and dashed line) modulation vs. the initial rigidity of GCR particles.

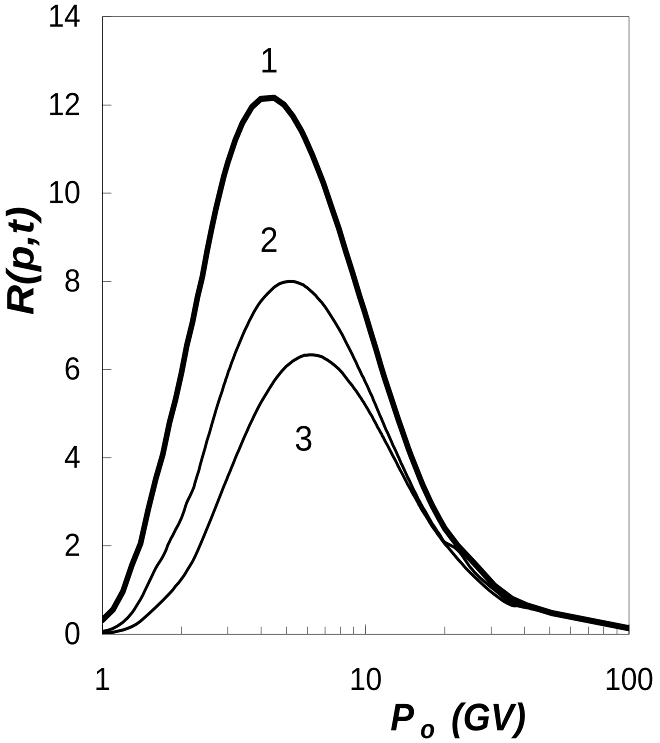

Fig. 2. Differential response function, R (in arbitrary units), of a sea-level NM to CR for unmodulated GCR (line 1), weak (2) and medium (3) modulation.

In a review paper, Nagashima et al. (1989) studied the differential response function of NM to GCR, $R(p,x,t)$, where p,x,t denote rigidity of particle, atmospheric depth of NM location and time, respectively. They considered that $R(p,x,t)$ consists of three parts: the spectrum of GCR outside the heliosphere, $G(p)$; a solar modulation function, $M(p,t)$; the specific yield function, $Y(p,x)$, which accounts for propagation of GCR particles in the Earth's atmosphere and detection of secondary nucleons. Nagashima et al. (1989) assumed the isotropic distribution of CR near the Earth and time constant geomagnetic cut-off. These assumptions are not crucial for the study of long-term variations of CR. Within this approach, only the modulation function, $M(p,t)$, is time-dependent. Therefore, one can untangle the time-dependent part of NM response from the time constant part.

In the present paper we suggest a real time-independent technique for the normalization of NM response to CR. This normalisation refers to the response of NM to unmodulated flux of GCR.

SENSITIVITY OF NEUTRON MONITOR TO GCR

Neutron monitor can effectively register neutrons of atmospheric nucleon cascade initiated by CR particles with rigidity on the top of the atmosphere, p, above some GV (Nagashima et al., 1989, and references therein). In this Section we study the sensitivity of NM to GCR vs. the initial rigidity of GCR, p_o (i.e. rigidity of partciles outside the Heliosphere). We use the following definition of this sensitivity, substituting the interstellar GCR spectrum $G(p)$ by δ-function:

$$S(p_o,x,t) = \int \delta(p' - p_o) M(p',p,t) Y(p,x) dp = \int_0^{p_o} M(p_o,p,t) Y(p,x), dp \tag{1}$$

where p and p_o is rigidity of the CR particle in the Earth's vicinity (i.e. after the modulation) and outside the Heliosphere (i.e. before modulation), respectively, and $M(p_o,p,t)$ is the modulation function. This modulation function gives the probability of a CR particle with initial rigidity p_o to be found in the Earth's vicinity with rigidity p. Note that, in our approach, it should be always that $\int M(p_o, p, t)dp < 1$ (particles cannot be created or multiplied in the Heliosphere) and $p < p_o$ (particles lose energy due to the modulation but cannot gain energy inside the Heliosphere). This modulation function was discussed by, e.g., Labrador and Mewaldt (1997), Gervasi et al. (1999). Here we consider only modulation of GCR. Anomalous and solar CR are beyond the scope of this study. The function $S(p_o, x, t)$ is then obtained by convolution of the modulation function with the specific yield function $Y(p, x)$. We used the modulation function as calculated in our recent paper (Gervasi et al., 1999) for two modulation regimes: weak modulation (modulation strength (Gleeson and Axford, 1968) Φ=350 MV) and medium modulation (Φ=750 MV). These two values of the modulation strength approximately correspond to the heliospheric conditions in the years 1977 and 1992, respectively (Labrador and Mewaldt, 1997). The specific yield function of NM, $Y(p, x)$ was taken from Debrunner et al. (1982) for the rigidity range below 20 GV and extended to higher rigidities according to Nagashima et al. (1989). We consider a sea-level ($x = 1033\ \mathrm{g \cdot cm^{-2}}$) NM with one counter of NM64 type, throughout the paper. Correspondingly we omit the variable x in the equations below unless specifically mentioned. Figure 1 shows the resulting sensitivity function S for the two modulation regimes. One can see that the function has rather sharp decrease at rigidity of primary CR about 1.5-2 GV. Thus, a NM is sensitive to primary (interstellar) CR with rigidity above few GV.

The differential response function of a NM to GCR can then be defined as:

$$R(p_o, t) = G(p_o) \cdot S(p_o, t) \tag{2}$$

The interstellar spectrum of GCR was taken according to Webber and Potgieter (1989). The resulting differential response function is shown in Figure 2 for the weak and medium modulation regimes as well as for a case when there is no modulation ($M(p', p, t) = \delta(p' - p)$). One can see that response of NM most effectively corresponds to GCR flux in the rigidity range from few GV to some 20-30 GV. The maximum of the differential response function slightly moves to higher rigidities with increasing the modulation strength because less energetic particles are modulated stronger.

NORMALISATION OF NM COUNT RATE

NM is an energy integrating device, and therefore its count rate can be written as follows:

$$N(P_c, t) = \int_{P_c} R(p, t) \cdot dp \tag{3}$$

where P_c is the local geomagnetic cut-off and $R(p, t)$ is the differential response function of NM (Eq. 2). Usually $N(P_c, t)$ is normalised per $N(P_c, t_o)$, where t_o is May 1965.

Let us consider the response function of NM as if there was no modulation (line 1 in Figure 2), R_o. The corresponding NM count rate is then (similarly to Eq. 3):

$$N_o(P_c) = \int_{P_c} R_o(p) \cdot dp \tag{4}$$

Assuming that P_c is constant in time, one can see that N_o is time-independent. We suggest to use N_o as the 100% reference level for NM count rate (see also, Usoskin et al., 1999). The normalized NM response

$$\Pi(P_c, t) \equiv N(P_c, t)/N_o(P_c) \tag{5}$$

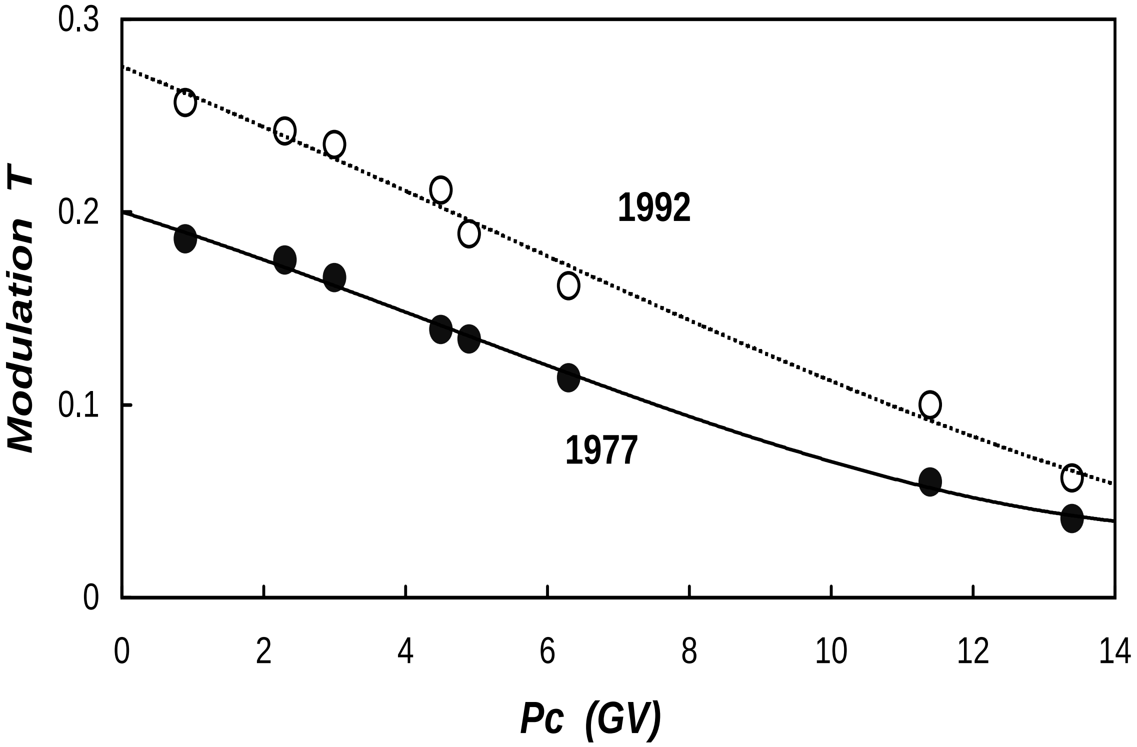

Fig. 3. Modulation efficiency, T, vs. geomagnetic cut-off rigidity for weak modulation in 1977 (solid line, filled circles) and for medium modulation in 1992 (dotted line, open circles). Points correspond to Table 1.

is a rigidity integrated measure of the solar modulation of GCR. It shows what part of GCR particles with rigidity above P_c has been "survived" after passing through the heliosphere. The value of Π is by definition below 100% and values close to 100% correspond to weak modulations. Correspondingly, we call the value of $T(P_c, t) = 1 - \Pi(P_c, t) = (N_o(P_c) - N(P_c, t))/N_o(Pc)$ as the momentary modulation efficiency. Although the value of T is connected to the modulation strength, it has different meaning. The modulation strength reflects the state of the heliosphere and is used for solution of the transport equation of GCR in the heliosphere. The normalised response Π, and hence the modulation efficiency T, is an empirical value. Therefore, a comparison of the actually obtained values of T with model calculations might allow for testing and calibration of model calculations. On the other hand, the normalised response can be used for estimation of the momentary solar modulation of GCR obtained directly from observations.

In order to minimise possible uncertainties (ones of the yield function (Pyle, 1997, Belov and Struminsky, 1997) and geomagnetic cut-off (Cooke et al., 1991), impact of obliquely incident particles (Clem et al., 1997), heavier spices of GCR, different altitude of NM's location etc.), we perform a "calibration" of the calculated count rate, $N(P_c, x, t)$. We calculated, using Eq. 3, the value of $N(P_c, x, 1977)$ for the year 1977 (weak modulation), for a number of NMs, using the corresponding spectrum of CR at the Earth's orbit as calculated for 1977 by Gervasi et al. (1999) (see also Labrador and Mewaldt, 1997). The calculated expected count rate was compared to the actually recorded one, averaged over the year of 1977. Then, using this calibration as a correction factor, we calculated the normalization count rate $N_o(P_c, x)$ for the NM.

Table 1 gives an example of our approach. The values of Π are shown for different NMs for the weak (1977) and medium (1992) modulation. The set of NMs in Table 1 represents cosmic ray stations located from the sea level up to high mountains and from polar to equatorial regions.

Table 1. Solar Modulation Measure, Π, as Derived from NM Count Rate

NM	Oulu	Kiel	Climax	Jungfrauj.	Hermanus	Rome*	Mt.Norikura*	Huancayo
Altitude (m)	15	54	3400	3550	26	60	2770	3400
P_c ,GV	0.9	2.3	3.0	4.5	4.9	6.3	11.4	13.4
$\Pi(P_c, 1977)$	0.814	0.825	0.834	0.861	0.866	0.886	0.94	0.959
$\Pi(P_c, 1992)$	0.743	0.758	0.764	0.789	0.811	0.838	0.90	0.938

*Characteristics have been changed between 1977 and 1992.

Figure 3 shows the momentary modulation efficiency T vs. geomagnetic cutoff for weak (1977) and medium modulation (1992). Both the modulation efficiency and difference between weak and medium modulation become smaller for higher rigidities.

CONCLUDING REMARKS

In the present work we suggest a new approach to the normalization of NM response to GCR. The usual normalization approach is only seemingly time-independent. We suggest a real time-independent function as the reference normalization count rate of a NM. This is the NM's response to the model unmodulated flux of GCR or, in other words, the expected count rate as if there was no solar modulation of GCR. A comparison of the actually recorded count rate of a NM with the calculated time-independent normalization count rate provides one with an observationally obtained true-of-date integral measure of the current level of solar modulation of GCR at NM energies. Note that we deal with long-term variations of CR deteremined by the global heliospheric modulation. Short-term variations caused by local transient phenomena, solar CR, anomalous CR, etc. are not considered here.

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REFERENCES

Belov, A.V., and B. Struminsky, Neutron Monitor Sensitivity to Primary Protons below 3 GeV Derived from Data of Ground Level Events, in *Proc. 25 Intern. Cosmic Ray Conf.*, Durban, **3**, 201-204, 1997.

Clem, J. M, J.W. Beiber, P. Evenson D. Hall, J.E. Humble, and M. Duldig, Contribution of Obliquely Incident Particles to Neutron Monitor Counting Rate *J. Geophys. Res.*, **102(A12)**, 26919-26926, 1997.

Cooke, D.J., J.E. Humble, M.A. Smart, D.F. Smart, and N. Lund, On Cosmic-Ray Cut-off Terminology, *Nuovo Cimento*, **14C**, 213-234, 1991.

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

Gervasi, M., P.G. Rancoita, I.G. Usoskin, and G.A. Kovaltsov, Monte-Carlo approach to Galactic Cosmic Ray propagation in the Heliosphere, *Nucl. Phys. B, Proc. Suppl.*, **78**, 26-31, 1999.

Gleeson, L.J., W.I. Axford, Solar Modulation of Galactic Cosmic Rays, *Astrophys. J.*, **154**, 1011-

1026, 1968

Labrador, A.W., and R.A. Mewaldt, Effects of Solar Modulation on the Low-Energy Cosmic-Ray Antiproton/Proton Ratio *Astrophys. J.*, **480**, 371-376, 1997.

Nagashima, K., S. Sakakibara, K. Murakami, and I. Morishita, Response and Yield Functions of Neutron Monitor, Galactic Cosmic Ray Spectrum and Its Solar Modulation, Derived from All The Available World-Wide Surveys, *Nuovo Cimento*, **12(C2)**, 173-209, 1989.

Pyle, K.R., Neutron Monitor Sensitivity to Solar Modulation Changes: Altitude vs. Cutoff Rigidity, in *Proc. 25 Intern. Cosmic Ray Conf.*, Durban, **2**, 197-200, 1997.

Usoskin, I.G., O.G. Gladysheva, P. Bobik, K. Kudela, and H. Kananen, Connections between Neutron Monitor Count Rate and Solar Modulation Strength, *Czech. J. Phys.*, **49**, 1743-1750, 1999.

Webber, W.R., and M.S. Potgieter, A new calculation of the cosmic-ray antiproton spectrum in the Galaxy and heliospheric modulation effects on this spectrum using a drift plus wavy current sheet model, *Astrophys. J.*, **344**, 779-785, 1989.