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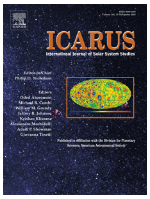

Charged particles radiation measurements with Liulin-MO dosimeter of FREND instrument aboard ExoMars Trace Gas Orbiter during the transit and in high elliptic Mars orbit

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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, plus an Entry, Descent and landing demonstrator Module (EDM), launched on March 14, 2016; and the other, featuring a rover and a surface platform, with a launch date of 2020. On October 19, 2016 TGO was inserted into high elliptic Mars' orbit. The dosimetric telescope Liulin-MO for measuring the radiation environment onboard the ExoMars 2016 TGO is a module of the Fine Resolution Epithermal Neutron Detector (FREND). Here we present first results from measurements of the charged particle fluxes, dose rates, Linear Energy Transfer (LET) spectra and estimation of dose equivalent rates in the interplanetary space during the cruise of TGO to Mars and first results from dosimetric measurements in high elliptic Mars' orbit. A comparison is made with the dose rates obtained by RAD instrument onboard Mars Science Laboratory during the cruise to Mars in 2011–2012 and with the Galactic Cosmic Rays (GCR) count rates provided by other particle detectors currently in space. The average measured dose rate in Si from GCR during the transit to Mars for the period April 22–September 15, 2016 is 372 ± 37 μGy d^{-1} and 390 ± 39 μGy d^{-1} in two perpendicular directions. The dose equivalent rate from GCR for the same time period is about 2 ± 0.3 mSv d$^{-1.}$ This is in good agreement with RAD results for radiation dose rate in Si from GCR in the interplanetary space, taking into account the different solar activity during the measurements of both instruments. About 10% increase of the dose rate, and 15% increase of the dose equivalent rate for 10.5 months flight is observed. It is due to the increase of Liulin-MO particle fluxes for that period and corresponds to the overall GCR intensity increase during the declining phase of the solar activity. 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—about 10 g cm^{-2}. The dosimetric measurements in high elliptic Mars' orbit demonstrate strong dependence of the GCR fluxes near the TGO pericenter on satellite's field of view shadowed by Mars.

1. Introduction

The possibility of life on Mars is one of the unresolved scientific problems of our time. ExoMars is a joint investigation of Mars car-

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ried out by ESA and Roscosmos. Two missions are foreseen within the ExoMars program: one consisting of the Trace Gas Orbiter plus an Entry, Descent and landing demonstrator Module, launched on 14 March 2016, and the other, featuring a rover and a surface platform, with a launch date of 2020. A top priority for the ExoMars mission is testing for any signs of life, either past or present.

Mars, like each celestial body, is unceasingly bombarded by energetic particles of GCR and sporadically–by particles of solar particle events (SPE). These ionizing particles modify the escape rates and the chemistry of Mars atmosphere; affect the evolution of the climate. Mars is known to have no strong magnetic field and very thin atmosphere. Particles of GCR penetrate down to the Martian surface, affect the chemistry at ground and can destroy complex organic materials if existing (see Gronoff et al., 2015 and references therein). Secondary neutrons are produced within an upper most layer about 1 m thick. These neutrons easily leak out to the near-Mars space and contribute into the local radiation environment of Mars. They also bear important information about the abundances and distributions of light elements, especially hydrogen. GCR and SEP (solar energetic particle) events affect the operation of satellites and the human exploration of the planet.

GCR represent a continuous radiation source and they are the most penetrating among the major types of ionizing radiation. The distribution of GCR is believed to be isotropic throughout the interstellar and interplanetary space. The energies of GCR particles can reach 10^{20} eV/nucleon. Most of the deleterious effects with regard to health produced by this radiation are associated with nuclei in the energy range from several hundred MeV/nucleon to a few GeV nucleon^{-1} (McKenna-Lawlor et al., 2012). The flux and spectra of GCR show modulation that anti-correlates with the solar activity. The GCR flux consists (Badhwar and O'Neill, 1992) mainly of protons (85–90%) and helium (about 11%), with about 1% electrons and another 1% heavy ions. The latter are sometimes referred to as "HZE" particles, for high charge (Z) and energy (E). These are defined as the bare nuclei of lithium ($Z=3$) and all heavier elements, fully stripped of their electrons. The HZE particles play a particularly important role in space dosimetry (Benton and Benton, 2001) as they are highly penetrating and affect strongly the biological objects and humans in space (Cucinotta et al., 2004).

Solar energetic particles (SEP) are randomly distributed events. Typical SEPs are known to pose a small health risk to astronauts and can be effectively attenuated by using relatively thin shield materials, although they can influence mission planning or interfere with mission activities such as extravehicular activities. However, large SEP events can be lethal, although they are rare (Committee for Evaluation of Space Radiation Cancer Risk Model, 2012). It is now widely agreed that SEPs come from two different sources with different acceleration mechanisms working: the flares themselves release impulsive events while the coronal mass ejection (CME) shocks produce gradual events (Cliver and Cane, 2002). High fluxes of charged particles (mostly protons, some helium and heavier ions) with energies up to several GeV and intensity up to 10^4 cm^{-2} s^{-1} sr^{-1} are emitted. The time profile of a typical SEP event starts with a rapid increase in flux, reaching a peak in minutes to hours. Although SEPs are more likely to occur around solar maximum, such events are at present unpredic with regard to their times of occurrence and it cannot be assumed that SEPs will not occur under solar minimum. The most intense solar proton fluencies observed near Earth were those on August 1972 and October 1989. An even larger "Carrington" event on July 23, 2012 was detected by the Stereo-A spacecraft at a different heliolongitude from that of Earth (Russell et al., 2013). The flare containing the largest peak flux of highly penetrating particles was a ground level event detected by neutron monitors on February 23, 1956. On this basis the so-called worst-case flare is composed, that is thought to occur once a century, but statistics are extremely poor.

The deep space manned missions are already a near future of the astronautics. Radiation risk on such a long-duration journey, a great part of which will take place in the interplanetary space, appears to be one of the basic factors in planning and designing the mission.

The estimation of the radiation effects for a long-duration manned space mission requires three distinct procedures: (i) Knowledge and modeling of the particle radiation environment; (ii) Calculation of primary and secondary particle transport through shielding materials; and (iii) Assessment of the biological effect of the dose.

(i) ***Direct measurements*** of the radiation environment in the interplanetary space and at celestial bodies other than Earth are quite sparse. The first evaluation of the radiation field at Mars orbit was performed by the experiments on board of Mars Odyssey orbiter (Zeitlin et al., 2010) using data of three different instruments: MARIE, a dedicated energetic charged particle spectrometer; the Gamma Ray Spectrometer GRS and the scintillator component of the High Energy Neutron Detector HEND. The time period of analyzed data covers 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 0.243 cm^{-2} sr^{-1} s^{-1} measured by MARIE A1 detector with a 15 MeV/nuc threshold, but comparison between data from the three experiments gave the authors the ground to evaluate the flux to 0.135 cm^{-2} sr^{-1} s^{-1}. The corresponding omnidirectional fluxes are 3.05 cm^{-2} s^{-1} and 1.7 cm^{-2} s^{-1}. Here and further the calculation of the omnidirectional fluxes is done under the assumption of isotropic distribution. 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} (the respective omnidirectional fluxes being 630 and 1260 cm^{-2} s^{-1}) measured by the same A1 detector of MARIE were seen only twice (July 2002 and October 2002). Only in the large event of October 2003 was a flux above 1000 cm^{-2} sr^{-1} s^{-1} (corresponding to 12,500 cm^{-2} s^{-1}) recorded by HEND probably for protons with energies higher than about 27 MeV. 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 about 1.5 times from 0.73 up to 1.1 cm^{-2} s^{-1}.

During the deep solar minimum at the end of 2008—first half of 2009—the RADOM dosimeter-spectrometer on the Chandrayaan-1 satellite (Dachev et al., 2011) registered during lunar transfer trajectory (4th to 6th November 2008) an average GCR flux of $\sim$3.14 cm^{-2} s^{-1}, producing an average dose rate of $\sim$312 µGy d^{-1} in the silicon detector of the instrument with a threshold energy of 17.5 MeV for protons and 0.85 MeV for electrons. In a 100 km circular orbit around the Moon the GCR dose rates fall down because of the Moon shielding to about 227 µGy d^{-1} and stayed stable around this value. The average flux was 2.45 cm^{-2} s^{-1}.

The CRaTER experiment on board the Lunar Reconnaissance Orbiter spacecraft provided another evaluation of GCR doses in Moon orbit during an adjacent period of the same deep and prolonged minimum between the 23rd and the 24th solar cycles (Spence et al., 2013). Using a validated radiation transport models of the instrument for the period from 16 September 2009–6 March 2010 they estimated a direct GCR dose in silicon of $\sim$320 μGy d^{-1}(energy threshold of 60 MeV for protons). The Moon albedo particles complemented the dose rate to 372 µGy d^{-1}. Thanks to the sophisticated instrument model they succeeded to