Lunar soil as shielding against space radiation

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ABSTRACT

We have measured the radiation transport and dose reduction properties of lunar soil with respect to selected heavy ion beams with charges and energies comparable to some components of the galactic cosmic radiation (GCR), using soil samples returned by the Apollo missions and several types of synthetic soil glasses and lunar soil simulants. The suitability for shielding studies of synthetic soil and soil simulants as surrogates for lunar soil was established, and the energy deposition as a function of depth for a particular heavy ion beam passing through a new type of lunar highland simulant was measured. A fragmentation and energy loss model was used to extend the results over a range of heavy ion charges and energies, including protons at solar particle event (SPE) energies. The measurements and model calculations indicate that a modest amount of lunar soil affords substantial protection against primary GCR nuclei and SPE, with only modest residual dose from surviving charged fragments of the heavy beams.

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1. Introduction

Exposure to space radiation may be a limiting factor in future manned lunar missions. In contrast to the brief stays by the Apollo astronauts, in the coming decades, humans will remain on the lunar surface for weeks and eventually months at a time. Chronic exposure to highly ionizing ions in the galactic cosmic radiation (GCR) and sporadic acute exposures to protons emitted in solar proton events (SPE) are health hazards that can be mitigated in part by radiation shielding. The spacecraft, spacesuits and rovers will provide only modest shielding, and the expense of transporting material to the moon will allow for little if any supplemental shielding material. An alternative is the essentially unlimited supply of lunar soil,\textsuperscript{1} if ways can be found to effectively use it. We have undertaken a study of the radiation transport and dose reduction properties of lunar soil, using samples returned by the Apollo missions and several types of synthetic soil glasses and lunar soil simulants, with the objectives of evaluating soil as potential shielding and of man-made soil as a surrogate for use in ground-based studies. Reliable synthetics and simulants are needed due to the extreme scarcity of Apollo soil samples. Beams of protons and heavier charged particles at energies comparable to the most biologically damaging components of the GCR are available at a few accelerator facilities, including the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the Japanese National Institute of Radiological Sciences, at which the data reported here were obtained.

2. Materials and methods

The Apollo soil samples, synthetic glasses with soil compositions, and man-made simulants (from terrestrial rocks) that were used in the radiation experiments performed during this study are listed in \textit{Tables 1 and 2}. According to lunar scientific usage, lunar regolith is all the broken rock materials that cover the Moon; soil is the \textless{}1 cm portion of this regolith (\textit{McKay et al., 1991}).
2.1. Apollo lunar soils and synthetic lunar soils

The lunar soils were chosen from soils that have been well-characterized (Pieters et al., 2000; Taylor et al., 2000, 2001a, b) and are representative of the different terrains on the Moon. The mare regions (dark regions of the lunar surface) are represented by the high-Ti soils at the Apollo 11 and 17 landing sites. Highland soils (light-colored surface regions) are represented by four Apollo 16 soils, which are high in Ca-plagioclase feldspars, low in Fe-Mg minerals, and have different degrees of maturity — i.e., times of exposure at the lunar surface. Glasses were synthesized from silica gels mixed with other cation components, and resulted in glasses with compositions similar to those of soils collected by the Apollo 15, 16 and 17 Missions.

2.2. Lunar soil simulants

Due to the precious nature of the Apollo lunar samples, it is not always possible to use the Apollo samples for experiments that are being performed in preparation for a manned lunar outpost. Lunar soil simulants, JSC-1, was made in 1993 by crushing a welded volcanic tuff quarried north of Flagstaff, AZ. It contained about 50% geotechnical properties similar to those of lunar soil, but had a composition that was unrepresentative of 95% of the lunar soils — it was, approximately half mare and half highland in composition. The original 20 ton of JSC-1 were distributed free of charge to the public by NASA. In 2007, a second batch of this same lunar soil simulant was made and denoted JSC-1A.

Shortly after the return of Apollo 11 in 1969, a hi-Ti diabase from Duluth, Minnesota was ground up to produce the Minnesota Lunar Simulant, MLS-1 (Weiblen et al., 1990). MLS-1 has a composition close to the hi-Ti Apollo 11 soil 10084 (Goldich, 1971). The same group also ground up anorthosite from the Duluth Gabbro Complex and made MLS-2, a lunar highland soil simulant. In 2007, the USGS in Denver produced a lunar highland soil simulant, NU-LHT-1, which has abundant glass, plagioclase, and a bulk composition similar to typical highland soil (i.e., 4–5 wt% FeO). Two other highland anorthosite simulants “Claudia” and “Hap” were produced for this study. These samples were collected at Bowles Butte, Idaho, and the Stillwater Complex, Montana, respectively, and are composed mainly of high-Ca-plagioclase feldspars. The compositions of the samples used in these radiation experiments are given in Table 2.

2.3. Radiation experiments

The radiation measurements were made at HIMAC in two phases. A pilot study in February 2007 explored the variation of shielding effectiveness for soil from different sites on the Moon, and the suitability for shielding studies of synthetic soil glasses and soil simulants as a surrogate for lunar soil. In the second phase (January 2008), the average energy depositions in silicon solid state detectors as a function of depth—alogous to a depth–dose distribution—were measured for a particular beam passing through one type of simulant. As explained elsewhere (Zeitlin et al., 2006), the average energy deposition can be used as a measure of the shielding effectiveness of various materials. There is considerable dependence of the results on the beam ion and energy (Guetersloh et al., 2006), and it has been shown that the best proxies for the heavy ion component of the GCR are high energy beams of oxygen or heavier species. The present study has been carried out with beam energies that are lower than optimal for purposes of simulating the GCR. Nonetheless, significant results have been obtained.
Calculated to be 5 mm thick, the pulse heights were converted to data acquisition electronics, and in the first-pass data processing of the target was converted to a pulse height and digitized by the detector upstream of the target, and that the acceptance cone of half-angle 9.5° centered on the beam axis downstream of the target, and the energy deposited in each detector was recorded. The detector setup (Fig. 1) was similar to that used in previous measurements by our group. (Typically we use a mix of detector sizes according to the beam and target (see, e.g., Zeitlin et al., 2007)). The beam spot at TR was an ellipse with major and minor axes less than 5 mm. Offline analysis yielded energy deposition (ΔE) spectra, from which the percent dose reduction per incident beam ion normalized to unit material depth was calculated by methods described in detail in Zeitlin et al. (2006). The data for each target were compared to one another and to results for standard shielding materials.

Energy deposited in one or more silicon detectors downstream of the target was converted to a pulse height and digitized by the data acquisition electronics, and in the first-pass data processing the pulse heights were converted to ΔE values. In subsequent analysis steps, sub-samples of well-measured events were obtained by requiring that one (and only one) primary beam ion was seen in the detector upstream of the target, and that the ΔE values recorded in the detector pair closest to the target exit were well-correlated with one another. For analysis of the Phase I data, we used PSD1, the first silicon detector pair after the target, which subtended an acceptance cone of half-angle 9.5° centered on the beam axis.

Following the method described in Zeitlin et al. (2006), the dose reduction per incident beam particle, δD, behind shielding was calculated to be

\[
\delta D = 1 - \left( \frac{\Delta E_{\text{avg - in}}}{\Delta E_{\text{avg - out}}} \right)
\]

where “in” and “out” refer to measurements with and without a target, respectively, and “avg” is an “event-averaged” rather than “track-averaged” quantity.2

The dose reduction was then normalized to the target’s areal density, \( \rho \Delta x \), in g cm\(^{-2} \) to give the dose reduction per unit areal density, \( \delta D_n \), in (g cm\(^{-2} \))\(^{-1} \).

2.4. Phase I

Samples of Apollo soil, synthetic soil glasses and soil simulant were placed in a beam of 400 MeV/nucleon \(^{10}\)B ions. Charged fragments and beam ions that survived traversal of the target passed through a stack of silicon detectors centered on the beam axis downstream of the target, and the energy deposited in each detector was recorded. The detector setup (Fig. 1) was similar to that used in previous measurements by our group. (Typically we use a mix of detector sizes according to the beam and target (see, e.g., Zeitlin et al., 2007)). The beam spot at TR was an ellipse with major and minor axes less than 5 mm. Offline analysis yielded energy deposition (ΔE) spectra, from which the percent dose reduction per incident beam ion normalized to unit material depth was calculated by methods described in detail in Zeitlin et al. (2006). The data for each target were compared to one another and to results for standard shielding materials.

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2.5. Phase II

In the second round of experiments, a number of depths of lunar highland soil simulant NU-LHT-1, were placed in a beam of 290 MeV/nucleon \(^{10}\)B ions. NU-LHT-1 was formulated to simulate the expected highland soil composition at the lunar south pole, a likely location for future human outposts. The detector setup and data analysis were similar to those used in Phase I. Data were obtained with soil depths between 0 and 30 g cm\(^{-2} \) with an average density of 1.71 g cm\(^{-3} \).

3. Results and discussion

3.1. Phase I

The δD\(_n\) values calculated from the Phase I data are tabulated in Table 3, along with \( \delta D_n \) for three other materials of interest: aluminum, used in conventional spacecraft hulls, polyethylene (CH\(_2\)) a common tissue surrogate, and graphite, a light and strong structural material with potential for use in spacecraft. The results are presented graphically in Fig. 2. In the figure the soil results are averaged and a calculated dose reduction for lead is included. We note that \( \delta D_n \) takes into account the weight penalty of importing shielding, e.g., 1 cm lead reduces dose by almost the same percentage as 1 cm polyethylene, but with a much greater mass penalty. The percent dose reduction per unit areal density of the soil, synthetic soil, and soil simulant varied between 0.7% and 1.0%, comparable to that of aluminum and approximately half that of polyethylene. Observed differences in normalized dose reduction between the Apollo soil samples, the synthetic soil glasses and the lunar soil simulants were small.

For this beam, the average percent dose reduction over all soil samples is 0.8%, compared to 0.9% for aluminum. This similarity is not unexpected: for Apollo sample A70051, for example, the weighted average mass number of the constituents is 26.3 and the weighted average atomic number is 12.85, compared to nominal A and Z for aluminum of 27 and 13, respectively. In other words, per unit areal density, lunar soil is only slightly less effective than aluminum, and only about half as effective as polyethylene at reducing dose for this particular ion and energy. Of course, soil has the great advantage of being available in situ on the Moon.

3.2. Phase II

The Phase I results established that for one heavy ion beam at a single energy in the midrange of the GCR, Apollo lunar soil from

\[ 2 \text{ As discussed in Zeitlin et al. (2006), we make two assumptions: (1) that the total dose is dominated by particles emitted within a narrow cone along the beam axis and (2) that the dose per beam particle is dominated by a single particle, even though for each interacting beam particle more than one particle may be emitted, hence the reference to “event-average” rather than “track-average” energy loss.} \]

\[ 3 \text{ Simply poured lunar soil has a density of approximately 1 g cm}^{-3} (\text{Carrier et al., 1991). The simulant was packed to an average density of 1.41 g cm}^{-3} \text{, but the density of the samples was subsequently measured to be 1.71 g cm}^{-3} \text{ due to settling during shipment.} \]
several different sites, synthetic soil glasses, and lunar soil simulants are approximately equally effective per unit areal density in reducing radiation dose. Further, the data show that soil is quite comparable to aluminum in its shielding properties. In Phase II, we measured the energy deposited in silicon detectors per incident beam ion as a function of depth in a single soil simulant (NU-LHT-1) and for a beam of 290 MeV/nucleon $^{10}$B ions. An energy spectrum was measured with no target and at eight depths of soil between 7.5 and 30 g cm$^{-2}$.

A heavy charged particle beam passing through a thick target is modified by electromagnetic and nuclear interactions with the target atoms. Electromagnetic interactions with the atomic electrons tend to slow the beam ions, so that they are more ionizing at the target exit than they were at the target entrance. Nuclear interactions break the beam ions into more lightly charged and therefore, less ionizing (but longer range) fragments. The interplay of these effects as a function of depth produces the characteristic ionization “Bragg curve”. As shown previously (Zeitlin et al., 1998; Guetersloh et al., 2006) with a $^{12}$C beam at the same energy, over the first few g cm$^{-2}$ of material, the effects approximately balance each other, and the average energy deposition per incident beam ion is close to constant. At greater depths, the slower and more highly ionizing beam particles begin to dominate and the average energy deposition rises rapidly to the Bragg peak. Beyond the Bragg peak, only lightly ionizing fragments remain, and the average energy deposition per incident beam ion decreases rapidly. This is illustrated in Figs. 3 and 4. With no target (Fig. 3a), the spectrum is dominated by the beam ions, only slightly modified by passage through a few cm of air, the 300 μm trigger silicon detector, and the 3 mm silicon detector. After passing through 16.4 g cm$^{-2}$ soil (Fig. 3b), the beam peak is shifted to higher energy deposition, and there is noticeable fragmentation, but this is compensated by the increased ionization of the surviving beam ions, and the average energy deposition is almost the same as the value with no soil. After 22 g cm$^{-2}$ (Fig. 3c) of lunar soil simulant, the primary ions are approaching their peak ionization, and after 26.6 g cm$^{-2}$ (Fig. 3d), the primary beam ions have all stopped, only lightly ionizing fragments remain, and the dose approaches a minimum. The solid line in Fig. 4 summarizes the results. Note that the beam is almost completely attenuated after 25 g cm$^{-2}$ of soil (approximately 20 cm assuming a density of approximately 1.4 g cm$^{-3}$).

4. Model comparison

The data reported here were taken with a single heavy ion at two similar energies. The GCR heavy ion flux, when weighted by dose, has significant components for elements from hydrogen through iron ($Z = 26, A = 56$) over several orders of magnitude in energy from $10^2$ to at least $10^4$ MeV/nucleon. A proper survey would sample several data points over these ranges, but such a study must await the availability of suitable accelerator beams. In the meantime, we have made use here of a model (Zeitlin et al., 1996) that has been shown (Miller et al., 2003; Guetersloh et al., 2006) to reproduce with good accuracy the energy deposition of a number of different heavy ion beams in thick targets. The model calculation for these data is shown as the dashed line in Fig. 4. There is good agreement between the data and the model. We then used the model to estimate the thickness of soil needed to stop several representative components of the GCR, and the energy deposited by the residual fragments. The results are shown in Table 4. The rightmost column is the ratio of the energy deposited by fragments downstream of the stopping peak (at a point analogous to the 25 g cm$^{-2}$ point in Fig. 4) to the peak energy deposition at the end

![Dose Reduction for Various Shielding Materials](image)

Fig. 2. Percent dose reduction $\delta D_n$ per unit areal density (in g cm$^{-2}$) for lunar regolith compared to polyethylene, graphite, aluminum and lead. (The dose reduction for lunar regolith is an average over all samples tested.)
of the particle’s range in soil, which gives an indication of the residual dose after the primary ion stops in the soil.

From the model calculation, we find that less than a half-meter of soil (compacted to a density of 1.4 g cm$^{-3}$) is sufficient in almost every case to stop primary GCR ions, and that the remaining dose from charged fragments is in all but two cases less than 10% of the dose in the Bragg peak. (The exceptions being $^{28}$Si and $^{56}$Fe at 1000 MeV/nucleon, heavy ions for which one expects there to be a relatively high number of high energy heavy fragments produced in the soil.) The same is true for protons up to 300 MeV, which is sufficient for all but the hardest SPE spectrum and energetic GCR protons.

5. Conclusion

We have studied the transport properties of lunar soil, synthetic soil glasses, and soil simulants with respect to protons and heavier nuclei representative of the radiation field at the lunar surface. The utility of synthetic soil glasses and simulant as surrogates for actual soil in radiation transport studies has been established by comparing the dose reduction across materials. A new type of lunar highland simulant was then used to take a depth–dose curve for one species of heavy ion at a single energy, and a fragmentation and energy loss model was used to extend the results over a range of nuclear charges and energies.

The measurements and model calculations indicate that a fairly small amount of soil, slightly compacted from 1 to 1.4 g cm$^{-3}$—46 cm or less—affords substantial protection against primary GCR nuclei and SPE protons, with only modest residual dose from surviving charged fragments of the heavy beams. It is important to note that we have not accounted for the dose from neutrons in either the data or the calculations. The dose from neutrons created by heavy ions and low energy protons can be estimated from thick target data [see, e.g., (Kurosawa et al., 1999)], but additional measurements and modeling efforts would be helpful in this regard.

Studies of this type will help mission planners determine the efficacy of lunar soil as shielding against GCR heavy ions for astronauts on future lunar missions. The results suggest that use of in situ resources on the lunar surface holds promise for radiation protection, with modest amounts of lunar soil providing substantial protection against both GCR and SPE particles.

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References


Table 4

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<th>Beam</th>
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