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Radiation exposure in the moon environment

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ABSTRACT

During a stay on the moon humans are exposed to elevated radiation levels due to the lack of substantial atmospheric and magnetic shielding compared to the Earth's surface. The absence of magnetic and atmospheric shielding allows cosmic rays of all energies to impinge on the lunar surface. Beside the continuous exposure to galactic cosmic rays (GCR), which increases the risk of cancer mortality, exposure through particles emitted in sudden nonpredictable solar particle events (SPE) may occur. SPEs show an enormous variability in particle flux and energy spectra and have the potential to expose space crew to life threatening doses. On Earth, the contribution to the annual terrestrial dose of natural ionizing radiation of 2.4 mSv by cosmic radiation is about 1/6, whereas the annual exposure caused by GCR on the lunar surface is roughly 380 mSv (solar minimum) and 110 mSv (solar maximum). The analysis of worst case scenarios has indicated that SPE may lead to an exposure of about 1 Sv. The only efficient measure to reduce radiation exposure is the provision of radiation shelters.

Measurements on the lunar surface performed during the Apollo missions cover only a small energy band for thermal neutrons and are not sufficient to estimate the exposure. Very recently some data were added by the Radiation Dose Monitoring (RADOM) instrument operated during the Indian Chandrayaan Mission and the Cosmic Ray Telescope (CRaTER) instrument of the NASA LRO (Lunar Reconnaisance Orbiter) mission. These measurements need to be complemented by surface measurements.

Models and simulations that exist describe the approximate radiation exposure in space and on the lunar surface. The knowledge on the radiation exposure at the lunar surface is exclusively based on calculations applying radiation transport codes in combination with environmental models.

Own calculations are presented using Monte-Carlo simulations to calculate the radiation environment on the moon and organ doses on the surface of the moon for an astronaut in an EVA suit and are compared with measurements. Since it is necessary to verify/validate such calculations with measurement on the lunar surface, a description is given of a radiation detector for future detailed surface measurements. This device is proposed for the ESA Lunar Lander Mission and is capable to characterize the radiation field concerning particle fluencies, dose rates and energy transfer spectra for ionizing particles and to measure the dose contribution of secondary neutrons.

1. Introduction

Each celestial planet is embedded in the space radiation environment composed of energetic particles of galactic and solar origin. These particles are modulated by interstellar magnetic fields, the solar magnetic field and the magnetic field of the planet (if the latter exists and is strong enough to deflect charged particles) before they interact with the molecules and atoms of the planetary atmosphere and soil. The galactic cosmic rays are composed of energetic particles which cover a broad spectrum of energy and mass values. About 98% are atomic nuclei and 2% electrons and positrons. The nuclear component consists of about 87% protons, about 12% helium ions and about 1% nuclei of $Z>2$, the so-called HZE particles (Simpson, 1983). These nuclei are stripped off all their orbital electrons and have travelled for several million years through the galaxy before entering the solar system. When these charged particles enter the solar system, they interact with the outbound stream of the solar wind. Cosmic ray fluxes in the heliosphere are not constant; they vary between two extremes which correspond in time to the maximum and minimum solar activity. Solar activity and cosmic ray 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.

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Besides electromagnetic radiation, the sun emits continuously particle radiation, consisting mainly of protons and electrons, the so-called solar wind. The intensities of these low energy particles vary during the 11 year solar cycle by two orders of magnitude between around some 10^{10} and 10^{12} particles $cm^{-2}\,s^{-1}\,sr^{-1}$ (Wilson, 1978). The related energies are so low (for a proton between a few hundred electron volt and a few kilo electron volt), that the particles are stopped within the first few hundred Angstrom of tissue or shielding material. Occasionally, the surface of the sun releases large amounts of energy in sudden local outbursts of gamma rays, hard and soft X-rays, radio waves in a wide frequency band and highly energetic particles, mainly protons. In these solar particle events (SPEs) large currents and moving magnetic fields in the solar corona accelerate solar matter (Bothmer and Zhukov, 2007). Coronal particles with energies up to several giga electron volt escape into the interplanetary space spiraling around the interplanetary magnetic field lines. Within the ecliptic plane field lines expand from the sun into the interplanetary medium like the beam of a rotating garden hose. They connect the Earth/moon system with a certain point on the western part of the sun. The number and energy spectrum of particles observed in SPEs at Earth among others depend on the size of the SPE and its location on the sun relative to this connection. SPEs show an enormous variability in particle flux and energy spectra and have the potential to expose space crew to life threatening doses. Their occurrence is linked to the solar cycle with a higher probability at the end of a solar maximum (Stassinopoulus, 1988; Kim et al., 2011).

In the vicinity of a planet, the flux of primary nuclei may be modulated by the magnetic field of the planet, if existing. This causes, on the one hand, deflection of particles having low energies, the so-called cut-off effect; on the other hand, the capture of light solar wind particles and protons and electrons from the decay of neutrons produced by the primary particles with the atoms of the atmosphere, may lead to the formation of radiation belts of trapped particles. The Earth is surrounded by partly overlapping radiation belts consisting mainly of electrons and protons and to a much smaller extent of heavier ions. The trapped proton population expands from about 500 km to about 13,000 km above Earth's surface and contains protons with energies up to a few hundred mega electron volt. The electron population is separated in an inner belt and an outer belt containing particles with energies up to a few mega electron volt (inner belt) and a few hundred mega electron volt (outer belt). In the so-called South Atlantic Anomaly (SAA) the trapped particles reach particularly low altitudes and lead to significantly increased radiation exposure at the orbit of the International Space Station (ISS). For fast transits, however, the radiation exposure from trapped particles is of minor importance. The moon has no global magnetic field, and therefore no radiation belt, although some surprisingly high local magnetic-field intensities are detected.

Due to the missing magnetosphere and atmosphere particles of galactic and solar origin reach the surface of moon unattenuated. Dwellings or radiation shelters, e.g. built from regolith, are required to reduce the exposure to safe levels for prolonged human presence on the surface of the moon. Even much more of concern are solar particle events occurring during the cruise to moon where doses of more than 1 Sv can occur. The hazards due to SPEs have been identified as one of the major risks during human interplanetary missions.

In colliding with the atoms and nuclei in lunar soil, the primary particles loose energy in ionization interactions and in nuclear interactions secondary radiation is generated, like hadrons (e.g. helium and heavier ions, protons, neutrons, π and K mesons) and leptons (e.g. muons and electrons) (Wilson et al., 1991). This causes a radiation environment comprising a complex mixture of primary and secondary particles of all types in a wide energy range. All particles may undergo further interactions or decay to other particles in the human body. An additional radiation exposure comes from emissions from the planetary surfaces due to the primordial radio nuclides ^{40}K, ^{235}U, the ^{238}U series and the ^{232}Th series (Surkov, 1981). The radio nuclides contribute to a total of 0.3 mSv/a to the dose equivalent on the Moon surface which is less that 1% of that resulting from cosmic rays.

Despite of the numerous measurements and simulations performed in low Earth orbit and in interplanetary space our knowledge on the radiation exposure on the lunar surface is rather limited. The lunar lander mission can give important insights on the dose rates on the moon and will delivery valuable measurements for the validation of the simulated radiation exposures.

In this work we summarize the current knowledge on the radiation exposure in lunar orbit from recent missions and from simulations performed for the lunar surface. Additionally, we present estimates of the radiation exposure by calculating organ dose rates based on Monte-Carlo simulations and using the ICRP human phantom in a low shielding environment on the lunar surface. In addition we present the design of the Moon Ionizing Radiation Sensor (MIRS) intended to be integrated in the lunar lander mission.

2. Materials and methods

2.1. Radiation exposures in space missions

Numerous manned space missions have already been performed in which the astronaut's exposure was determined by measurements. Based on these measurements effective doses as a quantity of radiation exposure were calculated by Cucinotta et al. (2001) and are given in Fig. 1 which summarizes the effective dose rates to be expected on a large number of different space flight missions. The highest doses were measured in the high altitude rocket and Shuttle flights, where a high contribution to the exposure is due to protons of the earth radiation belt. The dependence of the exposure on the solar activity is obvious for the Shuttle flights. The deep space mission of the Apollo flights range from 0.7 to about 3 mSv/d. No major exposures due to a SPE were experienced by astronauts so far; fortunately the large SPE (Ground Level Event/ GLE 24) occurred fortunately between Apollo 16 and 17 and not during the missions. GLE 24 would have led to severe radiation exposure of the Apollo astronauts. The exposure by primary particles on the lunar surface is expected to be about in the same scale as during the Apollo missions. Of course, there is a further modification of the exposure through differences in the solar activity conditions, the production of secondary particles in the shielding material and the lunar soil and the higher shadowing effect by the moon for galactic cosmic particles.

Measurements in the moon subsurface has been performed for low energy neutrons only during Apollo (Woolum et al., 1975). Measurements in the moon orbit were provided recently by the Radiation Dose Monitor (RADOM) onboard the Chandrayaan-1 mission (Dachev et al., 2011). The spacecraft reached on November 12, 2008 its operational 100 km circular orbit. Measurements showed a dose rate of 0.227 mGy d^{-1} averaged over 3545 h of measurement time (20/11/2008–18/5/2009). During the last three months of the mission (20/05/2009–28/08/2009) the spacecraft reached a 200 km orbit. The dose rate increased to 0.257 mGy d^{-1} owing to the reduction of the lunar shadow effect for cosmic rays and to the increase of the cosmic ray flux related