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Multi-Spacecraft and Multi-Instrument Observations of the Martian Radiation Environment During Solar Cycles 24 and 25

Semkova J. [1], *Bankov N.* [1], *Benghin V.* [2], *Dachev Ts.* [1], *Drobyshev S.* [2], *Georgiev G.* [1], *Golovin D.* [3], *Gopalswamy N.*[4], *Jordanova M.* [1], *Koleva R.* [1], *Krastev K.* [1], *Litvak M.*[3], *Lukyanov N.* [3], *Maltchev St.* [1], *Matviichuk Yu.* [1], *Mitrofanov I.* [3], *Mokrousov M.* [3], *Sanin A.* [3], *Shurshakov V.* [2], *Tomov B.* [1]

[1]Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria; jsemkova@stil.bas.bg
[2]State Scientific Center of Russian Federation, Institute of Biomedical Problems, Russian Academy of Sciences, Moscow, Russia
[3]Space Research Institute, Russian Academy of Sciences, Moscow, Russia
[4]NASA Goddard Space Flight Center, Greenbelt Maryland, USA

Abstract

Presented are multi-spacecraft – Trace Gas Orbiter (TGO), Mars Odyssey, Mars Science Laboratory, etc. and multi-instrument observations of the particle radiation environment in Mars vicinity during solar cycles 24 and 25. According the observations conducted by the dosimeter Liulin-MO onboard TGO at Martian orbit from May 2018 to May 2026, lowest dose equivalent rates for a 6-months period – the approximate time for a transit to Mars or vice versa, are registered during the decreasing phase, near to the maximum of solar cycle 25 – they are about 1.5-2 times less that the dose rates during the other phases of solar cycles 24 and 25. Highest dose rates are registered around the minimum of solar cycle 24 as a result of the galactic cosmic rays contribution. Particular attention is drawn to the results for the radiation parameters obtained by multiple detectors located at the orbit and on the surface of Mars during the most intensive solar energetic particle (SEP) events registered up to the moment during solar cycle 25 – those in October 2021, February 2022, May 2024, and August 2025. Responsible for most of these SEPs are halo coronal mass ejections (CMEs) associated with major X and M class flares. The results show the importance of long-term multipoint measurements of the radiation conditions in Mars vicinity. Such measurements will provide the data necessary for the planning of future manned missions to the planet. The data on the observed SEPs add details regarding the solar activity during solar cycle 25.

Keywords: multispacecraft particle radiation measurements; galactic and solar cosmic rays; Mars

1. Introduction

Sources of considerable health hazards for manned space missions to Mars are the omnipresent galactic cosmic rays (GCR), sudden solar energetic particle (SEP) events and secondary radiation from the interaction of the primary cosmic rays with the spacecraft structures, Mars atmosphere and surface. 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 GCR spectrum 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 (CMEs) [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].

Other permanent sources of radiation are the secondary charged particles and neutrons from interaction of primary radiation with the spacecraft structures and albedo radiation from Mars atmosphere and surface.

The current astronaut career exposure limits are between 0.6 Sv (NASA) and 1 Sv (other space agencies and countries) for astronauts in low earth orbits. The limits are age and gender specific [Shavers et al, 2023].

In this paper we present multispacecraft - Trace Gas Orbiter (TGO), Mars Odyssey, Mars Science Laboratory (MSL), etc. and multiinstrument observations of the particle radiation environment at Mars orbit and surface during the last 2 solar cycles. Shown are some examples and practical results of application of the Mars radiation environment observational data.

2. Particle radiation environment investigations on different space missions in Mars vicinity

The sunspot numbers and the period of available radiation data at Mars orbit and surface from multispacecraft observations are presented in Figure 1.

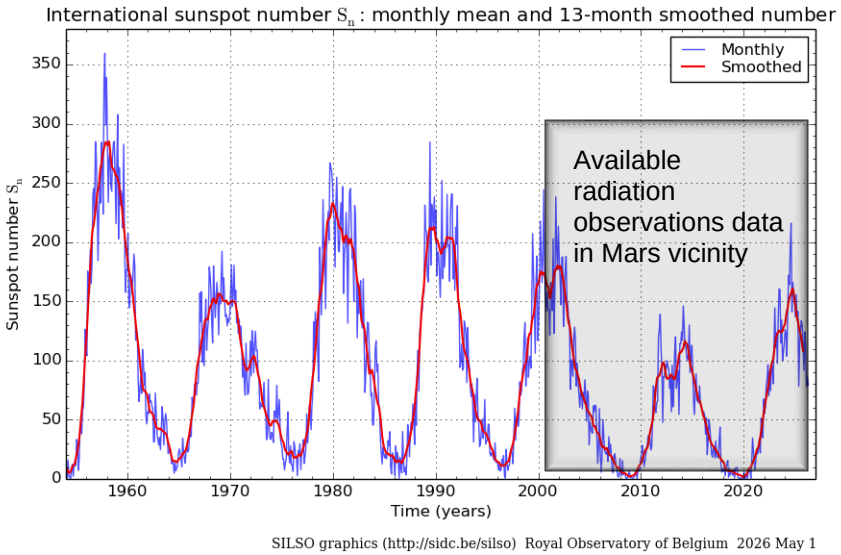


Figure 1. *Sunspot numbers and the period of available radiation data at Mars orbit and surface from multispacecraft observations*

Particle radiation environment investigations have been conducted during the transit to Mars, in Mars orbit and on the surface aboard several space missions in last three solar cycles.

Table 1 presents the radiation environment investigations on different space missions in Mars vicinity conducted since 2001. The columns from left to right contain: the mission, responsible space agency or country, type of the mission (orbiter or rover); start year of the operation at Mars; instrument(s) for particle radiation measurements aboard the mission; measured particles (charged, neutrons or both).

Table1. *Particle radiation environment investigations on different space missions in Mars vicinity*

Mission/Type	Mission operation at Mars since	Instrument/s	Measured particles
Mars Odyssey/ NASA/Orbiter	2001	HEND (High-Energy Neutron Detector)	neutrons protons
Mars Express (MEX)/ ESA/Orbiter	2003	ASPERA-3 IMA (Analyzer of Space Plasma and Energetic Atoms-Ion Mass Analyzer)	charged
Mars Science Laboratory (MSL)/NASA/Rover	2012	RAD (Radiation Assessment Detector), DAN (Dynamic Albedo of Neutrons)	charged, neutrons neutrons
Mars Atmosphere and Volatile Evolution (MAVEN)/NASA/Orbiter	2014	SEP (Solar Energetic Particle)	charged
Trace Gas Orbiter (TGO)/ESA, Russia/Orbiter	2018	Liulin-MO, (Dosimeter Liulin-MO), FREND (Fine Resolution Epithermal Neutron Detector)	charged neutrons
Tianwen-1(TW-1)/ China/Orbiter	2021	MEPA (Mars Energetic Particle Analyzer)	charged

3. Results and discussion

3.1. Long term measurements

The dose rate and particle flux of cosmic rays measured by Liulin-MO dosimeter on TGO in the period May 2016 - May 2026 are presented in Figure 2 (top and middle panels). The values from May to September 2016 were measured during the transit to Mars. The values in the period May 2018 - May 2026 were measured at Mars Science Orbit of TGO (circular orbit with 400 km altitude, 74° inclination, ~ 2 hours orbit period). TGO/Liulin-MO absorbed 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). During the 25th solar cycle till May 2026 a number of SEP events were observed on TGO (the spikes - not scaled) superposed on the GCR time profiles in the top panel of Figure 2.

The bottom panel of Figure 2 represents the dose rate measured by MSL/RAD during the transit to Mars in 2012 (left) and on Mars surface at Gale crater from 6 August 2012 to 9

September 2024 –right part of the panel [Löwe et al , 2025]. Red arrows indicate SEP events. Vertical dashed lines in the plot indicate the transition from the 24th to the 25th solar cycle.

The gradual increase of the dose rates and fluxes registered at Martian orbit and surface up to February 2020 corresponds to the increase of GCR intensity during the declining phase of solar cycle 24. During March–August 2020, the radiation values of GCR are maximal, corresponding to the minimum of cycle 24 and the transition to cycle 25. Since September 2020, a decrease of the GCR dose rates and fluxes is seen, corresponding to the increasing phase of solar cycle 25.

Table 2 presents the absorbed dose rates (in water) and dose equivalent rates at Mars orbit from TGO/Liulin-MO measurements during different phases of solar cycles 24 and 25. Data are averaged over 6-months periods. The 1st column contains the period of measurement, the radiation contributors – GCR or GCR plus SEPs and the solar cycle phase; the 2nd column shows the absorbed dose rates in water and the 3rd column - the dose equivalent rates.

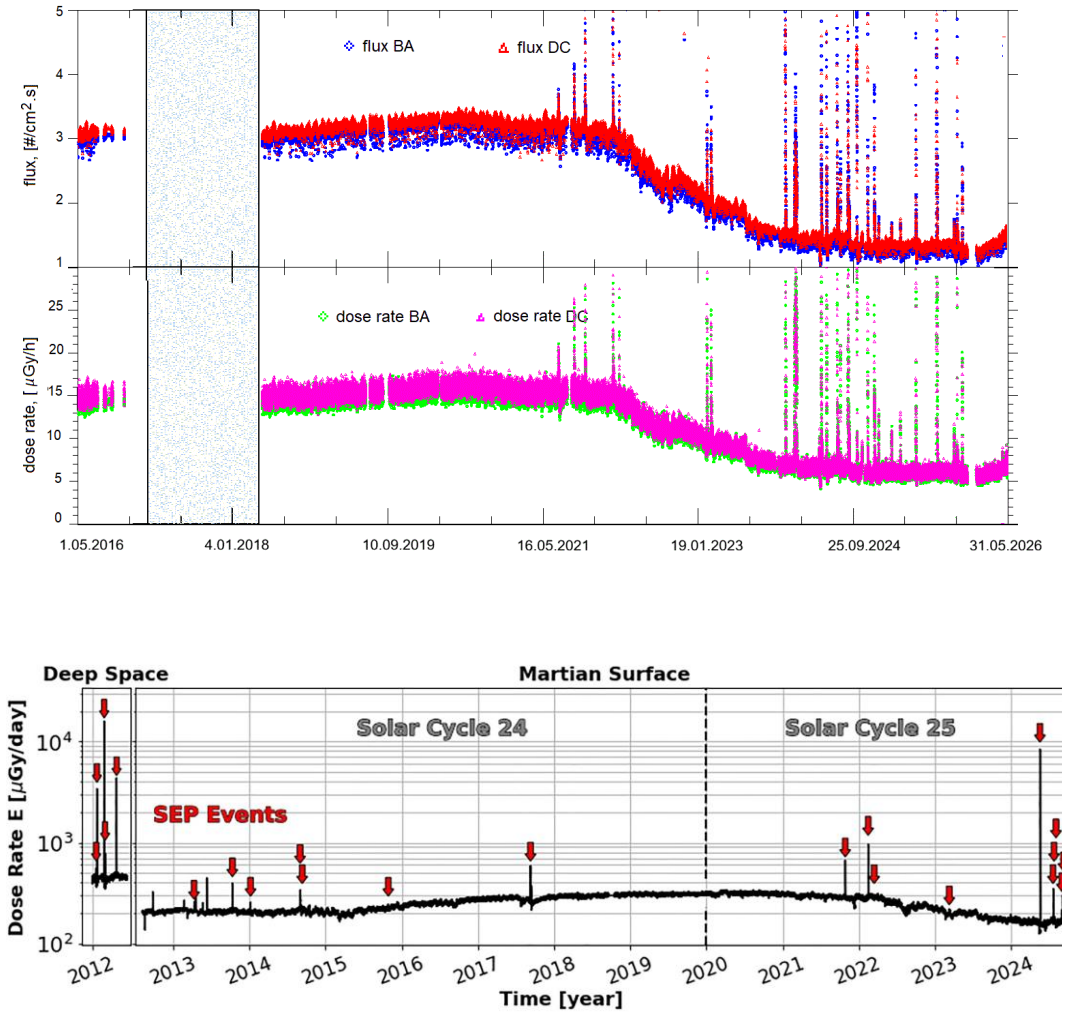


Figure 2. *Fluxes (top) and dose rates (middle) in free space (left) and in Mars orbit (May 2018 -May 2026) obtained from the measurements by TGO/Liulin-MO. The plots marked as BA and DC represent measurements from the Liulin-MO detectors in 2 perpendicular directions BA and DC. The shaded area indicates a period of missing data. Bottom - dose rate in free space (left) and on Mars surface (6 August 2012 to 9 September 2024) obtained from the measurements by MSL/RAD. Red arrows indicate SEP events. Bottom picture is taken from Löwe et al, 2025.*

The absorbed 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 absorbed 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) but nevertheless 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. This is because the radiation quality factor $<Q>$ of the combined field of GCR and SEPs is lower than $<Q>$ of the GCRs itself [Semkova et al, 2023; 2025].

Table 2. *Absorbed dose rate D and dose equivalent rate H from TGO/Liulin-MO measurements at Mars orbit during different phases of the solar cycle.*

Months, Year, (Radiation contributors) - Solar cycle phase	**D in water [mGy d^{-1}]**	**H [mSv d^{-1}]**
May-October, 2018, (GCR, no SEPs)-second half of decreasing phase of cycle 24	0.455	1.6
February-July, 2020, (GCR, no SEPs)-around the minimum of cycle 24	0.494	1.7
February-July, 2022, (GCR and SEPs)-first half of increasing phase of cycle 25	0.507	1.76
May-October, 2024, (GCR and powerful SEPs)-near to and at the maximum of cycle 25	0.429	1.2
December 2024-May 2025, (GCR and weak SEPs) maximum and start of the decreasing phase of cycle 25	0.182	0.73
July-December 2025 (GCR and a strong SEP) –first half of the decreasing phase of Cycle 25	0.247	0.81
February-May 2026 (GCR) –first half of the decreasing phase of Cycle 25	0.182	0.72

The lowest dose rates for 6-months time intervals are registered in December 2024 - May 2026 - the period covering the maximum and first half of the declining phase of cycle 25 – they are about 1.5-2 times less that the dose rates during the other phases of cycles 24 and 25.

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].

The absorbed dose rates and dose equivalent rates obtained from measurements at Martian orbit and surface during the solar minimum of cycle 24/5 are summarized in Table 3.

The absorbed dose rates and dose equivalent rates obtained from measurements at Martian orbit and surface in the period 28 November 2019 -3 October 2020 are due to contribution of GCRs and secondary radiation. No SEP events were registered in this period. One can see that the dose rates on Mars surface at Gale crater are significantly lower than the corresponding values at TGO Martian orbit – this is because the planet itself and its atmosphere shield a significant part of GCRs. Guo et al, 2019 show that only the most energetic particles are able to reach the surface through Martian atmosphere and the atmospheric cutoff energy under different surface pressures is 140–190 MeV/nuc.

Table 3. *Dose rates at Mars surface from MSL/RAD and at Mars orbit from TGO/Liulin-MO during solar minimum of Cycle 24/5 measured from 28 November 2019 to 3 October 2020*

Quantity	MSL/RAD data [Ehresmann et al, 2023]	TGO/Liulin-MO data	Ratio of TGO/Liulin-MO to MSL/RAD value
Absorbed dose rate in water [mGy d^{-1}]	0.314	0.48	1.53
Dose equivalent rate [mSv d^{-1}]	0.72	1.68	2.33

3.2. Measurements during SEP events

On TGO a total of 30 SEP events were observed till May 2026. More detailed information about SEP events registered at Martian orbit by TGO /Liulin-MO may be found in Koleva et al, 2025.

17 SEP events were measured on the Martian surface by MSL/RAD from 6 August 2012 to 9 September 2024 [Löwe et al, 2025].

The most powerful SEP events of Cycle 25 observed at Mars orbit and surface up to now are presented in Table 4. The columns from left to right show the start date of the event, the duration of the event at TGO orbit, the TGO/Liulin-MO absorbed dose from SEPs, the MSL/RAD absorbed dose from SEPs, and the ratio of SEP dose surface to SEP dose orbit in [%]. The ratio of SEP dose surface to SEP dose orbit in the table is only few percent. This show that the Mars surface at Gale crater was relatively well protected against SEPs during the giant SEP events in the current solar cycle. The reason for that is the fact that the Mars atmosphere stops the charged particles with energies below 140-190 MeV/nuc, while TGO/Liulin-MO measure particles of energies > 30 MeV/nuc at Mars orbit.

Multiple detectors located at the orbit and on the surface of Mars have registered SEP events shown in Table 4. Some more details on the multispacecraft and multiinstrument observations during these SEP events are given below.

Table 4*. Most powerful SEP events of Cycle 25 observed at Mars orbit and surface up to now*

Start date of SEP event	Duration [hours] (TGO/Liulin-MO) [Semkova et al, 2023; 2025]	Dose from SEPs (in water) [mGy] (TGO/Liulin-MO-orbit) [Semkova et al, 2023; 2025]	Dose from SEPs [mGy] (MSL/RAD-surface) [Löwe et al, 2025]	SEP dose surface/SEP dose orbit [%]
28 October 2021	~79	8.45	0.161	1.9
15 February 2022	~76	17.94	0.323	1.8
20 May 2024	~64	32.06	1.73	5.4
21 August 2025	~100	8.76	Presently no literature data	

4.2.1. Measurements during the SEP event on 28 October 2021

Dose rate and accumulated doses were measured by different detectors on Mars orbit and surface (Liulin-MO and RAD), Moon orbit and surface (CRaTER and LND), and Earth polar orbit (RAMIS) during the 28 October 2021 SEP event [Guo et al, 2023]. The doses during this event at Mars orbit and Earth polar orbit are very close. Highest doses were registered at Moon orbit, lowest –at Mars surface. The SEP event caused the first GLE of solar cycle 25 at Earth [Papaioannou, et al, 2022]. During this event Mars and Earth were on opposite sides of the Sun. These SEP are related to a X1.0 flare located at S26W05 and a halo CME on 28 October 2021 [Koleva et al, 2025].

4.2.2. Measurements during the SEP event on 15 February 2022

The SEP event on 15 February 2022 was investigated by almost all radiation environment measurement instruments operating at Mars orbit and surface. The proton flux was measured by MAVEN/SEP and TW-1/MEPA and dose rates were measured by TGO/Liulin-MO and MSL/RAD. Reconstructed were the spectra of the SEP event from MAVEN/SEP, MEPA/TW-1 and MSL/RAD datasets integrated for the initial 12 hs after the event onset [Zhang J. et al, 2024]. Penetrating particle count rates from MAVEN/SEP and MEX/ASPERA-3 IMA were registered [Khoo et al, 2024]. The time profiles of count rates of TGO/FREND, TGO/Liulin-MO, and Mars Odyssey/HEND were compared [Semkova et al, 2023]. The solar source of SEPs is behind the east limb halo CME which occurred on 15 February 2022 [Koleva et al, 2025].

4.2.3. Measurements during the SEP event on 20 May 2024

The biggest SEP event registered up to now in Mars vicinity started on 20 May 2024. The total absorbed dose from SEPs equals the dose from the GCR received for about 200 days at TGO orbit. The SEPs dose equivalent for the entire event according TGO/Liulin-MO data is 43.7 mSv - approximately the dose equivalent received for 57 days from GCR. The maximum count rates exceed by more than 300 times the count rate of GCR. Compared were the normalized SEP count rates measured by TGO/FREND, TGO/Liulin-MO, Mars Odyssey/HEND [Semkova et al, 2025]. On MSL the absorbed dose equals the GCR dose received for about 7 days according to MSL/RAD data [Löwe et al, 2025]. The neutron dose on the Martian surface during the SEP event provided by MSL/DAN is 0.6 mSv- equals the dose during approximately 11 days in quiet Sun environment; the maximum neutron count rate exceeds 3 times the background count rate [Mitrofanov et al, 2025]. Responsible for this SEP event was an eruption located at S18W171 involving an X12 flare and a backside halo CME on 20 May 2024 [Semkova et al, 2025; Koleva et al, 2025].

4.2.4. Measurements during the SEP event on 21 August 2025

The SEP event on 21 August 2025 was registered by TGO/FREND and TGO/Liulin-MO instruments. At present there is no literature data about other radiation measurements during this event in Mars vicinity. The total dose during this event according to TGO/Liulin-MO data is comparable to the dose received during the 28 October 2021 SEP event (see Table 4).

Figure 3 shows the time profiles of TGO/Liulin-MO dose rate (top plot) and the normalized count rates measured by the ^{3}He and scintillator detectors of TGO/FREND and by TGO/Liulin-MO (bottom plot). The unusual profile of the dose rate and particle flux during this event is a subject of an upcoming publication. The observed SEPs are probably related to >X3 class flare and a behind the limb halo CME that occurred on 21 August 2025.

4.2.5. Examples of Mars radiation environment observational data application and some practical results

- Estimated is the dose equivalent from GCR for a round-trip to Mars with current propulsion systems for different phases of Cycle 24 from MSL/RAD and TGO/Liulin-MO data [Zeitlin, et al, 2013; Semkova et al, 2018; Posner & Strauss, 2020; Guo et al, 2021]. The results show that the accumulated GCR dose equivalent, via a Hohmann transfer, is larger than the astronauts career limit of 1 Sv.
- Estimated is the albedo radiation at Mars orbit (4% -5% of the total flux) and on the surface (18% -24% of the total dose) [Semkova et al, 2022; Guo et al, 2026].
- Methods are developed to calculate the absorbed dose rate and particle flux of cosmic

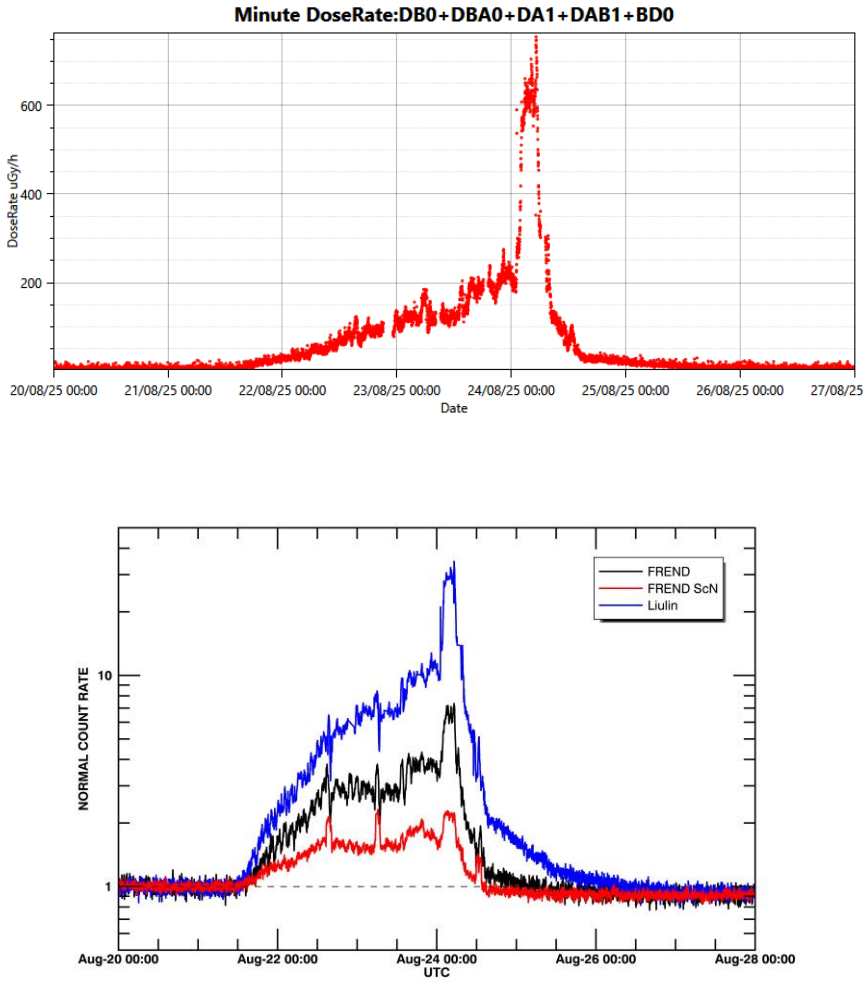


***Figure 3**. Time profiles of TGO/Liulin-MO minute dose rate in the direction BA (top) and normalized count rates measured by TGO/FREND detectors and TGO/Liulin-MO (bottom) during the SEP event on 21 August 2025*

rays in free space from the TGO/Liulin-MO measurements in Mars orbit [Krastev et al, 2019; Semkova et al, 2025b; Zhang C. et al, 2026].

- Based on MSL/RAD data a nowcasting system for SEP events has been developed that is applicable in deep space and on the surface of Mars. The avoidable SEP dose is at least 90% of the total SEP dose that can be mitigated using this system [Löwe et al, 2025].
- A map of the neutron dose on the surface of Mars has been created from TGO/FREND data [Litvak et al, 2025]. The neutron effective dose equivalent rate in the energy range up to 1000 MeV varies within 85 – 145 μSv/day depending on the content of subsurface water and the thickness of the atmosphere - consistent with Mars Odyssey/HEND and MSL/RAD observations.
- Simulated energy deposition spectra are compared with measured spectra from TGO/Liulin-MO during SEP events of October 2021, February 2022, May 2024. The results demonstrate that numerical simulations can offer an initial approximation of the composition of solar proton events detected by instruments of the Liulin-MO type [Krastev, 2025].
- A statistical analysis of SEPs rise times has been conducted using Earth and Mars observations [Cao et al, 2026]. Data were derived from SOHO/ERNE, TW-1/MEPA and TGO/Liulin-MO.
- The daily solar modulation potential Φ for Mars has been obtained based on TGO/Liulin-MO observations. The influence of Mars topography on radiation dose detected by MSL/RAD for the same values of Φ is investigated [Guo et al, 2026].
- The cumulative effective dose from GCRs has been obtained for 3 different Mars exploration missions (1964-2025) predicted by empirical models derived from measurements by TGO/Liulin-MO and LRO/CRATER [Zhang C. et al, 2026]. The result shows that even for the shortest mission (total 440 days, of which 410 days transit) around the solar min in the 23rd and 24th Cycles, NASA career exposure limit of 0.6 Sv is exceeded.

These results show the importance of careful planning for future manned Mars missions, regarding optimisation of the transfer trajectories, launch windows, Mars landing site selection, etc. in order to remain within the radiation limits. A real time nowcasting, warning of SEP events and a radiation shelter onboard the spacecraft may reduce the radiation risk to the crew.

Conclusion

The main results and conclusions from the multispacecraft and multiinstrument investigation of the Martian radiation environment can be summarized as follow:

- Confirmed and specified are the calculations that the expected crew dose for a Mars mission launched during the solar maximum is significantly less than the dose for a mission taken around the solar minimum.
- Shown is that in order to remain within the astronauts radiation limits during a manned flight to Mars it is necessary for mission planning to optimise transfer trajectories, launch windows, Mars landing site selection, etc. A real time nowcasting and warning of SEP events and a radiation shelter onboard the spacecraft may reduce the radiation risk to the crew. The most effective countermeasure for the radiation risk would be reducing the transit time using new technological developments.
- The data obtained may be used to verify and benchmark the cosmic ray models in the free space and in Mars vicinity.
- The data obtained contribute to space weather research and prediction.

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