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Role of heavier-than-proton nuclei in neutron monitor response

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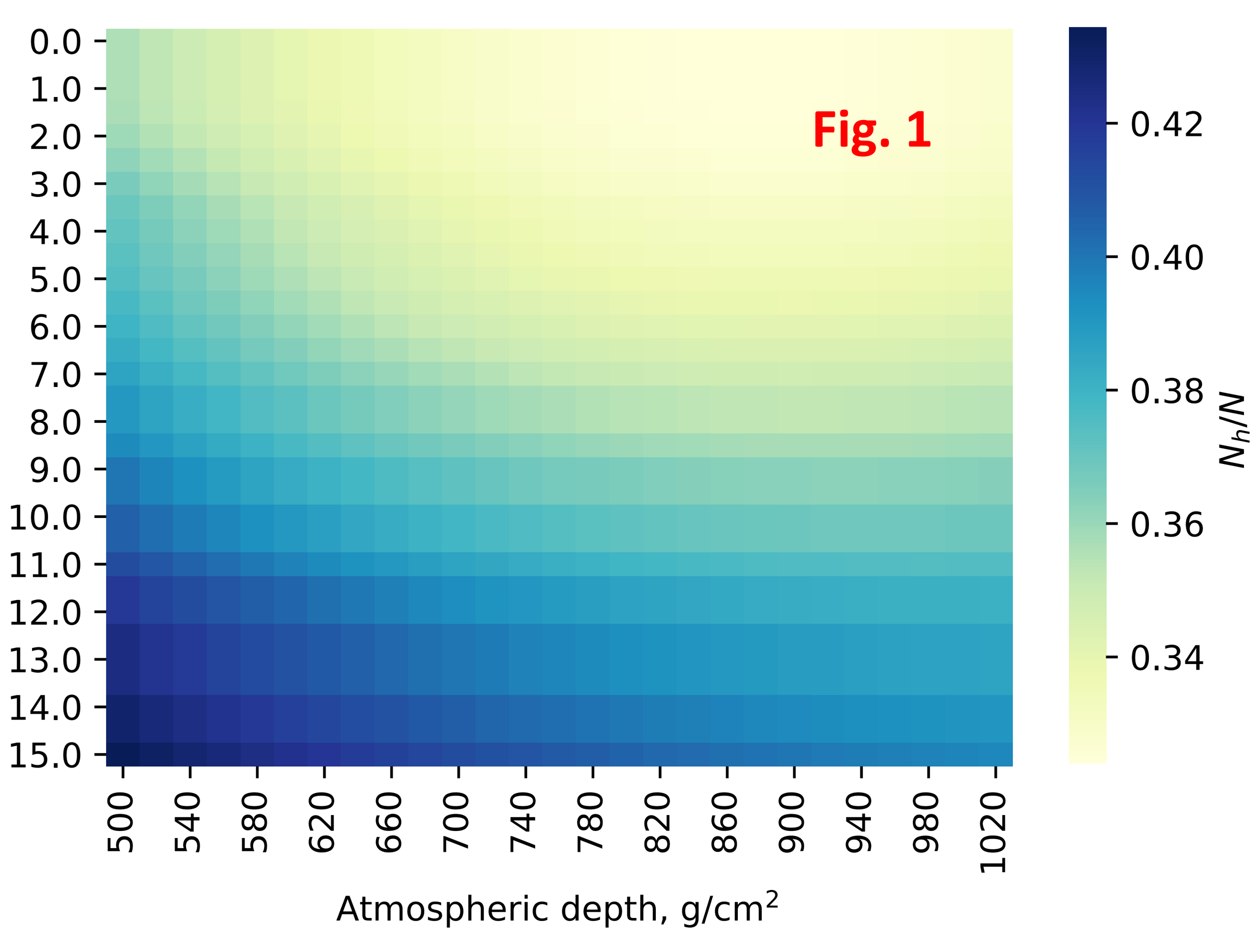
Neutron monitors (NMs) are the main detectors aimed to study the long-tern cosmic-ray variability, thanks to the long period (~70 years) of their operation. NMs register mainly the nucleon component of secondary particle showers, produced during interactions of primary cosmic rays with the nuclei of the atmosphere.

The most appropriate way of the NM analysis is the use of the NM yield function (YF) which allows to calculate the expected NM response *N*th knowing the flux of the primary particles *J*:

$$N_{\rm th} = \sum_i \int_{P_c}^{\infty} J_i(E) Y_i(E) dE, \qquad (1)$$

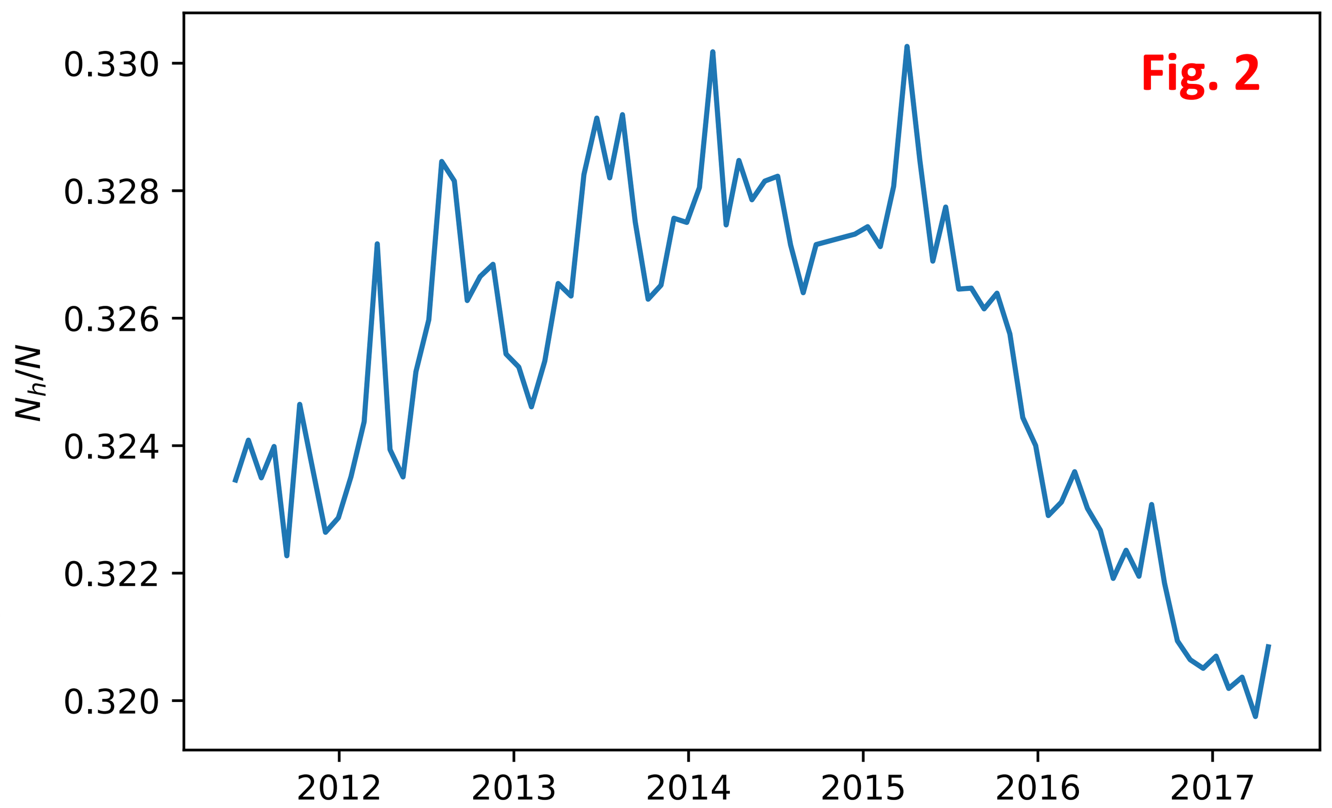
where the summation is over the number of considered cosmic-ray species, and P_c is the cutoff rigidity of a given NM location.

The nucleon component of GCRs is composed of protons (about 90% in the number of particles), helium nuclei (≃8%) and heavier-than-helium nuclei, which can be effectively represented by helium nuclei. Recently, a careful consideration of heavy nuclei was performed on the basis of AMS-02 measurements. The heliospheric modulation of heavier-than-helium CR species in terms of rigidity is expected to be similar to that of helium nuclei, since these heavy nuclei have almost the same charge-to-mass ratio, $Z/A \approx 0.5$, so that the ratio of heavy elements to helium was calculated and used for consideration of heavy nuclei.



In this work, the AMS-02 experiment data on proton and helium CR fluxes variability was used. The data with Bartels Rotation (BR, 27-day) cadence is available for the period 2011–2017 and covers the period of increasing solar activity, solar maximum and decreasing solar activity. In Fig. 1 we show the computed ratio N_h/N between the contribution to NM count rate from heavy particles (helium and heavier nuclei) N_h and the full NM count rate, N, computed for an ideal NM64-type NM for a wide range of atmospheric depths and cutoff rigidities using NM YF Mishev et al. 2020 (Mi20). Here the AMS-02 data for the maximum of solar activity (BR 2462, 11-Jan-2014 – 07-Feb-2014) was used. One can see that the ratio N_h/N rises with the cutoff rigidity and decreases with the atmospheric depth, being about 0.33 for a polar sea-level NM and ~0.43 for a high-altitude equatorial NM. We also note that the main part of active NMs are located in mid- and high latitudes and only a small number of NMs is located close to equatorial zone, where the big values of cutoff rigidities are observed.

The solar cycle dependence of N_h/N is shown in Fig. 2 for a polar sea-level NM (P_c=0.1 GV, d=1033 g/cm^2). This dependence is less prominent in comparison to location-depended changes, being of the order of 3% for the period of AMS-02 observations for polar sea-level NMs which are more sensitive to the solar cycle than low-latitude NMs.



If one wants to use the NM data for the study of solar-cycle induced variation of GCR fluxes, qualitative and quantitative consideration of heavy nuclei should be done. Here we emphasize that the approach of solar modulation potential (force-field model) is typically used for long-term variations. In the framework of this approach solar modulation is described with only one parameter.

Previously, in the framework of this approach, the constant coefficient of 0.3 was used to account for heavy nuclei, this coefficient was multiplied to the proton flux in Eq. 1 and multiplied by NM YF for α-particles. However, the AMS-02 data allow one to calculate this coefficient directly. In order to do it, the ratio of the response of a standard NM due to (Z >1) GCR species, $N_{h,AMS}$, to the corresponding response, $N_{h,mod}$, calculated by applying the standard force-field approach to the proton LIS, as a function of the modulation potential ϕ, namely, $C(\phi) = N_{h,AMS}(\phi)/N_{h,mod}(\phi)$ was calculated.

First, we tested the LIS of Vos & Potgieter 2015, constructed using the PAMELA proton observations for period 2006–2009, Voyager observations beyond heliosphere, GALPRPOP model for cosmic-ray propagation in the Galaxy and numerical simulations of cosmic-ray solar modulation by Potgieter et al. Using this LIS and also finding the best-fit value of ϕ using χ2 criterion (Fig. 3), we obtained the mean value of C = 0.353 and also we evaluated C as a function of the solar modulation potential ϕ (Fig. 4, red filled dots), so the clear tendency of increasing C with the increase of ϕ value was obtained.

We also test the recent LIS estimation by Boschini et al. 2020, obtained using AMS-02 and Voyager experimental data together with GALPROP and with the use of numerical simulation of cosmic-ray solar modulation using HelMod code.

Testing this estimation together with the AMS-02 data using the force-field approach allows us to conclude that it gives almost the same qualitative description of the solar modulation effects that differ in the value of the obtained solar modulation potential ϕ using LIS VP15 with the mean difference being about 20 MV. The C showed almost the same ϕ dependence as for LIS VP15, confirming obtained results.