Effective Energy of Neutron Monitors

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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 measured by neutron monitors. Using a 1D model of the heliospheric transport of cosmic rays and the specific yield function of a neutron monitor, we show that there is such an energy value, here called the 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, irrespective of the phase of the solar cycle. The new concept of the effective energy allows to regard the count rate of each neutron monitor as a direct measurement of the galactic cosmic ray flux with energy above the effective energy specified for tha station. The effective energy varies from about 5.5 GeV for polar up to about 20 GeV for equatorial stations. The effective energy for the cosmogenic polar ^{10}Be and global ^{14}C production is about 1.3 GeV and 2.8 GeV, respectively.

The data of the world-wide network of neutron monitors (NMs) provide a good, stable and consistent data set of 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 the yield function increasing sharply with energy. Therefore, it is not clear what is the effective energy of cosmic rays as measured by NM. 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. In other words, variations of NM count rate directly correspond to variations of the GCR flux above this effective energy.

Neutron monitor 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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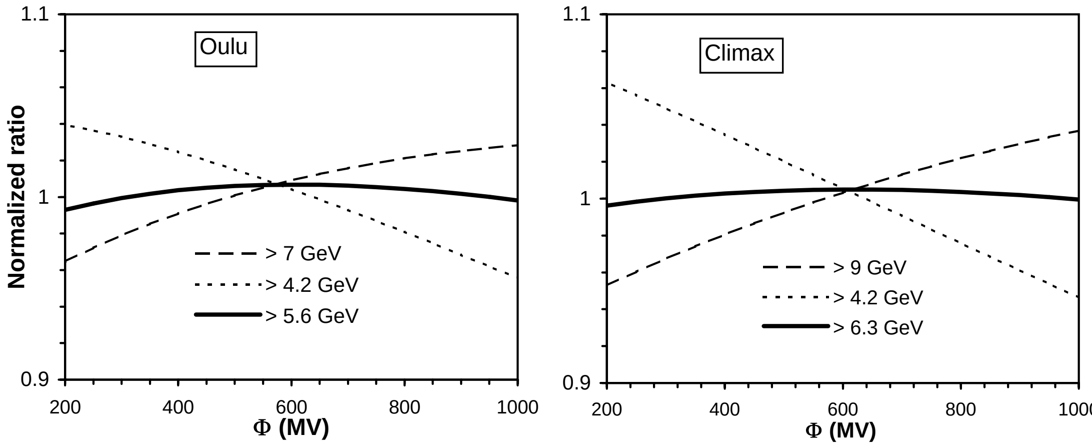

Fig. 1. Normalized ratios of the calculated GCR flux with energy above E_{eff} (as denoted in the legend) to the response of a neutron monitor, as a function of the modulation strength Φ for Oulu ($P_c = 0.8$ GV) and Climax ($P_c \approx 3$ GV).

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 at time t, T is the particle's kinetic energy and $Y(T,x)$ is the NM's specific yield function. In order to calculate GCR spectra we use a spherically symmetric quasi-steady stochastic simulation model described in detail elsewhere [8], which reliably describes the long-term GCR modulation rays during the last 50 years. In this model, the most important parameter of the heliospheric modulation of GCR is the modulation strength [5]: $\Phi = (D - r_E)V/(3\kappa_o)$, where $D = 100$ AU is the heliospheric boundary, $r_E = 1$ AU, $V = 400$ km/s is the constant solar wind velocity and κ_o is the rigidity independent part of the diffusion coefficient. We calculate the GCR spectrum at 1 AU for different values of the modulation strength Φ, using the local interstellar spectrum of GCR as given by [2]. In order to calculate the NM count rate we used the specific yield functions from [4]. In this study we accounted not only for cosmic protons but also for heavier GCR species (α-particles).

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: $J(> E_{eff}) \propto N(P_c)$. In order to study this quantitatively, we form the ratio R of the proton flux to the expected NM count rate (Eq. 1) as a function of the modulation strength Φ:

$$R(E_{eff}, P_c, \Phi) = J(> E_{eff}, \Phi)/N(P_c, \Phi) \qquad (2)$$

A similar approach has been used earlier to study the effective energy of solar neutrons [7]. Plots of normalized R as a function of Φ are shown in Fig. 1. for

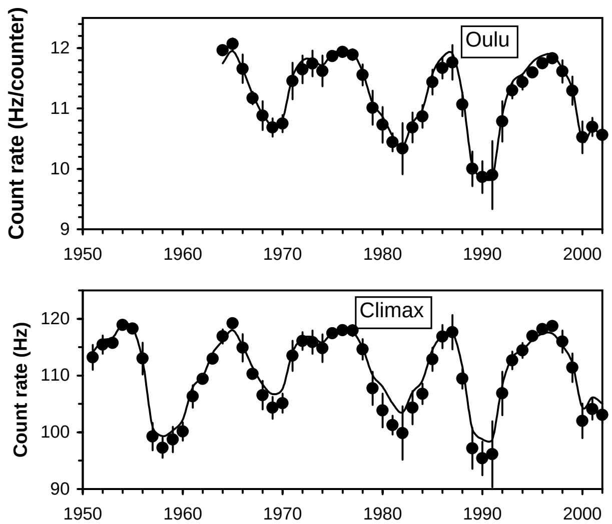

Fig. 2. Annual count rates of Oulu and Climax NMs. Dots denote the actual count rate with fluctuations of monthly values around the annual mean. Solid lines represent the calculated GCR flux ($> Eeff$) scaled to the NM count rate.

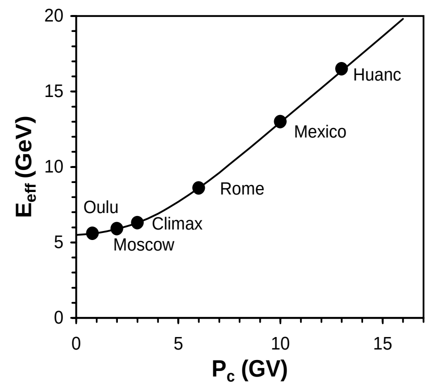

Fig. 3. The effective energy of a neutron monitor as a function of the geomagnetic rigidity cutoff. Dots correspond to some neutron monitors around the Globe.

two different NMs. Such a value of E_{eff} that minimizes the deviation

$$d = \sqrt{\frac{1}{n-1}\sum_{\Phi}(R-1)^2} \tag{3}$$

is called the effective energy of the neutron monitor. One can see in Fig. 1 that, e.g., the value $E_{eff} = 6.3$ GeV makes the ratio nearly constant (within 1%, d =0.003) 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 $E_{eff} = 6.3$ GeV, irrespectively of the modulation strength. For all other values of E_{eff}, the ratio varies over the solar cycle. Proper values of E_{eff} exist also for the other NMs (Fig. 3), e.g., it is 5.6 GeV for Oulu NM (d =0.004). The value of E_{eff} depends on the NM's geomagnetic cutoff (Fig. 3.), and it can be approximated by the following formula within 2% accuracy: $E_{eff} = 5.5 + 0.45 \cdot P_c^{1.25}/(1 + 4 \cdot \exp(-0.4 \cdot P_c))$, where E_{eff} and P_c are given in GeV and GV, respectively.

In order to verify our approach, we calculated the GCR flux $J(> E_{eff}, \Phi)$ using the values of Φ obtained recently for the last 50 years [8] and compared it with the actual annual NM count rates (Fig. 2.). The calculated $J(> E_{eff})$ is scaled to correspond to the NM count rate. The correlation between the actual

NM count rates and the calculated flux of GCR ($> E_{eff}$) is very good ($r > 0.99$ in all shown cases). The good agreement between modeled and observed values confirms the above calculation of E_{eff} and validates the used assumptions.

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. However, this term is not well-defined. E.g., the location of the peak of the differential response function (integrand of Eq. 1) changes by a factor of two between about 3 GeV (solar minimum) and 6 GeV (solar maximum) [8]. Sometimes, the median energy (which halves the integral of Eq. 1) is regarded as the effective energy of NM [6]. However, the median energy is also changing quite significantly over the solar cycle. On the other hand, for each NM, 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. This effective energy is a kind of an intrinsic quantity for a given NM. The effective energy varies from about 5.5 GeV for polar up to about 20 GeV for equatorial stations.

The above formalism can be applied also to the production of cosmogenic isotopes (^{10}Be and ^{14}C) in the atmosphere with the corresponding yield function used instead of the NM yield function. We repeated the above calculations using the yield functions for ^{10}Be [9] and ^{14}C [3] production in the atmosphere. We estimated the effective energy of ^{10}Be production in the polar atmosphere to be about 1.3 GeV. The effective energy of global ^{14}C production appears to be about 2.8 GeV. The effective energy of a NM is higher than the effective energy of cosmogenic isotope production. Therefore, caution should be taken when comparing signals from different kinds of cosmic ray detectors.

We thank the Academy of Finland for financial support.

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