

## Radiation Doses on the Lunar Surface and in the Vertical Hole

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The radiation environment on the Moon is quite different from that on the Earth's surface in spite of the nearest celestial objects from the Earth. Since the Moon has an extremely thin atmosphere, it does not protect the lunar surface from Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs).

Moreover, the Moon has almost no magnetosphere which works as a barrier preventing for GCRs and SEPs. Therefore, the radiation on the Moon mainly consists of highly penetrative GCRs and SEPs. Then the surface of the Moon is directly bombarded with GCRs and SEPs.

The SELENE (KAGUYA) was launched as the forefront of the exploratory lunar missions after the Apollo and Luna missions, and then followed by vehicles of China, India and USA. Moreover, many new lunar missions including landing ones are planned by several countries within a coming few years. Future plans for a manned base on a long term human activity are now under consideration. Habitants at the base will have to stay for a long period under the hostile radiation environment. The study of the effects on humans is an important concern of lunar exploration. In this work, lunar radiation doses are calculated based on the effective dose and the ambient dose equivalent with simulation code, GEANT4 and PHITS. GCRs, SEPs, secondary neutrons and gamma rays on the surface and in the vertical hole are taken into account in the dose calculation.

1. GCR: The radiation dose due to GCRs on the surface was estimated. The annual ambient dose equivalent reaches  $\sim 570$  mSv/yr during the intermediate period between the solar Max. and the Min. phases. The annual ambient dose equivalent due to Fe nuclei is  $\sim 130$  mSv/yr, more than 20% of the total dose on the lunar surface. Moreover, the dose due to neutrons among the secondary particles reaches 50 mSv/yr, suggesting that the neutron dose must be considered from the viewpoint of the human activity.

2. SEP: While staying for a long period on the lunar surface, they may be exposed to such large SEPs, in which proton ( $>30$  MeV) fluence sometimes reaches beyond  $10^9$  particles/cm<sup>2</sup>. Most SEPs do not seem to be life-threatening to habitants being protected with nominal shielding of  $\sim 10$  g/cm<sup>2</sup> of aluminum. However, unusually large SEPs may be hazardous to lunar habitants, though such events rarely occur. In this work some large SEPs are considered in order to estimate ambient dose equivalent on the lunar surface. The dose equivalents are estimated to be respectively as about 7.5 and 4.0 Sv for 1972.8 and 1989.10 events. In these cases, a thick shielding material must be mandatory through the event period.

3. Gamma-rays and neutrons: Using the data of gamma-rays and neutrons observed by Kaguya Gamma Ray Spectrometer (KGRS), the global map of ambient dose equivalent due to lunar neutrons are obtained for the first time. The neutron dose ranges from 61 to 81 mSv/yr on the lunar surface, depending on the lunar regions, which is 20 times or larger than that of the Earth surface.

4. Vertical Hole: A lava tube and rills in the Marius Hills region are discovered by one of authors (Haruyama). Lunar caverns are quite safe shelters for long-term manned activity; habitants can escape from impacts of numerous meteorites, constantly showering radiation, and widely changing temperature on the surface. Radiation doses of GCRs and their secondary particles in vertical hole are also estimated and compared for future lunar exploration with human. The Effective dose of 832 mSv/y due to GCRs at solar Min. at the top surface of vertical hole could be decreased to 92 mSv/y at the bottom of the hole. In the horizontal lava tube, the dose is much lower than that, which is roughly the same level to the that of Earth surface. Finally, lava tubes are the best places as for constructing sites. Vertical holes are possible entrances to the caverns. The discovery has opened a new era for humans to explore the Moon.

Keywords: Radiation environment of the Moon, Galactic Cosmic Ray, Solar Particle Event, Gamma-ray, Neutron, Heavy Charged Particle