Reconstruction of solar activity based on $^{14}$C and other isotope profiles in lunar regolith

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Abstract. The Moon might be considered as an integral detector of Galactic Cosmic Rays (GCR) as it contains on its surface cosmogenic isotopes produced by nuclear reactions. Since the retrieval of lunar regolith cores by Apollo missions, there were numerous attempts to measure concentrations and depth profiles of those isotopes and reconstruct the level of cosmic radiation at 1AU at various time scales, ranging from thousands to millions of years. The data also contains encoded levels of solar activity, as the Sun affects the differential flux of GCRs in a well-known manner. All those attempts showed that our nuclear interaction codes, GEANT4 for example, need corrections to describe the lunar data, be it tweaking of cross-sections or any other methods. There are also such archives on Earth: ice cores and trees. Based on terrestrial modulation potential reconstruction we try to calibrate GEANT4 code in a transparent manner, and also present our estimates on the solar activity on time scales of 0.02 and 3 Myrs. The estimates made using our calibration procedure show values consistent with modern understanding of history of solar modulation potential, and demonstrate the necessity to establish an agreed correction method for the analysis of lunar data. We also compare our results and method with another estimation of solar modulation potential during the last 1 Myr.

1. Introduction
Galactic cosmic rays (GCR) produce nuclear reactions in lunar rocks and terrestrial atmosphere. On the Moon these interactions result in generation and accumulation of long-lived radioactive isotopes such as $^{14}$C ($T_{1/2} = 5700$ years), $^{26}$Al ($T_{1/2} = 717000$ years) and others in lunar rocks and regolith. The depth profiles of these radionuclides were measured in Apollo 15 drill core with good accuracy by [1,2]. As the GCR spectrum inside the heliosphere is heavily influenced by the solar activity, one may use these data to estimate the mean solar activity on varying time-scales, dependent on the half-life of the radionuclides. Actually, such estimates have already been made, for example by [3] based on $^{26}$Al. In this paper we compare our estimates with these results and discuss the differences of our approaches.

2. Method and results
Previously, we have successfully used GEANT4 toolkit (version 4.10.05) [4] for modeling the cosmogenic isotopes production in terrestrial atmosphere [5,6] and in this paper we use similar pipeline to model the depth profiles in lunar regolith, which was represented as a medium with the chemical composition as in [7]. We have calculated yield function profiles $Y_i(E,h)$ of the radionuclides
for protons and α- particles as a function of primary particles' energy. Isotopes per incident proton were integrated inside a layer of 1 g/cm² (see Figure 1 for example of the yield function for protons).

![Figure 1](image_url)

**Figure 1.** Yield function for protons calculated in GEANT4 as a function of incident particle energy and depth: a) $^{14}$C; b) $^{26}$Al.

The major part (95%) of measured activity of a specific radionuclide is determined by irradiation within 3 lifetime periods, e.g. for radiocarbon the accumulation time is around 20000 years. To account the solar modulation of GCR a standard method is to use the force-field approximation (Eq.1) where $E$ is the proton energy in GeV/nucleon, $E_0$ is the proton rest energy 0.938 GeV and $J_{\text{LIS}}(E)$ is the GCR proton intensity in the local interstellar medium (LIS). One can also use this data to estimate solar activity, assuming a mean modulating potential $\Phi$ during the whole period of radionuclide accumulation until the production/decay equilibrium is reached.

$$\frac{dJ_p}{dE}(E, \Phi) = J_{\text{LIS}}(E + \Phi) \times \frac{E(E + 2E_0)}{(E + \Phi)(E + \Phi + 2E_0)^2} \left( \frac{cm^2 sr s GeV}{nucleon} \right)^{-1}$$  \hspace{1cm} (1)

Certainly, great variations of GCR flux and spectrum might have occurred on the long time scale. Therefore, in this work we have tried to use the reconstruction of the $\Phi(t)$ on a time scale of 20000 years which is based on existing data of $^{14}$C concentration in tree rings [8] to account the possible spectrum variations. As the formula (1) includes LIS in the literature, we have made our simulations for Moon and Earth’s atmosphere using two different LIS models: one from [9], which we will call $J_{\text{US05}}$ and a compilation of last experimental and theoretical results from [10], which is further addressed as $J_{\text{ORL}}$. For the alpha particles the fluxes were assumed to be 10% of that of the protons in energy per nucleon. Calculation of the isotope production rate depth profile $Q(h)$ assuming mean modulation potential is then straightforward:

$$Q(h) = \pi \int_{E_{\text{min}}^p}^{E_{\text{max}}^p} Y_p(E, h) \times J_p(E, \Phi) \, dE + \pi \int_{E_{\text{min}}^a}^{E_{\text{max}}^a} Y_a(E, h) \times J_a(E, \Phi) \, dE$$  \hspace{1cm} (2)

From Eq.2 in an assumed production/decay equilibrium the activity $A(h)$ in dpm/kg is obtained by multiplying Q(h) by $6 \times 10^4$. The integration limits were chosen according to the calculated datapoints of $Y$, and were 0.08-60 GeV for protons and 0.05-40 GeV/nucleon for alpha-particles. If the modulation potential changes over time, as in the considered reconstruction, one must then calculate a convolution with radioactive decay function (Eq. 3). Here, $\Phi(t)$ means modulation potential at time $t$. 

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(years BP), and $\lambda$ is the radioactive decay constant of the considered radionuclide. We also introduce in our framework an additional scaling factor $Y_0$, which is just a linear factor to fit $A(h)$ to the experimental data. The motivation for including this factor will be given further in the text.

$$Q(h, t) = \pi \int_{E_0}^{E_{\text{max},p}} Y_p(E, h) \times J_p(E, \Phi(t)) \, dE + \pi \int_{E_0}^{E_{\text{max},\alpha}} Y_\alpha(E, \Phi(t)) \times J_\alpha(E) \, dE$$

$$N(h) = \int_{t=0}^{t=\text{fin}} Q(h, t) \times \exp(-\lambda t) \, dt \quad \left( \frac{\text{atoms}}{\text{g}} \right)$$

$$A(h) = 10^3 \times N(h) \times 60 \times \lambda \left( \frac{\text{dpm}}{\text{kg}} \right)$$

The results are shown on Figure 2. It is clearly seen that there is a significant difference between our direct calculations with GEANT4 yield function and the experimental data. Although the form of the modeled $^{14}$C depth profile is similar to the measured profile, the absolute level of $^{14}$C activity is almost two times greater. If we attribute the error entirely to the incorrect calculation of the yield function in GEANT4, we can estimate that the yield function should be decreased approximately 1.7 times for all energies of GCR protons to fit $^{14}$C data in Apollo 15 drill core.

![Radiocarbon activity depth profiles in lunar regolith](image)

**Figure 2.** Radiocarbon activity depth profiles in lunar regolith. $J(\Phi(t))$ are the profiles, calculated using $\Phi(t)$ reconstruction based on $^{14}$C data from tree rings at different LIS and scaling factors $Y_0$. $J(\Phi_{\text{mean}})$ marks the profiles, calculated using a minimum $\chi^2$ fit with its 68% confidence interval marked by red.

Using $\Phi(t)$ reconstructed from terrestrial $^{14}$C data, we have computed scaling factors $Y_0(\text{Orl})=0.60\pm0.01$ and $Y_0(\text{JUS05})=0.57\pm0.01$ required to match that profile with experiment. We have also considered the ordinary model, which uses the $\Phi$ value averaged over the long time as the only fitting parameter ($Y_0=1$) to describe the experimental data. The fitting was performed by minimizing $\chi^2$, and the uncertainties of the method were estimated by varying $\chi^2$ as described in [3,11]. In this case we obtain $\Phi_{\text{mean}}(\text{JUS05})=930$ MV for uncorrected yield function which suggests a very high level of the solar activity during the last 15000 years. At $Y_0(\text{JUS05})=0.57$ the fitting procedure results in $\Phi_{\text{mean}}(\text{JUS05})=360\pm20$ MV, which is more consistent with modern estimates of the solar activity. Note that the modern solar activity with mean $\Phi = 500$-700 MV is considered as significantly increased. Radiocarbon depth profile of this fit is also presented on Figure 2.
Figure 3. Modeled activity profiles of $^{26}$Al in lunar regolith. Color bands represent 68% confidence interval: a) $J_{\text{US05}}$; b) $J_{\text{ORL}}$.

In previous works authors corrected cross sections of individual nuclear reactions in order to fit lunar radionuclides data in the framework of different radionuclide production models [7,12]. However, such corrections had no independent experimental or theoretical justification. $^{14}$C is produced in reactions of neutrons and other secondary particles with different elements of lunar rocks. The same decrease of cross section for different reactions in a wide energy range is very improbable. Most probable explanation of such a result is the inaccurate calculation of the secondary particle cascade. Several experiments had demonstrated that the difference of GEANT4 model fluxes of secondary particles and real measured ones can reach two times for different targets. In the paper [13] this problem was considered especially for the case of lunar regolith, and authors considered a multiplicative scale factor, which we will write as $Y_0$, between neutron fluxes predicted by GEANT4 and measured by Apollo 17 Lunar Neutron Probe Experiment. Their estimates lie in range $Y_0 = 0.6 - 0.84$ and are dependent on the intranuclear cascade model. Therefore, our results for lunar regolith do not contradict the successful calculations of $^{14}$C production in the Earth atmosphere using the same GEANT4 toolkit.

The situation is similar with $^{26}$Al. The use of uncorrected yield function (without $Y_0$ factor) for fitting results in a very high estimated value of $\Phi_{\text{mean}}(J_{\text{US05}})=1350\pm40$ MV within the last three million years. It requires a significantly higher level of solar activity in that period in comparison to modern activity level. Poluianov et al. [3] have already made this calculation, however, their assumption of lunar soil irradiation time of only 1 million years results in 40% underestimation of $^{26}$Al activity. We, however, apply the calibration parameter $Y_0$, estimated from radiocarbon data, to fit $^{26}$Al profile on the moon and have calculated the values for $\Phi_{\text{mean}}(J_{\text{US05}})=480\pm50$ MV and $\Phi_{\text{mean}}(J_{\text{ORL}})=880\pm60$ MV over the last 3 million years. One should note that, as it is mentioned for example in [14], direct comparison of modulation potentials obtained using different LIS is not possible, as one has to use a conversion formula. This conversion is out of the scope of the present paper. The modulation potential for $J_{\text{US05}}$ is used widely in the literature as a reference one, so all the conclusions on the level of solar activity in this paper are based on the results for $J_{\text{US05}}$ LIS parameterization. To compare our method with [3], we have also calculated $^{26}$Al production rate assuming 1 million years irradiation time (which is actually equivalent to assuming $Y_0=0.63$). That way we obtain the estimate for $\Phi_{\text{mean}}= 600\pm30$ MV, which differs from their result of $496\pm40$ MV, however, that might be due to the fact that those authors have used additional data points (from [15]), which are significantly higher than those in [2]. All the
profiles are presented on Figure 3. It is clear that use of the corrected yield function also gives the best explanation of data compared to the uncorrected alternatives.

3. Conclusions

$^{14}$C is mainly produced by the spallation nuclear reactions of high energy particles with oxygen, and $^{26}$Al by different nuclear reactions with Si, Al and other heavy elements. Accumulation times of $^{14}$C and $^{26}$Al differ by more than a hundred times. However, the values of calculated mean modulation potentials for both radionuclides differ only by 30%, if one uses the proposed calibration procedure. It supports our hypothesis of the inaccurate calculations of the fluxes of secondary particles by GEANT4 toolkit. The alternative way must include the simultaneous and similar correction for cross sections of several nuclear reactions with different elements for all energies of interaction that is highly improbable.

Modelling the GCR radiocarbon production in the terrestrial atmosphere and lunar rock using GEANT4 toolkit on a long time scale uncovers the necessity of introducing a correction procedure for the yield function in lunar rocks. The proposed calibration procedure utilizes $\Phi(t)$ history reconstruction based on measurements in tree rings on Earth to obtain a linear scaling factor $Y_0 \sim 0.6$, which fits the depth profile of $^{14}$C activity in Apollo 15 drill core. With this scaling factor the estimation of the mean value of $\Phi$ during the last three million years results in $\Phi=480\pm50$ MV. This is very close to the mean value $\Phi=360\pm20$ MV for the last 20000 years ($^{14}$C accumulation time). An inaccurate calculation of secondary particles cascade by GEANT4 toolkit might be an explanation for the necessity of this calibration. This result could also be applied to other radionuclides production on the Moon.

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