RADIATION ENVIRONMENT IN THE INTERPLANETARY SPACE AND MARS ORBIT IN 2016-2020 ACCORDING MEASUREMENTS ABOARD EXOMARS TGO

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Abstract: *ExoMars is a joint ESA - Rosscosmos program for investigating Mars. Two missions are foreseen within this program: one consisting of the Trace Gas Orbiter (TGO), that carries scientific instruments for the detection of trace gases in the Martian atmosphere and for the location of their source regions, launched on March 14, 2016; and the other, featuring a rover and a surface platform, with a launch date of 2022. In March 2018 TGO was inserted into circular Mars science orbit with a 400 km altitude. The dosimetric telescope Liulin-MO for measuring the radiation environment onboard the ExoMars TGO is a module of the Fine Resolution Epithermal Neutron Detector (FREND). Here we present recent results from measurements of the charged particle fluxes, dose rates and estimation of dose equivalent rates at ExoMars TGO science orbit, provided by Liulin-MO dosimeter. The obtained data from May 2018 to October 2020 show that: 1) Increase of the dose rate, dose equivalent rate and flux is observed during this period, which corresponds to the increase of GCR intensity during the declining, minimum of the solar activity in 24th Solar cycle and transition to the 25th cycle; 2) A strong dependence of the measured fluxes on the part of the field of view (FOV) shadowed by Mars is observed, while the absorbed dose rate is not significantly affected by FOV shadowing; 3) A good agreement between the normalised GCR count rates from Liulin-MO and HEND neutron detector on Mars Odyssey is observed.*

Described is a method and results for recalculating the cosmic ray fluxes and doses measured in Mars orbit into values meaningful for the deep interplanetary space at about 1.5 AU. The effect of "shading" the particle flux by Mars, the albedo particles effect on the measured values and the effect of the detectors orientation are taken into account. The results demonstrate that the radiation conditions in the interplanetary space worsen in the minimum of the solar activity in 24th Solar cycle. The evaluations show that with respect to the values measured during TGO transit to Mars in December 2019 the particle flux has increased by 13% and the dose rate – by 18%. This increasing continues in January-October 2020 during the beginning of 25th Solar cycle.

The results obtained are of importance for planning the future manned missions to Mars.

Introduction

The exploration of Mars gets on a new wider scale nowadays. Six active satellites orbit around the planet and provide data. On Mars surface the MSL Curiosity rover [1] explores Gale crater for more than 7 years and the InSight lander [2] studies the interior of Mars. Four space agencies – NASA, ESA&Roscosmos, China and the United Arab Emirates – already launched or plan to launch missions to Mars during the 2020 and 2022. Knowledge of the space radiation environment in s/c transition to Mars, around Mars and on Mars surface becomes a significant factor in missions' planning.

In the interplanetary space and on Mars orbit the radiation field consists of two types of primary particles: galactic cosmic rays (GCRs) and solar energetic particles (SEPs). SEPs are sporadic and impulsive events and take place much more frequently during the active phase of the solar cycle. SEPs are mainly protons, electrons and α particles with energy typically ranging from 10 to several hundreds of MeV. GCRs generally originate from outside the Solar System, e.g. in supernova remnants, and their composition consists [3] mainly of protons (85%-90%) and helium (about 11%), with about 1% electrons and another 1% heavy ions. In the Solar system GCR flux is isotropic and in the long term their flux and spectra show modulation that anti-correlates with the solar activity, the modulation being more efficient to the low-energy GCR.

Only two experiments measured the radiation environment on a transit orbit to Mars: MSL RAD [4] and the FREND dosimeter Liulin MO on ExoMars Trace Gas Orbiter [5]. RAD measurements took place in the period from 6 December 2011 to 14 July 2012 – conditions of increasing solar activity. For solar quiet times (without SEPs) RAD reported an average daily dose rate in silicon 332 $\pm$ 23 μGy d^{-1} (including the contribution of secondaries from instrument's shielding). The fluence rate of GCR was 3.87 $\pm$ 0.34 cm^{-2} s^{-1} and the dose equivalent rate was evaluated to 1.84 $\pm$ 0.30 mSv d^{-1} [6]. The 4 SEP events during this period produced ~ 25 mGy, from 1.2 to 19.5 mGy/event.

During the transit to Mars, from 22 April to 15 September 2016 – conditions of decreasing solar activity – Liulin-MO measured average GCR dose rates in silicon of 372 $\pm$ 37 μGy d^{-1} and 390 $\pm$ 39 μGy d^{-1} in two perpendicular directions, the difference due to the different shielding of the telescopes. The average flux for the same time was 3.12 cm^{-2} s^{-1} and 3.29 cm^{-2} s^{-1} correspondingly. No SEP events were observed in this period. Data show that during the cruise to Mars and back (6 months in each direction), taken during the declining of solar activity, the crewmembers of future manned flights to Mars will accumulate at least 60% of the total dose limit for the cosmonaut's/astronaut's career in case their shielding conditions are close to the average shielding of Liulin-MO detectors, then evaluated to about 10 g cm^{-2}.

The first evaluation of the radiation field at Mars orbit was performed by the experiments on board of Mars Odyssey orbiter [7] using data of three different instruments: MARIE, a dedicated energetic charged particle spectrometer [8]; the Gamma Ray Spectrometer GRS [9] and the scintillator component of the High Energy Neutron Detector HEND [10, 11]. The time period analyzed data cover the time span from early 2002 through the end of May 2007, encompassing the maximum, the declining of Solar cycle 23 and most of the extraordinarily deep solar minimum. During a quiet period in 2002 the GCR flux was evaluated to be 0.135 cm^{-2} sr^{-1} s^{-1}. Weakening of the interplanetary magnetic field over this period of time led to an observed doubling of the galactic cosmic ray flux. 23 SEP events (with 25 peaks) were recorded during the period, the large majority of events were quite weak. Peak SEP fluxes between 50 and 100 cm^{-2} sr^{-1} s^{-1} were seen only twice (July 2002 and October 2002), and only in the large event of October 2003 was a flux above 1000 cm^{-2} sr^{-1} s^{-1} recorded. According to HEND data (Mitrofanov et al. 2009) the flux of the secondary (epithermal) neutrons from the Mars surface, produced by GCR only, has increased during this time period in about 1.5 times from 0.73 up to 1.1 cm^{-2} s^{-1}.

RAD on MSL is the only experiment measuring the complex radiation environment on Mars' surface. From 7 August 2012 to 1 June 2013 (solar maximum) the average dose rate (in water) from GCR was 210 μGy d^{-1}, the only SEP event delivered a dose of 25 μGy [6]. The dose rate in Si reached ~170 μGy d^{-1} at the end of February 2013 under very low solar modulation and gradually decreased to ~ 150 μGy d^{-1} in 2014 with increasing of solar modulation [12]. In 2017 the average dose rate in Si was 240 μGy d^{-1} and continued to increase, but rise appears to correlate with a decrease in the quality factor Q, likely due to changing in ion abundances [13]. The dose equivalent rate H decreased ~ 2 times compared to cruise. Increasing dose rate in Si with decreasing Q tends to keep H fairly constant. During the more of 7 years stay of Curiosity on Mars 5 SEP were observed. Most prominent was the September 2017 SEP event. The dose rate in Si peaked at 718 μGy d^{-1}, with an average rate during the SEP of 464 μGy d^{-1}. MSL RAD data exhibited diurnal variations, which allowed to investigate the dependence of the radiation dose on atmospheric pressure [14]. At the relatively low atmospheric pressures of Mars, the total dose rate increases (decreases) as pressure decreases (increases). Furthermore, the atmospheric shielding was found to be disproportionately effective on heavy ions - the heavy ions undergo much larger variation than the light ions.

The FREND instrument on ExoMars TGO measures epithermal and high energy neutrons, whose variations are an excellent signature of hydrogen bearing substances presence in the Mars regolith at up to 1 meter depth [15]. FREND provides high-resolution maps of hydrogen-abundant regions on Mars. FREND contains four ^{3}He counters for neutrons with energies from 0.4 eV to 500 eV, one stilbene-based scintilator for high energy neutrons (up to 10 MeV) and the dosimetry module Liulin-MO.

The FREND's dosimetry module Liulin-MO provided information about the radiation environment during the cruise stage of TGO and now - on Mars' orbit. In this paper we discuss the measurements in a Mars circular orbit with 400 km altitude obtained in the period from 1 May 2018 to October 2020 and compare with the measurements during the transit to Mars. We also compare the measured fluxes of GCR by Liulin-MO, FREND and HEND neutron detectors in Mars orbit.

Methodology, measured parameters and description of Liulin-MO

Liulin-MO contains two dosimetric telescopes - AB, and CD arranged at perpendicular directions. A schematic view of the location of the detectors inside the box of Liulin-MO is presented in Fig. 1. Each pair of the dosimetric telescopes consists of two 300 μm thick, 20x10 mm area rectangular Si PIN photodiodes. The distance between the parallel Si PIN photodiodes is 20.8 mm. The geometry factor [16] of the telescope for isotropic radiation is ~ 1.38 cm^2 sr.

The geometry factor of a single detector is ~ 12.56 cm^2 sr. The energy deposition spectrum in the single detector B(A) is obtained by combining the energy deposition spectrum measured by B in the range ~ 0.08 - 15.9 MeV with the energy deposition spectrum measured by A in the range ~ 16 - 190 MeV. The same procedure is used to obtain the energy deposition spectrum in the single detectors C and D. In that way each pair of two parallel detectors provide data in the energy deposition range ~ 0.08 - 190 MeV.

The parameters, provided by Liulin-MO simultaneously for two perpendicular directions BA and DC have the following ranges: absorbed dose rate from 10^{-7} Gy h^{-1} to 0.1 Gy h^{-1}; particle flux in the range 0 - 10^4 cm^{-2} s^{-1}; energy deposition spectrum in the range 0.08 - 190 MeV, linear energy transfer (LET) spectrum in water in the range 0.13 – 177 keV/μm. The dose rates and the fluxes are resolved every minute, while the energy deposition spectra and the LET spectra are resolved every hour.

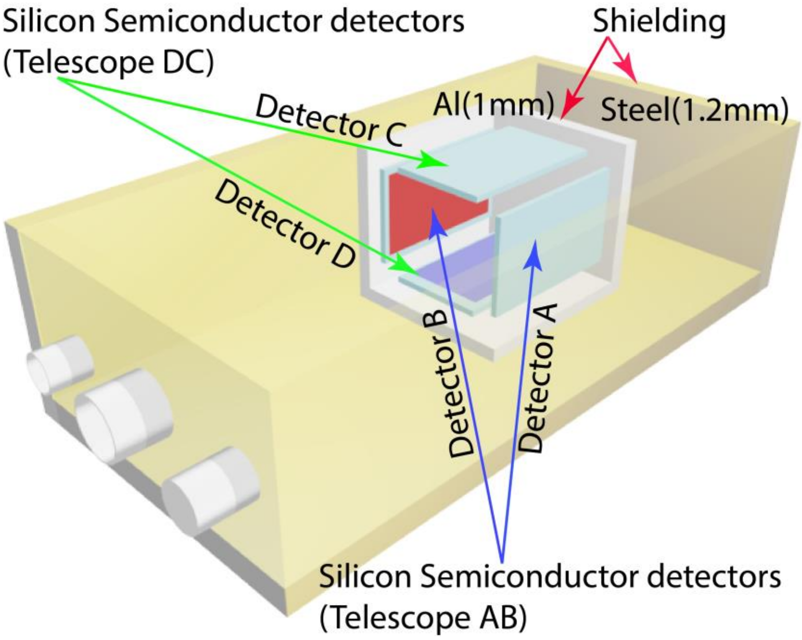

Fig. 1. A schematic view of Liulin-MO detectors' location in the dosimeter box. The upper steel cover of the Liulin-MO external box is not shown. The external box is made from steel 1.2 mm thick; the internal box with the detectors is made from aluminium 1 mm thick.

More detailed description of the measurement methodology and parameters of Liulin-MO may be found in [5].

In Mars science orbit (MSO) when TGO is pointed to nadir (along its Y axis), the angles of the dosimeter axes to the nadir are 90^0 (along - X and Z axes of TGO). This is the nominal orientation.

Periods and conditions at which the data have been collected

FREND and its dosimeter Liulin-MO were turned on for the first time on 6 April 2016 during initial check of the science instruments onboard TGO.

During TGO cruise to Mars in 2016 Liulin-MO operated nominally and gathered a good statistic of more than 3 months continuous measurements of galactic cosmic rays in free space. After TGO insertion in Mars high elliptic orbit Liulin-MO operated in all available for the science experiments periods - 2.5 months in Mars Capture Orbit 1 (also called Mars arrival orbit) (MCO1: 98 000 -230 km, 0^0 inclination to the equator, 4.2 days orbit period) and 10 days in MCO2 (37150 - 200 km, 74^0 inclination, 24 h 39 min orbit period). These measurements were performed during the declining phase of the 24^{th} Solar cycle. A detailed analysis of these data is published in Semkova et al., 2018.

On 15 March 2017 the aerobraking phase of TGO started and all science instruments were switched off.

TGO was inserted into Mars science orbit (MSO). MSO is a circular orbit with about 400 km altitude, 74^0 inclination, ~ 2 hours orbit period) on 9 April 2018. On 16 April 2018 FREND, including Liulin-MO was switched on and since then operates almost continuously.

Here were present the data obtained by Liulin-MO dosimeter in the period 1 May 2018 – October 2020, and compare them with data from previous periods of measurements. Data must be understood in the context of the shielding from the free-space radiation environment provided by the mass of materials surrounding the instrument's detectors. Previously [5] it was estimated that there are no significant differences in the shielding by FREND and the dosimeter itself of each of the four Liulin-MO detectors. Representative for the shielding of Liulin-MO detectors is the central point between the detectors located at equal distances from the detectors. The average shielding of Liulin-MO detectors provided by FREND structure was evaluated to be 10 g cm^{-2} in [5]. The shielding of Liulin-MO detectors caused by the dosimeter itself plus the rest of FREND modules plus TGO construction with the fuel quantity which remained at the beginning of the flight in a circular orbit around Mars has been evaluated recently. This shielding distribution for Liulin-MO detectors is between 1 g cm^{-2} and 180 g cm^{-2}. The average shielding integrated over the full distribution is about 20 g cm^{-2}. The shielding values are assumed to be aluminum-equivalent, the actual shielding consists of several different materials. The energy threshold for the minimum shielding is 1.7 MeV for electrons, 30 MeV for protons and 6.8 GeV for iron ions.

In MSO the dosimeter has measured the dosimetric parameters of GCR. SEP events were not registered. Measurements were taken near and during the minimum of the 24^{th} Solar cycle, its transition to the 25^{th} Solar cycle and the beginning of the 25^{th} cycle.

Liulin-MO data in TGO Mars science orbit and analysis

Particle fluxes, dose rates and dose equivalent rates

The fluxes and dose rates recorded in the perpendicular detectors B(A) and D(C) of Liulin-MO and count rates of Oulu neutron monitor (http://cosmicrays.oulu.fi/) for the period from 1 May 2018 to 10 June 2020 are shown in Fig. 2. The fluxes and dose rates are calculated from hourly measurements of the corresponding energy deposition spectra. An increase of all quantities – flux, dose rate and Oulu count rate due to solar cycle modulation is observed. In this period in two perpendicular detectors B(A) and D(C) the average values are: dose rate 14.8±1.5/15.4±1.5 μGy h^{-1}, planar flux 3.11/3.21 cm^{-2} s^{-1}. Here we calculate the planar flux as the number of particles, which hit a unit planar area. The observed narrow sharp drops of the measured flux will be discussed below. The short term modulations of GCR fluxes and dose rates have the same characteristics as those registered during TGO cruise. The latter were analysed in details in [17], where it was shown that they were due to the interaction of GCR with the corotating interaction regions (ICR) of the solar wind. Note that in summer 2018 (near opposition) Earth and Mars are in close interplanetary magnetic field lines and ICR reach Mars (Liulin-MO) and Earth (Oulu) nearly simultaneously. After that period one and the same ICR reaches both planets in different times.

An increase of all quantities – flux, dose rate and Oulu count rate due to solar cycle modulation is observed. The increasing is slightly different for the different values. Liulin-MO monthly mean quantities show an increase of about 7% - 7.6%, while Oulu count rate increases only by ~ 1.1%. Solar activity modulates strongly the low energy GCR. Oulu is situated at 64.5^0 geomagnetic latitude and its effective cut off rigidity is ~ 0.8 GV, so the most sensitive to the solar activity low energy GCR do not reach it. The decrease in Oulu count rate around 10 May 2019 is due to two coronal mass ejections arriving at Earth but not hitting Mars as modelled using the WSA-Enlil model showed (http://iswa.ccmc.gsfc. nasa.gov/). The small difference between the corresponding values of the dose rates and fluxes in B(A) and D(C) is due to the different locations of the two telescope detectors. The sensitive area of D and C detectors is located parallel and just beneath the FREND collimator and beneath a massive spacecraft structure. Due to this location more secondary particles, generated in these considerable masses, hit D and C than B and A detectors and contribute to the higher doses and count rates in D(C) compared to B(A).

An evaluation of the LET spectra and the radiation quality factor was performed, and the dose equivalent rates were obtained from the measurements taken between 1 May 2018 and 10 June 2020. The methodology described in [5] was applied. We use the energy deposition spectrum in the single detectors B(A) and D(C), and evaluate the LET spectra in the directions BA and DC, assuming a mean path length 600 μm of a particle trough the 300 μm thick detector.

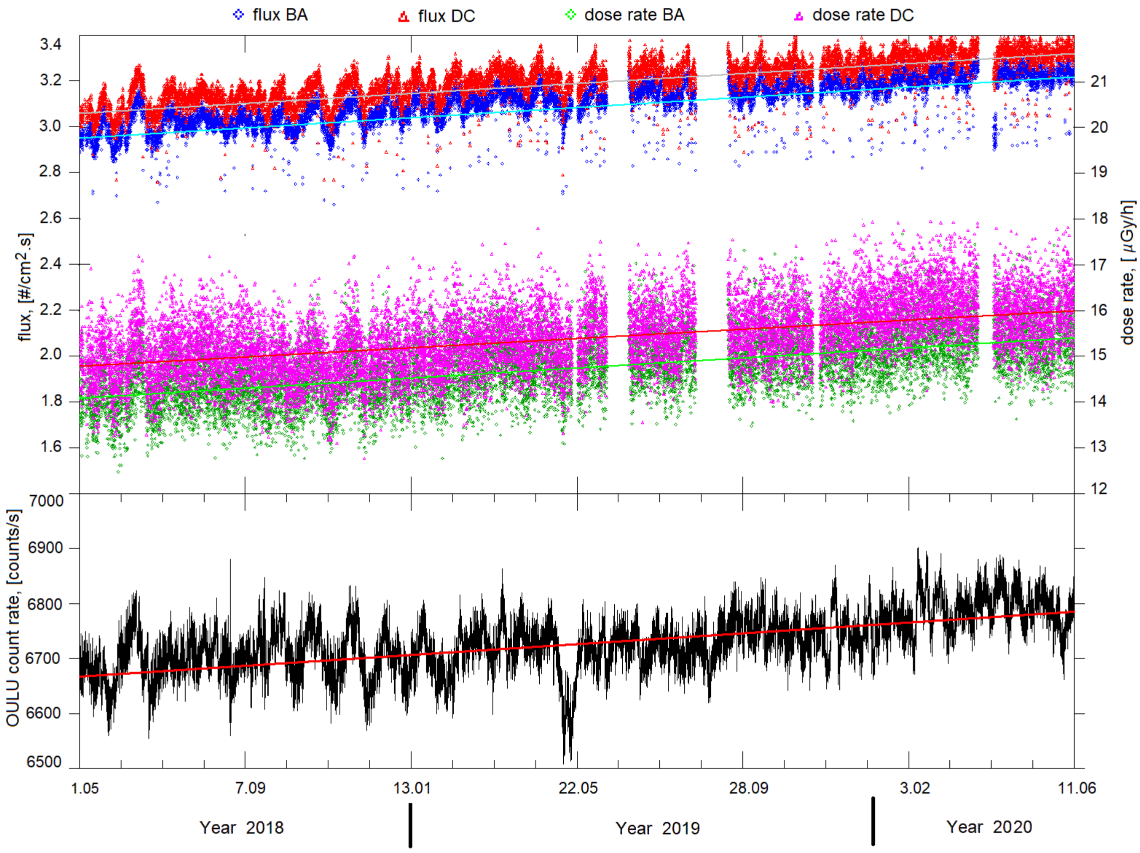

Fig. 2. Overview of GCR fluxes (top) and dose rates (middle) measured by Liulin-MO in Mars science orbit and Oulu neutron monitor count rates (bottom) in the period 01.05.2018 – 10.06.2020

Like in [5] to convert the dose rate measured in silicon to dose rate in water and relate *dE/dx* in silicon to LET in water we used a factor of 1.3 ± 0.08. We used the resulting LET spectra to obtain the average quality factors Q. It was found that for GCRs, quality factor Q is 3.5 ± 0.26, (for comparison during the transit to Mars in April-September 2016 Q was 4.08 ± 0.3 in BA direction and 4.02 ± 0.3 in DC direction). After conversion of the dose rate in silicon to a dose rate in water and multiplying by Q it was found that in BA direction the average dose equivalent rate is 1.61 ± 0.33 mSv d^{-1}, in DC direction the dose equivalent rate is 1.66 ± 0.34 mSv d^{-1}.

Mars shading effect on GCR flux and dose rate

In Mars circular orbit the planet shades single detectors' field of view (FOV), thus cutting part of GCR flux. The cut part of FOV is an angle dependent on TGO orientation and its altitude. TGO orientation can vary by 180^0 though not often; TGO altitude varies within 50 km in every orbital pass. We investigate the dependence of the flux and dose rate measured by Liulin-MO on the distance of TGO from Mars and the orientation of dosimeter detectors.

When calculating the effect of shading we neglect the size of the detector and take into account only its orientation and the distance to Mars. The principal configuration is shown in Fig. 3 [18]. Let $j(\theta, \varphi)$ denotes the differential flux and F_{sh} - the part of GCR flux shaded by Mars. Then

(1) $$F_{sh} = \int_0^{2\pi}\int_0^{\theta_1} J(\theta,\varphi)|\cos\theta'|\sin\theta\, d\theta\, d\varphi$$

where Θ' is the angle between the normal to the plane of the detector and the differential flux, Θ_0 is the angle between the normal and the Mars direction, $\Theta = \Theta_0 - \Theta'$,

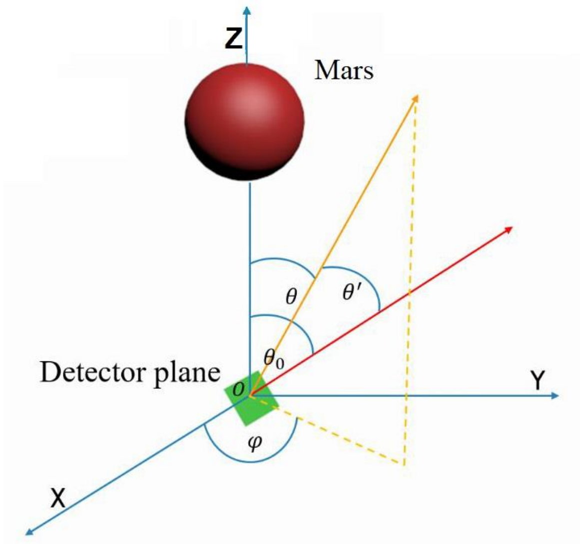

Fig. 3. Scheme for calculation of the shading effect by Mars of GCR flux. The red line marks the normal to the detector plane, θ' is the angle between the normal and the differential flux, θ_0 is the angle between the normal and Mars direction.

(2) $$\sin\theta_1 = \frac{\text{Mars radius}}{\text{Distance to Mars}}$$

We define the shading coefficient K_{sh} as

(3) $$K_{sh} = \frac{F_{sh}}{2\pi J(\theta, \varphi)}$$

The comparison of the experimental flux and dose rate data with the analytical estimates of the shadow coefficient is shown in Fig 4. From top to bottom are plotted: particle dose rate measured by B(A) detectors from 8 July to 9 July 2018; the particle flux measured by the same B(A) detectors;

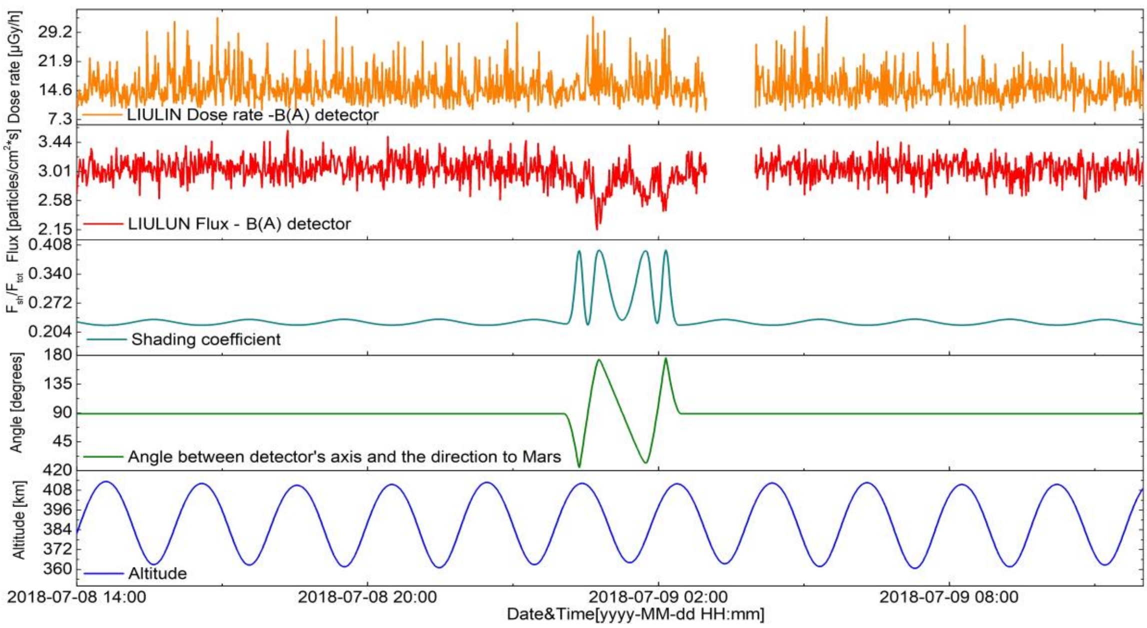

Fig. 4. Comparison of the experimental dose rate and flux data with the analytical estimates of the shadow coefficient. From top to bottom are plotted: minute values of the dose rate measured by B(A) detectors from 8 July to 9 July 2018; minute values of the particle flux measured by the same detector; the shading coefficient; the angle between detector's axis and Mars direction; the altitude of TGO.

the shading coefficient; the angle between detector's axis and Mars direction; the altitude of TGO. Most of the time the angle between detector's axis and Mars direction is ~ 90^0 and the shading effect is about 0.23, the change in the altitude results small variations in the shading coefficient K_{sh}. The narrow sharp drops of the measured flux coincide with the increases of the shading effect up to about 0.4 due to changing of the angle between detector's axis and Mars direction.

It can be seen that, as a first approximation, the absorbed dose depends insignificantly on the change of the shading coefficient. Two mutually compensating effects can explain the above peculiarity. When the detectors normal is perpendicular to the nadir to Mars – we call this 'nominal position' - the planet blocks GCR particles that would hit the detectors at sharp angles. These particles would have a small effective area on the detectors and would contribute less to the registered particle flux but their path in the detector would be long thus contributing more significantly to the absorbed energy. In case when the detector normal is parallel to the nadir, the hampered GCR particles would hit the detectors at small angles with considerable absorbed energy. As a result the decrease in the dose rate is insignificant when compared to the dose rate measured in nominal position.

Comparison of the radiation values obtained during different phases of TGO mission

Table 1 presents particle fluxes, dose rates in silicon, Q and dose equivalent rates measured during different phases of TGO mission since 22 April 2016 to 20 October 2020. In TGO science orbit in May 2018 - December 2019, the flux is about 92%, the dose rate is about 86%, the dose equivalent rate is 71% of those in February - March 2017 in MCO2- due to two competing effects: the Mars' shadow of GCR and the increase in GCR flux because of the decreased solar modulation. Since December 2019 to October 2020 already at the beginning of ascending phase in 25th Solar cycle, the flux and dose rate in MSO continue to increase. During the first weak of measurements from 22 to 29 April 2016 at average distance of TGO to Sun 1.094 AU the averaged values measured by detectors B(A)/D(C) and the corresponding calculated quantities were (not shown in Table 1): flux – 3.01/3.17 cm^{-2} s^{-1}; dose rate – 358/378 μGy d^{-1} (± 10% error) and dose equivalent rate 1.91/1.96 mSv d^{-1} (± 20% error). For the last period of the transit to Mars (in MCO2 at average distance to Sun 1.47 AU, when all measurements at distances less than 1500 km to Mars are excluded, the averaged values measured by detectors B(A)/D(C) and the corresponding calculated quantities were (also not shown in Table 1): flux – 3.28/3.43 cm^{-2} s^{-1}; dose rate – 413/427 μGy d^{-1} (± 10% error) and dose equivalent rate 2.32/2.31 mSv d^{-1} (± 20% error). Thus during 10.5 months transit to Mars in the decreasing phase of the Solar cycle, when the solar modulation considerably decreases, we observe about 8.2 - 9% increase in GCR flux of which about 1.7% could be due to the increase of the heliocentric distance [19]), 13.1 - 15.3% increase of dose rate and 17.9 - 21.5% increase of dose equivalent rate.

Table 1. Particle fluxes, dose rates in silicon, Q and dose equivalent rates measured during different phases of TGO mission since April 22, 2016 to October 20, 2020

Time frame/TGO phase	F (BA)/ F (DC) #cm $^{-1}$s $^{-1}$	D(Si) (BA)/ D(Si) (DC) μGy d^{-1}	Q(BA)/ Q(DC)/	H (BA)/ H (DC) mSv d^{-1}
22 April - 15 September 2016/ Cruise	3.12/ 3.29	372 ± 37/ 390 ± 39	4.08 ± 0.3/ 4.02 ± 0.3	1.97± 0.4/ 2.04± 0.4
1 November 2016 – 17 January 2017/ MCO1	3.26/ 3.42	406 ± 41/ 422 ± 42	4.23 ± 0.33/ 4.12 ± 0.3	2.23± 0.5/ 2.26± 0.5
24 February – 7 March 2017/ MCO2	3.28/ 3.43	410 ± 41/ 425 ± 42.5	4.31 ± 0.33/ 4.17 ± 0.3	2.3± 0.55
1 May 2018–10 December 2019/ Mars' Science Orbit	3.08/ 3.18	352±35/ 366±36	3.49±0.26/ 3.47±0.26	1.6±0.33/ 1.65±0.34
1 January 2020- 20 October 2020/ Mars' Science Orbit	3.22/3.31	370±37/ 387±39	3.47±0.26 /3.44±0.25	1.67±0.34/ 1.73±0.35

Time profiles of particles measured by Liulin-MO and neutron detectors on Mars orbit

We have compared time profiles of particles and neutron detections from Liulin-MO, FREND/TGO and HEND onboard Odyssey spacecraft measured for the same period of time (2 May 2018 – 2 January 2020). Similar to FREND, HEND/Odyssey is a neutron spectrometer based on ^{3}He proportional counters but with smaller sensitivity and without collimation as in FREND [10, 11]. For the comparison with Liulin-MO we have selected FREND and HEND count rates measured in ^{3}He detectors.

The ^3He nucleus has a large cross section for capture of low-energy neutrons in the reaction $n + ^3He \rightarrow ^3H + p$ + 764 keV. The shape of pulse height spectrum measured in ^3He detector does not depend on the energy of incident low-energy neutron. Low energy part of the spectrum presents detections when proton or triton reaches detector's wall and as result not all released energy was deposited in the detector volume. The proportional counters are also sensitive to the detections of GCR charge particles. Due to ionization losses these particles could deposit a part of its energy in low spectral channels.

In Figure 5 is shown the comparison between the normalised (relatively to the mean daily value for the full period) daily mean Liulin-MO data and HEND data accumulated in energy channels 1 – 8, most sensitive to the charge particles of GCR. These profiles demonstrate good correlation both on a local time scale (days) and long term scale (months). The total amplitude of variations observed during 20 months of TGO mapping is about 8%.

In addition to that, Fig. 6 presents the comparison between the normalised FREND total counts rate and HEND data accumulated in the energy channels 9 – 16, mostly populated with counts from Martian neutron albedo (which is produced by GCR by interaction with matter in the shallow

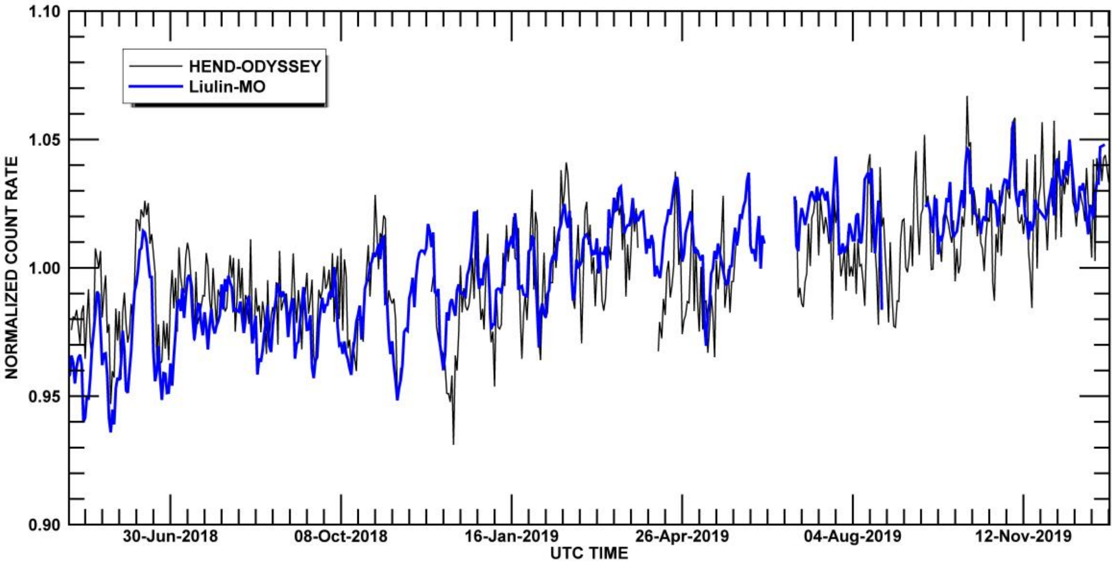

Fig. 5. Time profiles of GCR daily variations measured by Liulin-MO and HEND/Mars Odyssey during May 2018 – December 2019. Energy channels 1 – 8 of HEND are selected as the most sensitive for GCR.

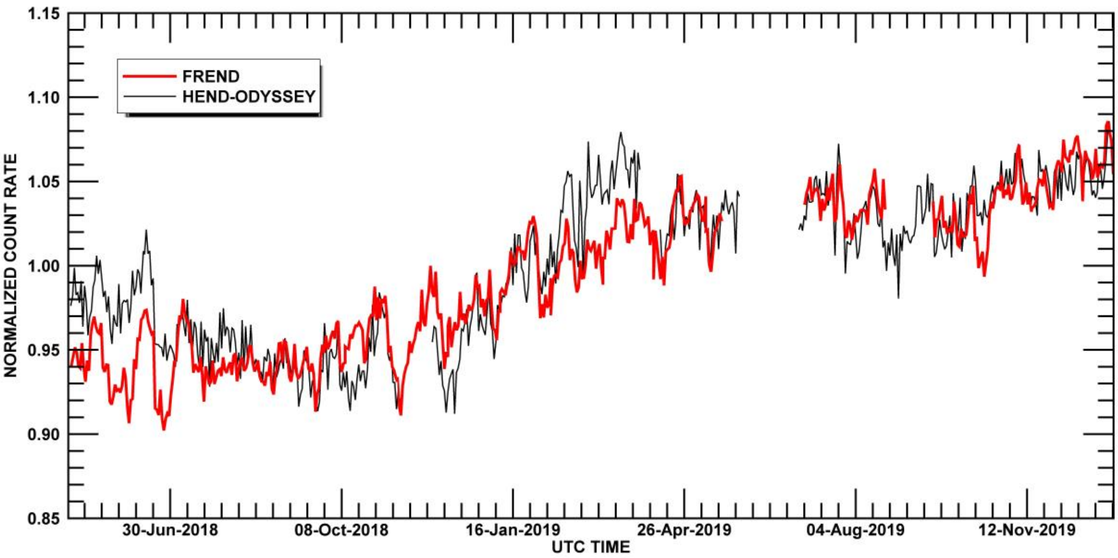

Fig. 6. Time profiles of Mars neutron albedo variation measured during TGO mapping by FREND and HEND/Odyssey. Energy channels 9 – 16 of HEND are selected as the most sensitive for neutron albedo of the Martian surface.

subsurface). The time period is the same as in Fig. 5. These curves also show high correlation with each other both on short and long term scales.

The difference in the long term variations between profiles at Fig. 5 and Fig. 6 is obvious. It might be addressed to how the solar modulation changes directly the flux GCR (Fig. 5) and how it changes emission of neutron albedo by interaction with a matter in the Martian shallow subsurface (Fig. 6).

Galactic cosmic rays parameters in deep space at about 1.5 AU

One of the science objectives of Liulin-MO is together with the neutron detectors of FREND to provide data for verification and benchmarking of the radiation environment models and assessment of the radiation risk to the crewmembers of future exploratory flights.

To achieve this objective Liulin-MO data measured on Mars circular orbit (400 km altitude) should be extrapolated to deep space, i.e. corrected for the shading of the detectors and for the presence of Mars (shading of the GCR flux from Mars and the contribution of albedo particles from Mars atmosphere and surface). The effect from Mars shading was already discussed above. Here we will discuss the contribution of the albedo particles.

To account for the albedo particles contribution we used the measurements conducted near the pericenter in high elliptic TGO orbit [20]. In Fig. 7 on the top are plotted the flux (left) and dose rates (right) measured by Liulin-MO on 25 February 2017 near and at the pericenter of TGO. On the

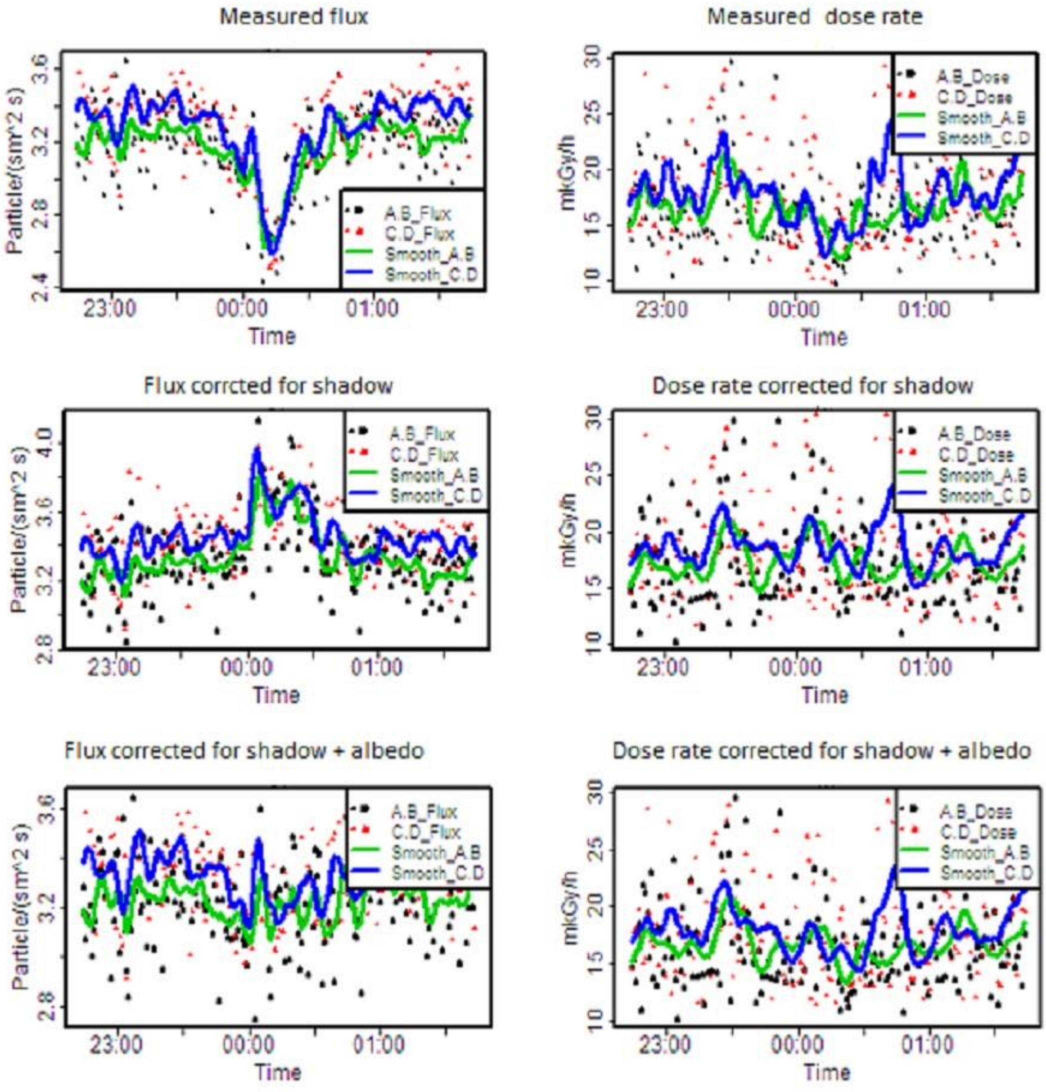

Fig. 7. Top: the flux (left) and dose rates (right) measured by Liulin-MO on 25 February 2017 near and at the pericenter of TGO; middle plots: the same values corrected by a simple geometrical correction of FOV shading by Mars; bottom: the same values corrected for the FOV shading and for the albedo particles.

middle plots are plotted the same values corrected by a simple geometrical correction of FOV shading by Mars. The result from this correction systematically overestimates the flux. We interpret this overestimation as a consequence of the presence of albedo radiation in the measured flux. A statistical study gives albedo contribution of 6 – 12 percents. As a zero approximation we assume that in Mars orbit the flux is 0.88 of the flux in deep space and the dose rate is 0.82 from that in deep space. This estimation is based on analyses of all 38 cases of data available for pericenter crossing during aerobraking phase in MCO1 and MCO2. On the bottom plot in Fig. 7 are shown the flux and dose rate corrected for the FOV shading and for the albedo particles, i.e. these are the flux and dose rate in free space at about 1.5 AU. A more detailed approach for assessment of the albedo particles contribution is in progress.

Using the described procedure we had calculated monthly mean values of fluxes and dose rates in free space at about 1.5 AU for each detector. Calculations were carried out both for a full sample of data for the month, and with the removal of variations due to changes in the orientation of the spacecraft. The difference in the results due to changes in the orientation of the spacecraft did not exceed 0.2%. In Fig. 8a and 8b are presented the GCR fluxes and dose rates, measured by detectors B(A) and D(C) during the cruise phase and in Mars science orbit and recalculated to values in the free space at about 1.5 AU for Mars science orbit under 20g cm^{-2} Al shielding.

Worsening of the radiation conditions in interplanetary space

Our data give the possibility to evaluate the effects of GCR increase due to the decreasing of solar activity.

Table 2 demonstrates the increase of the GCR flux and dose rates measured in December 2019 relatively to those measured during the previous periods of TGO mission and comparison with the values measured in September - October 2020. The data on Mars orbit are recalculated for deep space accounting for Mars shading and albedo, as described in the previous section under the ‘most

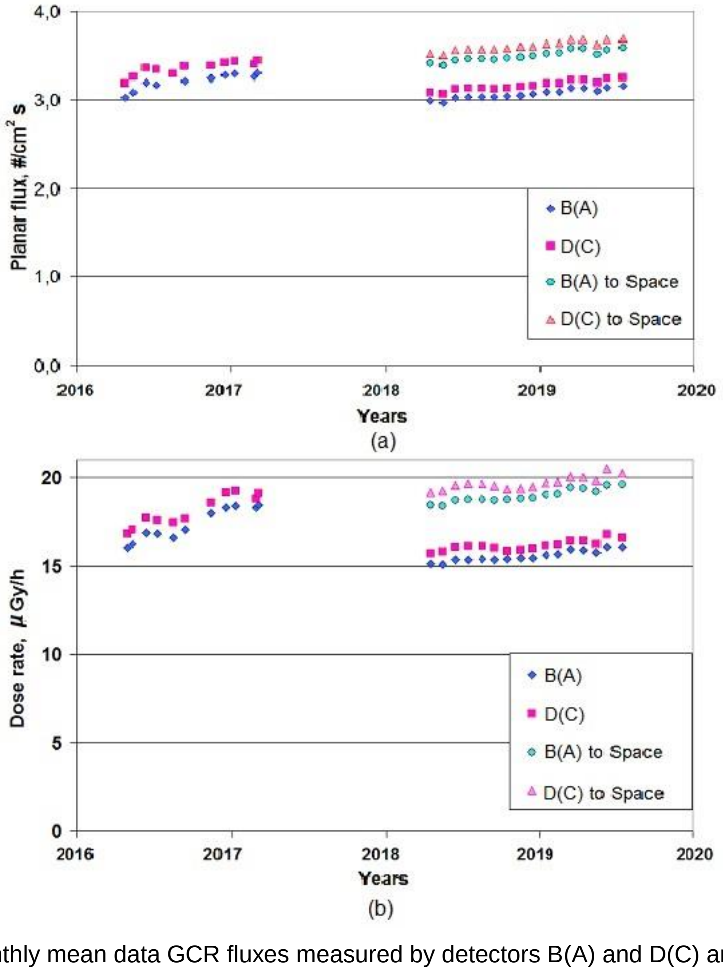

Fig. 8. a) Monthly mean data GCR fluxes measured by detectors B(A) and D(C) and recalculated to values in free space; b) Monthly mean data GCR dose rates, measured by detectors B(A) and D(C) during the cruise phase and in Mars science orbit and recalculated to values in free space at about 1.5 AU.

favourable condition’, when the contribution of the albedo particles to the measured flux is in the order of 11% leading to the least flux in free space.

The obtained data show that the radiation conditions in the interplanetary space worsen with approaching the minimum of the solar activity. From December 2019 to October 2020 at the beginning of 25th Solar cycle the dose rate and flux continue to increase, though very slight.

Table 2. Increase of the GCR flux and dose rates in the measured in December 2019 in detector D(C) relatively to those measured during the previous periods of TGO mission The last column shows the values obtained in September - October 2020. The data in Mars orbit are recalculated to values meaningful for the free space.

December 2019 to	22 April – 15 September 2016 Cruise	1 November 2016 – 17 January 2017 MCO1	24 February – 7 March 2017 MCO2	May 2018	September – 20 October 2020 MSO
Flux 3.73 $cm^{-2}s^{-1}$	13 %	9.7 %	9 %	7.2 %	Flux 3.75 $cm^{-2}s^{-1}$
Dose rate 19.3 μGy h^{-1}	18 %	9 %	9 %	9.2%	Dose rate 19.6 μGy h^{-1}

Conclusion

We presented and discussed the data obtained by Liulin-MO dosimeter of FREND instrument onboard ExoMars TGO in Mars circular orbit in the period 1 May 2018 – 20 October 2020 and compared them with data from previous periods of its measurements and with data from neutron detectors on Mars orbit. Our results are representative for the GCR flux and dose rates behind 20 g cm^{-2} of Al shielding. The results are:

1) From May 2018 to December 2019 increase of the dose rate, dose equivalent rate and flux is observed, which corresponds to the increase of GCR intensity during the declining and minimum of the solar activity in 24th Solar cycle. Measurements in two perpendicular directions along axes -X and Z of TGO show that the average fluxes for the period are 3.08 and 3.18 cm^{-2} s^{-1}, the average dose rates are 352 ± 35 and 366 ± 36 μGy day^{-1}, the average dose equivalent rates are 1.6 ± 0.33 and 1.65 ± 0.34 mSv day^{-1}, the average values for Q are 3.49 ± 0.26 and 3.47 ± 0.26 respectively. From January 2020 to October 2020 at the beginning of 25th Solar cycle the dose rate and flux continue to increase slightly.

2) A strong dependence of the measured fluxes on the part of the field of view shadowed by Mars and particularly on the orientation of Liulin-MO detectors is observed. There is no significant dependence of the absorbed dose rate on detectors’ shading.

3) Compared are time profiles of particles and neutron detections from Liulin-MO, FREND/TGO and HEND/Odyssey measured from 2 May 2018 to 2 January 2020. The time profiles of GCR daily variations measured by Liulin-MO and HEND demonstrate good correlation both on a local time scale (days) and long term scale (months). The comparison between the normalised FREND total counts rate and HEND data accumulated in the energy channels mostly populated with counts from Martian neutron albedo also show high correlation with each other both on short and long term scales. The difference in the long term variations between the profiles of GCR and neutron albedo might be addressed to how the solar modulation changes directly the GCR flux and how it changes emission of neutron albedo by interaction with a matter in the Martian shallow subsurface.

4) Developed is a method for evaluating the cosmic ray fluxes and doses meaningful for the deep interplanetary space at about 1.5 AU from values measured in Mars orbit. The effect of shading the primary GCR particle flux by Mars and the albedo particles effect on the measured values are taken into account. Using this method the flux in deep space at about 1.5 AU in December 2019 is estimated to be 3.73 $cm^{-2}s^{-1}$, the dose rate is 463 μGy day^{-1}. With respect to the values measured in April - September 2016 during TGO transit to Mars in December 2019 the particle flux in detector D(C) has increased by 13% and the dose rate – by 18%, showing the worsening of the radiation conditions while approaching the 24th Solar cycle minimum. In September-October 2020 the particle flux has increased by 0.5% and the dose rate – by 1.5% compared to December 2019, showing that an improvement of the radiation conditions in the free space at the beginning of 25th Solar cycle is not observed. Very similar are the results from the perpendicular detector B(A).

The obtained results may be used for benchmarking of the space radiation environment models and for assessment of the radiation risk to future manned missions to Mars.

A similar to Liulin-MO module, called Liulin-ML for investigation of the radiation environment on Mars’ surface as a part of the active detector of neutrons and gamma rays ADRON-EM is expected to be launched on the ExoMars Surface Platform in 2022.

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