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Observation of Solar Energetic Particle Events Onboard ExoMars TGO in July 2021-March 2022

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1. Abstract

The dosimeter 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 results from measurements of the charged particle fluxes, dose rates and estimation of dose equivalent rates at ExoMars TGO Mars science orbit, provided by Liulin-MO since May 2018. The period of measurements covers the declining and minimum of the solar activity in 24th solar cycle and the inclination phase of the 25th cycle. Particular attention is drawn to the observation of the solar energetic particle (SEP) events in July, September and October 2021, February and March 2022 as well as their effects on the radiation environment on TGO during the corresponding periods. The SEP event on 15-19 February 2022 is the most powerful event observed in our data. Compared are the time profiles of the particle fluxes and count rates measured by Liulin-MO and the neutron detectors of FREND during these events. The data for SEP events on TGO in July 2021-March 2022 contribute to the details for the solar activity at a time when Mars is on the opposite side of the Sun from Earth.

Keywords: *dosimetric measurements; Mars orbit; solar energetic particles*

2. Introduction

The exploration of Mars gets on a new wider scale nowadays. The radiation environment during the transit, on Mars and its vicinity can be very hazardous for future human exploration of the red planet. Because of its thin atmosphere and the lack of global intrinsic magnetic field, Mars is very exposed to space radiation. 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 [Badhwar and O'Neill, 1992] mainly of protons (85%–90%) and α particles (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.

The radiation environment on a transit orbit to Mars and on Mars surface have been studied since 2012 by MSL RAD instrument [Zeitlin et al. 2013, Guo et al, 2017, 2021].

The radiation environment at Martian orbit has been previously measured onboard Mars Odyssey, whose radiation detector, the Martian Radiation Environment Experiment, stopped working under the SEP event of October 2003, but data could still be retrieved from the Gamma Ray Spectrometer and the scintillator component of the High Energy Neutron Detector (HEND)

[Zeitlin et al., 2010]. Recent studies have also analyzed data from Mars Express [Knutsen et al., 2021]. The ExoMars TGO spacecraft launched in April 2016 carries the FREND instrument, one module of the latter being the Liulin-MO dosimeter [Mitrofanov et al., 2018], that has provided and providing in-situ measurements of the radiation environment during the TGO interplanetary travel and in Martian orbit [Semkova et al., 2018, 2021]. Since May 2018 Liulin-MO investigates the radiation conditions in Mars Science Orbit (MSO). MSO is an almost circular orbit with 400 km altitude (varies within ±25 km in every orbital pass), 74^0 inclination, ~ 2 hours orbit period.

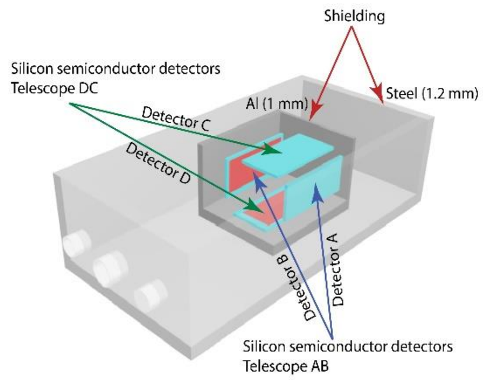

Figure 1. *A schematic view of Liulin-MO detectors' location in the dosimeter box [Semkova et al., 2021]*

The Liulin-MO dosimeter contains two dosimetric telescopes- BA and DC arranged at two perpendicular directions. Figure 1 is a sketch of the sensor unit. Each pair of the dosimetric telescopes consists of two 300 µm thick, 20x10 mm area rectangular Si PIN photodiodes. The parameters, provided by Liulin-MO simultaneously for two perpendicular directions 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. The dose rates and the fluxes are resolved every minute, while the energy deposition spectra are resolved every hour. The instrument also provides data for the linear energy transfer spectra, radiation quality factors and dose equivalent rates in two perpendicular directions. In this paper we use the data provided by single detectors B(A) and D(C) in the energy deposition range > 0.08 MeV. All events with energy deposition > 190 MeV are registered and are considered as events with 190 MeV energy deposition in the subsequent calculations. 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 first momentums of the shielding distribution probability density is about 20 g cm^{-2}. The energy threshold for the minimum shielding is 1.7 MeV for electrons, 30 MeV for protons and 6.8 GeV for iron ions.

3. Liulin-MO data in TGO Mars science orbit and discussion

3.1. Particle fluxes and dose rates from GCR in the period May 2018-June 2022

The fluxes and dose rates recorded in the single perpendicular detectors B(A) and D(C) of Liulin-MO and the proton flux>30 MeV measured by SIS instrument on ACE satellite for the period from May 2018 to June 2022 are shown in Figure 2.

Increase of the dose rates and fluxes from May 2018 to February 2020 which corresponds to the increase of GCR intensity during the declining of the 24^{th} solar cycle is observed. The averaged dose rate for the period is 15 µGy h^{-1}, the averaged particle flux is 3.14 $cm^{-2}s^{-1}$. In March-August 2020 the radiation values are maximal, corresponding to the minimum of the 24^{th} cycle and transition to the 25^{th} cycle. The dose rate is 15.9 µGy h^{-1}, flux is 3.3 cm^{-2} s^{-1}. Dose equivalent rate is 72 µSv h^{-1}. Since September 2020 a decrease of the dose rates and fluxes is seen corresponding to the increasing phase of the 25^{th} solar cycle.

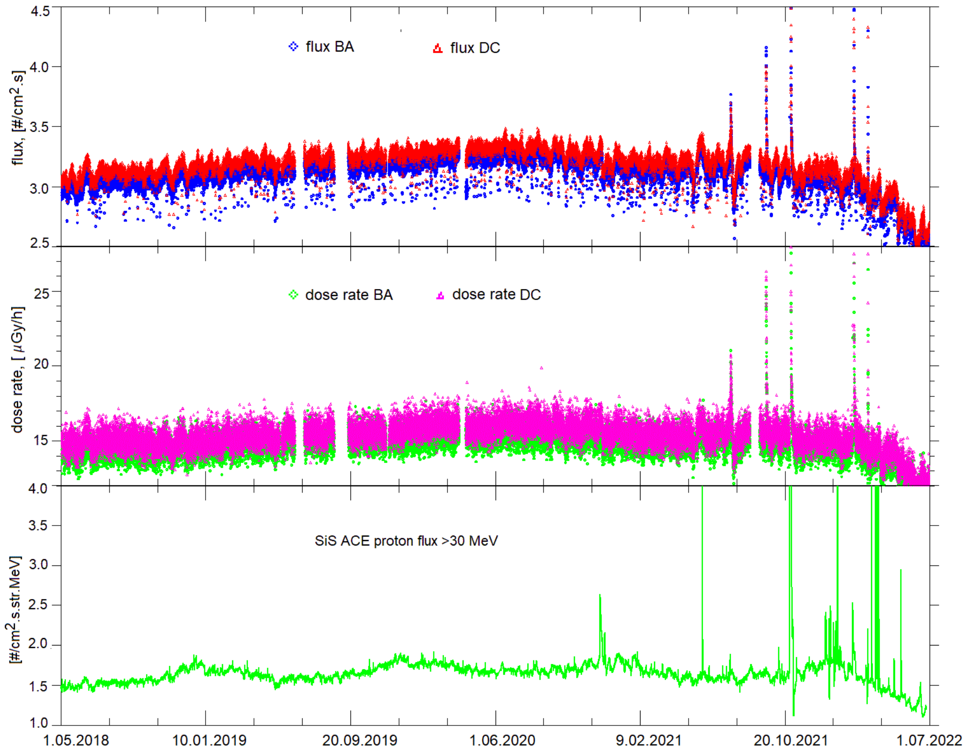

***Figure. 2**. Fluxes (top) and dose rates (middle) measured by Liulin-MO in MSO and SIS-ACE proton flux>30 MeV (bottom) in the period 01 May 2018 – 30 June 2022*

Until July 2021 the dosimeter measured the dosimetric parameters of GCR. No solar particle events (SPE) were registered.

Five SEP events are observed from July 2021 to March 2022. SEP events in October 2021 are observed also on ACE. During all these SEP events Earth and Mars are on opposite sides from Sun.

The data for the parameters of the coronal mass ejections (CMEs) related to the observed on TGO SEP events discussed below are taken from the catalogue SEEDS (http://spaceweather.gmu.edu/seeds/).

• *3.2. SEP event and Forbush decrease of GCR observed on 17-28 July 2021*

This event was discussed in more details in Krastev et al, 2021. A CME responsible for the increase of Liulin-MO flux and dose rates could be that observed by LASCO (SOHO) coronagraph C2 at 05:24. The time at which it was ejected from the sun surface is about 04:55 UT. Later CME developed as a halo CME. The speed of the CME was over 1000 km s^{-1}.

On 17.07.2021 at 07: 12 UTC started an increase in the flux and dose rate of Liulin-MO due to SEP. During 20-28.07.2021 a Forbush decrease of GCR is observed. The time profiles of the particle flux and dose rate during the event are shown in Figure 3. For the entire event from 17 to 28.07.2021 a decrease of the dose rate by 0.5 μGy h^{-1} compared to quite conditions before the event is observed.

3.3. SEP event observed on 17-18 September 2021

A high speed CME (over 1000 km s^{-1}) directed to Mars with onset about 04:00 UT was registered by SOHO and STEREO-A on 17th September 2021.

The time profiles of the particle flux and dose rate measured by Liulin-MO during this event are shown in Figure 4.

The total dose from SEP received during 17-18 September 2021 event is 156 µGy which is less than the half of daily dose from GCR.

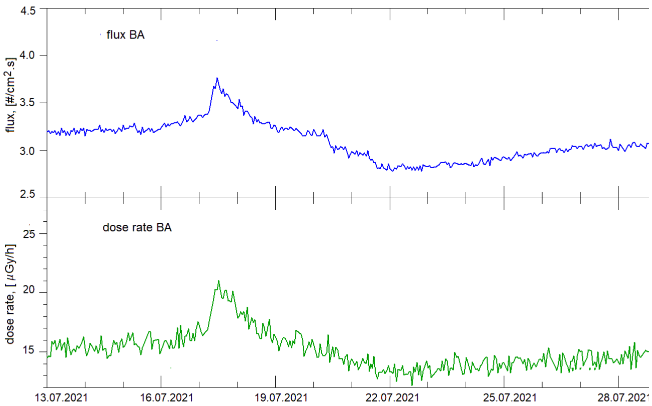

Figure 3. *Time profiles of the particle flux (top) and dose rate (bottom) during SEP event on 17-28 July 2021*

3.4. SEP event observed on 28-31 October 2021

Both LASCO and STEREO A registered the launch of a halo CME on 28 October 2021.

A fast CME originated from the southern hemisphere and caused strong SEP events over a wide longitude range from Earth, STEREO-A, to Mars (Xiaolei Li et al, 2022).

During this event the first ground level enhancement (GLE) of Solar Cycle 25 was observed (Papaioannou et al, 2022).

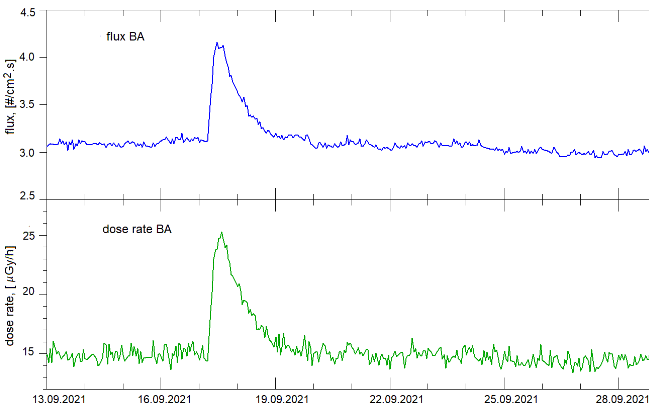

Figure 4. *Time profiles of the particle flux (top) and dose rate (bottom) during SEP event on 17-18 September 2021*

The time profiles of the particle flux and dose rate measured by Liulin-MO during this event are shown in Figure 5. On 28.10.2021 at 16:55 UT began a large increase in Liulin-MO flux and dose rates which lasted till 31.10.2021.

The total dose from SEP for 28-31 October 2021 event is about 7 mGy, which is equal to the dose received from GCR for 19 days during quite conditions. At the peak of the event the dose rate is about 30 times larger and the flux is about 15 times larger than the corresponding values of GCR. The dose equivalent from SEP during this event is 10 mSv.

3.5. SEP event observed on 15 February 2022

On 15 February 2022 Solar Orbiter has captured the largest solar prominence eruption ever observed in a single image together with the full solar disc according ESA press release. The eruption have originated from the side of the Sun facing away from Earth. The eruption was registered by all coronagraphs at about 22 UTC. The CME propagated in northeast direction, includes the ecliptic. Its speed was about 1000 km s^{-1} and the consequent shock wave accelerated the SEP that could reach Mars.

The time profiles of the particle flux and dose rate measured by Liulin-MO during this event are shown in Figure 6. The increase of the dose rate and flux is observed from 15.02.2022 22:23 UT to 19.02.2022 04:23 UT.

The SEP dose measured by Liulin-MO during this event is 14.2 mGy - equal to the dose for 38.5 days from GCR in quite conditions. At the peak of the event the dose rate is about 2 orders larger than the dose rate in quite conditions. The dose equivalent from SEP during this event is 27.6 mSv. This is the most powerful event observed in our data.

One can see a short burst, after that a drop and another period of increase in the time profiles of the flux and dose rate. This is sometimes observed when an interplanetary shock wave passes near a spacecraft.

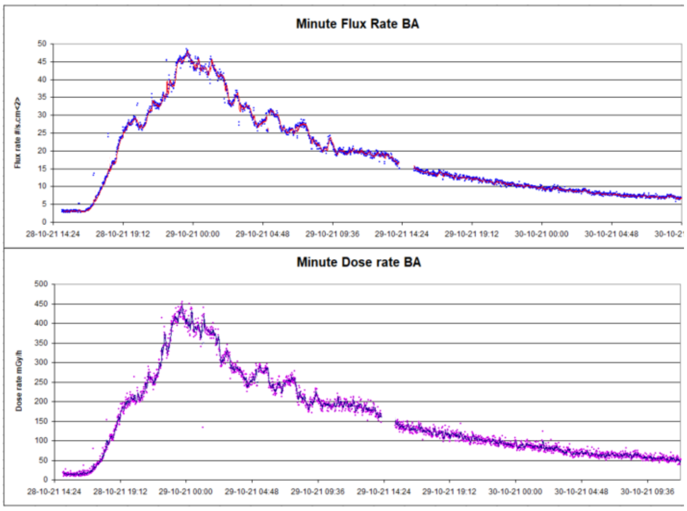

Figure 5. *Time profiles of the particle flux (top) and dose rate (bottom) during SEP event on 28-31 October 2021*

3.6. SEP event observed on 14 March 2022

Liulin-MO flux and dose rates start to increase at 17:55 UTC on 14 March 2022, the increase is modest in comparison with 28 October 2021 and 14 February 2022 events.

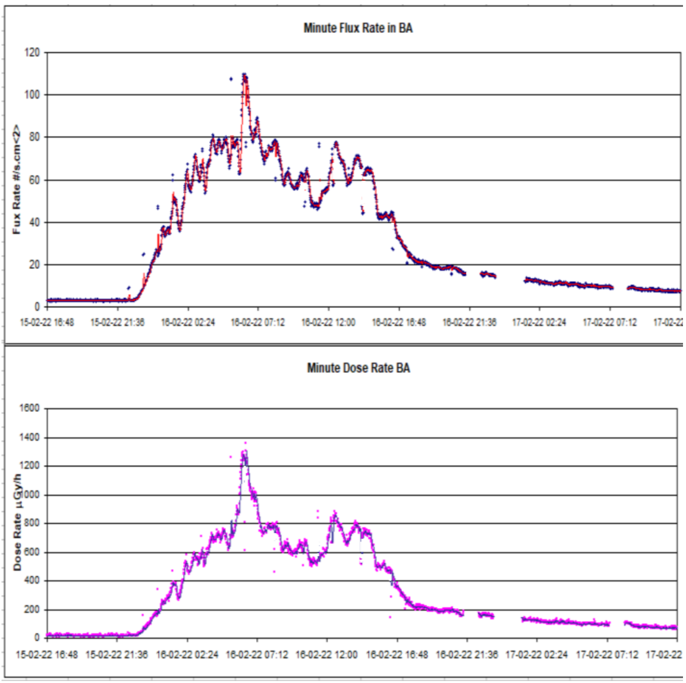

Figure 6. *Time profiles of the particle flux (top) and dose rate (bottom) during SEP event on 15-19 February 2022*

3.7 Comparison of measurement of different detectors in Mars orbit during February 2022 SEP event

Compared are the time profiles of the normalized count rates of Liulin-MO, neutron detectors of FREND instrument on ExoMars TGO and the neutron detector HEND aboard Mars Odyssey spacecraft (Mitrofanov et al, 2003) during February 2022 SEP event (Figure 7). A very good agreement between the measurements of the different detectors located on different spacecrafts in Mars orbit during this event is observed.

Conclusions

The measurements of the radiation environment on ExoMars TGO Mars science orbit show that: At the minimum of 24th and transition to 25th solar cycle the dose rate from GCR is 15.9 μGy h^{-1}, particle flux is 3.3 cm^{-2} s^{-1}, dose equivalent rate is 72 μSv h^{-1}; The total dose from SEP for 28-31 October 2021 event is about 7 mGy (in Si). The dose equivalent from SEP is 10 mSv; The SEP dose from 15-19 February 2022 SEP event is 14.2 mGy (in Si). The dose equivalent from SEP is 27.6 mSv; The SEP events in July 2021, September 2021 and March

2022 have no significant effect on the radiation environment on TGO; The dosimeter and the neutron detectors on TGO and Mars Odyssey spacecrafts show similar time profiles of SEP count rates.

The data for SEP events on TGO in July 2021 – March 2022 contribute to the details for the solar activity at a time when Mars is on the opposite side of the Sun from Earth.

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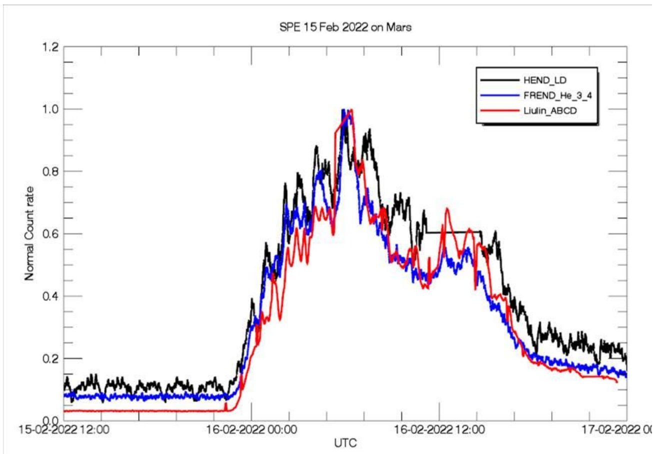

Figure 7. *Time profiles of the normalized count rates of FREND neutron detectors (blue), Liulin-MO (red) and HEND-Mars Odysee (black) during 15-17 February 2022 SPE*

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