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HELIOSPHERIC MODULATION STRENGTH: EFFECTIVE NEUTRON MONITOR ENERGY

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

[1]*Department of Physical Sciences, P.O.Box 3000, FIN-90014 University of Oulu, Finlan*
[2]*Sodankylä Geophysical Observatory (Oulu unit), FIN-90014 University of Oulu, Finland*
[3]*Ioffe Physical-Technical Institute, 194021, St.Petersburg, Russia*

ABSTRACT

The widely used concept of the neutron monitor energy range is not well defined. Also, the median energy of a neutron monitor varies in the course of the solar cycle. Here we present a new concept of the effective energy of cosmic rays as measured by neutron monitors. Using a spherically-symmetric model of the heliospheric transport of cosmic rays and the specific yield function of a neutron monitor, we show that there is such an effective energy that the count rate of a given neutron monitor is directly proportional to the flux of cosmic rays with energy above this effective energy, irrespectively of the phase of the solar cycle. The new concept of the effective energy allows to regard the neutron monitor count rate as a direct measurement of the galactic cosmic ray flux with energy above this value. The effective energy varies from about 6 GeV for polar up to about 50 GeV for equatorial stations (e.g., it is about 6.5 GeV for high-latitude Oulu, 8 GeV for mid-latitude Climax and 40 GeV for equatorial Huancayo NM).

INTRODUCTION

The data of the world-wide network of neutron monitors (NMs) provide a good, stable and consistent data set of routine galactic cosmic ray (GCR) intensities for more than 50 years. However, a NM is an integral device measuring all cosmic rays above a certain energy (local geomagnetic or atmospheric rigidity cutoff) with a yield function increasing sharply with energy. Therefore, it is not straightforward what is the effective energy of cosmic rays as measured by NM. Usually, the term "neutron monitor energy range" is used for the energy range between the local geomagnetic cutoff and the energy of about 100 GeV or even higher. Neither this nor other used concepts (e.g., median energy of a NM discussed below) are well defined.

In this paper, we introduce a concept of the effective energy of a NM, E_{eff}, so that the count rate of a given neutron monitor is directly proportional to the flux of cosmic rays with energy above this effective energy, irrespectively of the phase of solar cycle. The new concept allows to regard the NM count rate as a direct measurement of the GCR flux above this energy. In other words, variations of NM count rate directly correspond to variations of the GCR flux above this effective energy.

NEUTRON MONITOR DIFFERENTIAL RESPONSE FUNCTION

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

$$N(P_c, x, t) = \int_{P_c}^{\infty} G(T,t) \cdot Y(T,x) \cdot dT \qquad (1)$$

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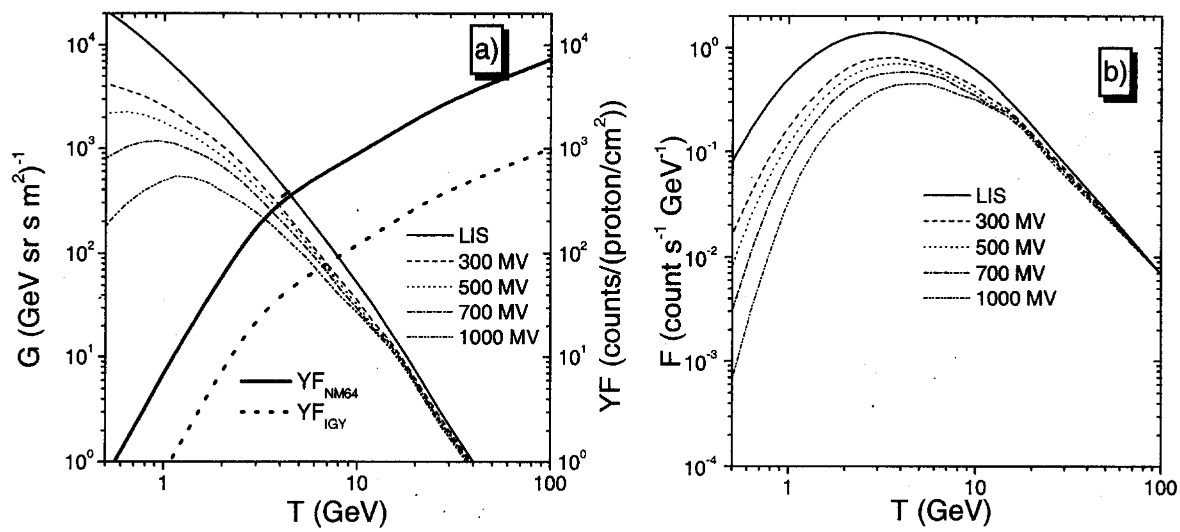

Fig. 1. a) Differential proton spectra G at the Earth's orbit for different values of the modulation strength Φ as denoted in the legend. The specific yield functions are shown by thick lines (right axis) for two type of neutron monitors, NM64 (YF_{NM64}) and IGY (YF_{IGY}), at the sea level for vertically incident primary protons. b) Differential response function of the standard neutron monitor (1-NM64 at the sea-level) to cosmic rays for different values of the modulation strength.

where x and P_c are the atmospheric depth and the geomagnetic rigidity cutoff of the NM location, $G(T,t)$ is the differential CR energy spectrum in the Earth's vicinity (i.e., after modulation) at time t, T is the particle's kinetic energy and $Y(T,x)$ is the NM's specific yield function which accounts for the development of an atmospheric nucleon cascade and the detection of secondary nucleons (Nagashima et al., 1989; Clem and Dorman, 2000). The modulated CR spectrum can be presented as

$$G(T,t) \doteq \int_T^{\infty} G_{LIS}(T_o) \cdot M(T_o,T,t) \cdot dT_o, \tag{2}$$

where $G_{LIS}(T_o)$ is the local interstellar spectrum (LIS) outside the heliosphere, i.e., before heliospheric modulation, and $M(T_o,T,t)$ is the modulation function which gives the probability distribution function of a CR particle with initial kinetic energy T_o to be found in the Earth's vicinity with kinetic energy T at time t. In our study, we require that $\int M(T_o,T,t)dT \leq 1$ (particles cannot be created or multiplied in the heliosphere) and $T < T_o$ (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.

A significant fraction of GCR (about 6% of particle number or 25% of nucleon number) is composed of heavier species, mostly α-particles according to, e.g., high-precision cosmic ray measurements by the AMS space (Alcaraz et al., 2000; 2000a) or CAPRICE balloon (Boezio et al., 1999) experiments. However, our model considers only protons, i.e., it substitutes heavier species by the corresponding (nucleonic) number of protons with the same kinetic energy per nucleon, which is important for the development of a secondary nucleon cascade in the atmosphere. Heavier species are generally less modulated in the heliosphere because of their higher rigidity for the same energy per nucleon, which makes the real GCR spectrum slightly different from the model proton spectrum. Nonetheless, this modification is small since the direct measurements of cosmic He and protons at the Earth's orbit (Boezio et al., 1999; Alcaraz et al., 2000, 2000a) show that the difference in differential spectra between protons and a more realistic composition is only about 10% at low energies (about 1 GeV/nucleon) and less than 1% at high energies (10 GeV/nucleon), and the difference is negligibly small for integral spectra above 6 GeV which is important for NM count rates. Accordingly, we

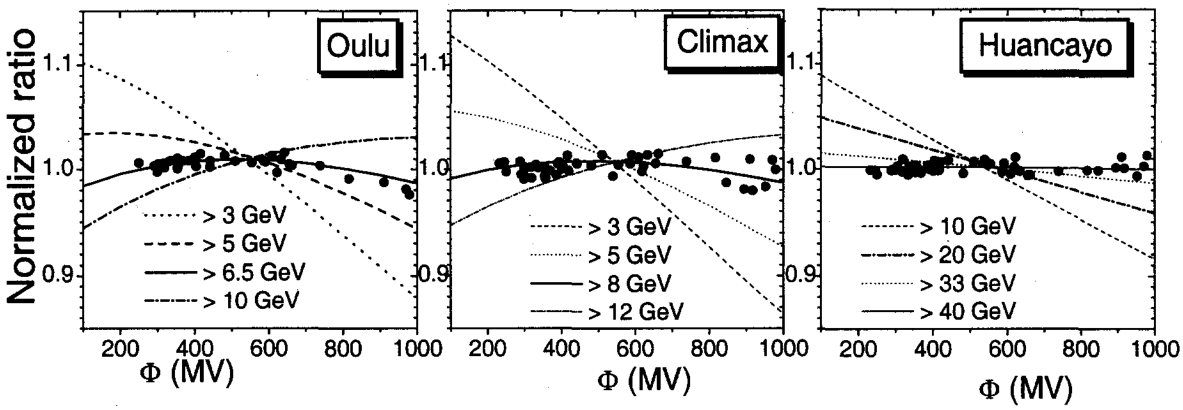

Fig. 2. Normalized ratios of the model calculated flux of GCR with energy above E_{eff} (as denoted in the legend) to the response of a neutron monitor, as a function of the modulation strength Φ. Lines correspond to model calculations of the NM response, and dots correspond to the actual NM annual count rates. The neutron monitors are: Oulu (sea-level NM64, $P_c = 0.8$ GV), Climax (mountain IGY, $P_c \approx 3$ GV) and Huancayo (mountain IGY, $P_c \approx 13$ GV).

neglect here the difference between realistic and proton spectra.

The only time-dependent part in Eqs. 1-2 is the modulation function $M(T_o, T, t)$. A commonly used parameter of heliospheric modulation is the modulation strength Φ given in units of MV (Gleeson and Axford, 1968) which is defined in a spherically symmetric case for the Earth's orbit and constant V as follows

$$\Phi = \int_{r_E}^{D} \frac{V}{3\kappa_o}\, dr = \frac{(D - r_E)V}{3\kappa_o}, \tag{3}$$

where D = 100 AU is the heliospheric boundary (termination shock), r_E = 1 AU, V is the solar wind velocity and κ_o is the (constant part of the) diffusion coefficient. Within the solar cycle, the modulation strength varies from the minimum of about 200 MV to maximum of about 1000 MV (Usoskin et al., 2002). The value of $\Phi = 0$ MV corresponds to the unmodulated LIS spectrum.

In order to calculate modulated differential spectra of GCR at 1 AU, we have used a spherically-symmetric model of the heliospheric transport of GCR (Gervasi et al., 1999; Usoskin et al., 2002). This model solves the 1D quasi-steady state transport equation of GCR in the heliosphere by a stochastic simulation method which is based on the equivalence between Fokker-Planck equations and stochastic differential equations (e.g., Van Kampen, 1992). The transport equation is solved by tracing test particle orbits in the guiding center approximation, and it was proven to be a reliable tool to study cosmic ray variations on the time scale of one year and longer (Usoskin et al., 2002, 2002a). Fig. 1a depicts the calculated differential proton spectra $G(T)$ at the Earth's orbit for different values of the modulation strength. The unmodulated spectrum (LIS) was taken from Burger et al. (2000). (Note that there is a typo in formula (2) of Burger et al., 2000, and $\ln P$ should be taken instead of P; Burger and Potgieter, personal communication, 2000).

Here we used the specific yield functions for the two basic types of neutron monitors, IGY and NM64 (see Fig. 1a) as given by Clem and Dorman (2000). The product of the two curves in Fig. 1a (the modulated spectrum and the specific yield function) forms the differential response function of NM which is the integrand of Eq. 1 (see also Clem and Dorman, 2000; Moraal et al., 2000). This differential response function $F(T) = G(T) \cdot Y(T)$ is shown in Fig. 1b for different values of the modulation strength Φ. One can see that the differential response function varies over the solar cycle. The peak energy changes by a factor of two between about 3 GeV (solar minimum, Φ =250 MV) and 6 GeV (solar maximum, Φ = 1000 MV). Sometimes, the median energy (which halves the integral of Eq. 1) is regarded as the effective energy of NM (e.g., Ahluwalia and Dorman, 1994). However, the median energy is also changing quite significantly over the solar cycle.

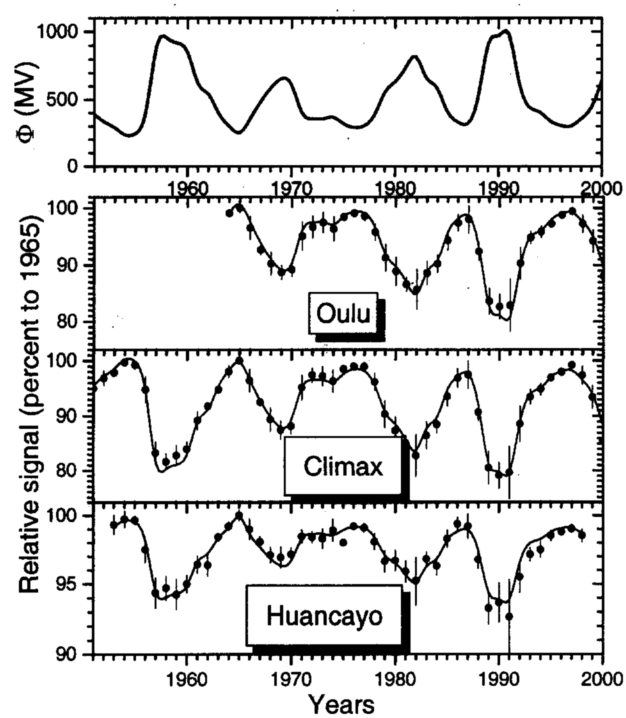

Fig. 3. Top panel: Annual modulations strength Φ. Lower panels: Actual annual count rates of Oulu, Climax and Huancayo NMs (dots) and the calculated GCR flux with energy above 6.5 GeV, 8 GeV and 40 GeV, respectively, at the Earth's orbit (curve), in percent to the values in 1965. Error bars represent fluctuations of monthly values around the annual mean.

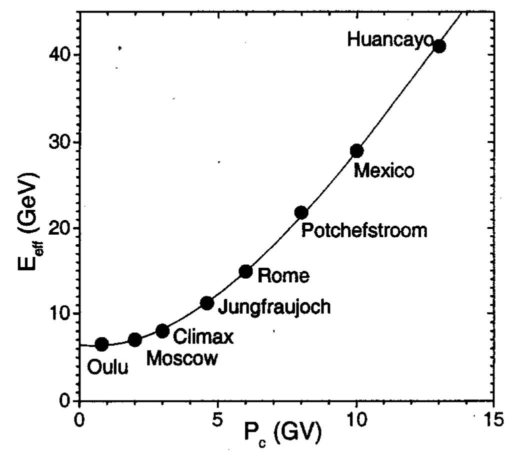

Fig. 4. The effective energy of a neutron monitor as a function of the geomagnetic rigidity cutoff. Dots correspond to some neutron monitors around the Globe (see Table 1).

E.g., the median energy for Oulu NM (P_c =0.8 GV) changes from about 9 GeV during solar minimum to about 14 GeV at solar maximum. The corresponding variations of the median energy for Climax NM (P_c =3 GV) are from 10 GeV to about 15 GeV.

EFFECTIVE ENERGY OF NEUTRON MONITOR

Let us define the flux of cosmic protons above a given energy E as

$$J(>E,\Phi) = \int_E^\infty G(T,\Phi)dT \tag{4}$$

Now we are looking for such an effective energy E_{eff} that the GCR flux above this energy is directly proportional to the NM count rate $N(P_c, x, \Phi)$ in the wide range of modulation strength Φ from 100 MV to 1000 MV:

$$J(>E_{eff}) \propto N(P_c). \tag{5}$$

In order to study this quantitatively, we form the ratio R of the proton flux to the expected NM count rate (calculated using Eq. 1) as a function of the modulation strength Φ:

$$R(E_{eff}, P_c, \Phi) = \frac{J(>E_{eff},\Phi)}{N(P_c,\Phi)} \tag{6}$$

Table 1. The effective energy for some locations.

station	P_c, GV	E_{eff}, GeV
Oulu	0.8	6.5
Moscow	2	7
Climax	3	8
Jungfraujoch	4.5	10.5
Rome	6	15
Potchefstroom	7	18
Mexico	10	29
Huancayo	13	40
–	15	50

(We note that a similar approach has been used earlier to study the effective energy of solar neutrons as using data from the world network of neutron monitors; Usoskin et al., 1997). The ratio R was normalized so that its value averaged over Φ from 100 to 1000 MV is equal to 1. Plots of R as a function of Φ are shown in Fig. 2 for three neutron monitors, Oulu (P_c=0.8 GV, NM64), Climax (P_c =3 GV, IGY) and Huancayo (P_c=13 GV, IGY). Such a value of E_{eff} that minimizes the discrepancy

$$d(E_{eff}, P_c) = \sqrt{\frac{1}{n-1}\sum_{\Phi}(R(E_{eff}, P_c, \Phi) - 1)^2} \quad (7)$$

is called the effective energy of the neutron monitor. One can see in Fig. 2 that, e.g., the value E_{eff} = 8 GeV is such that the ratio is nearly constant (within 1%, d =0.007) for Climax NM in the given range of the modulation strength. Therefore, the Climax NM count rate is directly proportional to the flux of GCR with energy above E_{eff} = 8 GeV, irrespectively of the modulation strength. For all other values of E_{eff}, the ratio is not constant but varies over the solar cycle. Proper values of E_{eff} exist also for the other NMs (Fig. 2): 6.5 GeV for Oulu NM (d =0.009) and about 40 GeV for Huancayo NM (d =0.002). The E_{eff} values are summarized in Table 1 for some locations.

In order to verify the results, we have compared our calculations with the actually observed data. First we calculate the expected flux of cosmic protons $J(> E_{eff}, \Phi)$ using the above heliospheric model (Fig. 1a) and the recent reconstruction (Fig. 3, top panel) of annual values of the modulation strength during the neutron monitor era (Usoskin et al., 2002). Then we compare these calculated fluxes $J(> E_{eff}, \Phi)$ with the actual annual NM count rates. The comparison is shown in Fig. 3 for the above three neutron monitors. One can see from Figure 3 that there is a very good relation between the actual NM count rates and the calculated flux of GCR with energy above E_{eff} (the cross-correlation is better than 0.95 in all shown cases). The values of the ratio R with the actual NM count rates in the denominator (Eq. 6) are shown in Fig. 2 as dots which are in a good agreement with the theoretical calculations shown as lines. This further confirms the above calculation of E_{eff} and validates the used assumptions.

As seen in Table 1, the effective energy changes with the local geomagnetic rigidity cutoff P_c. We have calculated the dependence of E_{eff} on P_c for a range of P_c from high-latitude to equatorial locations (Fig. 4). The dependence can be approximated by the following formula within 2% accuracy:

$$E_{eff} = 6.4 + 1.45 \cdot P_c^{1.25}/(1 + 10 \cdot \exp(-0.45 \cdot P_c)) \quad (8)$$

where E_{eff} and P_c are given in GeV and GV, respectively.

CONCLUSIONS

We have calculated, using a spherically-symmetric model of the heliospheric transport of cosmic rays and the neutron monitor specific yield functions, the effective energy of cosmic rays as measured by neutron monitors. We have shown that, for each neutron monitor, there is such an effective energy E_{eff} that the count rate of this NM is directly proportional to the flux of cosmic rays with energy above E_{eff} at the Earth's orbit, irrespectively of the phase of the solar cycle. The new concept of the effective energy allows to regard the NM count rate as a direct measurement of the GCR flux with energy above E_{eff}. The effective energy varies from about 6 GeV for polar up to about 50 GeV for equatorial stations. E.g., E_{eff} is 6.5 GeV, 8 GeV and about 40 GeV for Oulu (P_c = 0.8 GV), Climax (P_c = 3 GV) and Huancayo (P_c = 13 GV) neutron monitors, respectively. The effective energies are shown in Table 1 for some other stations around the Globe.

Although our model includes some simplifying assumptions, its predictions of the effective energy for neutron monitors are confirmed by a comparison to the actual NM count rates, which validates the results presented here.

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REFERENCES

Ahluwalia, H. S., and L. I. Dorman, Transverse cosmic ray gradients in the heliosphere and the solar diurnal anisotropy, *J. Geophys. Res.,* **102,** 17433-17444, 1997.

Alcaraz, J., B. Alpat, G. Ambrosi, et al. (The AMS collaboration), Cosmic protons, *Phys. Lett. B,* **490**, 27-35, 2000.

Alcaraz, J., B. Alpat, G. Ambrosi, et al. (The AMS collaboration), Helium in near Earth orbit, *Phys. Lett. B,* **494**, 193-202, 2000a.

Burger, R. A., M. S. Potgieter, B. Heber, Rigidity dependence of cosmic ray proton latitudinal gradients measured by the Ulysses spacecraft: Implication for the diffusion tensor, *J. Geophys. Res.,* **105**, 27447–27455, 2000.

Boezio, M., P. Carlson, T. Francke, et al., The cosmic-ray proton and helium spectra between 0.4 and 200 GV, *Astrophys. J.,* **518**, 457–472, 1999.

Clem, J. M., L. I. Dorman, Neutron monitor response functions, *Space Sci. Rev.,* **93,** 335–359, 2000.

Gervasi M., P. G. Rancoita, I. G. Usoskin, 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., and W. I. Axford, Solar modulation of galactic cosmic rays, *Astrophys. J.,* **154**, 1011–1026, 1968.

Masarik, J., and J. Beer, Simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere, *J. Geophys. Res.,* **104**, 12099–12111, 1999.

Moraal, H., A. Belov and J. M. Clem, Design and co-ordination of multi-stational international neutron monitor network, *Space Sci. Res.,* **93**, 285–303, 2000.

Nagashima K., S. Sakakibara, K. Murakami, 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.

Usoskin, I. G., G. A. Kovaltsov, H. Kananen, P. Tanskanen, The world neutron monitor network as a tool for the study of solar neutrons, *Annales Geophysicae,* **15**, 4, 375–386, 1997.

Usoskin, I. G., K. Alanko, K. Mursula, G. A. Kovaltsov, Heliospheric modulation strength during the neutron monitor era, *Solar Phys.,* **207**, 389–399, 2002.

Usoskin, I. G., K. Mursula, S. Solanki, M. Schüssler, G. A. Kovaltsov, Physical reconstruction of cosmic ray intensity since 1610, *J. Geophys. Res.,* **107(A11)**, SSH 13-1–6, doi: 10.1029/2002JA009343, 2002a.

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

E-mail address of I. Usoskin: Ilya.Usoskin@oulu.fi

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