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Proton flux and radiation dose from galactic cosmic rays in the lunar regolith and implications for organic synthesis at the poles of the Moon and Mercury

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ABSTRACT

Galactic cosmic rays are a potential energy source to stimulate organic synthesis from simple ices. The recent detection of organic molecules at the polar regions of the Moon by LCROSS (Colaprete, A. et al. [2010]. Science 330, 463–468, http://dx.doi.org/10.1126/science.1186986), and possibly at the poles of Mercury (Paige, D.A. et al. [2013]. Science 339, 300–303, http://dx.doi.org/10.1126/science.1231106), introduces the question of whether the organics were delivered by impact or formed in situ. Laboratory experiments show that high energy particles can cause organic production from simple ices. We use a Monte Carlo particle scattering code (MCNPX) to model and report the flux of GCR protons at the surface of the Moon and report radiation dose rates and absorbed doses at the Moon's surface and with depth as a result of GCR protons and secondary particles, and apply scaling factors to account for contributions to dose from heavier ions. We compare our results with dose rate measurements by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) experiment on Lunar Reconnaissance Orbiter (Schwadron, N.A. et al. [2012]. J. Geophys. Res. 117, E00H13, http://dx.doi.org/10.1029/2011JE003978) and find them in good agreement, indicating that MCNPX can be confidently applied to studies of radiation dose at and within the surface of the Moon. We use our dose rate calculations to conclude that organic synthesis is plausible well within the age of the lunar polar cold traps, and that organics detected at the poles of the Moon may have been produced in situ. Our dose rate calculations also indicate that galactic cosmic rays can induce organic synthesis within the estimated age of the dark deposits at the pole of Mercury that may contain organics.

1. Introduction

Galactic cosmic rays (GCR) are energetic charged particles, predominantly protons, which originate outside the Solar System and though mediated by the solar magnetic field retain energies from a few MeV to much greater than 100 GeV per nucleon at the orbit of the Earth (Longair, 1992). When these particles encounter the regolith of an airless body like the Moon, they interact with the surface materials and release cascades of secondary particles including neutrons and gamma rays that exit the surface and are diagnostic of the surface composition. Neutron and gamma ray spectrometers have made use of this process to study the surface composition of many bodies including the Moon (e.g. Feldman et al., 1999; Mitrofanov et al., 2010a,b), Mars (e.g. Boynton et al., 2004), Mercury (Goldsten et al., 2007), and Vesta (Prettyman et al., 2003). Experiments have also shown that proton irradiation can stimulate organic synthesis in simple C, H, O, and N-bearing ices, and as a result GCR protons have been cited as a possible energy source for organic production on comets, icy satellites, and interstellar ices (e.g. Moore et al., 1983; Hudson and Moore, 1995; Moore and Hudson, 1998, 2003; Gerakines et al., 2001).

It has also been suggested that GCR proton irradiation could provide an energy source to stimulate organic synthesis at the lunar poles (Lucey, 2000), since many of the same cometary ices studied in experiments may also be present at the lunar polar cold traps (e.g. Zhang and Paige, 2009; Colaprete et al., 2010; Gladstone et al., 2012; Paige et al., 2010). This process is also relevant to Mercury's poles, where extensive water ice deposits are thought to be present at permanently shaded regions, covered in some areas by an organic-rich surface deposit (Lawrence et al., 2013; Neumann et al., 2013; Paige et al., 2013). We investigate the possibility of radiation-induced organic synthesis at the lunar poles by modeling the proton flux within the lunar surface to determine whether the proton flux is high enough to accumulate radiation doses equivalent to those determined experimentally (Moore and Hudson,

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1998) to stimulate organic synthesis, within the probable age of the lunar polar cold traps.

2. Methods

We use the radiation transport code MCNPX 2.6.0 (Monte Carlo N-Particle eXtended) (Pelowitz, 2008) to model the flux of GCRs at the lunar surface and the resulting radiation dose accumulated in the regolith. MCNPX is a Monte Carlo radiation transport code created by the Los Alamos National Laboratory and is the result of several decades of development. Monte Carlo methods track the behavior of many individual particles from source to termination to provide information about the average behavior of particles in the system for tallies of interest to the user (e.g. proton flux through a surface or energy deposition in a material). The method is well suited to three-dimensional, time-dependent problems and is especially useful for statistical processes like nuclear interactions with materials. MCNPX has the ability to track the interactions of 34 types of particles including protons, neutrons, light ions up to alpha particles, and 2205 heavy ions up to ^{259}Fm, in three dimensions and at energies up to 1 TeV/nucleon. Stopping power algorithms have been validated against the SRIM software (James et al., 2006; Ziegler et al., 2003). It uses continuous cross-section data to model interactions up to 150 MeV, and physics models for interactions beyond this energy range (Pelowitz, 2008). It is a general-purpose code that is widely used for interpretation of planetary neutron and gamma ray spectroscopy (e.g. Prettyman et al., 2006; Lawrence et al., 2006, 2010), as well as in the fields of medical physics, high-altitude radiation dose modeling, spent nuclear fuel storage, and for many other applications (e.g. Newhauser et al., 2005; Anid et al., 2009; Hordósy, 2005). The code is accessible at no cost from the Radiation Safety Information Computational Center (RSICC) at Oak Ridge National Laboratory (rsicc.ornl.gov).

The MCNPX code includes among its inputs the energy spectrum and flux of the source, in this case, GCRs. The GCR energy spectrum is modified by interactions with magnetic fields created by solar plasma, which varies with solar activity (Castiglioni and Lal, 1980) so we include assumptions about the Sun's activity in our calculations. These effects have been described in analytical form by Castagnoli and Lal (1980) and Masarik and Reedy (1996) who incorporate a modulation parameter, ϕ, to describe the energy loss by GCR particles as a result of solar magnetic field effects. In this parameterization, a larger value of ϕ means a more active Sun and lower GCR flux. McCracken and Beer (2007) have shown using a combination of cosmogenic ^{10}Be, neutron monitoring, and instrumental cosmic ray data that GCR fluxes and energy levels have been lower on average during the past 50 years of measurement of the GCR flux via neutron monitors than over the previous 580 years, and Castagnoli and Lal (1980) suggest that a solar modulation parameter as low as $\phi = 100$ MV would be a conservative estimate for the modulation expected in solar minimum periods. We selected a solar modulation parameter of $\phi = 300$ MV, the lowest modulation measured by neutron monitors since the 1960s (Castagnoli and Lal, 1980), as an approximate proton flux from GCR at the Moon over Solar System history.

The model also requires the source particle type. Galactic cosmic rays consist mostly of protons, but also feature up to 12% alpha particles and a much smaller percentage of heavier nuclei (Simpson, 1983; McKinney et al., 2006). We model the GCR flux as protons alone for our most basic simulations, and scale the proton flux up to account for the contribution of alpha particles for a second set of simulations (Dagge et al., 1991; Masarik and Reedy, 1996; McKinney et al., 2006). For protons alone, since the input energy spectrum is normalized per source nucleon, we scale our input using a proton flux of 5 protons/cm^2 s for $\phi = 300$ from McKinney et al. (2006). For the simulations including the effects of alpha particles, we followed the procedure described by McKinney et al. (2006) and multiplied the alpha particle flux for $\phi = 300$ (0.68 alpha particles per cm^2 s, obtained assuming 88% protons and 12% alpha particles and a proton flux of 5 protons/cm^2 s) by 3.8 before adding this number to the proton flux for a final scale factor of 7.6 particles/cm^2 s. The final scale factor was obtained using the equation $flux_{a,protons} = protons + 3.8 * alpha_{eff}$, where $alpha_{eff} = protons * 12/88$. An additional normalization factor of 1/4 was included in both sets of simulations to account for the particularities of defining a 4π source in MCNPX (McKinney et al., 2006). Fig. 1 shows our input energy spectrum for GCR protons with $\phi = 300$, compared with measurements of the cosmic ray proton flux from the BESS spectrometer in 1997 with $\phi = 491$ (Shikaze et al., 2007).

The final model input was the body of the Moon, modeled as a uniform sphere of radius 1737 km composed of ferroan anorthosite (FAN). Table 1 shows the chemical makeup used, similar to that used by Lawrence et al. (2006), Elphic et al. (2000), and others. The density of FAN regolith in the simulations was 1.8 g/cm^3, the upper limit of in situ bulk density at the Apollo 16 site as estimated by Mitchell et al. (1972) from core tube measurements. Results were returned in quantities of flux (protons/cm^2 s) and energy deposition rate per unit volume (MeV/cm^3 s).

3. Results

3.1. Simulation results

Because the ice content of the lunar polar cold traps is unknown, and because of the known strong effect of water ice on moderation of neutrons (Feldman et al., 1993), we model the effects of GCR on FAN regolith containing percentages of H_2O varying from 0 wt% to 30 wt%. Fig. 2A and B shows the proton flux in a dry lunar regolith along with two wet cases with 3 wt% and 30 wt% H_2O. Fig. 2C and D shows similar plots for dose rate in units of centiGrays (cGy) per year (1 Gray = 1 J/kg). The conversion to these units from the MCNPX output in units of MeV/cm^3 s is based on simple stoichiometry and uses the density of the material used in the simulations (1.8 g/cm^3 for FAN, 1.76 g/cm^3 for FAN with 3 wt% H_2O, and 1.45 g/cm^3 for FAN with 30 wt% H_2O) for the medium in which the dose is deposited. We find that the water content of the regolith does not affect the proton flux as it drops off with

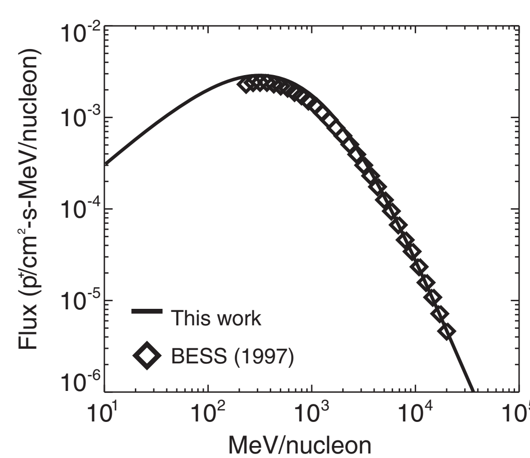

Fig. 1. Input energy spectrum of protons with $\phi = 300$ used in our simulations. Boxes indicate the data points for measurements of the energy spectrum of the cosmic ray proton flux by the BESS spectrometer in 1997 (Shikaze et al., 2007). Small differences in the energy spectrum result from the higher modulation ($\phi = 491$) of cosmic rays at the time of the BESS measurements.