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Mars neutron radiation environment from HEND/Odyssey and DAN/MSL observations

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ABSTRACT

High Energy Neutron Detector (HEND) onboard the orbital Mars Odyssey mission and Dynamic Albedo of Neutrons (DAN) onboard the Curiosity rover are measuring neutron albedo of Mars produced by Galactic Cosmic Rays (GCR). The numerical simulations of HEND/Odyssey and DAN/MSL and comparison between model predictions and experimental data has been implemented to unfold Mars neutron spectra both on orbit and surface and evaluate biological impact contributed by neutrons. It was found that the maximum neuron equivalent dose rate by neutrons below 10 MeV could be as high as 45 ± 7 μSv per day, which is about 6–7% of the expected charged-particle dose equivalent rate.

1. Introduction

Space agencies from different countries plan for comprehensive Moon and Mars exploration programs with robotic and manned missions in the future. The main goals of these programs require the creation of a permanent lunar base with scientific and engineering infrastructure and a preparation for the first manned expedition to Mars. It opens new possibilities of human exploration of deep space far away from the Earth. The implementation of such plans shall take into account a presence of high radiation background outside the Earth's magnetosphere. This includes a flight to the Moon, Mars, and operations on their orbits and on the surfaces.

The omnipresent space radiation produced by high energy charge particles of Galactic Cosmic Rays and transient Solar activity (Solar Energetic Particle Events) are the main hazards affecting the life of astronauts and functionality of electronic equipment during long interplanetary flights and surface operations. Several missions (such as Mars Odyssey, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), Mars Science Laboratory (MSL), ExoMars) carried radiation detectors, which provided a series of measurements of the absorbed and equivalent doses from charged particles and neutrons outside terrestrial magnetosphere (Goswami Jitendra and Mylswamy, 2009; Saunders et al., 2004; Grotzinger et al., 2012; Chin et al., 2007; Semkova et al., 2018). During the last solar minimum (when the GCR environment was higher than during the solar maximum period) the CRaTER experiment on board the Lunar Reconnaissance Orbiter spacecraft estimated the direct GCR dose of 320 μGy/d (Spence et al., 2013). It correlates well with previous estimates onboard the Chandrayaan-1 mission performed by the RADOM instrument during the same phase of solar cycle (Dachev et al., 2011). The measurements in the deep space during cruise to Mars were made by the RAD instrument onboard the Mars Science Laboratory mission (2011–2012) and the Liulin instrument onboard the ExoMars mission (April–September 2016). They have shown that the GCR doses were 332 ± 23 μGy/d from RAD and 370–390 μGy/d from Liulin (Zeitlin et al., 2013; Hassler et al., 2014; Guo et al., 2015a; Ehresmann et al., 2016; Semkova et al., 2018). The difference between these two measurements are mainly explained by increase of GCR flux due to the periodic modulation expected within a solar cycle. It is important to note that the RAD instrument is the first radiation dosimeter which has been delivered to the Mars surface to evaluate local radiation environment. It measures not only different components of radiation dose in cruise and on Mars surface, but its short and long term variations due to diurnal processes and heliospheric modulation of GCRs (Hassler et al., 2012; Ehresmann et al., 2014; Guo et al., 2015b, 2017; Köhler et al., 2014, 2015; Rafkin et al., 2014).

Mars is a future ambitious target for the human exploration, which will require as much as possible information and analysis about the Mars surface radiation environment. The radiation environment on the Mars

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surface is very complex. It is mainly composed by energetic charge particles of GCR but also their secondary products (secondary charge particles, neutrons and photons) via interactions with nucleus in Martian atmosphere and in the top layer of surface material. The radiation dose for biological systems (called “dose equivalent”) is usually expressed in Sievert (or Sv) which accounts for different quality factors for different types of radiation. The dose equivalent rates measured by RAD/MSL on surface and during cruise were evaluated as ~0.6 mSv/d and ~1.8 mSv/d, respectively. It means that the total dose equivalent which an astronaut can get during a direct and return flight to Mars plus staying on surface for 500 days approaches to 1 Sv, which is about the astronaut life time limit defined by several space agencies (Zeitlin et al., 2013; Hassler et al., 2014). It could be even higher during an intense solar activity period. While the charge particles are the main contributor of radiation dose, the effect from secondary particles (primarily from secondary neutrons) should be also taken into account due to its higher biological impact and difficulties with radiation protection. The neutron component of the radiation background presents quite significant factor during cruise, since the dose equivalent from neutrons can vary from 1% to tens of percent of the total dose, depending on the design and type of the spacecraft and selected protection method against ionizing radiation. Thicker body of a spacecraft decreases the flux of charged particles but enhances the production of secondary radiation and its subsequent contribution to the total dose. However, potential effect of these secondary neutrons is not well studied, simulated, and documented. For example, we do not have a comprehensive picture of the spatial distribution and temporal variability of the neutron dose equivalent inside and outside International Space Station. The neutron component of the radiation dose (for fast neutrons with energies below 15 MeV) outside the station could vary by orders of magnitude from ~0.1 μSv/h above equatorial regions up to 50 μSv/h during flybys above South Atlantic anomaly (Litvak et al., 2017). For deep space missions, the situation is even less certain. This is due to lack of a comprehensive analysis of available data from various missions operating outside of Earth’s magnetosphere and their comparison with charged particles doses and with results of numerical simulation.

The first neutron dose measurements in the deep space have been done by RAD/MSL which is currently operating on the Mars surface and measuring neutral particles including >10 MeV neutrons. These high energy neutrons have the highest biological effect. The RAD/MSL cruise and surface data were used to deconvolve neutron spectra and evaluate neutron dose equivalent. It was found that the neutron dose equivalent rate was about ~30 μSv/d during cruise (the effective neutron energy range is 0–1000 MeV) and ~60 μSv/d during surface operations (the effective neutron energy range from 8 to 740 MeV). It was found that neutron equivalent dose measured on the martian surface is about 10% of the total dose (Köhler et al., 2014, 2015) produced by neutral and charge particles. Later analysis of the RAD data covering a shorter time interval from November 15, 2015 to the January 15, 2016 revised the intensities of RAD neutron spectra and found that the revised neutron dose equivalent could be less by a factor of 2–3, 22–25 μSv/d vs. ~60 μSv/d (Guo et al., 2017).

It is also important to note that neutron flux level and spectral characteristics in the near-surface layer of the Mars can vary as a function of depth down to a couple of meters. It significantly complicates the assessment of equivalent dose because it requires complicated numerical modeling with variable model parameters. The outcome of this study can be valuable in that it provides information on how a habitable module can be constructed using in-situ surface materials or on where a habitat can be placed on Mars.

In addition to RAD/MSL several neutron spectrometers were flown to Mars with primary goal to search and measure water/water ice abundance in the near-subsurface layer (Mitrofanov et al., 2002, 2012, 2018; Litvak et al., 2008; Feldman et al., 2002). They are measuring Martian neutron albedo and these measurements could be also used to reconstruct neutron spectra and convert it into neutron dose equivalent both in orbit and on the surface of Mars.

In our study we have used the data from the HEND/Mars Odyssey and DAN/MSL instruments flown to Mars at different times. The HEND instrument is a part of Gamma Ray Spectrometer (GRS) suite onboard the Mars Odyssey spacecraft (Boynton et al., 2004; Mitrofanov et al., 2003). It was launched in April 2001 and started mapping Mars in February 2002. HEND is a neutron spectrometer which is measuring neutron albedo of Mars in different energy ranges and is mapping water distribution in Martian subsurface. It is still operating for the period more than 15 years, providing a unique opportunity to record long term variations of neutron albedo in the Martian annual seasonal cycle. Taking into account that the neutron albedo of Mars is produced by GCR bombarding Martian subsurface, its long-term variations reflect solar cycle variations of GCR. GCR variations could be as large as about two times, which means that neutron radiation environment is also changing by this order of magnitude. Comparison of the HEND data with results of numerical modeling can deconvolve the Mars albedo neutron spectrum, provide estimates of dose equivalent rate, and then help analyze on how it changes along the Martian surface and as a function of time.

DAN is another Martian thermal and epithermal neutrons detector which was selected as a part of MSL Curiosity payload, the data from which one can estimate water abundances along the rover path. Its measurements can be compared with HEND data to evaluate neutron spectrum at the surface and helps to define neutron dose for future Martian manned mission. DAN/MSL is the first neutron spectrometer delivered to the Mars surface. DAN started its operation right after the successful landing of the MSL rover in August 2012 and continues until the present time.

These instruments measure neutrons in energy range starting from thermal/epithermal neutron up to fast neutrons (~10 MeV). It is less hazard energy band of neutron spectrum but its contribution to the overall neutron dose could be quite significant (about 40%) and should be evaluated. It is complimentary to the existing RAD/MSL estimates of neutron radiation dose based on higher energy range above 8–10 MeV. The combination of two bands could be used to develop a full view of neutron radiation background in the broad energy range.

2. Description of HEND/Odyssey and DAN/MSL instruments

The High-Energy Neutron Detector (HEND) is a part of Gamma Rays Spectrometer suite onboard the Mars Odyssey mission. The HEND instrument was specially developed to measure Martian neutron albedo in different energy ranges from low energy epithermal neutrons to fast neutrons (see more detailed description below). It integrates a set of neutron sensors including three ^{3}He proportional counters and a scintillation unit with two scintillators (Boynton et al., 2004; Mitrofanov et al., 2003).

The ^{3}He neutron proportional counters are sensitive to thermal and low energy epithermal neutrons via capture reaction with ^{3}He which produces an α particle and a proton. The HEND detectors are based on the industrial LND 2517 counters with 1.3 cm in diameter, active length about 5 cm and filled with ^{3}He gas at the 6 atmospheric pressure. All three counters are wrapped in cadmium enclosure but are surrounded by different polyethylene moderator layers. When incident neutrons propagate through the detector volume they are moderated in polyethylene to epithermal and thermal energies and are detected by the proportional counters. The moderation in polyethylene is defined by its thickness. Therefore, the detector with the thickest moderator layer (about 30 mm) is most sensitive to the neutrons with energies 10 eV–1 MeV. The detector with medium 14-mm-thick moderator detects neutrons with energies 10 eV–100 keV. Finally, the detector with the thinnest (3 mm) moderator effectively records only low energy epithermal neutrons below 1 keV. Together, this set of these detectors based on ^{3}He proportional counters covers a wide range of neutron energies, from 0.4 eV up to several MeV (see Fig. 1).

The scintillation detector uses organic stilbene crystal and is capable to detect fast neutrons with energies starting from 0.8 MeV (energy

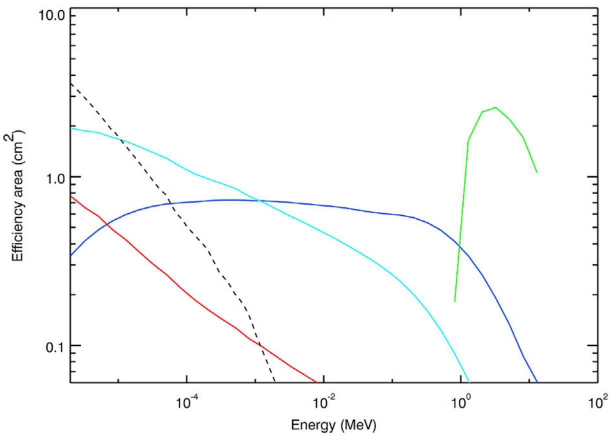

Fig. 1. The efficiency functions for different HEND/Odyssey neutron detectors (shown by different color) and DAN/MSL (shown by black dash line) neutron detectors. The HEND ^{3}He proportional counter wrapped in thinnest (3 mm) polyethylene moderator is shown by red color; The HEND ^{3}He proportional counter wrapped in medium (14 mm) polyethylene moderator is shown by cyan color; The HEND ^{3}He proportional counter wrapped in thickest (30 mm) polyethylene moderator is shown by blue color. The efficiency function of HEND fast neutron detector is shown by green color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

threshold) up to 10 MeV (see Fig. 1). Fast neutrons hit stilbene crystal lattice and produce recoil protons which are recorded by the scintillation detector. In Mars orbit stilbene also detects GCR protons and gamma radiation. To suppress the GCR protons component of counting rate the external part of stilbene (looking to the open space but not to Mars) is surrounded with anticoincidence shielding (CsI scintillation detector). To distinguish between recoils protons and gammas the time shaping analysis is implemented. The pulses produced by proton and electron (gammas detected by electrons via photoelectric effect, Compton scattering, and pair production) have different shapes which are distinguished by the HEND electronics. The efficiency of HEND fast neutron detector is also presented in Fig. 1.

As it was already mentioned in Introduction HEND/Odyssey is measuring the secondary neutrons produced by the charge particles of GCR in the Martian subsurface due to collision with soil nuclei. The fast neutrons born in these spallation reactions leak out subsurface losing their energy via elastic and inelastic scattering reactions. Many neutrons are completely thermalized, therefore on the Mars surface and from orbit one can observe neutron flux in very broad energy range starting from 10^{-9} up to thousands of MeV (see Fig. 5). The moderation of fast neutrons in the subsurface strongly depends on the presence H nuclei because it is the most efficient moderator. That is why observations of variations of thermal and epithermal neutrons are usually used to determine variability of subsurface water (as the most abundant chemical compound bounding H atoms in Martian subsurface) or water ice.

The Dynamic Albedo of Neutrons (DAN) experiment was integrated onboard the MSL mission to provide observations of water distribution in subsurface of Gale crater along the path of the Curiosity rover. It consists of two separate subsystems: a pulsed neutron generator (DAN/PNG) and a detector element (DAN/DE) and can operates in passive (DAN/PNG is off) or active (DAN/PNG is on) measurements modes.

DAN detectors unit includes two ^{3}He proportional counters specially developed for the DAN instrument by the LND company. They have diameter of 5 cm, active length of 6 cm and filled the ^{3}He gas at the 3 atmospheric pressure. One of them is surrounded with cadmium enclosure to reject the detection of thermal neutrons. It is sensitive to the epithermal neutrons in the energy range up to 1 keV (Litvak et al., 2008; Mitrofanov et al., 2012). Its efficiency function is also shown in Fig. 1.

In the DAN active mode, the Martian soil under the rover is irradiated by high-energy neutrons emitted by DAN/PNG. These neutrons are scattered in the subsurface interacting with soil nuclei and lose their energy. They can subsequently escape from the regolith and be detected by DAN/DE. Their arrival time relative to the moment of neutron pulse provides information about depth distribution of hydrogen concentration (water, hydrated minerals, water ice) in the subsurface.

In the passive mode DAN/MSL operates like HEND/Odyssey by measuring the subsurface neutron flux produced by charge particles of GCR or neutrons emitted by Multi Mission Radio Thermal Generator (MMRTG) which is used as the power source to the Curiosity rover. For our study we have used DAN measurements of epithermal neutrons in the passive mode. The MMRTG induced component of epithermal count rate is roughly constant (see for example Figure 11 in (Jun et al., 2013)) and practically all changes in count rate could be addressed to variation of neutron background produced by GCR.

In our study we are interested not in monitoring relative regional variations of neutron flux, which tells us on how water is distributed in the different areas of Mars. Rather, the primary goal is to estimate absolute values of neutron flux in different energy ranges both on surface and orbit to convert it into neutron dose equivalent rate.

3. Data processing

To study properties of neutron component of radiation background at Mars it is necessary to reconstruct the energy spectrum of ambient neutron flux. Analysis of neutron spectrometers observations can provide this information, but neutron detectors are measuring neutron count rate only and do not provide a simple and direct evaluation of incident spectrum. Evaluation of neutron spectrum from experimental data presents significant challenge due to uncertainties in solving complex integral equations relating incident neutron flux with resulting counting rates produced in the volume of neutron detectors. In many cases such a deconvolution leads to the non-unique solutions and requires model dependent assumptions and comprehensive numerical modeling of space experiment. The numerical modeling shall account for the data from ground calibrations (i.e., knowledge about neutron detectors response functions), geometry of observations, properties of ambient environment influencing on neutron production and transport, and GCR spectrum as a primary source of radiation in space. Thus, the numerical approach allows to model complete neutron's path starting from the source to the neutron production and transport in the subsurface/atmosphere, and continuing up to the instrument detection onboard the spacecraft, and thus can help predict count rate in neutron detectors. Some parameters of numerical model could be taken from a priory information but some are unknown or have significant uncertainty. A list of such parameters may include unknown properties of Martian subsurface composition or uncertainty in the GCR flux. For numerical simulations these parameters are usually set as free ones and their values are being varied within some limits. To find their best approximations comparisons between numerical predictions and observational data are performed. The correspondence between the model predicted detector count rates and the measured count rates is evaluated via statistical criteria (for example, Pearson criterion). If the correlation is not satisfactory (that is, if a statistical criterion claims low probability) then one need to change values of free parameters in the model and then repeat the simulation again and to perform a new comparison. This loop should be repeated until the correlation between modeled and experimental count rates is accepted which provides the best fit estimates of free parameters.

We have implemented model dependent deconvolution of the experimental data gathered by the HEND/Odyssey and DAN/MSL instruments. The major goal was to evaluate the energy spectrum of neutron flux in Martian orbit and on the surface based on comparisons between the available HEND/Odyssey and DAN/MSL data and the model predictions.

To implement it we have fixed the following parameters of numerical modeling by taking their best fit estimates from currently available observations: Martian subsurface and atmosphere properties.

The Martian subsurface is a primary medium where high energy neutrons are produced and moderated down to epithermal and thermal energies. In the Gale crater it could be approximated with a homogeneous model of Martian regolith using the average elemental composition taken from observations by Curiosity. For our numerical task we have selected all existing datasets of APXS measurements from Planetary Data System (Gellert et al., 2014). It is Alpha Particle X-ray Spectrometer installed on the Curiosity robotic arm, which has been providing multiple measurements of surface elemental composition along the rover traverse. In our study we have averaged all of them (see for details (Gellert et al., 2014; Campbell et al., 2012; Gellert and Clark, 2015)). The subsurface water distribution has been also added to the numerical model. It could change neutron radiation background because even a tiny concentration of hydrogen can moderate the high energy neutrons (which are the main contributor to the neutron dose equivalent) to the epithermal and thermal neutrons (which are a minor addition to the neutron dose equivalent).

The average column density of Martian atmosphere is about 16 g/cm^2 which is thick enough to produce and scatter neutrons (including neutrons produced in the martian subsurface). The multiple studies demonstrated that it should be properly accounted in the data reduction of neutron spectroscopy data and in the numerical model of martian neutron albedo, see for example (Maurice et al., 2011). The main impact of martian atmosphere is related with fast neutron flux. The amplitude of fast neutron flux variations significantly depends on CO_2 column density and surface composition (water content is a dominating factor). Thus, changes of CO_2 column density from 5 up to 30 g/cm^2 for martian surface with 2–4% of water may changes fast neutron flux as much as a factor of 1.5 (Maurice et al., 2011). To take into account atmospheric effects the General Circulation Models (GCM) are generally incorporated in the numerical code to model neutron measurements in orbit or on the surface of Mars. The (GCM) describes atmospheric thickness and depth as a function of altitude and seasons for a given location on Mars surface. For our analysis we used data provided by Mars Climate Database (MCD, version 5.3) developed by LMD (Paris), AOPP (Oxford), The Open University, and IAA (Granada). For each studied area on the Mars surface the multilayered altitude profile with variable column densities predicted by the LMD GCM was taken and integrated into the numerical model of Martian neutron albedo.

The numerical modeling could predict absolute values of neutron flux, but to do it we should accurately account for all possible factors impacting on neutron production and transport. Nevertheless, the total uncertainty is still affected by known and unknown systematic errors that are difficult to identify and remove from the simulations. It includes uncertainties in evaluation of the solar modulation parameter describing variations of the GCR flux, unknown spacecraft's mass distribution, systematic errors resulted from the incorporation of various physics models and an incomplete library of cross-section data. The best way to mitigate the problem is to normalize and adjust absolute values of neutron flux derived from numerical simulations using comparison with available experimental data. It means that numerical model should correctly predicts count rates measured by neutron detectors in different energy ranges.

To convert incident neutron flux into the HEND and DAN counting rates the GEANT4 Monte Carlo code has been used to create the response matrix for each instrument describing their energy and angular efficiency. The simulation was based on a detailed 3-D instruments models taking into account real geometry of detectors and electronics, mass distribution, and elemental composition. The fidelity of the simulations was verified and adjusted with the data gathered in ground tests in Joint Institute for Nuclear Research (Dubna, Russia). To evaluate instruments sensitivity neutron detectors were being calibrated with neutron fluxes of known energy spectrum and intensity. Certified isotope sources like Californium-252, plutonium–beryllium, or monoenergetic neutron beams (produced in accelerators) have been used in these calibrations. On Figs. 2 and 3 we provided some examples illustrating how instrument numerical model fits the experimental data acquired during calibration tests.

It is important to note that the suggested approach strongly depends on appropriate modeling of GCR flux. It requires that numerical simulation of Mars neutron measurements should include the correct model of GCR as an initial source and be able to reproduce secondary particles production in various environments. The GCR is omni-present source but it is not constant with time. The interplanetary magnetic field and the solar wind affect the GCR charged particles in the heliosphere, forcing variations of their energy spectrum and flux. Thus, the GCR flux inversely correlates with the 11-year solar cycle. The common mathematical model of GCR presents a combination of local interstellar spectrum of GCR outside the heliosphere and modulation inside the heliosphere. The GCR modulation is usually described by the solar modulation potential, φ, describing energy loss of GCRs in the heliosphere [see for example (Gleeson and Axford, 1968; Scherer et al., 2006; McCracken et al., 2004; Usoskin et al., 2005; Usoskin et al., 2011; Usoskin et al., 2017; Herbst et al., 2010)]. The energy spectrum of GCR in the vicinity of Earth could be described as follows:

$$J_i(T,\varphi) = J_{LIS,i}(T+\Phi)\frac{T(T+2T_0)}{(T+\Phi)(T+\Phi+2T_0)} \tag{1}$$

where i is a given nuclei type, $J_{LIS,i}$ is the non-modulated local interstellar (LIS) GCR spectrum, T is the kinetic energy (in MeV per nucleon) of the nuclei i with charge number Z and mass number A, $\Phi = (Ze/A)\varphi$, and T_o is the proton rest mass (938 MeV).

The local interstellar spectrum $J_{LIS,i}$ has not been directly measured and is approximated by different models (Usoskin et al., 2005; Herbst et al., 2010). For our study we have used an approximation proposed by Garcia-Munoz et al. (1975) and then adopted by Castagnoli and Lal (1980) and Masarik and Beer (1999, 2009) for various GCR applications (Garcia-Munoz et al., 1975; Castagnoli and Lal, 1980; Masarik and Beer, 1999, 2009). It is the most popular model of LIS used in the planetary studies including modeling for lunar and Mars missions [for example, see (Masarik and Reedy, 1996; Lawrence et al., 2006; McKinney et al., 2006; Litvak et al., 2006)]. For protons it is expressed as follows in units of particles/(cm^2 s MeV):

$$J_{LIS}(T) = 1.244\times10^6\times(T+780\times\exp(-0.00025T))^{-2.65} \tag{2}$$

To predict the absolute value of GCR flux as a function of time it is necessary to adjust solar modulation parameter for a given phase of solar cycle which is not a simple task. Usoskin et al. (2005, 2011, 2017) published a series of monthly values for the modulation potential, φ, since February 1951 up to the 2016. For the analysis they have used the Burger, Vos and Potgieter models of GCR LIS (Usoskin et al., 2017), which is based on the experimental data from Earth neutron monitor network and the PAMELA space spectrometer observations. The value of modulation potential is model dependent and should be applicable only for the GRS LIS models used in its calculation. It is a useful parameter to describe variations of GCR energy spectrum but only for the selected LIS model. On the other hand, Usoskin et al. (2005, 2011) and Herbst et al. (2010) (Usoskin et al., 2005; Usoskin et al., 2011; Herbst et al., 2010) have demonstrated that the modulation potential for different GCR LIS are roughly linearly related and could be relatively easily converted into each other. Using equations introduced in (Usoskin et al., 2005; Herbst et al., 2010) and the time history of modulation potential presented by (Usoskin et al., 2011, 2017) one can estimate the average solar modulation potential φ for different LIS models including the Garcia-Munoz model presented in Eq (2).

We illustrated time variability of Martian neutron flux in Fig. 4 where the HEND neutron count rate is compared with the measurements of Earth neutron monitors at the McMurdo and Oulu stations. The neutron measurements conducted on these stations have been used to derive solar potential in (Usoskin et al., 2005, 2011, 2017) studies. This figure

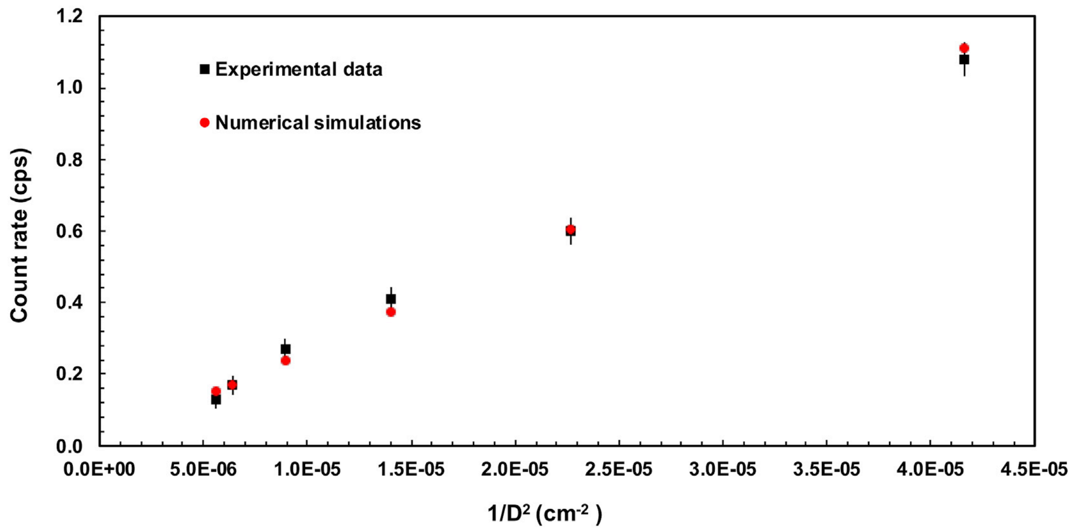

Fig. 2. Calibration of epithermal neutron detectors (used in HEND and DAN instruments) on isotope source Californium-252 is presented. The x-axis corresponds to inverse square of distance between source and detector. Black squares with uncertainties present background subtracted experimental count rates and red circles are their numerical fit. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

presents variations of neutrons flux during 23–24 solar cycles. Mars Odyssey orbit insertion in October 2001 coincided with the maximum of solar activity and as a result we see minimal values of the Martian neutron flux. On the other hand the period of September–December of 2009 is characterized by abnormal minimum of solar activity during the 24th solar cycle and corresponds to the highest peaks in GCR and neutron fluxes ever observed so far (see Fig. 4). Using these data, different periods of time could be selected as reference points to establish direct connection with absolute values of GCR flux at Mars and estimate the dose equivalent of neutron component of radiation background.

4. Results

Using the data from the neutron spectrometers HEND/Odyssey and DAN/MSL we studied the neutron component of radiation environment both in Mars orbit and on the surface at the Gale crater, and estimated variations of neutron dose equivalent rate during a solar cycle.

As an initial step we have considered the time period from August 2012 up to August 2013. It is an ideal reference time interval that matches goals of our analysis. It corresponds to the first year of MSL Curiosity surface operations when solar activity was at the intermediate level in the current epoch. One may postulate that the data gathered for this time period reflects an average level of radiation background within the current solar cycle. Both HEND/Odyssey and DAN/MSL observations are available for this period of time, providing unique opportunity to compare measurements from two “neutron probes” simultaneously in orbit and on the surface.

The GCR observations and the analysis performed with Earth network

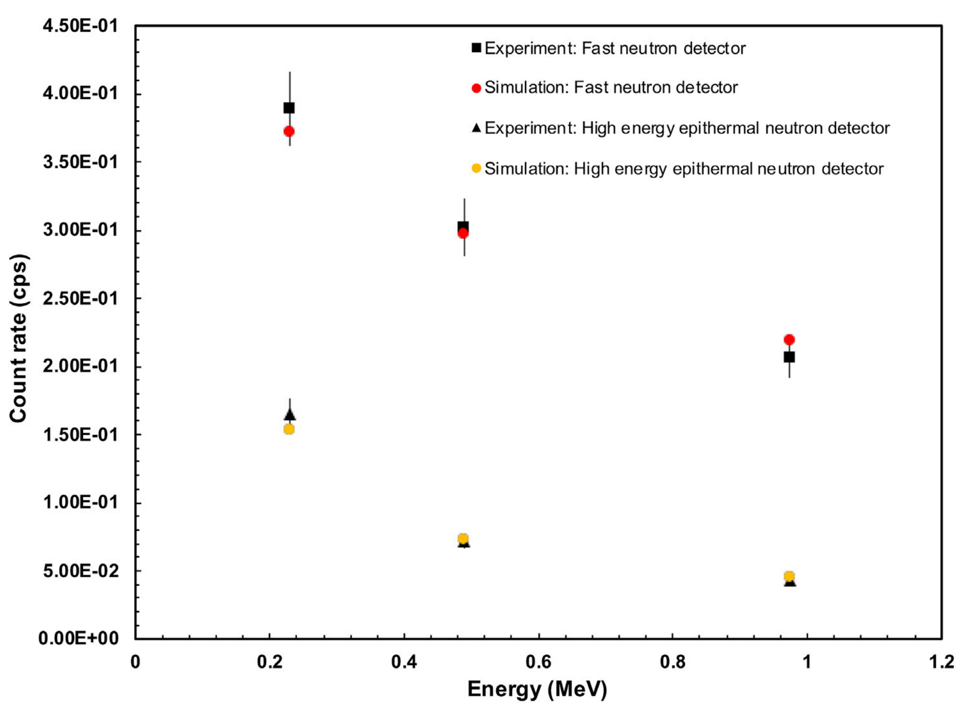

Fig. 3. Calibration of high energy epithermal and fast neutron detectors (HEND instrument) on monoenergetic neutron beams produced by charge particle accelerators (JINR, Dubna). Black color corresponds to experimental count rates measured during calibrations and red and orange colors are their numerical fits. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

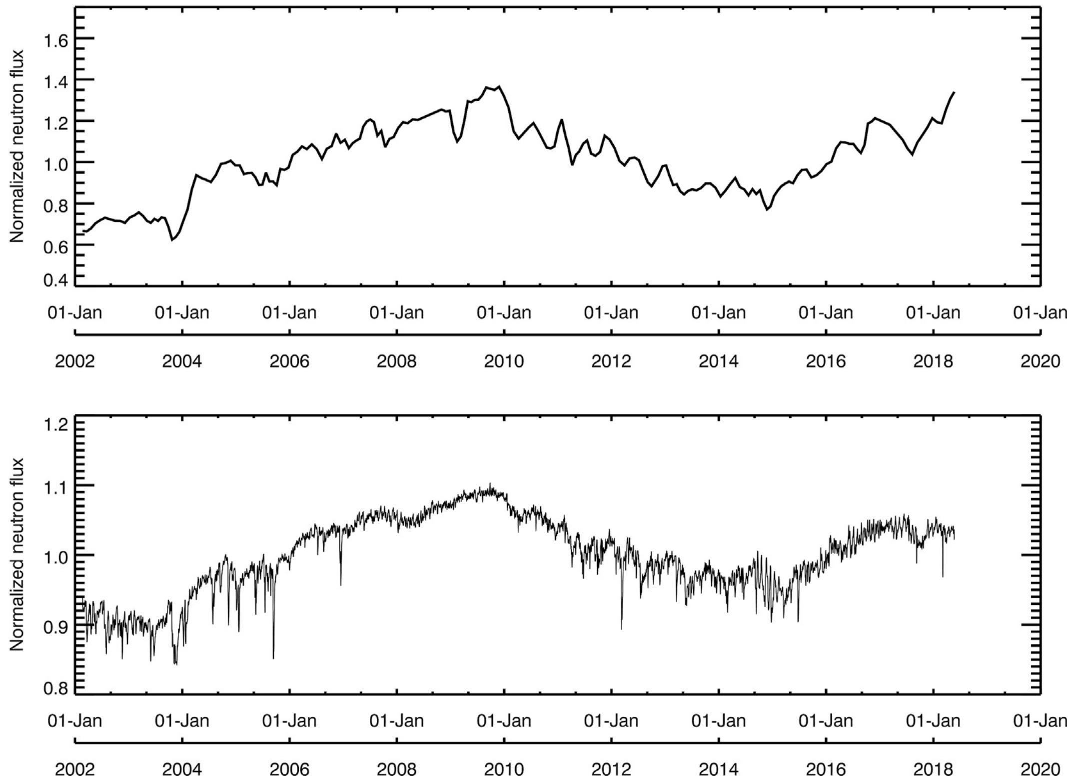

Fig. 4. Long term variations of high energy epithermal martian neutron flux measured on Mars orbit above the Gale crater area by HEND/Mars Odyssey (top graph) and GCR variations recorded by Earth neutron monitors at the McMurdo and Oulu stations (bottom graph).

of neutron monitors provide an estimate of solar modulation potential for this period. It has been shown that it is about 620 MV for the Vos and Potgieter LIS model (Usoskin et al., 2017). Using the relationships between different LIS models established in (Usoskin et al., 2005; Herbst et al., 2010) one may conclude that it becomes ~ 520 MV for the Garcia-Munoz LIS model which we used in our numerical simulation of GCR.

We simulated orbital measurements above the Gale crater and then compared it with the HEND data. Following the approach presented in the previous section we setup the solar modulation parameter equal to 520 MV in the Garcia-Munoz LIS model, but allow the amplitude of GCR spectrum to be a free parameter. The other model parameters responsible for the neutron production and transport have been fixed using their current best estimates. The GCM (see previous section) was used to describe the Martian atmosphere properties in the equatorial region around Gale crater. It is known that atmospheric thickness is varying with Martian seasons, so we used values averaged for the period of time considered. The elemental composition of subsurface was taken from averaging of all APXS measurements made onboard the Curiosity rover. The subsurface water abundance was also taken from the already available estimates. HEND/Odyssey is an omni-directional neutron spectrometer which collects data from the huge spatial region under the spacecraft. The HEND spatial resolution could be approximately characterized by the surface spot with radius about 300 km, which substantially larger then Gale crater. That is why Odyssey orbital mapping of subsurface water concentration differs from the surface measurements performed by Curiosity. Orbital observations from GRS/HEND/NS instruments onboard Mars Odyssey indicate that the average water abundance in broad area around Gale crater is about 4–5% by weight (see Feldman et al., 2004; Boynton et al., 2007; Feldman et al., 2011; Litvak and Sanin, 2018) while the local measurements made by different instruments onboard Curiosity inside Gale are more consistent with 1–3% (Mitrofanov et al., 2014; Sutter et al., 2017). For the proper comparison we setup the subsurface water concentration in our numerical model as

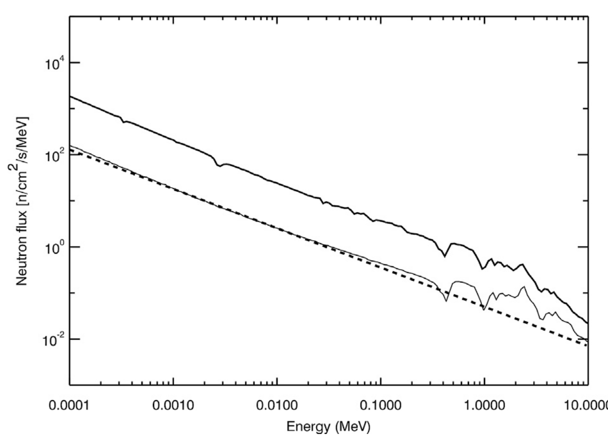

Fig. 5. Modeled neutron spectra on Mars orbit (thin line) and Mars surface (thick line) which are normalized to fit HEND/Odyssey and DAN/MSL measurements for the period Aug 2012–Aug 2013. The dash line represents neutron spectrum from a power law inversion of the HEND/Odyssey measurements.

4.5% by taking into account the real HEND surface footprint.

Numerical simulations offer absolute values of energy spectra of orbital and surface neutron fluxes. Their true normalization depends on how they could predict experimental counting rate measured by HEND/Odyssey and DAN/MSL. The convolution of the neutron flux with the HEND/Odyssey instrument response function has shown that the best correlation between the predicted and measured counting rates is achieved if the simulated neutron orbital spectrum is divided by a correction factor of 1.3. The neutron spectra in Mars orbit after this normalization is shown in Fig. 5.

It is known that at some energy ranges the shape of neutron spectrum (orbit or surface) could be approximated by a power law. HEND/Odyssey does not provide enough number of spectral measurements to reconstruct full variations of spectrum shape, but at some broad energy range starting from epithermal neutrons (~1e^{-4} MeV) up to the high energy epithermal and fast neutrons (0.1–0.5 MeV) the power law inversion of experimental measurements could be applied to predict the amplitude of neutron flux. It could be presented as

$$C = \int_{E1}^{E2} A \cdot E^{B}(E) \times Eff(E)dE \tag{3}$$

where C is the count rate, A and B are the free parameters of power law describing neutron energy spectrum and Eff is the instrument response function. The power law inversion is much easier than full path numerical modelling of experiment, and can provide verification of numerical procedure at relevant energy range.

Therefore, as a verification of our numerical analysis we have completed the power law inversion to derive orbital neutron spectrum and found that both approaches are in a very good agreement in energy range 10^{-4} – 0.5 MeV where the power law describing neutron leakage spectrum from the martian subsurface is applicable. This comparison is presented in Fig. 5.

Finally, verifying the spectrum deconvolution procedure we also investigated how the derived modeled surface neutron spectrum at the Gale crater with normalization of GCR flux could predict DAN/MSL passive (without artificial irradiation of underlaying subsurface by pulse neutron generator) measurements. The description of data reduction procedures and numerical simulations of DAN passive data are presented in (Jun et al., 2013; Tate et al., 2015). It was shown that in the passive operation mode DAN/MSL is measuring several components of neutron signal. First one is the direct response to the neutrons emitted by the Multi Mission Radioisotope Thermoelectric Generator (MMRTG) installed onboard the Curiosity rover. The MMRTG converts the heat produced in the radioactive α-decays of plutonium into the electrical power. The spontaneous fission neutron spectrum of MMRTG is well represented by a Maxwellian distribution $\sim\sqrt{E}e^{-E/T}$ where T = 1.34 MeV is the equivalent temperature of nucleus (described as a Fermi gas), see (Jun et al., 2013) for details of MMRTG spectrum evaluation. The special DAN calibration measurements during the prelaunch test at Kennedy Space Center have shown that the direct MMRTG component is about half of the counting rate measured by DAN on the martian surface. The remained fraction is produced by MMRTG neutrons backscattered in the martian subsurface and neutrons produced by GCRs (neutron leakage spectrum as illustrated on Fig. 3). In our analysis we found that the convolution of derived neutron energy spectrum with the DAN/MSL response function correlates with the expected component of DAN/MSL epithermal count rate (about 1 count per second) produced by GCR. In Fig. 5 we have shown derived neutron leakage spectrum on the Mars surface (Gale area) which fit the HEND and DAN experimental data.

After getting necessary information about the neutron energy spectra both in orbit and on the surface we now move to estimate of neutron dose equivalent rate.

Neutron spectrometers HEND/Odyssey and DAN/MSL were originally proposed and designed to search subsurface water and were not calibrated as neutron dosimeters. It creates some difficulties if conversions from neutron spectrum to absorbed dose or dose equivalent rate are needed. Relatively simple procedure in this situation is to use conversion coefficients (fluence per unit dose equivalent) formalized by regulatory agencies. We calculated dose equivalent by applying conversions coefficients recommended by the International Commission on Radiological Protection (ICRP) and International Commission on Radiation units & measurements (ICRU). It is explained by Eq. (4) where neutron dose equivalent rate (D) is calculated as an integral of the product of neutron energy spectrum *dN/dE(E)* and conversion coefficient *g(E)* over the selected energy rangy range.

$$D = \int_{E1}^{E2} \frac{dN}{dE}(E) \times g(E)dE \tag{4}$$

In our analysis we selected the energy band from low energy epithermal (~1 eV) up to fast neutrons (~10 MeV). It approximately corresponds to the sensitivity of HEND/Odyssey instrument. In this range we use the normalization of neutron spectra derived from agreement between the measured and simulated HEND/Odyssey count rates. Higher energy neutrons are theoretically more important for neutron dose equivalent rate, but the uncertainty will be very large. It is also known that above 10 MeV there are significant discrepancies between different numerical model predictions as well as between measurements (RAD/MSL) and commonly used numerical models (e.g., Planetocosmics) (Köhler et al., 2014).

The deconvolution from neutron fluence to equivalent dose should also account for angle distribution of incident neutron flux. Calculations of absorbed dose in human organs are usually performed in several standard geometries where irradiation comes from the front, from the back, and from the sides (lateral). These simple configurations are combined with complex ones where human body is rotating under neutron beam to simulate that irradiation may come from different directions (isotropic case). The neutron irradiation in Martian environment comes from different directions to an exposed body. That is why the isotropic conversion coefficients were selected for Eq. (4) to calculate neutron dose equivalent. It was shown that in such approach the neutron dose equivalent rate in Martian orbit could be estimated as 7.9 ± 1.2 μSv/d. It could be considered as a minimal value because it takes into account Mars neutrons only and neglect fast neutrons produced in the spacecraft body. For the Martian surface our estimate predicts 27 ± 4 μSv/d.

It is interesting to compare it with existing RAD/MSL estimations of radiation environment for charge and neutral (neutron and gammas) particles (Hassler et al., 2014; Guo et al., 2015b; Köhler et al., 2014, 2015). Regarding neutron measurements RAD/MSL is sensitive to the ~10–1000 MeV energy range. After correction to instrumental effects the RAD science team came to the conclusion that neutron equivalent dose rate in this energy range could be about ~25 μSv/d (previous estimate was about 60 μSv/d), see (Köhler et al., 2014; Guo et al., 2017). Our estimates came from the analysis of HEND data in energy range 1–10 MeV. The energy range 1–10 MeV is not as harmful as ultra-high energy neutrons measured by RAD/MSL but it deposits substantive portion of total neutron equivalent dose rate.

In this study we also have used another opportunity to use the availability of long term observations from Mars Odyssey and have estimated the maximum possible radiation dose, which could be observed within a solar cycle. The maximal values of Martian neutron flux should correspond to the minimum of solar activity and could be most likely deduced from the observations made during abnormal 24th solar cycle. GCR observations show that the period from September 2009 until January 2010 could be representative for such analysis (Usoskin et al., 2011; Herbst et al., 2010; Usoskin et al., 2017). For this period of time we repeated all procedures discussed above (except comparison with DAN/MSL which was not launched at that time yet) and evaluated neutron component of the radiation background in Mars orbit and on the surface. The estimates of GCR flux based on Earth network of neutron monitors show that solar modulation potential for this period could be adjusted as 190 MV(Garcia-Munoz LIS model). Using this value and performing a comparison with the HEND orbital observations we normalized the absolute value of neutron flux and concluded that neutron equivalent dose rates is about 13 ± 2 μSv/d in Mars orbit and 45 ± 7 μSv/d on the Martian surface. It is more than 1.5 times higher than averaged values observed within solar cycle.

5. Discussion and conclusions

We have used the data gathered by the HEND/Odyssey and DAN/MSL neutron spectrometers to evaluate the neutron component of radiation background both in Mars orbit and on the surface for different periods of solar cycle. The comprehensive numerical modeling of full path of neutron production and transport in Martian environments (subsurface and atmosphere) was implemented to derive the energy spectrum of Martian neutron flux. It was normalized to the absolute values via comparison with HEND/Odyssey and DAN/MSL measurements. Two time periods have been considered. The first one corresponds to one year of MSL surface operations starting from the landing event. It is roughly representative to the average values of GCR flux and Martian neutron albedo usually observed within a solar cycle. Another period was selected to analyze the maximum values of GCR flux (and as a result the maximum values of Martian neutron albedo) detected during abnormally low solar activity during the 24th solar cycle. This combination provides an opportunity to evaluate and study average and maximum neutron dose equivalent rates that future human expeditions may face.

We found that the average surface neutron dose equivalent rate at Mars equatorial latitudes (Gale as a test area) could be as large as 27 ± 4 μSv/d. For the most adverse periods when solar activity is lower and neutron flux is higher it may increase by 1.5 times. It is estimated only for the soft energy range below 10 MeV. The overall rate could be at least twice higher, which provides 6–7% of the charged-particle dose equivalent rate.

The Curiosity rover carries the dosimeter RAD which measures the fluxes of charge and neutral particles, which in turn can help reconstruct the corresponding radiation doses. Our estimates are complementary to this experiment because HEND/Odyssey, DAN/MSL and RAD/MSL are measuring neutrons in non-overlapping energy bands. We discovered that our estimates are higher than expected from the extrapolation of RAD/MSL data. We are in a good agreement with initial RAD/MSL estimates (Köhler et al., 2014), but significantly higher than the most recent ones (Guo et al., 2017). This deviation is mainly related with estimates of energy spectrum of neutron flux on the Mars surface. HEND/Odyssey and DAN/MSL data analysis suggests that the soft range of neutron spectrum (below 1 MeV) on the Mars surface should be twice more than what is expected from the extrapolation of hard band (>10 MeV) of Martian spectrum derived from the RAD/MSL data. It should be resolved by involving of additional analyses. New Martian missions could help resolve this discrepancy. TGO/ExoMars mission is an example which carry a collimated (spatial resolution 10 times better than HEND/Odyssey) neutron spectrometer FREND (Mitrofanov et al., 2018) and a charge particle dosimeter Liulin (Semkova et al., 2018). This mission already started its mapping on the Martian orbit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

M.L. Litvak: Conceptualization, Methodology, Software, Data curation. **A.B. Sanin:** Methodology, Software, Investigation. **I.G. Mitrofanov:** Validation. **B. Bakhtin:** Formal analysis, Visualization. **I. Jun:** Writing - review & editing. **L.M. Martinez-Sierra:** Writing - review & editing, Data curation, Formal analysis. **A.V. Nosov:** Data curation, Formal analysis. **A.S. Perkhov:** Data curation, Formal analysis.

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