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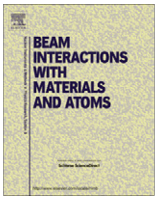

Modeling the earth’s cosmic radiation

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ABSTRACT

In this study, we use physics based cross sections and the radiation transport code MCNPX to develop a purely physics based global model of cosmogenic nuclide production. Modeling the earth as a series of concentric, spherical shells of various media, we propagate the radiation cascade resulting from bombarding the model with primary protons and helium nuclei. The hadronic component of the radiation cascade is tracked throughout the atmosphere as well as the upper region of simple, rock earth-planets. Tallying the energy spectrum throughout the geometry allows us to fold the energy dependent flux with excitation functions to determine nuclide specific spallogenic production rates and attenuation lengths. Using these results, we characterize facets of the radiation cascade and resulting productions rates that are currently unaccounted for in modern scaling schemes.

Preliminary results of our deep atmosphere model show nuclide dependent attenuation lengths, therefore, altitude dependent production ratios. Preliminary results from simple, homogeneous rock planets show production rate depth profiles that diminish at a rate inconsistent with a simple exponential, the currently accepted assumption.

1. Introduction

In situ cosmogenic nuclides provide powerful tools to quantify erosion, surface exposure ages, burial ages and other aspects of geomorphic history [1,2]. Cosmogenic nuclide methods are all dependent on knowing nuclide production rates well at the sampling location. The latitude and altitude variation of production rates are predicted by scaling schemes [3–7]. More complete understanding of the physics of the radiation cascade will reduce systematic uncertainties in current global scaling schemes and help to predict nuclide production rates in the atmosphere and over the earth’s surface. As part of the CRONUS-Earth project, a collaboration of researchers has undertaken an extensive sampling campaign to constrain the production rates of the primary *in situ* produced nuclides, ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl.

Our goal is to calculate nuclide production rates using a physics-based model and compare the results to these experimental values. By applying modern radiation transport codes to cosmic ray propagation through the atmosphere, and combining the calculated fluxes with the latest cross section data, we predict the cosmogenic nuclide production rates at all altitudes and latitudes, for air and for rocks of different chemical composition. We use the Monte Carlo N-Particle eXtended (MCNPX) code to characterize the particle flux responsible for cosmogenic nuclide production in a variety of geologic scenarios. In this paper, we report production rates as functions of altitude at high latitude, for the nuclides listed above.

Scaling schemes currently in use [3–8] assume that production rates of all nuclides vary with altitude in an identical manner and have generally been calibrated with ^{10}Be production. Global scaling models have been based on cosmic ray fluxes derived from extensive sets of photographic emulsion measurements [7] or from neutron monitor measurements [4–6]. Although both methods are sensitive to the range of cosmic ray energies that produce nuclides by spallation reactions, neither captures the detailed particle energy spectrum. Without information about variation in energy spectra, these scaling models have been applied assuming that production rates of the different nuclides vary identically. This assumption has been questioned based on theoretical and experimental data (e.g. [9–12]). Excitation functions are unique to each nuclide production reaction, and there is evidence the energy distribution of cosmic ray neutrons and protons in the atmosphere changes with altitude and geomagnetic latitude [13–15] – hence it is likely that production rate scaling might differ from nuclide to nuclide. Our results presented below suggest that the assumption that nuclide production ratios are constant is incorrect, and that variations in production ratios may range up to 8% at sampling altitudes (between sea level and 6 km).

Recently, Goldhagen et al. [14], Sheu and Jiang [16] and Kowatari et al. [15] have measured differential neutron spectra at different altitudes, solar conditions and geomagnetic fields using

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Bonner Spheres, which are multiple neutron monitors with unique energy response functions [14]. These measurements provide data on the cosmic ray neutron energy spectrum that we can use for detailed comparisons with our calculations. High energy cross sections (excitation functions) for neutrons, the dominant particle responsible for spallation production of cosmogenic nuclides in the lower atmosphere, are also being measured for use with this model [17]. By combining these excitation functions with our calculated cosmic ray spectra, the model results can be directly compared with measured nuclide production rates. Note however, in this case, we are comparing instantaneous model results with time integrated results of the irradiation history.

Radiation transport codes are designed to simulate the movement, generation and attenuation of various radiation types. MCNPX is the latest of several codes developed over the decades at Los Alamos National Laboratory for various physics particle transport applications. Modeling the cosmic-ray radiation cascade in MCNPX allows us to explore characteristics of the radiation field, which are difficult to measure. Direct measurements of the energy spectrum of the neutron component are extremely difficult, making data very sparse; and many particles' energy distributions are impossible to measure. With MCNPX, we can calculate the energy spectrum and direction of travel of all particles, at all altitudes.

2. Methods

The atmosphere is modeled as a series of approximately 100 concentric spherical shells of varying density (depending on the simulation). We use the US Standard atmospheric model [18] for those densities. The atmosphere is modeled up to 100 km, approximately the region where molecular diffusion affects the composition. Although atmospheric density is very low at this altitude ($<10^{-10}$ g/cm^3), the model is extended to ensure realistic treatment of the development of the muon spectrum from pion decay. Below the atmosphere, the lithosphere or the ocean is also modeled as concentric spherical shells.

We used the energy spectrum described in Castagnoli and Lal [19] and McKinney et al. [20] for the primary proton and alpha radiation respectively. We use the estimated long term solar average solar modulation of 550 MV [20–22]. For the high latitude ($>\sim60°$ geomagnetic latitude), the source is isotropic at the upper surface of the atmosphere with particle energies from 10^1 MeV to 10^6 MeV/nucleon. Low latitude models are still in development.

Protons, alpha particles, neutrons, deuterons, tritons, He-3 nuclei, kaons, pions, and muons are all tracked and tallied throughout the geometry. In tracking these particles, MCNPX tallies both energy and direction of travel. For this paper we report particle spectra integrated over all incidence angles. Sato et al. [13,23] have done similar work using a different radiation transport code, PHITS. Their work is primarily targeted towards radiation safety calculations for air travel.

Excitation functions for the production rates of each nuclide from every target, from both neutrons and protons are used to determine total production rates. For instance, for the production rate of ^{10}Be in quartz (SiO$_2$), we use the excitation functions of both O and Si. Each excitation function is then convolved with the corresponding energy spectrum at each atmospheric depth. The excitation functions used in this study [24] were determined from a combination of irradiation measurements and theory. By folding in these excitation functions with our neutron and proton fluxes throughout the atmosphere, we have developed nuclide specific production rates as functions of altitude. Furthermore, attenuation lengths for each specific nuclide production rate can be determined and compared against each other.

Two general geometries have been developed, both of which are spherical:

(i) *Deep atmosphere*: We ran one set of simulations with an artificially deep atmosphere that extends to twice the mass depth of the normal terrestrial atmosphere. This allows us to investigate the development of the radiation cascade propagating through a pure medium without the effect of particles reflected from the surface of the earth. Results reported are for atmospheric depth of 1033 g/cm^2 (sea level) and above.

(ii) *Homogeneous planets beneath the standard atmosphere*: Models with granite and basalt layers below a standard atmosphere were used to investigate *in situ* production rates and the effect of the underlying surface composition on the nucleonic flux above and below the air-ground boundary. This approach allows us to investigate phenomena such as changes in the energy spectra of the nucleonic flux, neutron moderation and changes in the angular scattering characteristics of the radiation as it penetrates into materials of different compositions. Furthermore, folding these flux results with excitation functions allows individual nuclide production rates to be determined and compared to experimentally calibrated rates in similar rock types.

3. Results

3.1. Deep atmosphere

Data from Goldhagen et al. [14] were used to benchmark the deep atmosphere model. Their study describes results of measurements of

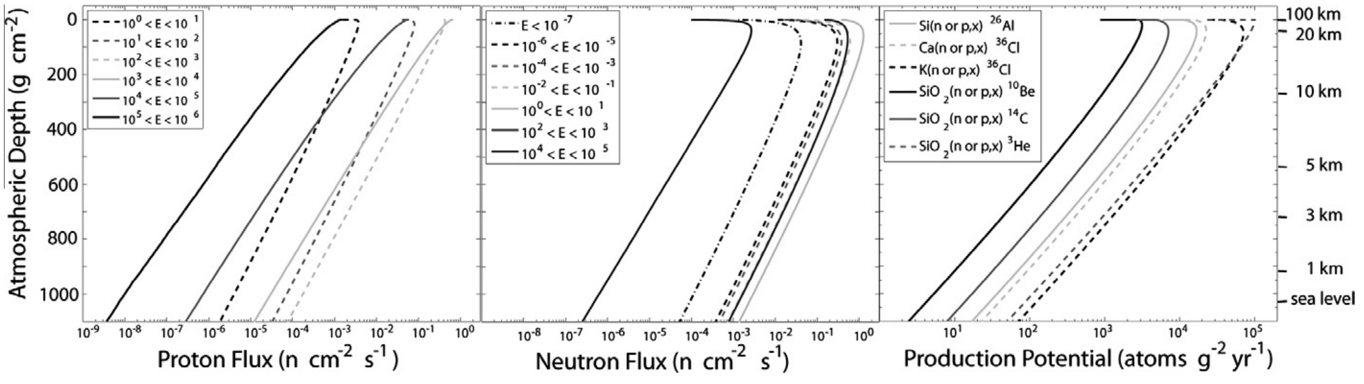

Fig. 1. Particle fluxes and productions rates of select nuclides in a deep atmosphere as functions of atmospheric depth. (A) MCNXP proton flux results, binned in energy of MeV. (B) Select MCNPX neutron flux results binned in energy of MeV. (C) Production rate potentials for ^{26}Al, ^{10}Be, ^{14}C and ^{3}He from silica (SiO$_2$), and ^{36}Cl from pure elemental calcium and potassium.