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Radiation Conditions in Mars Vicinity during Different Phases of the Solar Cycle According Measurements by Liulin-MO Dosimeter aboard the Trace Gas Orbiter

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Abstract

Presented are the results for the dose rates and particle fluxes of the galactic and solar cosmic rays in the interplanetary space at about 1.5 AU and in Mars orbit at 400 km altitude, obtained during different phases of solar cycles 24 and 25, in the period April 2016 - May 2025. Data are provided by the Liulin-MO dosimeter aboard ExoMars Trace Gas Orbiter. Discussed is the selection of the best time interval in the solar cycle for a future manned trip to Mars, regarding the radiation safety. The obtained results may be used for verification and benchmarking of the galactic and solar cosmic rays models in free space and in Mars orbit.

Keywords: space radiation measurements; galactic and solar cosmic rays; Mars

1. Introduction

Mars is an ambitious target for future human exploration. The radiation environment during the transit and in Mars vicinity can be very hazardous for future human missions to the planet [Miroshnichenko and Petrov, 1985; Shafirkin and Grigoryev, 2009; Cucinotta, 2015]. In the interplanetary space and at Mars orbit the radiation field consists of two types of primary particles: galactic cosmic rays (GCR) and solar energetic particles (SEPs). GCR are a permanent source of radiation hazard in space. In the Solar system GCR flux is isotropic and their flux and spectra show a long term modulation that anti-correlates with the solar activity. The spectrum of the GCR is wide in both composition (from protons to the heaviest nuclei) and energies (from a few keV to 10^{21} eV) [Potgieter, 2013]. Radiations induced by GCR nuclei, especially those with high energy (e.g., protons above 100 MeV) and high charge ions, remain one of the major concerns in the planning of long-term deep-space human and robotic missions [Townsend et al., 1994; Cucinotta et al, 2013; Dachev et al, 2020; Guo et al, 2021]. SEP events are transient injections into the heliosphere of protons, electrons, and higher mass charged particles with a wide range of energies (tens of keVs to GeVs), spectra, compositions, and intensities. They follow energetic solar eruptions that are generally associated with flares and coronal mass ejections [Reames, 2013; Velinov et al, 2013]. SEP events take place much more frequently during the increasing phase of the solar cycle. Typical SEPs are known to pose a small health risk to astronauts and can be effectively attenuated by using relatively thin shielding materials, even though they can influence mission planning or interfere with mission activities such as extravehicular activities. Previous investigations based on calculations show that the expected doses to a future manned trip to Mars with start at the solar maximum are significantly lower than the doses to be obtained during other phases of the solar cycle [Shafirkin and Grigoryev, 2009; Cucinotta, 2015]. Nevertheless, although rare, large SEP events can be lethal [Committee for Evaluation of Space Radiation Cancer Risk Mode, 2012].

The Trace Gas Orbiter (TGO) spacecraft launched in March 2016 carries the Fine Resolution Epithermal Neutron Detector (FREND) instrument [Mitrofanov et al, 2018]. The Liulin-MO dosimeter is a FREND module which has provided and is providing in-situ measurements of the radiation environment during the TGO interplanetary travel and at Martian orbit [Semkova et al, 2018].

Liulin-MO data about the radiation environment during TGO cruise to Mars and in high elliptic Mars orbits (Mars capture orbits MCO1 with 98000 - 230 km altitude and MCO2 with 37150 - 200 km altitude) were taken in the period from April 2016 to March 2017. Since May 2018 Liulin-MO investigates the radiation conditions at Mars science orbit (MSO), which is a circular orbit with 400 km altitude (varying within ±25 km in every orbital pass), 74^0 inclination, ~ 2 hours orbit period.

Liulin-MO measurements to date cover the decreasing and minimum phases of the solar activity in solar cycle 24 and the rising phase, maximum, and decreasing phase near the maximum of cycle 25. Up to July 2021, the dosimeter measured the dosimetric parameters of GCR in the interplanetary space and at TGO Martian orbit, without registering any SEP events. The highest values of the dose rate and flux from GCR in MSO were registered from March to August 2020. Since July 2021, during the increasing phase and at the maximum of solar cycle 25, a number of SEP events have been observed at TGO MSO. Some of the investigated SEP events contribute significantly to the radiation environment at Martian orbit. The most powerful SEP event registered up to now at TGO orbit started on 20 May 2024. The maximum dose rate during this SEP event was 2800±280 µGy h^{-1} and the maximum particle flux – 383±19 cm^{-2} s^{-1}. The total dose from SEPs for this SEP event was 24.7±2.5 mGy - equal to the dose from the GCR received for about 200 days at this phase of solar cycle 25, the SEPs dose equivalent for the entire event is 43.7±8.7 mSv - approximately the dose equivalent received for 57 days from GCR [Semkova et al, 2025]. The other very strong SEP event was observed on 15 February 2022 – it is about twice weaker than the event of 20 May 2024 [Semkova et al, 2022a; Semkova et al, 2023].

One of the scientific objectives of the Liulin-MO investigations is 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 [Semkova et al, 2018].

Models of GCR describe their spectra and intensity in free space, away from any celestial body.

To use Liulin-MO data measured at MSO for verification and benchmarking of the radiation environment models and assessment of the radiation risk in free space, the effect of Mars presence on the measured fluxes and dose rates in TGO MSO has to be accounted. In MSO the planet shades single detectors' field of view (FOV), thus reducing part of free-space GCR flux. The shaded part of FOV is an angle dependent on TGO orientation and altitude. TGO altitude varies within 50 (±25) km in every orbital pass. In previous works the shading effect of Mars for different orientation of TGO, and the contribution of albedo particles and gamma rays from Mars atmosphere and surface to the measured particle fluxes and dose rates by Liulin-MO at TGO MSO were estimated [**Krastev et al, 2019;** Semkova et al, 2022b**].**

In this paper we present and discuss the results for the charged particle fluxes and dose rates at 1.5 AU during different phases of the solar activity cycle based on measurements by the Liulin-MO dosimeter on TGO.

2. Instrumentation and method for calculation of the dose rate and particle flux of cosmic rays in free space at 1.5 AU based on measurements by Liulin-MO dosimeter on TGO at MSO

Liulin-MO contains two dosimetric telescopes –BA and DC, arranged at perpendicular directions [Semkova et al, 2018]. A schematic view of the location of the detectors inside the Liulin-MO box is presented in Figure 1a. Each pair of the dosimetric telescopes consists of two 300 µm thick, 20x10 mm area rectangular Si PIN photodiodes-– A, B, C and D. The parallel detectors A and B make up the BA telescope, detectors D and C make the DC telescope. One of the detectors in each pair of parallel detectors and its corresponding electronics measures the energy deposition spectrum in the range ~ 0.08÷18 MeV. Those are detectors B and D. The other detector in each pair of parallel detectors measures the energy deposition spectrum in the range ~ 0.3 ÷ 190 MeV. Those are detectors A and C. The energy deposition spectrum in the single detector named further B(A) is obtained by combining the energy deposition spectrum measured by B in the range of ~ 0.08 - 15.9 MeV with the energy deposition spectrum measured by A in the range of ~ 16 - 190 MeV. The same procedure is used to obtain the energy deposition spectrum in the single detector D(C). In that way, each pair of two parallel detectors and their corresponding electronics provide data in the energy deposition range of ~ 0.08 - 190 MeV.

Using the energy deposition spectrum in the detectors one can calculate the dose rate *D*, particle flux *F*, linear energy transfer, and to obtain the radiation quality factor <*Q*> and the biologically significant dose equivalent rate. We calculate the flux as the number of particles crossing a unit plane of one square centimeter during one second.

In this paper we use and discuss the parameters provided by the single detectors B(A) and D(C) in the two perpendicular directions BA and DC.

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. The shielding distribution covers a thickness range from 0.9 to 178 g cm^{-2}. The mean shielding is about 20 g cm^{-2} [Semkova et al, 2021]. The energy threshold for the minimum shielding is 1.7 MeV for electrons, 30 MeV for protons and 6.8 GeV for iron ions.

At MSO when TGO is pointed to nadir (along – Y axis), the angles between the detector's axes and the nadir direction are 90^0 (Figure 1b). In this 'nominal'

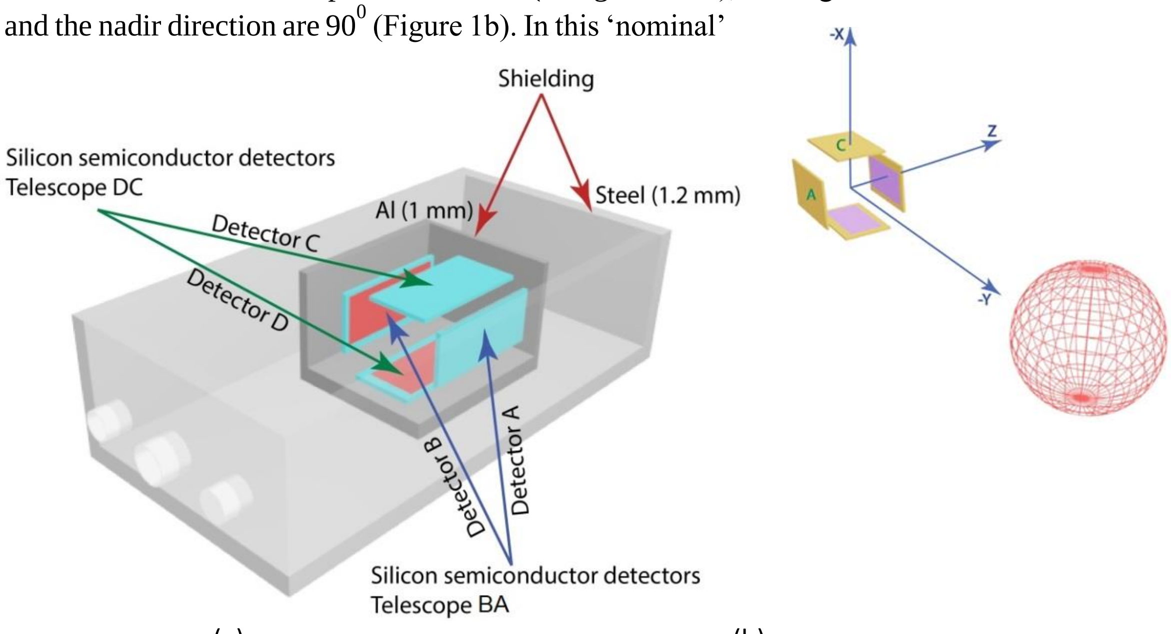

Figure 1. ***(a)*** *A schematic view of Liulin-MO detectors' location in the dosimeter box;* ***(b)*** *Dosimeter axes orientation relatively to TGO nadir (Semkova et al., 2021).*

orientation, which holds most of the time, the shading effect of Mars on the GCR flux (reduced part of free-space GCR flux) is about 23%. In first approximation the measured doses depend mainly on the distance to the planet, not on the TGO orientation [Krastev et al, 2019].

Estimation of the albedo flux from Mars surface and atmosphere, performed by Semkova et al, 2022 showed that its contribution to the total flux (GCR plus albedo) at TGO altitude in MSO is about 4-5%.

Based on these results a method was developed for calculation of the dose rate and particle flux of cosmic rays in free space at 1.5 AU from the Liulin-MO dosimeter measurements in MSO, accounting for the shading of cosmic rays fluxes from Mars and for the contribution of Mars albedo. Thus, the particle flux of cosmic rays in free space at 1.5 AU is obtained by dividing the average flux measured at TGO MSO in the single detectors B(A) and D(C) by 0.822. The dose rate of cosmic rays in free space at 1.5 AU is obtained by dividing the average dose rate measured in TGO MSO in the single detectors B(A) and D(C) by 0.766.

3. Results and discussion

The dose rate and particle flux of cosmic rays in free space at 1.5 AU based on measurements by Liulin-MO dosimeter on TGO in the period May 2016 - May 2025 are presented in Figure 2. The values from May to September 2016 were measured during the transit to Mars. The values in the period May 2018 - May 2025 were calculated from measurements at MSO as described above.

The gradual increase of the dose rates and fluxes from May 2018 to February 2020 corresponds to the increase of GCR intensity during the declining of solar cycle 24. During March–August 2020, the radiation values are maximal, corresponding to the minimum of cycle 24 and the transition to cycle 25. Since September 2020, there has been seen a decrease of the GCR dose rates and fluxes, corresponding to the increasing phase of solar cycle 25. A number

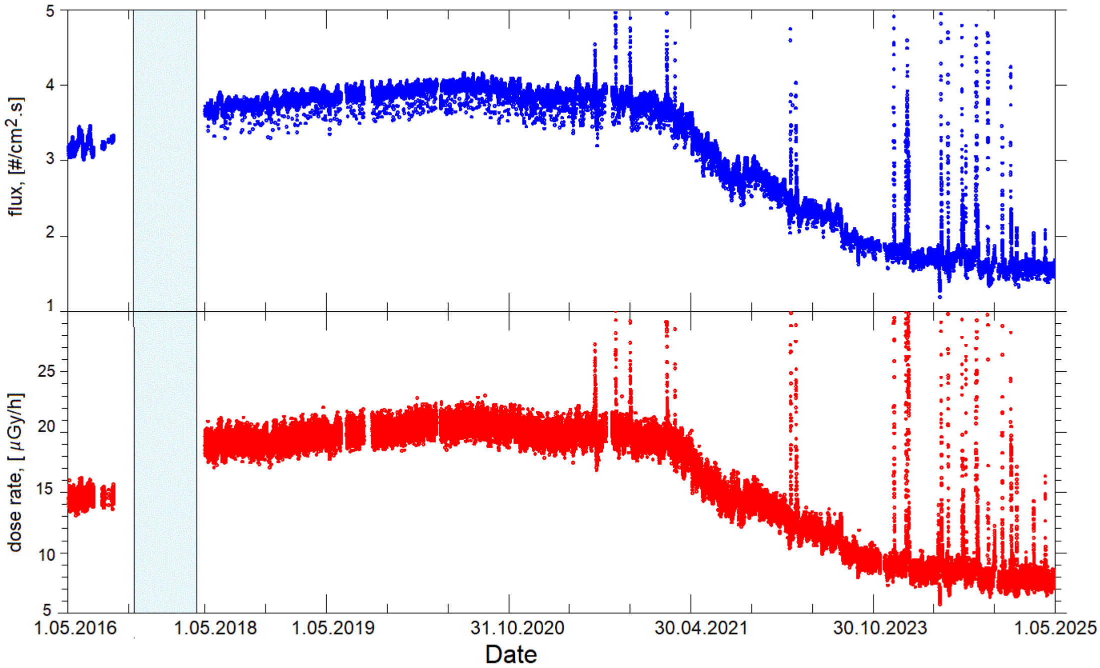

***Figure 2.** Fluxes (top) and dose rates (bottom) in free space at about 1.5 AU obtained from measurements by Liulin-MO on TGO in May 2016 –May 2025. The shaded area indicates a period of missing data.*

of SEP events were observed from July 2021 to May 2025 (the spikes superposed on the GCR time profiles in Figure 2). More detailed infommation about SEP events registered at Martian orbit by Liulin-MO during 25th solar cycle may be found in Koleva et al, 2025.

Table1 summarizes the dose rate and particle flux of GCR obtained in free space and in TGO MSO during different phases of solar activity from April 2016 to May 2025.

Table1. *Dose rate D and particle flux F of GCR during different phases of the solar cycle. Superscripts* ^{a} *and* ^{b} *show correspondingly the measured and calculated values.*

Month, Year, Solar cycle phase	***D* in Si [μGy h^{-1}] (TGO MSO)**	***D* in Si [μGy h^{-1}] (free space 1.5 AU)**	***F* [cm^{-2} s^{-1}] (TGO MSO)**	***F* [cm^{-2} s^{-1}] (free space 1.5 AU)**
September, 2016, first half of decreasing phase of cycle 24	12.4±1.9^{b}	16.2±1.6^{a}	2.6±0.26^{b}	3.2±0.16^{a}
March, 2020, minimum of cycle 24	15.8±1.6^{a}	20.7±3.1^{b}	3.3±0.165^{a}	4±0.4^{b}
March 2022, first half of increasing phase of cycle 25	14.4±1.4^{a}	18.8 ±2.8^{b}	3±0.15^{a}	3.4±0.34^{b}
October, 2024, maximum of cycle 25	6±0.6^{a}	7.8±1.17^{b}	1.3±0.065^{a}	1.6±0.16^{b}
May, 2025, start of the decreasing phase close to the maximum of cycle 25	6±0.6^{a}	7.8±1.17^{b}	1.3±0.065^{a}	1.6±0.16^{b}

Table 2 presents the total dose rate from GCR and SEPs obtained in free space and in TGO MSO during different phases of the solar cycle. Chosen are 6-months periods corresponding approximately to the time necessary for a transit Earth - Mars or vice versa.

Table 2. *Total dose rate D during different phases of the solar cycle. Superscripts* ^{a} *and* ^{b} *show correspondingly the measured and calculated values.*

Months, Year, (Radiation contributors) - Solar cycle phase	***D* in Si [μGy h^{-1}] (TGO MSO)**	***D* in Si [μGy h^{-1}] (free space at 1.5 AU)**
April-September, 2016, (GCR, no SEPs)-first half of decreasing phase of cycle 24	12.2±1.8^{b}	15.9 ±1.6^{a}
May-October, 2018, (GCR, no SEPs)-second half of decreasing phase of cycle 24	14.6±1.5^{a}	19.1±2.9^{b}
February-July, 2020, (GCR, no SEPs)-around the minimum of cycle 24	15.8±1.6^{a}	20.6±3.1^{b}
February-July, 2022, (GCR and SEPs)-first half of increasing phase of cycle 25	16.2±1.6^{a}	21.2±3.2^{b}
May-October, 2024, (GCR and powerful SEPs)-near to and at the maximum of cycle 25	13.9±1.4^{a}	18.2±2.7^{b}
December 2024-May 2025, (GCR and weak SEPs) maximum and start of the decreasing phase of cycle 25	6.4±0.64^{a}	8.4±1.26^{b}

The calculation of the dose rates in free space shown in Table 2 is made under the presumption that the SEPs distribution at 1.5 AU is isotropic, like the distribution of GCR. This is not always the case, but the simulations conducted for some of the most powerful SEP events observed by Liulin-MO [Krastev et al, 2023] show that the modeled isotropic distribution of SEPs correlates satisfactorily with the measurement results. Besides that, as was already mentioned, the shading coefficient of the dose rate at TGO MSO does not depend significantly on the TGO orientation [Krastev et al, 2019]. Because of that we use the same coefficient 0.766 for converting the measured in TGO MSO dose rate for GCR and for mixed radiation of GCR and SEPs.

The results show that at 1.5 AU the dose rate and particle flux of GCR during the maximum of solar cycle 25 (October 2024) are about 38-39% of the corresponding values during the minimum of solar cycle 24 (March 2020).

The dose rate both from GCR and SEPs near to and at the maximum of solar cycle 25 in May-October 2024 is below, but comparable to the dose rate received from GCR near to and at the minimum of solar cycle 24 in February-July 2020. This is an important result as in the period May-October 2024 six strong SEP events were registered, including the most powerful SEP observed up to now by Liulin-MO – the event of 20 May 2024 (see Semkova et al, 2025). The dose from SEPs is larger than the dose from GCRs in this period. Taking into account that the radiation quality factor $<Q>$ of the combined field of GCR and SEPs is lower than $<Q>$ of the GCR [Semkova et al, 2023; Semkova et al, 2025], the biologically significant dose equivalent rate during the maximum of cycle 25 is significantly lower than the dose equivalent rate during the minimum of cycle 24.

The lowest dose rates for a 6-months time interval are registered in December 2024 - May 2025 - the period covering the maximum and start of the decreasing phase of cycle 25 – they are about 2 times less that the dose rates during the other phases of cycles 24 and 25. The relatively weak SEPs during this period contribute to the increase of the average dose rate of GCR by less than 10%.

These results are in agreement with calculations, showing that the expected doses to a future manned trip to Mars, that will start at solar maximum are lowest [Shafirkin and Grigoryev, 2009; Cucinotta, 2015]. This is also consistent with the previous experimental investigations conducted by RAD instrument onboard Curiosity rover during the transit to Mars and on Mars surface [Guo et al, 2021].

4. Data availability

The data from the Liulin-MO measurements used in this paper are part of the Unified web-based database with Liulin-type instruments available at https://esa-pro.space.bas.bg/datasources.

Conclusion

The long-term measurements of the radiation values, performed by the Liulin-MO dosimeter on Trace Gas Orbiter at MSO, behind a mean shielding of about 20 g cm^{-2}, and estimation of the dose rate and particle flux of cosmic rays in free space at 1.5 AU based on them show that:

- The dose rate and particle flux both from GCR and powerful SEP events near to and at the maximum of solar cycle 25 in May-October 2024 is below, but comparable, to the corresponding values received from GCR near to and at the minimum of solar cycle 24 in February - July 2020. The dose equivalent rate during the maximum of cycle 25 is significantly lower than the dose equivalent rate during the minimum of cycle 24.

- The lowest dose rates for a 6-months period, corresponding approximately to the time necessary for a transit to Mars or vice versa, are registered in December 2024 - May 2025 - the period that covers the maximum and the start of the decreasing phase of cycle 25. They are about 2 times less that the dose rates during the other phases of cycles 24 and 25.
- These results are important about the selection of the best time interval in the solar cycle for a future manned trip to Mars. They confirm and specify previous studies that the expected dose for a Mars mission launched during the solar maximum is significantly less than the dose for a mission taken during other phases of the solar cycle. But a trip during the solar maximum is accompanied with a potential risk of significant, unpredictable dose contributions by SEPs. A real time warning of SEP events and a radiation shelter onboard the spacecraft may reduce the radiation risk to the crew during the transit to the planet and back. The most effective countermeasure for the radiation risk would be reducing the transit time using new technological developments.

The obtained results for dose rates and particle fluxes during different phases of solar cycles 24 and 25 may be used for verification and benchmarking of cosmic rays models in free space at 1.5 AU and at Mars orbit.

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