CONNECTIONS BETWEEN NEUTRON MONITOR COUNT RATE AND SOLAR MODULATION STRENGTH

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We suggest a new approach to the normalisation of neutron monitor response to galactic cosmic rays. The reference normalisation count rate is the neutron monitor response to the model unmodulated flux of galactic cosmic rays. A comparison of the actually recorded neutron monitor count rate with the calculated normalisation count rate can provide one with an observationally obtained true-of-date integral measure of the current level of solar modulation of galactic cosmic rays.

1 Introduction

There is the World Network of Neutron Monitors developed for the study of Galactic Cosmic Rays (GCR) by means of detection of secondary atmospheric nucleons produced by GCR in the Earth's atmosphere. The Network consists of more than fifty stations located around the Globe at various geographical locations and altitudes. Therefore, there is a difficulty of comparison of different neutron monitor count rates with each other. Sometimes it is difficult to compare the results obtained by different groups without knowledge of the normalisation they used. Therefore, in order to compare different observational results the response of a neutron monitor (NM) to GCR should be normalised in the same way. As it is hard to compare absolute values of NM's count rates, usually responses of NM to CR are normalised in percent to a certain reference level of the count rate.

For the study of long-term variations of GCR it is usual to use the monthly averaged observed count rate of a certain 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 seems to be time independent. However, there is a problem of the reference level definition for stations which were not in operation in May 1965. Another problem of the approach is that the reference level is referred to the fixed time while the characteristics of a NM (number and type of counters, etc.) might be changed with time. Therefore, in order to study the real physical parameters of the GCR 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 normalisation indirectly varies with time or, in other words, is quasi time-independent.

In the present paper we suggest techniques for the normalisation of NM response to GCR which is really time independent because it refers to the response of NM to unmodulated flux of GCR which is assumed to be constant in time.

2 Solar modulation

In a large paper by Nagashima et al. [1] they consider, in details, the response of NM to GCR. Following that paper, one can present the differential response function of NM, $R(p,x,t)$, to consist of three parts: the spectrum of GCR outside the heliosphere, $G(p)$; the modulation function, $M(p,t)$, which accounts for the solar modulation of GCR flux in the heliosphere; the specific yield function, $Y(p,x)$, which accounts for propagation of GCR particles in the Earth's atmosphere and detection of secondary nucleons. Values of p,x,t denote rigidity of particle, atmospheric depth of NM location and time, respectively. Hereafter, when speaking on the yield function of NM we will mean a system consisting of the detector itself plus the Earth's atmosphere where the cascade of secondary nucleons is developed. Note that we assume (see also [1]) the angular distribution of GCR near the Earth to be isotropic and geomagnetic cut-off to be constant in time. These assumptions are not crucial for the study of long-term variations of CR.

One can see that all the three parts of the NM response function depend on particle rigidity(energy), and only the modulation function is time-dependent. Therefore, we can untangle the time-dependent part of NM response to GCR and the time constant part.

Since the solar modulation not only modulates the flux of GCR but also changes energy of particles due to adiabatic deceleration, the differential spectrum of CR near the Earth, $G_{\rm m}(p,t)$ can be written, in a simplified form, as

$$G_{\rm m}(p,t) = \int_p G(p')\, m(p,p',t)\, {\rm d}p', \tag{1}$$

where $m(p,p',t)$ is a function which connects the intensity of CR flux with rigidity p at the Earth's orbit at time t with the intensity of flux of particles with p' in the Galaxy (see [2,3]). In the present paper we do not put attention on the $m(p,p',t)$ function but rather make use of the modulated GCR spectra, $G_{\rm m}(p,t)$, as they have been recently calculated by Labrador and Mewaldt [2] for two certain periods: weak modulation (modulation strength [4] $\Phi = 350\,$MV which corresponds to the year 1977) and medium modulation ($\Phi = 750\,$MV which corresponds to the year 1992).

In Fig. 1 these modulated spectra are shown together with the unmodulated local interstellar GCR spectrum as given by Webber and Potgieter [5].

Since NM is an energy integrating device, we can write for the NM count rate

$$N(P_{\rm c},x,t) = \int_{P_{\rm c}} G_{\rm m}(p,t)\, Y(p,x)\, {\rm d}p. \tag{2}$$

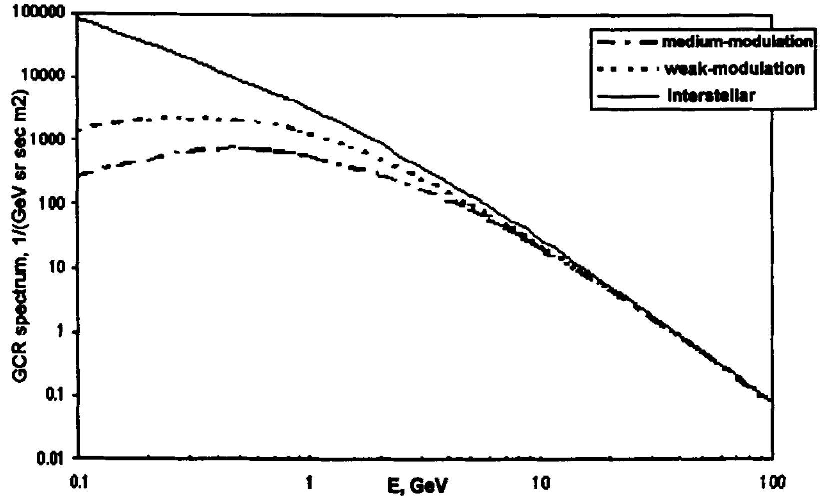

Fig. 1. Spectra of galactic cosmic rays: unmodulated local interstellar spectrum (solid line), spectra at the Earth's orbit for weak (dotted line) and medium (dash-dotted line) solar modulation of cosmic rays.

For the usual quasi time-independent normalisation (see Introduction) they normalise $N(P_c, x, t)$ per $N(P_c, x, t_0)$, where t_0 is May 1965.

Here we suggest really time-independent normalisation technique. Let us consider the value

$$N_r(P_c, x) = \int_{P_c} G(p)\, Y(p, x)\, \mathrm{d}p, \tag{3}$$

to be the reference level for the NM count rate. Generally speaking, N_r is the count rate of a certain NM as if there was no solar modulation of GCR. One can see that it is time-independent and the entire range of energy available for the NM is accounted for.

On the other hand, one can see from Eqs. (1–3) that the normalised NM response

$$\Pi(P_c, t) = \frac{N(P_c, x, t)}{N_r(P_c, x)} = \frac{\int_{P_c} Y(p, x)\, G_m(p)\, \mathrm{d}p}{\int_{P_c} Y(p, x)\, G(p)\, \mathrm{d}p}, \tag{4}$$

means an energy/rigidity integrated (above P_c) measure of the solar modulation of GCR. It shows what part of GCR with rigidity above P_c at the earth's orbit has been "survived" after passing through the heliosphere. The value of Π is always below 100% and values close to 100% correspond to weak modulation. Note that the normalised response Π is close to the energy integrated modulation function $M(p, t)$ of Nagashima et al. [1]. Although the value of Π is connected to the modulation strength, it has different meaning. The modulation strength [4] reflects the state of the heliosphere and is used for solution of the Parker equation of GCR transport in the heliosphere. The normalised response Π is an observational value dealing with no theoretical model of GCR propagation in the heliosphere. Therefore, a comparison of the actually obtained values of Π with model calculations might allow one to test and calibrate the calculation. On the other hand, the normalised response might be useful as an estimated measure of the momentary solar modulation of GCR directly from the actual observations.

3 Normalization of neutron monitor response

Let us consider the differential NM response function of a NM to GCR which is

$$R(p,x,t) = G_{\rm m}(p,t)\,Y(p,x). \tag{5}$$

For our calculations we make use of the NM response function, $Y(p,x)$, as given by Debrunner et al. [6] in the energy range below 20 GeV extended to the higher energy range according to Nagashima et al. [1]. The yield function of NM is shown in Fig. 2.

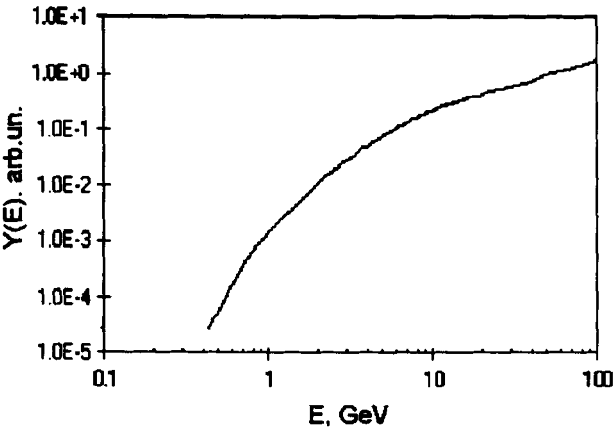

Fig. 2. Specific yield function used for calculations.

In Fig. 3, one can see the function $R(p,t)$ calculated for the sea-level station ($x = 1033\,\mathrm{g/cm^2}$) for the two modulated spectra of GCR (weak $\Phi = 350$ MV and medium $\Phi = 750$ MV modulation).

Figure 3 shows also the normalisation function $R_{\rm r}(p,t)$ which is an analogy of $R(p,x,t)$ for the unmodulated spectrum of GCR

$$R_{\rm r}(p,x) = G(p)\,Y(p,x). \tag{6}$$

One can see that though the yield function is rising with energy and the GCR spectra are rather steep, the differential response function has the maximum at several GeV of particle's kinetic energy (see also [1]). For the particle's energy above 20 GeV, all functions are the same.

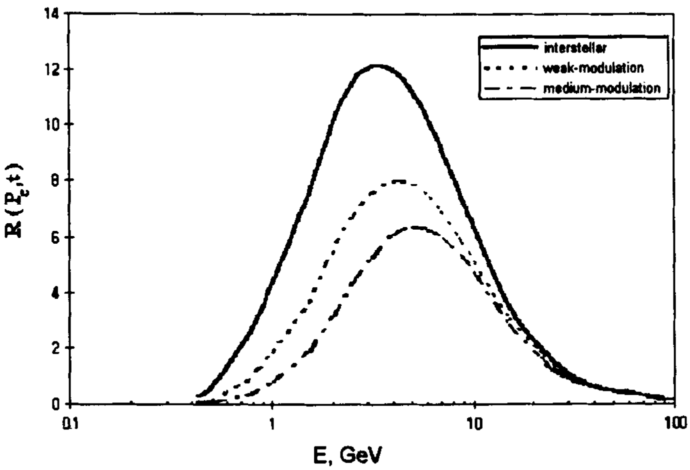

Fig. 3. Differential response function $R(p, t)$, for weak and medium modulation as well as for unmodulated spectra.

The normalisation count rate, $N_r(x)$ (see Eq. (3)), of NM can be obtained by means of integration of the function $R_r(p, x)$ over rigidity/energy for certain atmospheric depth x of the NM location using local geomagnetic cut-off rigidity as P_c in Eq. (3).

Note that the response of a NM $N(1033\,\mathrm{g/cm^2}, t_0, P_c)$ at the sea-level at certain time t_0 calculated using Eq. (2) for different geomagnetic cut-off rigidities, P_c, corresponds to an experimental latitude survey of cosmic ray intensity (*e.g.* [7–9]). Latitude survey is usually approximated with the Dorman function [10]

$$N = N_0\,(1 - \exp\,(-\alpha\, P_c^{-k})). \tag{7}$$

The rigidity dependence of the normalisation count rate (a latitude survey as if there was no solar modulation) is shown in Fig. 4 The best fit Dorman function for the normalisation count rate is ($N_0 = 5.17 \times 10^4$counts/hour/NM64, $\alpha = 9.0212$, $k = 1.0447$).

In order to minimise possible uncertainties (uncertainties of the yield function, *e.g.* [11,12]), impact of obliquely incident particles [9], heavier spices of GCR, different altitude of NM's location etc.), we perform a "calibration" of the calculated count rate, $N(x, t_o, P_c)$. For this purpose we calculated, using Eq. (2), the value of $N(x, 1977, P_c)$ for the weak modulation conditions occurred in the year 1977, for a number of NMs. The corresponding GCR spectrum at the Earth's orbit, $G_m(p, 1977)$ has been taken as calculated for 1977 in [1,2]. The calculated count rate has been compared and "calibrated" to the actually recorder count rate of NMs averaged over the year of 1977. Then, using this "calibration" as a correction factor, we calculate the normalisation count rate $N_r(x, P_c)$ for NM.

As an example of our approach, we calculated the normalisation count rates, N_r for a number of NMs operated in 1977. The corresponding solar modulation

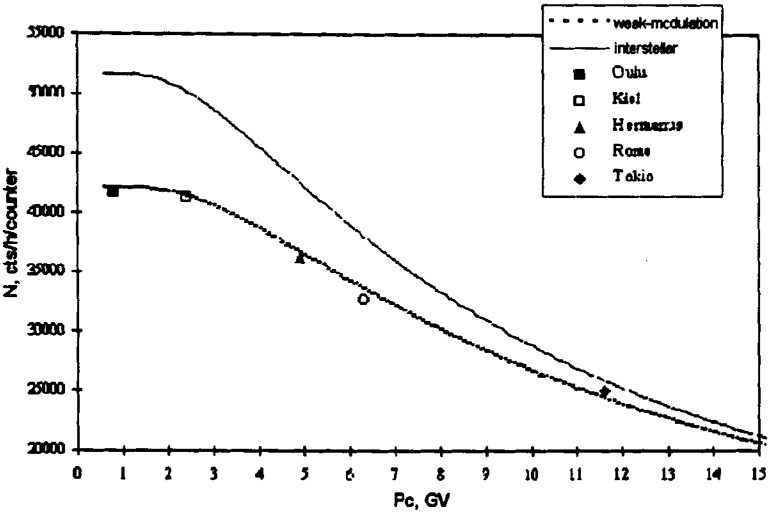

Fig. 4. Rigidity dependence of sea-level NM normalization count rate $N_R(P_c)$ and the best fit Dorman function (see text).

Table 1. Normalisation count rate for some neutron monitors.

Neutron	altitude (m)	P_c (GV)	modulation $\Pi(P_c, 1977)$
Inuvik	21	0.2	0.814
Oulu	15	0.8	0.814
Kerguelen	0	1.2	0.814
Durham	0	1.4	0.815
Kiel	54	2.3	0.825
Climax	3400	3.0	0.834
Jungfraujoch	3550	4.5	0.861
Hermanus	26	4.9	0.866
Rome	60	6.3	0.886
Mt.Norikura	2770	11.4	0.94
Huancayo	3400	13.4	0.959

strength, $\Pi(P_c, 1977)$ is shown in Table 1 together with parameters of the NMs (altitude and vertical geomagnetic cut-off rigidity, P_c).The set of NMs in Table 1 represents cosmic ray stations located from sea-level up to high mountains and from polar to equatorial regions. It is seen that for lower geomagnetic cut-off the modulation is stronger.

4 Concluding remarks

Concluding, in the present work we suggest a new approach to the normalisation of NM response to GCR. The usual normalisation approach seems to be time-independent, however, this time independence is obtained by "freezing" of a time-depending function (NM count rate) at some certain moment (May 1965). We suggest the really time-independent function as the reference normalisation count rate of a NM which 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 NM count rate (which depends on the current level of solar modulation of GCR) with the calculated time-independent normalisation count rate (which refers to the unmodulated flux of GCR) provides one with an observationally obtained true-of-date integral measure of the current level of solar modulation of GCR at NM energies.

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