Radiation dose and its protection in the Moon from galactic cosmic rays and solar energetic particles: at the lunar surface and in a lava tube

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Received 21 May 2020; revised 30 July 2020
Accepted for publication 20 August 2020
Published 22 September 2020

Abstract
The lunar surface is directly and continuously exposed to Galactic Cosmic ray (GCR) particles and Solar energetic particles (SEPs) due to the lack of atmosphere and lunar magnetic field. These charged particles interact with the lunar...
surface materials producing secondary radiations such as neutrons and gamma rays. In a departure from precise GCR and SEP data, we estimated the effective dose equivalent at the lunar surface and in a lunar lava tube in this paper by using PHITS, a Monte Carlo simulation tool. The effective dose equivalent due to GCR particles at the lunar surface reached 416.0 mSv yr$^{-1}$ and that due to SEPs reached 2190 mSv/event. On the other hand, the vertical hole of the lava tube provides significant radiation protection. The exposure by GCR particles at the bottom of the vertical hole with a depth of 43 m was found to be below 30 mSv yr$^{-1}$ while inside a horizontal lava tube, the value was less than 1 mSv yr$^{-1}$ which is the reference value for human exposure on the Earth. We expect that the lunar holes will be useful components in the practical design of a lunar base to reduce radiation risk and to expand mission terms.

Keywords: lunar dose, space radiation, radiation shielding, lunar vertical hole, lunar lava tube

(Some figures may appear in colour only in the online journal)

1. Introduction

For over 50 yr, radiation exposure data have been collected and monitored by many astronauts who have traveled into space as parts of such space programs as Gemini, Apollo, Skylab, Space Shuttle, Mir, and the International Space Station (ISS) (e.g. Badhwar et al. 1996, Benton et al. 2002, Reitz et al. 2009, Kodaira et al. 2013, Berger et al. 2016). As future missions travel outside of the low-Earth orbit (LEO) region and thus away from the protection of the Earth’s magnetic shielding, the radiation exposure rates that space workers receive will be higher than any experienced in the history of human space exploration.

Astronauts working at the ISS are partially protected by Earth’s magnetic field because the ISS stays in the LEO, but during a deep space journey to the Moon or Mars, they will travel far outside of this protective geomagnetic shield. Exposures and biological risks will be larger during future long term missions outside the LEO region. The period that Apollo astronauts were away from the protection of the Earth lasted only a maximum of 12 d. Future proposed missions to the Moon could last a half year or more. Furthermore, any possible missions to Mars, lasting up to 3 yr, would lead to about 1 Sv or more whole-body radiation exposure (Zeitlin et al. 2013).

Future space explorations are looking towards the lunar orbital platform gateway, the Moon, asteroids and Mars. Many preparatory explorations are underway around the world, especially ISEC.Participating countries (ISECG 2018). These efforts to the Moon and its vicinity represent the beginning of robotic and human missions paving the way to Mars.

Earth’s thick atmosphere and strong geomagnetic field protect it from radiation exposure of about 2.5 mSv yr$^{-1}$ as a world averaged effective dose; 0.39 mSv yr$^{-1}$ is due to cosmic radiation, 0.48 mSv yr$^{-1}$ is due to external terrestrial radiation, 0.29 mSv yr$^{-1}$ is due to ingestion and 1.26 mSv yr$^{-1}$ is due to inhalation (UNSCEAR 2008). In contrast, the Moon has an extremely thin atmosphere and weak magnetic field allowing charged particles and micrometeorites to easily reach its surface. The main radiation in space takes the forms of Galactic Cosmic rays (GCRs) and Solar energetic particle (SEP) events. High-energy protons and highly charged particles (HZE particles; high charge ($Z$) and energy ($E$)), and secondary radiation, including neutrons and recoil nuclei produced by nuclear reactions in target materials or in tissues, can damage both shielding materials and biological systems. The exposure rate of space
radiation is typically low, but the effects are cumulative. Therefore, there is significant concern for long term human space travels. Possible health risks include cancer, damage to the central nervous system, cataracts, risk of acute radiation sickness, and hereditary effects (Cucinotta et al. 2008, 2014, 2015). Additionally, the evaluation of the radiation environment on the Moon is essential to identify a proper protection method.

In 2009, deep holes in the Moon’s Marius Hills, Mare Tranquillitatis, and Mare Ingenii were discovered by cameras onboard SELENE, a lunar polar orbiter (Haruyama et al. 2009). The vertical holes are considered to be constructed by the collapse of roof on lava tubes. More recently radar echo patterns acquired by the SELENE lunar radar sounder suggested the existence of intact lava tubes at the Marius Hills (Kaku et al. 2017). One possible lava tube was estimated to be 50 km in length.

In this study, we modeled a lava tube as a radiation shield. The thick ceiling of a lava tube offers significant shielding against HZE particles and micrometeorites. In addition, the temperature fluctuation in a lava tube is much smaller than that observed for the lunar surface. (Angelis et al. 2002, Haruyama et al. 2012). A lava tube can be expected to be a promising candidate site to host a lunar base (Haruyama et al. 2012, Reitz et al. 2012). The use of lunar lava tubes for radiation protection has been evaluated by Angelis et al. (2002). However, evaluation of a radiation environment at the actual entrance of a lava tube, a vertical hole, has never been done.

Our purpose in this study is to evaluate radiation exposure at the lunar surface and in a vertical hole lava tube. We adopted effective dose equivalent, which is determined by absorbed dose, radiation quality factors, Q, and tissue/organ weighting factors, wT (ICRP 2013). We assumed GCRs and SEPs as the radiation sources. GCRs are charged particles with high energies, originating outside the solar system (e.g. Wang et al. 2002, de Nolfo et al. 2006, George et al. 2009, Matthiä et al. 2013). The calculations were performed at the solar minimum and maximum activities. SEPs are charged particles emitted by solar activities such as coronal mass ejections and solar flares. Most of SEPs associated with solar flares have energies under 10 MeV n$^{-1}$. However, a ground level enhancement event (GLE) observed at the Earth’s surface is extremely large, influencing also the Earth’s vicinity. Therefore, we consider GLE-like events as the worst case of radiation exposure for the lunar environment in this study. We estimated the radiation exposure at the lunar surface and in the vertical hole through Monte Carlo simulations using PHITS.

2. Simulation methods

2.1. Simulation code

Many transport simulation codes have been developed for the study of fundamental high-energy particles, that are used for shielding in radiation facilities, radioprotection in space and in treatment planning systems, such as heavy ion cancer therapy. PHITS has received considerable attention due to its applications in heavy ion transport calculations (Sato et al. 2018). Several interaction models for calculating heavy ion reactions, such as JQMD and GEM, are incorporated into PHITS (Niita et al. 1995, Furihata 2000). We estimated radiation production and transport by both protons and heavy particles.

Fluxes of radiation at the lunar surface and below were calculated using PHITS ver. 3.17 as well as effective dose equivalent, which can be obtained using fluence-to-dose conversion coefficients. The ICRP (2013) has defined the conversion coefficients including heavy ions only by isotropic irradiation for space use. We used these defined conversion coefficients (ICRP 2013). However, the radiation incidence on the Moon is not isotropic because of the Moon shadow. Comparing calculation results obtained by using the isotropic conversion
coefficients and superior hemisphere semi-isotropic conversion coefficient in the old literature (ICRP 2010) for the GCR protons during the solar minimum phase, there was $\sim 20\%$ difference. This implies additional $\sim 20\%$ uncertainties in the calculation. Secondary particles of charged particles, electrons, neutrons, photons, pions and muons were taken into account for the estimation of effective dose equivalent.

2.2. Geometry

Schematic drawings of the lunar body (target) and the primary sources used in our numerical simulations are shown in figures 1 and 2. In figure 1, a cylinder with a radius of 20 m and a height of 10 m was assumed as the lunar surface model, and the plane radiation source with cosine angular distribution, producing isotropic radiation, was placed 2 m above the surface. The observation volume was $1 \text{ m}_\phi \times 1 \text{ m}$ on the center of the surface. In figure 2, the observation volume was assumed to be the vertical hole with a radius of 25 m and a depth of 43 m with the semicircular lava tube of a 17 m cavern radius. These dimensions are based on a hole observed at the Marius Hills (Robinson et al 2012). The Marius Hills hole, which is the smallest among the three holes described in Robinson et al (2012), was selected since the smallest hole will provide the most effective radiation shielding. The effective dose equivalent at the observation volume in figure 1 and spatial distribution of the effective dose equivalent around the hole in figure 2 were obtained by a ‘track tally’ provided by PHITS.
| Elements   | Abundance (wt%) |
|------------|-----------------|
| SiO₂       | 46.1            |
| TiO₂       | 2.7             |
| Al₂O₃      | 12.6            |
| FeO        | 16.5            |
| MnO        | 0.21            |
| MgO        | 10.2            |
| CaO        | 10.3            |
| Na₂O       | 0.46            |
| K₂O        | 0.24            |
| Cr₂O₃      | 0.38            |
| P₂O₅       | 0.30            |
| S          | 0.08            |
| Sm (µg g⁻¹) | 16              |
| Gd (µg g⁻¹) | 20              |

### 2.3. Target

The surface of the Moon has different properties on nearside and farside. The Moon side facing the Earth is termed the nearside. It is divided into light areas called the lunar highlands and darker areas called maria. The side of the Moon unseen from the Earth is called the farside. In particular, the number of maria is fewer on the farside. The elemental compositions are different in maria and highlands. The dark material filling the maria is basalt, produced by partial melting due to lunar volcanism. Basalt is richer in Fe and Mg and more depleted in Ca and Al than anorthositic rock in the highlands. Here, we assumed the elemental composition of sampled soils obtained by Apollo 12 from the Mare Procellarum on the lunar nearside as a representative composition of lunar maria (Lucey et al. 2006). The composition of the soils sampled by Apollo 12 is listed in table 1. The density of the lunar surface was set to 2.0 g cm⁻³ assuming regolith, and that of the lava tube was set to 3.1 g cm⁻³ (Yamashita et al. 2008, Alshibli and Hasan 2009). However, according to Slaba et al. (2011), the elemental composition of the lunar surface gives a 9% variation in neutron effective dose at most. We can expect that the elemental composition at the lunar surface; i.e. lunar nearside or farside, does not provide large differences in the total radiation exposure.

### 2.4. Radiation source

#### 2.4.1. Galactic cosmic rays.

The GCRs are composed of energetic particles with a broad spectrum of energy and elements. About 98% are nuclei components and 2% are electrons and positrons. Among the nuclear components, ~87% are protons, ~12% are helium ions and ~1% are nuclei of Z > 2, i.e. the HZE particles (e.g. Simpson 1983, George et al. 2009). When these GCR charged particles enter the solar system, they interact with the outbound streams of the solar wind. GCR fluxes in the heliosphere vary between two extremes which correspond in time to the solar maximum and minimum activities. Solar activity and GCR fluxes are anticorrelated, the maximum of the particle intensity occurs during solar minimum conditions and the minimum exposure is reached at times of large solar activity.

In this study, we checked the elemental contribution to effective dose equivalent dividing it into Z = 1 (H), 2 (He), 3–10 (Li–Ne), 11–20 (Na–Ca) and 21–26 (Sc–Fe). The following


Figure 3. Differential energy spectra of GCR H and He particles (Matthiä et al 2013). Solid and doted lines represent the spectra during the solar minimum and maximum phases, respectively.

\[
J_{\text{GCR}}(E, \varphi) = \frac{C_i \beta^\alpha A_i Z_i^{1/\beta}}{W} \left( \frac{R}{R + R_0} \right)^{0.02W+4.7},
\]

\[
R_0 = 3 \times 10^{-4} W + 0.37.
\]

Here subscript \( i \) is the GCR element, \( R \) is the particle rigidity (GV), \( \beta \) is the ratio of particle speed and light speed, \( Z \) is the atomic number, \( A \) is the mass number, \( W \) is the mean sun spot number for taking into account the influence of solar modulation and \( C \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) GV\(^{-1}\)), \( \alpha \) and \( \gamma \) are fitting parameters given in the literature (Matthiä et al 2013). In this study, we calculated using \( W = 0 \) (in 2010) and, 118.5 (in 2001) for the minimum and maximum phases of solar activity, respectively. Statistics of all ions are fixed to \( 1.0 \times 10^5 \) particles for the lunar surface (figure 1) and \( 5.0 \times 10^5 \) particles for the vertical hole (figure 2) to obtain the total dose rate by merging their dose rates.

Figure 3 shows the energy spectra of GCR hydrogen and helium determined by these equations. The fluxes during the solar maximum phase are lower than that during the solar minimum phase, and the peak energies are smaller. The GCR source particles are nuclei from hydrogen to iron with energies between 10 MeV n\(^{-1}\) and 100 GeV n\(^{-1}\). The spectrum at the lunar surface differs from the original GCR spectrum interacting with the surface and producing secondary particles. Figure 4 shows the calculated results for the proton flux at the surface during the solar minimum phase. The spectrum in the low energy region (<300 MeV) is almost flat so that the flux of secondary proton exceeds that of the primary protons below 300 MeV.

2.4.2. Solar energetic particles. Occasionally, the solar surface releases large amounts of energy in explosive outbursts on a wide electromagnetic band from radio waves, soft and hard x-rays, gamma rays, and highly energetic particles. In these SEP events, strongly varying
Figure 4. Differential energy spectra of GCR proton flux, secondary leakage proton flux and their total at the lunar surface.

Magnetic fields from the solar corona accelerate the solar materials. Coronal particles with energies up to several GeV or higher escape into the interplanetary space spiraling around the interplanetary magnetic field lines. The energy spectra of particles observed in SEP events on Earth greatly depend on the size of the SEP events and its location on the sun relative to this connection. The measured flux of SEP varies from event to event up to about 5–6 orders of magnitude and also shows a large variability in energy spectra and elemental composition, having the potential to expose space crews to life threatening exposures. The occurrence is closely related to the solar activity cycle with a higher probability for the active phase of solar activity.

Most of particle energies in SEP events are typically less than 10 MeV n\(^{-1}\). As protons with several MeV or lower energies have a short range, such protons will be shielded easily by shielding materials. However, in the worst case, large SEP events include a large amount of protons with GeV range energies.

There are anomalously large emissions of particles among SEP events which are sometimes observed as GLEs by Earth’s ground neutron monitors since incident particles have sufficiently high energy at the top of the Earth atmosphere to generate a nuclear cascade producing an increased background intensity from cosmic radiation origin. The most extremely intense SEP events during the last five solar cycles were the November 1960 GLE event with a flux of \(8 \times 10^{9}\) cm\(^{-2}\) and the August 1972 one with \(5 \times 10^{9}\) cm\(^{-2}\). In this work, we took the results estimated by Mewaldt et al (2012) for the recent three large events in solar cycle 23, July 14, 2000, October 28, 2003 and January 20, 2005 as benchmarks.

The following two equations of the differential energy spectrum of the GLE proton \(J_{\text{GLE}}(E)\) are used to describe GLEs.

\[
J_{\text{GLE}}(E) = KE^\gamma_1 \exp \left( -\frac{E}{E_0} \right) \quad (E \leq (\gamma_1 - \gamma_2) E_0)
\]

\[
J_{\text{GLE}}(E) = KE^\gamma_2 \left[ (\gamma_1 - \gamma_2) E_0 \right]^{\gamma_1 - \gamma_2} \exp (\gamma_1 - \gamma_2) \quad (E \geq (\gamma_1 - \gamma_2) E_0)
\]
Figure 5. Differential energy spectra of the three GLE events (Mewaldt et al. 2012). GCR energy spectra are also shown for comparison.

Here $K$, $\gamma_1$, $\gamma_2$, and $E_0$ (MeV n$^{-1}$) are the fitting parameters from the literature (Mewaldt et al. 2012). As shown in figure 5, the intensity and the slope are different in each event. The energy range was fixed as 10 MeV n$^{-1}$–100 GeV n$^{-1}$ the same as for the GCR source. The energy spectra for 2000 and 2003 events bend at around 100 MeV, while the event in 2005 shows a simple power law spectrum. The energy spectrum slope of the 2005 event is much steeper than slopes from events of 2000 and 2003, although the 2005 event is similar in the GCR energy spectrum. Statistics of GLE protons are fixed as $1.0 \times 10^7$ particles.

3. Results and discussion

3.1. Lunar surface

3.1.1. Galactic cosmic rays. The effective dose equivalents from GCR irradiation at the lunar surface are summarised in table 2. ‘Others’ in table 2 contains secondary ions and particles except neutron. The effective dose equivalents in solar minimum and maximum phases were 416.0 mSv yr$^{-1}$ and 160.5 mSv yr$^{-1}$, respectively. Although the GCR exposure evaluation highly depends on the model and environment, our results were generally consistent with previous estimations (e.g. Ballarini et al. 2006, Slaba et al. 2011, Zeitlin et al. 2013, Dobynde and Shprits 2020).

The career exposure limit of crews on the ISS is given in table 3 (JAXA 2013). Strategic radiation shielding is encouraged for long term stays in the radiation environment found at the lunar surface. As seen from table 2, the contribution due to the secondary particles is $\sim$20% of the total exposure due to GCR particles at most. This implies that the contribution of the lunar surface to the radiation exposure by producing secondary particles is not so high.

Figure 6 shows the contribution of various elements to both the effective dose equivalents at solar minimum and maximum phases. Note that each contribution in this figure includes the
Table 2. The effective dose equivalent on the Moon due to GCR particles.

| Particle   | Solar minimum | Solar maximum |
|------------|---------------|---------------|
|            | Effective dose equivalent (mSv yr⁻¹) | Statistical error | Effective dose equivalent (mSv yr⁻¹) | Statistical error |
| Primary ions | 356.3 | 16.6 | 124.8 | 4.3 |
| Neutron     | 40.6  | 4.2  | 24.7  | 1.5 |
| Others      | 19.0  | 5.2  | 11.1  | 1.7 |
| Total       | 416.0 | 17.7 | 160.5 | 4.8 |

Table 3. Career exposure limits of ISS crews as compiled by JAXA (2013).

| Ages at the time of the first space flight | Effective dose equivalent (mSv) |
|------------------------------------------|---------------------------------|
|                                          | Males  | Females |
| 27–30                                    | 600   | 500     |
| 31–35                                    | 700   | 600     |
| 36–40                                    | 800   | 650     |
| 41–45                                    | 950   | 750     |
| 46–                                       | 1000  | 800     |

Table 4. Effective dose equivalent due to direct exposure to the three GLEs.

| Particle | 2000.07 GLE | 2003.10 GLE | 2005.01 GLE |
|----------|-------------|-------------|-------------|
|          | Effective dose equivalent (mSv) | Statistical error | Effective dose equivalent (mSv) | Statistical error | Effective dose equivalent (mSv) | Statistical error |
| Primary ions | 2190       | 18          | 1700        | 14          | 202          | 1.9          |
| Secondaries | 3.2        | 0.6         | 4.8         | 0.7         | 3.2          | 0.2          |
| Total      | 2190       | 18          | 1700        | 14          | 205          | 2.0          |

contribution of their secondary particles. In spite of the fact that the fluxes of Z > 2 particles are only ~1%, the radiation exposure from those particles was larger than 50% of the total. It is obvious that the evaluation of HZE particles is essential.

3.1.2. Solar energetic particles. The effective dose equivalents due to direct exposure to the three GLEs are summarised in table 4. These results and their ratios are consistent to previous estimations (Benghin et al 2005, Hayatsu 2012). The solar event of July 14, 2000 yielded the largest effective dose equivalent of 2190 mSv among the three events. This value is so large that body damages are expected. On the other hand, radiation protection by shielding materials effectively reduces radiation doses by the GLEs since the GLEs are dominated by relatively low energy particles (Slaba et al 2011). A large contribution of low energy particles can also be expected by the small values of secondary doses in table 4. It is clear that shielding is fundamental.
3.1.3. Lunar radioactive elements. Other contributor to the lunar exposure is radioactive elements. Long time exposure to high energy particles produces cosmogenic nuclides such as $^{22}\text{Na}$, $^{24}\text{Na}$, $^{26}\text{Al}$, $^{54}\text{Mn}$ and $^{56}\text{Co}$. These radioactive elements emit gamma-rays providing radiation exposure as well as natural radioactive elements of K, Th, and U series. Here, the cosmogenic nuclides of $^{22}\text{Na}$, $^{24}\text{Na}$ and $^{26}\text{Al}$, which have relatively large intensities on the lunar surface (Reedy 1978), and the natural radioactive elements were taken into account to obtain the effective dose equivalent. The production rates of the cosmogenic nuclides were based on Reedy (1978). The abundances of the natural radioactive elements on the lunar surface have been measured by gamma-ray spectrometers onboard lunar orbiters (e.g. Lawrence et al)
They become maximum at around Fra Mauro with values of \( \sim 4300 \) ppm K, 13 ppm Th and 7.3 ppm Th (Prettyman et al 2006, Yamashita et al 2010). These maximum abundances were assumed for estimation.

The effective dose equivalent due to the radioactive elements was calculated as \( \sim 0.3 \) mSv yr\(^{-1}\). It is found that the contribution of the radioactive elements is low comparing to those of GCR and GLE particles.

### 3.2. Lunar lava tube

Hereafter, we only discuss the GCR exposure worst case, the solar minimum phase, since it is reasonable to assume that the dose distribution does not change with the incoming radiation intensity, i.e. the absolute value depending on the incoming rate varies with a similar spatial distribution. The spatial distribution of the effective dose equivalent from GCR protons in the lava tube is shown in figure 7. Particularly, the depth dependence of the GCR exposure at the central 10 m\(^2\) area in the hole is shown in figure 8. The effective dose equivalent at the bottom of the vertical hole decreased by a factor of 20 comparing to that at the lunar surface. The reduction of effective dose equivalent is mainly due to that of the solid angle subtended by the primary GCR source. The solid angle variation as a function of the depth is also indicated in figure 8 as a magenta line. This reduction rate is significantly large comparing with that by radiation shielding by materials. According to previous researches (Slaba et al 2011, Durante 2014), shielding by 100 g cm\(^{-2}\) polyethylene reduces the GCR exposure during the solar minimum phase by \( \sim 60\% \). The contribution of radiation exposure due to secondary particles increased with depth, and reaches \( \sim 50\% \) at the bottom. This is a result of the increasing solid angle subtended by the secondary neutron sources such as the wall and bottom of the hole.

The effective dose equivalent dependence on the lateral distance from the hole center at its bottom is shown in figure 9. The ICRP (2007) has established the reference value of public exposure as 1.0 mSv yr\(^{-1}\) and that of occupational exposure as 50 mSv yr\(^{-1}\) and 100 mSv 5yr\(^{-1}\). We found that the effective dose equivalent becomes less than the reference value of occupational exposure, 20 mSv yr\(^{-1}\), at the edge of this vertical hole. If there is a space exceeding 50 m, 75 m from the hole center, the effective dose equivalent becomes less than 1.0 mSv yr\(^{-1}\). The SELENE radar observation implied the lava tube had a length of 30 km (Kaku et al 2017), and numerical estimations suggested a width of the lava tube as a few hundred meters or a few kilometers at most (Haruyama et al 2009, Blair et al 2017). Oblique
Figure 8. Depth dependences of the effective dose equivalent at the central 10 m diameter area of the vertical hole.

Figure 9. The effective dose equivalent distributions as a function of distance inside the lava tube measured from the center of the vertical hole.

observation by Lunar Reconnaissance Orbiter (LRO) found about a 10 m tube in the Marius Hills hole and about a 20 m tube in the Mare Tranquillitatis hole at least (Robinson et al 2012, Wagner and Robinson 2014). Therefore, a 50 m space in the hole to obtain a radiation environment below 1.0 mSv yr\(^{-1}\) is sufficiently possible. Our results show that the lunar vertical and horizontal lava tubes are effective for radiation shielding, and a promising site candidate for a lunar base supporting human activities.

According to the GLE statistics, anomalously large solar proton events are rare in any phase of the solar cycle and ordinary GLEs generally occur more frequently during the solar active phase than during the quiet phase (e.g. Smart and Shea 2007). There are almost no GLE events during the 2–3 yr around the solar minimum phase of the solar cycle. Construction of a lunar
base should be started in the holes during the initial time of this phase because there is no place or facility to protect human beings from radiation except for the lava tube.

4. Conclusion

The Moon is the most important and nearest celestial body for human kind and naturally it is also the first step in expanding human activity to space. However, the radiation environment at the lunar surface is hazardous as this natural satellite has effectively neither an atmosphere nor a magnetic field. For the future presence of humans on the Moon, it is necessary in advance to investigate the environmental radiation of the lunar surface which is quite different from that of the Earth’s surface. The largest contribution to dangerous radiation levels for crews and/or habitants is given by GCRs, SEPs and their secondary particles, mainly neutrons.

To evaluate the radiation environment on the Moon, we estimated and discussed the effective dose equivalent on the lunar surface and in a lunar vertical hole with a horizontal lava tube. The radiation exposure on the lunar surface was much higher than that observed on the Earth making radiation protection fundamental. In particular, the effective dose equivalent on the lunar surface at the solar minimum was the highest in the results for radiation exposure to GCRs. In the vertical hole, the effective dose equivalent mainly decreased depending on the solid angle. The effective dose equivalent at the bottom of the hole, 50 mϕ × 43 m, decreased to ∼1/20 of that at the lunar surface. Even at the solar minimum, when moving horizontally away from the vertical hole into the lava tube the dose decreased to the level below 1 mSv yr⁻¹ at 75 m from the center of the hole bottom. The vertical holes and lava tubes are one of the promising options for radiation protection on the Moon. They will be useful for a practical design of a lunar base reducing radiation risk and expanding mission terms.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

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