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Two sub-GLE events detected with South Pole and Vostok neutron monitors in 1968 and 1969

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High-altitude polar neutron monitors (NM) have exceptionally high sensitivity to solar energetic particles (SEP) due to the reduced atmospheric cutoff compared to sea-level stations and negligible geomagnetic cutoff in their locations. Along with the classic Ground-Level Enhancement (GLE) events caused by SEP, high-altitude polar NMs are able to register so-called sub-GLE events still significantly strong but not detectable by instruments at sea level. There are only two relatively short periods when at least two such instruments, which is the minimum requirement to detect SEP, were/are available for the research: from 2016 onwards with the neutron monitors Dome C and South Pole and from 1964 to 1972 with the South Pole and Vostok NMs.

In this work, we carefully investigated the period from 1964 to 1972 using the data from South Pole (2820 m a.s.l.) and Vostok (3488 m a.s.l.) NMs, as well as from sea-level McMurdo and Thule NMs. We searched for SEP event signatures in the data with several detailed SEP catalogues. Along with the well-known GLEs #15–25, we found two previously unknown sub-GLE candidates: on 09 June 1968 and 27 January 1969, seen as statistically significant increases in South Pole and Vostok NM data, but not observed by sea-level McMurdo and Thule NMs.

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1. Introduction

The Sun sporadically accelerates charged protons, other nuclei and electrons up to very high energies. Those species are called solar energetic particles (SEP). During an event when SEP are produced, the population of those particles propagates mainly outwards the Sun and can reach the Earth. If the event is strong enough in the intensity and energies of accelerated particles, SEP can be registered on the ground by neutron monitors (NM), instruments designed to measure the cosmic-ray variability. The registration looks like an enhancement of the count rate over the galactic-cosmic-ray background and is accordingly called a "Ground-Level Enhancement" (GLE). Formally, the standard GLE should be observed by at least two NMs in different locations and confirmed by an independent SEP registration with, e.g., space-borne instruments [1]. However, there is also a recently introduced class called sub-GLEs, which appeared because of the existence of high-altitude polar NM stations with higher sensitivity to SEPs due to their negligible geomagnetic and reduced atmospheric cutoffs compared to sea-level polar ones [2, 3]. The work by Poluianov et al. (2017) [1] defines those events as the following:

> *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.*

This class is located between non-observable on the ground "weak" SEP events and relatively strong ones causing standard GLEs.

So far, sub-GLEs were found only in data of two high-altitude polar NM stations South Pole (standard and bare NMs, SOPO and SOPB) and Dome C (standard and bare NMs, DOMC and DOMB) [4]. However, the period of the mid-1960s – early 1970s, when high-altitude polar neutron monitors SOPO and Vostok (VSTK) were in operation, was not studied for those events, as far as we know. In this work, we carefully analyse that period in data from SOPO and VSTK, as well as in other low geomagnetic cutoff NM. We present two found sub-GLE events that were unknown before and describe them.

2. Method and Data

Our searching method for sub-GLEs, in brief, consists of the following steps: (a) collection of data from neutron monitors and space-borne instruments, as well as SEP event catalogues; (b) compilation of a list of SEP events that are candidates to sub-GLE events using the catalogues first, but also complemented with enhancements of the proton intensity seen by space-borne instruments; (c) careful examination of the sub-GLE candidates in the NM data and conclusion on every event based on the definition shown above, is it a sub-GLE or not.

The list of SEP events (sub-GLE candidates) registered over the studied period was compiled using the following SEP event catalogues: [5–14]. Overall, we had 39 entries to be examined in the NM data.

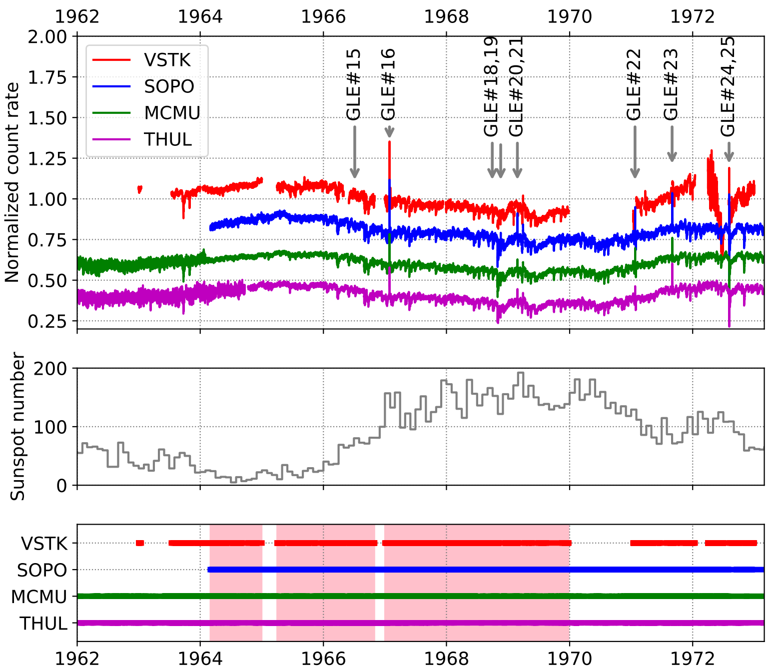

Figure 1: Upper panel: VSTK, SOPO, MCMU, and THUL neutron monitor count rates in 1962–1973. The data are normalized and have offsets for better visibility. Vertical arrows point to the dates when GLE events occurred. Middle panel: Monthly mean sunspot number from `https://www.sidc.be/silso/`. The lower panel: The pink area shows the studied period when those four NM were in reliable operation.

In this work, we particularly focused on the data from high-altitude polar neutron monitors South Pole (SOPO, Amundsen-Scott research station, Antarctica, 2820 m above sea level (asl)) and Vostok (VSTK, Vostok research station, Antarctica, 3488 m asl), as well as from two sea-level polar NMs McMurdo (MCMU, McMurdo research station, Antarctica, 26 m asl) and Thule (THUL, Greenland, 48 m asl). The availability of the data from those instruments is shown in Figure 1. We studied the period from March 1964 to December 1969, when all four NM were in operation. The period between 1971 and 1972 was excluded because the count rate of VSTK had deviant behaviour compared to the count rates of other NMs. For very final verification of sub-GLE candidates, we also used the data from the following NMs with low geomagnetic cutoff rigidities: ALRT, CALG, CAPS, INVK, MRNY, MWSN, OULU, TERA, and TXBY. One can find more information about all mentioned NMs in, e.g., database NMDB (`https://www.nmdb.eu/`). The data were downloaded from database IZMIRAN (`http://cr0.IZMIRAN.ru/common/links.htm`). The best time resolution there is 1 hour for the studied period of time.

Our search of sub-GLE was supported with information from spacecraft. We relied on the OMNI database [15, `https://omniweb.gsfc.nasa.gov`], which contains the proton intensities $J(>E)$ measured by various space-born instruments with 1-hour resolution. In particular, we used the highest available energy channel $J(>60\ \mathrm{MeV})$ for our studies. Unfortunately, the proton intensity is available in OMNI only since May 1967, but there is information about the peak intensity and event fluence of SEP events for the period before that date published in some catalogues, e.g.,

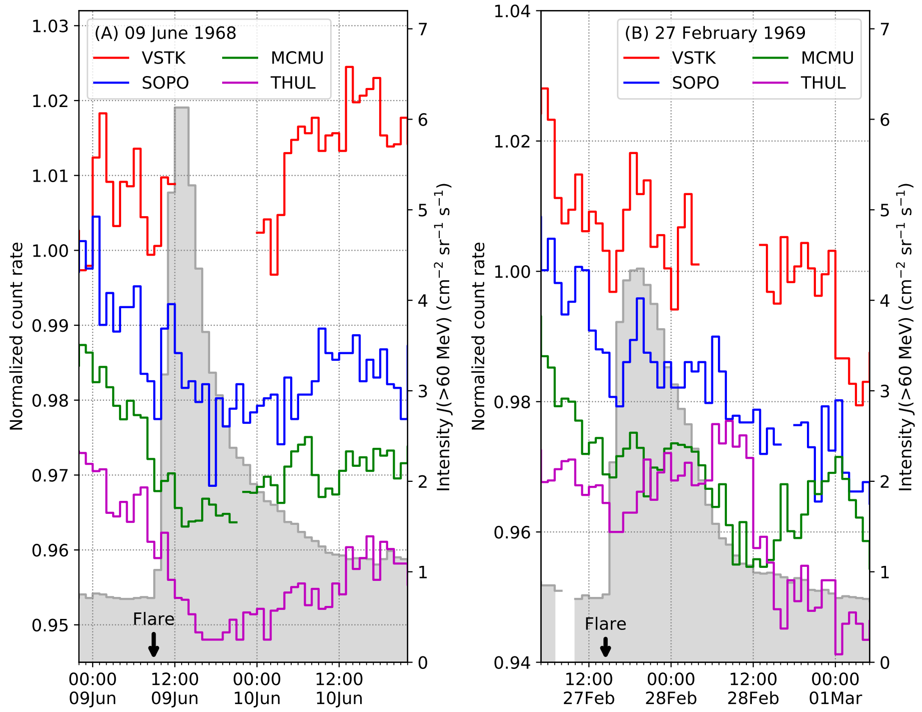

Figure 2: Sub-GLEs found is this work: event on 09 June 1968 (panel (A)) and event on 27 February 1969 (panel (B)). The color lines indicate the hourly count rates from VSTK, SOPO, MCMU, and THUL neutron monitors. The grey shaded curves show the proton intensity $J(>60$ MeV) measured by space-borne instruments and obtained from database OMNI. Vertical arrows point to the times when solar flares associated with the SEP events occurred.

in [12].

3. Results

After careful examination of the studied period from March 1964 to December 1969, we found two sub-GLE events formally matching the definition from [1] that is also presented in Introduction. The sub-GLEs occurred at about 10 UT 09 June 1968 and about 17 UT 27 February 1969, the corresponding count rate enhancements in NM data, as well as the proton intensity $J(>60$ MeV) increases registered in space-borne measurements are shown in Figure 2, panels (A) and (B), respectively.

The first sub-GLE on 09 June 1968 is characterised by the count rate enhancements of SOPO and VSTK (+1.28% and +0.97%, respectively) and duration of about 3 hours. No significant increases were seen in the MCMU and THUL data. The peak SEP intensity $J(>60$ MeV) was 6.13 protons cm^{-2} s^{-1} sr^{-1}. The second sub-GLE on 27 February 1969 was observed as +1.58% and +1.82% increases in the SOPO and VSTK data and null responses from MCMU and THUL. The peak SEP intensity above 60 MeV was 4.35 protons cm^{-2} s^{-1} sr^{-1}.

The NM data corresponding to the described events can be found in the International GLE Database (IGLED, https://gle.oulu.fi) in the standard GLE format. The estimates of the particle spectra during those events with the neutron monitor data are pending.

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