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Atmospheric cutoff energies for cosmic rays registered by polar neutron monitors

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Similarly to the geomagnetic cutoff, which is the lower energy (rigidity) limit for charged particles that are able to pass the geomagnetic field and reach the Earth's atmosphere, there is the atmospheric cutoff. It represents the lower limit in energy for cosmic-ray particles propagating in the atmosphere, so that can be registered on the ground by, e.g., neutron monitors. The atmospheric cutoff was previously estimated at the sea level as about 1 GV in rigidity, which is approximately 430 MeV in energy for protons. We calculated the atmospheric cutoff value for energetic protons over the range of altitudes from about 3600 m to 0 m above sea level in polar regions, which corresponds to the depths from 600 to 1030 g/cm2, with: (a) Monte Carlo simulation of the cosmic ray cascade end (b) the altitude-dependent yield function of a standard neutron monitor 6NM64. The results agree with the earlier finding at sea level, though the yield function method shows more conservative, higher values of the cutoff compared to the cascade simulation method. It can be explained by the nature of the yield function, which takes into account the non-100% sensitivity of the detector to incident particles. Additionally, we calculated the effective atmospheric cutoff energies for two different conditions using the yield-function method, when only galactic cosmic rays are present, and when a strong solar energetic particle event occurred. In this work, the case of GLE#05 was considered, which occurred on 23 Feb 1953. The resulting cutoff values for protons detected by polar neutron monitors are presented. It is shown that a strong solar energetic particle event could result on a significantly lower effective atmospheric cutoff of a polar neutron monitor.

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1. Introduction

Neutron monitors (NM) are ground-based instruments that measure the variability of galactic cosmic rays (GCR) in time. However, they can detect also strong solar energetic particle (SEP) events called as ground-level enhancements (GLE) over the GCR background. Every NM location is characterised by geomagnetic and atmospheric cutoffs with regard to cosmic rays, these properties are different for different locations. The geomagnetic cutoff represents the lower energy (rigidity) limit for particles that are able to pass the geomagnetic field shielding and reach the Earth's atmosphere. The atmospheric cutoff represents the lower limit in energy for cosmic-ray particles propagating through the atmosphere, so that can be registered on the ground by, e.g., neutron monitors. The effective atmospheric cutoff has been previously estimated at sea level as around 1 GV in rigidity, i.e., approximately 430 MeV in energy for protons [e.g., 4]. Therefore, since the geomagnetic cutoff in the polar regions is usually lower than 1 GV, the lower-energy detection limit of polar neutron monitors is mainly defined by the atmospheric cutoff.

The energy of the effective atmospheric cutoff is expected to decrease with increasing altitude (decreasing depth). However, there were no computations regarding this property published for altitudes above sea level. This work provides those quantitative estimates, which turn out to be particularly important for evaluation of the sensitivity of high-altitude polar NM to moderately strong SEP events causing so-called sub-GLEs. Currently, there are two definitions of sub-GLE events given by Poluianov et al. [10] and Raukunen et al. [11], that look at those events from the points of view of observation by high-altitude polar NM and of registration of particles with energies > 300 MeV. The question of whether they contradict or agree with each other, is also addressed in this work.

2. Data and Methods

In this section, the employed methods are briefly presented. The detailed descriptions of the used data and methods are presented in Mishev and Poluianov [5], Poluianov and Batalla [9].

To calculate the effective atmospheric cutoff, two approaches were utilized: (a) Monte Carlo simulation of the atmospheric cascade induced by the incident cosmic-ray particles and (b) computation of the NM count rate by using an altitude-resolved yield function for a standard NM64 neutron monitor. For the Monte Carlo simulations, Geant4-based code PLANETOCOSMICS [2] was used. The incident particles were considered to be protons with isotropic and vertical angular distributions representing the two boundary different approaches during a SEP event. The kinetic energies for the protons were taken within 250–500 MeV, i.e., around the expected values of the atmospheric cutoff. Secondary neutrons were detected at different atmospheric depths from 600 g/cm^2 (about 3600 m above sea level (asl) in polar regions) up to 1033 g/cm^2 (sea level). The neutron detection threshold was set at 1 particle/(m^2 sr). It is important to note that this method does not take into account the efficiency of registration of secondary hadrons by a neutron monitor(s).

For the atmospheric cutoff calculation using the data about the NM response, the limited registration efficiency of the instrument was taken into account. Throughout this process, the altitude-resolved yield function developed by [8] was used. We calculated the total count rate of a standard 6NM64 neutron monitor at different altitudes, as well as the count rate contribution

$N_2(h, E_c)$ induced by low-energy protons under a certain energy threshold E_c. We assumed that this fraction can be indistinguishable due to the natural random noise in the NM signal, and evaluated the detection parameter as N_2/σ, where σ corresponds to the standard deviation of the total count rate. The detection threshold was defined from the atmospheric cutoff at sea level estimated with the Monte Carlo simulations [5], viz. 428 MeV, which agrees with other theoretical and experimental estimations of around 430 MeV [e.g., 3, 4]. Using the detection threshold and the parameter N_2/σ, we found the atmospheric cutoff values at different atmospheric depths h. The provided explanation above shows a brief summary, and we advice to read the full description of the method in Mishev and Poluianov [5], Poluianov and Batalla [9].

The atmospheric cutoff is sensitive to the assumed spectrum shape of incident particles, hence, three scenarios were considered: quiet solar conditions when only GCR are present and existing very strong and hard-spectrum SEP event (namely, GLE#05) in its prompt and delayed phases. We note that high or low solar modulation of GCR do not significantly affect the results. For the calculations, we used the GCR spectrum in the force-field approximation with the local interstellar spectrum of Vos and Potgieter [13]. The spectra of the prompt and delayed components of GLE#05 were taken from Vashenyuk et al. [12].

3. Results

The Monte Carlo simulation method showed that the isotropic angular distribution of cosmic rays provides higher atmospheric cutoff energies at all altitudes compared to the case of vertical incident particles. We took the isotropic case for further comparisons as more realistic [1, 6].

The resulting calculated effective atmospheric cutoff for different altitudes (depths) obtained with the Monte Carlo and NM count rate methods considering the"GCR-only" scenario, are shown in Figure 1. One can notice that the Monte Carlo method provides an estimate of the cutoff energy near the ground close to the known value of 430 MeV [4]. We cannot comment the sea-level cutoff with the NM count rate method because those calculations were based on the assumption that it is equal to 428 MeV taken from the Monte Carlo calculations. However, for higher altitudes (lower depths), one can see that the more conservative "instrumental" method, which takes into account imperfect registration of particles, shows notably higher cutoff energy values. We tend to think that the "instrumental" method based on the calculation of the NM count rate with the yield function is more conservative and realistic than the one with Monte Carlo simulations of the cascade.

We used the second "instrumental" method based on the NM count rates and calculated the atmospheric cutoff values for the conditions of absence of a SEP event, so-called "GCR-only" and also in the conditions of the strongest ever observed GLE#05 (23 February 1956) and for the list of existing, existed and proposed polar neutron monitors [7] with the geomagnetic cutoffs being under 1 GV, i.e., where the atmospheric cutoff can be dominant over the geomagnetic one. See the result atmospheric cutoff values for different scenarios shown in Table 1. The atmospheric cutoff for the "GCR-only" scenario for the neutron monitors is also shown in Figure 2. There we see that most of polar neutron monitors have the atmospheric cutoff around 410–430 MeV, while there are so-called high-altitude NM (altitude about 3000 m asl, depth 600–700 g/cm^2) with the cutoff being around 300–320 MeV, and also there is one station between two classes (SANAE IV, 380 MeV). During a very strong GLE, the effective atmospheric cutoff can drop down to about 270 MeV and

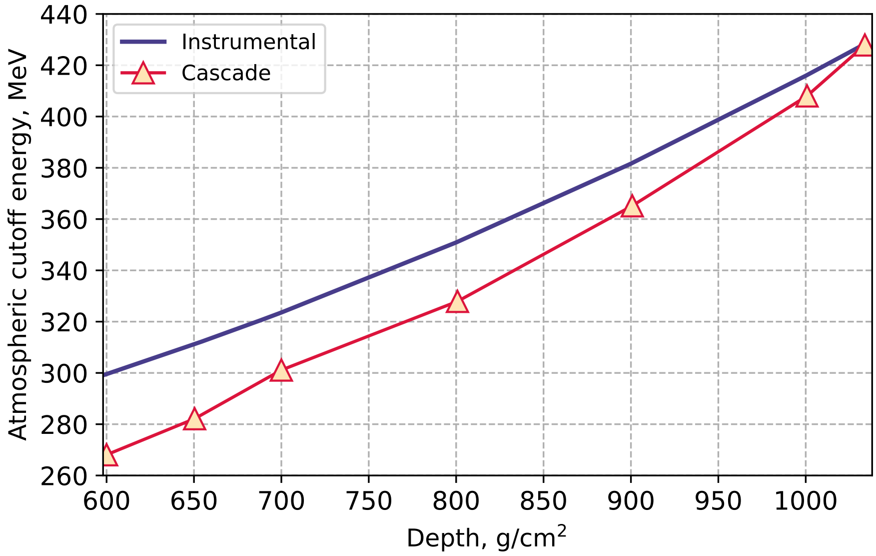

Figure 1: Atmospheric cutoff energy calculated with Monte Carlo simulation of the cosmic-ray cascade (isotropic) and with the NM count rate calculations. The methods are denoted as “Cascade” and “Instrumental” in the legend, respectively.

130 MeV (the prompt and delayed phases) for the near-sea-level stations, and down to 200 and 97 MeV, respectively, for the high-altitude ones. We note that the used GLE#05 is an extreme case, and most of GLEs will not lead to a significant difference of the effective atmospheric cutoff from the “GCR-only” scenario.

4. Discussion and Summary

The topic of the atmospheric cutoff energy is important in the light of two co-existing definitions of so-called sub-GLE events, which are SEP events that have the magnitude on the edge to be counted as a full-scale GLEs. The two definitions are:

By Raukunen et al. [11]:

> *... so-called sub-GLEs, i.e., large SEP events with increases of protons above 300 MeV, but not with sufficient intensities to be detected with ground level neutron monitors.*

By Poluianov et al. [10]:

> *A sub-GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located high-elevation neutron monitors and a corresponding enhancement in the proton flux measured by a space-borne instrument(s), but no statistically significant enhancement in the count rates of neutron monitors near sea level.*

With the calculations presented here, one can see that indeed, high-altitude polar neutron monitors can register SEP events that have protons with energies $>$ 300 MeV. We conclude that the

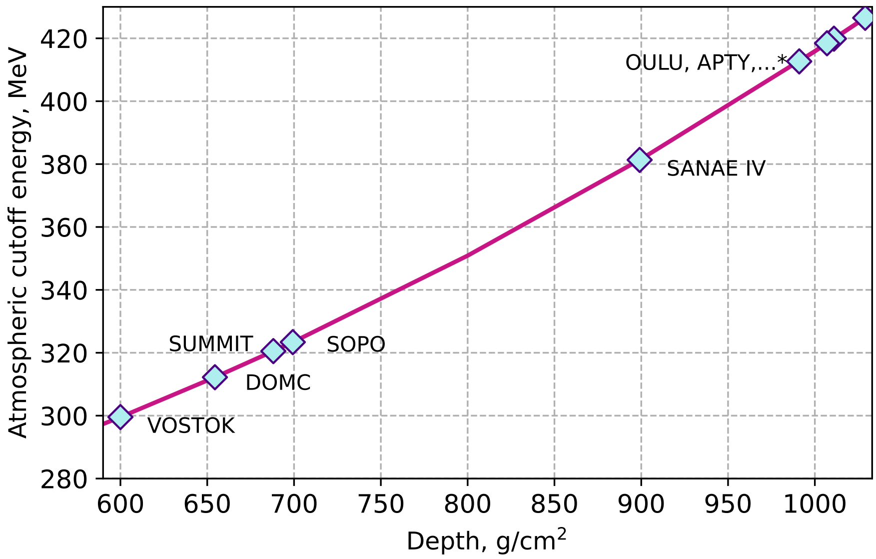

Figure 2: Effective atmospheric cutoff energy as a function of the atmospheric depth with existing polar neutron monitor stations. The label "OULU, APTY,...*" indicates a family of markers corresponding to near-sea-level NM, namely, to APTY, BRBG, FSMT, GSBY, INVK, JBGO, MCMD, MRNY, MWSN, NAIN, NRLK, PWNK, TERA, THUL, and TXBY.

sub-GLE definitions proposed by Poluianov et al. [10] and Raukunen et al. [11] agree with each other.

In summary, we presented the effective atmospheric cutoff energy for detection of cosmic rays with neutron monitors at the ground as a function of the atmospheric depth. The effective atmospheric cutoff energy changes from about 430 MeV at the sea level to about 300 MeV at 600 g/cm^2 (3600 m asl in polar regions). We showed the cutoff values for a list of polar neutron monitors that have the atmospheric cutoff dominant over the geomagnetic one. We also showed that during a very strong and hard-spectrum GLE#05 (23 February 1956), the effective atmospheric cutoff value can significantly drop down by about two hundred MeV. The presented calculations reveal that there is no contradiction between two sub-GLE definitions proposed by Poluianov et al. [10] and Raukunen et al. [11].

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Table 1: List of polar neutron monitor stations and the effective atmospheric cutoff energies for protons calculated for three scenarios: "GCR-only" (i.e., no SEP event), GLE#05, prompt phase, and GLE#05, delayed phase [12]. The atmospheric depths were derived from the mean atmospheric pressure observed at the stations in 2020. The data about the NM stations were obtained from NMDB (`https://www.nmdb.eu`) and private communications with station leaders.

Station	Altitude [m asl]	Depth [g/cm^2]	Geomagnetic cutoff		Atmospheric cutoff [MeV]		
			$P_{\mathrm{gm.cut}}$ [GV]	$E_{\mathrm{gm.cut}}$ [MeV]	GCR only	GLE#05 prompt	GLE#05 delayed
APTY	181	1011	0.51	129.6	419.9	270.7	131.3
BRBG	70	1016	0.06	1.9	421.7	271.9	132.0
DOMC	3233	654	0.0	0.0	312.1	203.3	94.7
FSMT	180	1007	0.30	46.8	418.4	269.8	130.7
GSBY	46	1033	0.96	404.1	428.0	275.9	134.4
INVK	21	1032	0.13	8.9	427.6	275.6	134.4
JBGO	30	1001	0.0	0.0	416.2	268.4	129.9
MCMD	48	991	0.0	0.0	412.6	266.1	128.6
MRNY	40	1001	0.02	0.2	416.2	268.4	129.9
MWSN	15	1002	0.14	10.4	416.6	268.6	130.0
NAIN	46	1029	0.60	175.4	426.5	274.9	133.8
NRLK	0	1026	0.43	93.8	425.4	274.2	133.4
OULU	15	1030	0.67	214.6	426.9	275.1	133.9
PWNK	53	1026	0.38	74.0	425.4	274.2	133.4
SANAEIV	856	899	0.62	186.3	381.3	246.3	117.1
SOPO	2820	695	0.08	3.4	322.3	209.5	97.7
TERA	32	1003	0.0	0.0	416.9	268.9	130.2
THUL	26	1025	0.0	0.0	425.0	273.9	133.2
TXBY	0	1030	0.42	89.7	426.9	275.1	134.0
VOSTOK	3488	580	0.0	0.0	295.1	193.1	90.1
SUMMIT*	3216	688	0.06	1.9	320.5	208.4	97.1

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