A NEW TIME-DEPENDENT MODEL FOR THE MARTIAN RADIATION ENVIRONMENT.

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Introduction: Manned space activities have been until present time limited to the near-Earth environment, most of them to low Earth orbit (LEO) scenarios, with only some of the Apollo missions targeted to the Moon. In current times most human exploration and development of space (HEDS) activities are related to the development of the International Space Station (ISS), and therefore take place in the LEO environment. A natural extension of HEDS activities will be going beyond LEO, and reach asteroids, Mars, Jupiter, Saturn, the Kuiper belt and the outskirts of the Solar System. Such long journeys onboard spacecraft outside the protective umbrella of the geomagnetic field will require higher levels of protection from the radiation environment found in the deep space for both astronauts and equipment. So, it is important to have available a tool for radiation shielding which takes into account the radiation environments found all along the interplanetary space and at the different bodies encountered in the Solar System. Moreover, the radiation protection is one of the two NASA highest concerns and priorities [1]. A tool integrating different radiation environments with shielding computation techniques especially tailored for deep space mission scenario is instrumental in view of this exigency [2].

In view of manned missions targeted to Mars (for a review see e.g. [3]), for which radiation exposure is one of the greatest problems and challenges to be tackled [4], it is of fundamental importance to have available a tool which allows to know which are the particle flux and spectra at any time at any point of the Martian surface. With this goal in mind, a new model for the radiation environment to be found on the planet Mars due to Galactic Cosmic Rays (GCR) has been developed. Solar modulated primary particles [5] rescaled for Mars conditions are transported within the Martian atmosphere, with temporal properties modeled with variable timescales, down to the surface, with altitude and backscattering patterns taken into account. The tool allows analysis for manned Mars landing missions, as well as planetary science studies, e.g. subsurface water and volatile inventory studies [6]. This Mars environmental model is available through the SIREST website [7], a project of NASA Langley Research Center.

Radiation Source Models:

Galactic Cosmic Rays (GCR). Galactic Cosmic Rays originate outside our Solar System in ways yet not totally clear [8]. They are composed of highly energetic fully ionized nuclei of all charges from hydrogen to uranium, with a large decrease in the intensity of particles with charge higher than 28 [9]. From interstellar space the GCR enter the Solar System, where they come into contact with the particles of the solar wind, which transports outward the solar magnetic field [10]. The distribution of cosmic rays in the heliosphere and the time dependence due to solar activity of the variations of the solar wind velocity and diffusion coefficient are taken into account as in [11-13], relating the sunspot number to the cosmic ray induced neutron monitor count rate measured at the Deep River location, Ontario, Canada, with an evident inverse relationship between sunspot number (solar activity indicator) and count rates (cosmic rays flux indicator).

Planetary Surfaces. A planetary body, i.e. a planet or one if its satellites, need to be modeled to assess the radiation dose a crew will take during surface activities. If the body is atmosphereless, it has to be modeled in position (astrometry), size, topography, and surface chemical composition, to get the atomic surface composition needed for transport computation, to evaluate the backscattering radiation component, especially neutrons. If the target body has an atmosphere, a profile of the atmosphere in terms of density, temperature and composition vs. altitude (and time) should be provided, to compute how the primary particle fluxes are modified by the interaction with the atmosphere. The knowledge of the body topography is particularly important in the case an atmosphere is present, to know down to which surface altitude the effects of the atmosphere have to be taken into account. In the Solar System bodies (see, e.g. [14]) two kinds of surface composition are prevalent, namely a silicatic rocky composition on the bodies of the Inner Solar System (i.e. Mercury, Venus, the Earth, the Moon, Mars and its satellites, asteroids), and a mostly icy (water ice, methane ice, ammonia ice) composition of the solid bodies of the Outer Solar System (satellites of Jupiter, Saturn, Uranus, Neptune, Pluto with his moon Charon, comets, the Kuiper Belt and all Trans-Neptunian objects). The giant planets of the Outer Solar System have a gaseous composition all along their body (Jupiter, Saturn, Uranus, Neptune), and seem not to have any solid surface [15] on which any surface activity looks to be practicable. Interesting phenomena take place on the surface of bodies with locally mixed rock/ice composition, like in planets with seasonal or perennial volatile-generated polar caps (e.g. carbon dioxide ice and water ice caps on Mars). Neutron backscattering from silicatic surface is important particularly at the lower energies [16], whereas the interaction with ices produces far less neutrons [13].

Radiation Dose Computations: The radial rescaling for GCR has been discussed in [17] and will be not further discussed in this paper. Positive charged particles, i.e. protons and heavier ions, have been transported by using a current version of the NASA Langley Research Center (LaRC) heavy ion deterministic code HZETRN [18], which provides particle energy spectra at predefined positions in the material layer of interest as well as the pertinent dosimetric quantities, with energy deposition from both primary and secondary particles, including nuclear target fragments, accounted for. The materials are modeled as a thickness file including distance of each material traversed in the order progressing from the outer boundary inward toward the target point. With the specified environment, i.e. the specified charged particle flux boundary conditions, the transport code is used to generate dose vs. depth functions for each material under consideration over a range of thicknesses adequate for interpolation for the shielding analysis. Results for doses at planet distances at intermediate time between solar minimum and maximum epochs are obtained as discussed above, through the simplified diffusion model shown in [9]. For points at the surface, the transport techniques adopted are mostly the same as those developed for the free space case, but with two main modifications: the primary particles are limited to come only from above the surface, so the solid angle of acceptance of primary particles is limited to 2π, and it is not the full 4π solid angle like in the free space case. In some cases, due to local topography feature like valleys or craters, the solid angle might be even smaller than 2π [19]. Moreover, the backscattering component, mostly neutrons, created by the interaction between the incoming particles and the nuclei composing the surface, is to be added to the particle flux at the surface. For atmosphereless bodies this component is about 1% of the dose given by GCR alone [20], with little dependence on the composition of the surface materials. For target bodies with an atmosphere, a profile of the atmosphere in terms of density, temperature and composition vs. altitude (and time) should be provided, to compute how the primary particle fluxes are modified by atmospheric interactions. At the surface the modified particle fields interact with the nuclei composing the surface, whose chemical composition should be known too. For each considered point at the surface, transport calculations have been carried out.

Mars Radiation Modeling: Mars is a planet with an atmosphere, so the modeling of the Martian radiation environment has to deal with both atmospheric and surface properties. The Martian atmosphere has been modeled by using the Mars Global Reference Atmospheric Model – version 2001 (‘Mars-GRAM 2001’, see [21]), based on input data generated as output of the NASA Ames Mars General Circulation Model (MGCM) for the lower atmosphere, from the surface to 80 km altitude [22,23], the University of Arizona Mars Thermosphere General Circulation Model (MTGCM) for the higher atmosphere, from 80 km to 170 km altitude [24,25], and a modified Stewart-type thermospheric model, a latitude-longitude dependent model also depending on solar activity [26], above 170 km altitude. This model can provide at any time a profile of the Martian atmosphere in terms of density, pressure, and temperature vs. altitude, needed to compute the atmosphere thickness for the incoming particle flux. The atmospheric chemical and isotopic composition has been modeled over results from the in-situ Viking Lander measurements for both major [27] and minor [28] components (see Table 1). The surface altitude, or better the atmospheric depth for incoming particles, to compute the atmospheric thickness profile has been determined by using a model for the Martian topography based on the data provided by the Mars Orbiter Laser Altimeter (MOLA) instrument on board the Mars Global Surveyor (MGS) spacecraft [29]. The MOLA topography is measured with respect to a zero elevation surface level known as the MOLA aeroid [30], which is defined as the gravitational equipotential surface whose average value at the equator is equal to the mean planetary radius determined by MOLA data. Among the various data resolution available [31], in this work half-degree latitude-longitude resolution data for both MOLA aeroid surface and topography have been used (i.e. 30 km spatial resolution at the equator), but this value can be tuned in case of different user needs. The Mars regolith composition has been modeled based on averages over the measurements obtained for Mars 5 [32] with gamma-ray spectroscopy, and at the various landing sites Viking Landers 1 and 2 [33,34], Phobos 2 [35,36] and Mars Pathfinder missions [37,38]. From the averaging process an average composition has been obtained (see Table 2). In this first project a value of 1.6 g/cm^3 [39] for the Mars soil density has been adopted. The composition, different with respect to the regolith (e.g. CO_2 ice, H_2O ice), of seasonal and perennial polar caps [40] has been taken into account by modeling the deposition of the possible volatile inventory over the residual caps, along with its geographical variations all throughout the Martian year, for both the Mars North [41] and South Pole [42], from results from imaging data of orbiter spacecraft. No such 3D Mars time dependent polar caps modeling was previously available for radiation analysis. Particle transport has been performed with the HZETRN heavy ion code with an adaptation for planetary surface, as said above. The new Mars Radiation Environment Model has been made available worldwide through the Space Ionizing Radiation Effects and Shielding Tools (SIREST) website, a project of NASA Langley Research Center. This site has been developed to provide the scientific and engineering communities with an interactive site containing a variety of environmental models, shield evaluation codes, and radiation response models to allow a thorough assessment of ionizing radiation risk for current and future space missions [7,43,44]. This model is instrumental to deal with the Planetary Surface Phase of manned missions targeted to Mars [3]. A radiation dose and a dose rate can be computed at any time at any location on the planet. As an example, a SIREST-generated Mars neutron radiation environment map due to GCR for 1977 Solar Minimum conditions is shown in Fig. 1, with a striking correspondence between neutron flux and Mars topography, putting clearly into evidence the effects of even this so tenuous atmosphere on particle transport. The present Mars Radiation Environment Model will be tested by comparison with the data from the Mars Odyssey mission MARIE and HEND instruments in the near future.

Conclusions: A new model for the radiation environment to be found on the planet Mars due to Galactic Cosmic Rays (GCR) has been developed at the NASA Langley Research Center. Solar modulated primary particles rescaled for Mars conditions are transported through the Martian atmosphere, with temporal properties modeled with variable timescales, down to the surface, with altitude and surface backscattering patterns taken into account. The Mars Radiation Environment Model has been made available worldwide through the Space Ionizing Radiation Effects and Shielding Tools (SIREST) website. This Mars Radiation Environment Model will be tested with the data from the Mars Odyssey instruments in the near future.

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CO_2	**%**	**95.32**
SiO_2	**%**	**44.2**
Fe_2O_3	**%**	**16.8**
Al_2O_3	**%**	**08.8**
CaO	**%**	**06.6**
MgO	**%**	**06.2**
SO_3	**%**	**05.5**
Na_2O	**%**	**02.5**
TiO_2	**%**	**01.0**

Table 2. Adopted chemical composition for the Martian surface.

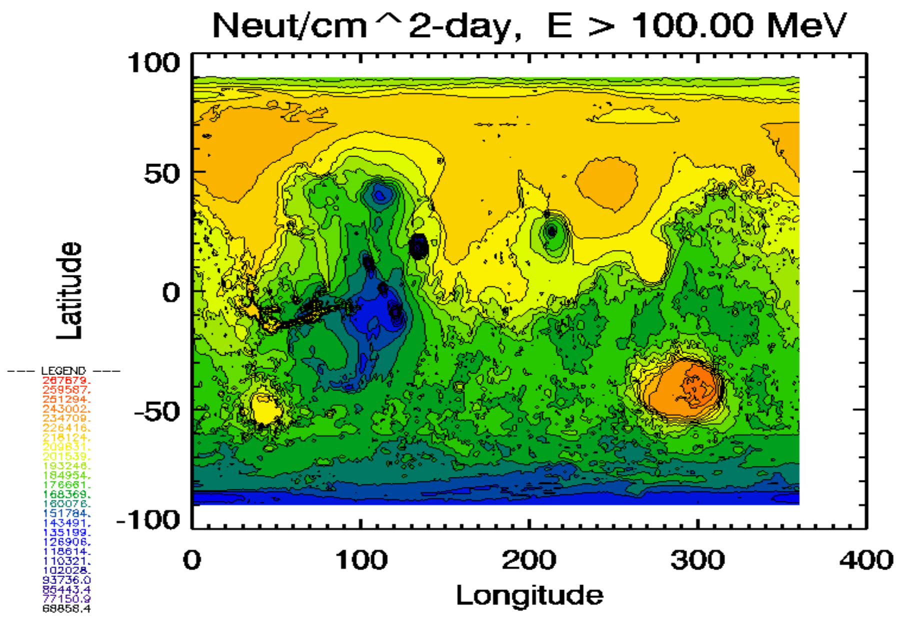

Figure 1 Map of neutron integral flux on the Mars surface for GCR at 1977 Solar Minimum.