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Modelling of the dose-rate variations with depth in the Martian regolith using GEANT4

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Abstract

The environmental radiation field at the Martian surface consists mainly of Galactic Cosmic Rays (GCR) and charged particles ejected during the Solar Particle Events (SPE). Interactions between these radiation fluxes and the regolith result in a complex radiation field that varies both as a function of depth and time and can only be quantified using radiation transport models. We first describe here the main issues and constraints in deriving Martian dose rates. Preliminary results, obtained using the GEANT4 Monte Carlo simulation tool kit, suggest the surface dose rate is $\sim 63\,\text{mGy}\,\text{a}^{-1}$ during quiet periods in solar activity. The accuracy of the model predictions has been tested by comparison with published observations of cosmic ray dose-rate variation in the Earth's atmosphere.

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1. Introduction

Luminescence dating has the potential to contribute considerably to our understanding of the history of recent climatic change on Mars [1]. This technique requires knowledge of the total absorbed dose (Gy) in the material of interest since last resetting, and of the rate at which the dose is deposited ($\text{Gy}\,\text{a}^{-1}$) from the surrounding radiation field [2]. The latter requires (i) quantification of this radiation field and its variability with time and (ii) a reliable model of the interaction of this field with the Martian regolith (the surface layer consisting of unconsolidated material) to give the dose-rate variation with depth. In this study, we have modeled the variation of dose rate with depth using GEANT4. Results of this modeling are presented and compared with terrestrial experimental data.

2. Radiation environment on mars

The radiation environment on Mars is dominated by Galactic Cosmic Rays (GCR) and the charged particles from the Solar Energetic Particle (SEP) events. The GCR is made up of particles from H to Fe, with an energy ranging from 100 MeV to 1 TeV per nucleon, approximately. All the particles are fully ionized. The SEPs have a similar nucleon composition but of lower energy range (up to 1 GeV per nucleon); these particles are only partially ionized. One of the effects of SEP events is to modulate the lower energy spectra of the GCR because of changes in the heliospheric magnetic field (see Fig. 1).

Unlike on Earth, the Martian magnetic field is regional, with intensities in the range 30–60 nanoTesla (nT). The atmosphere is mainly composed of CO_2 (95%). Due to the large variations in topography, the atmospheric thickness varies from 5 to $38\,\text{g/cm}^2$ [4]. For comparison, both the atmospheric thickness and the intensity of the magnetic field is approximately 1000 times less than on Earth. As a result of

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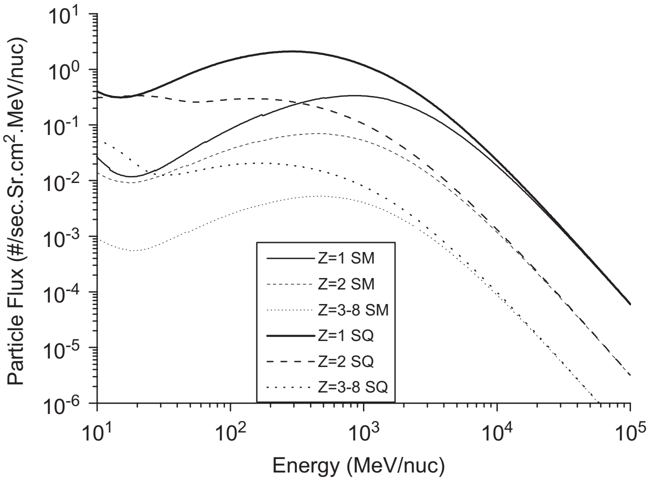

Fig. 1. GCR energy spectra during solar quiet (SQ) and solar maximum (SM) conditions, obtained using CREME96 [3].

the much thinner atmosphere and weaker magnetosphere, GCR and SEPs are only slightly attenuated above the Martian surface; most of their energy is deposited in the Martian regolith.

3. Dose rate at the Martian surface

The Martian Radiation Environment Experiment (MARIE) in the Mars Odyssey, in orbit around Mars at 400 km, has provided a measurement of the dose rate as 76 mGy a^{-1} [5]. This value has been reproduced using the HZETRN transport code for that orbit. Kim et al. [6] estimated the surface dose rate to be 194 mGy a^{-1}, in an investigation of the use of a basaltic Martian regolith as a shield for microbes against GCR. This value agrees with the calculated surface dose rate in the Martian regolith by Mileikowsky et al. [7]. In a study of possible radio-resistant organisms in Martian sediment, Pavlov et al. [8] estimated the surface dose rate to be 200 mGy a^{-1}. All the above studies made use of the HZETRN transport code [9], based on solving the Boltzmann transport equation with proper boundary conditions and inputs. It should also be noted that these dose rates are approximately 250 times greater than the expected value from typical concentrations of uranium, thorium and radioactive potassium in the Martian regolith, of about 0.8 mGy a^{-1} [10].

4. Dose rate in Martian regolith

Using the same HZETRN transport code, McKeever et al. [11] simulated the dose rate in Martian regolith. They derived a surface dose rate during solar quiet conditions of only 78 mGy a^{-1}; this decreased monotonically with depth to 35% of the surface dose rate at 2 m. However, results from balloon experiments in the Earth's atmosphere clearly shows a build up of secondary particles and photons as a result of primary particle interaction with the atmosphere, with a maximum (known as Pfotzer maximum) at ~50 g cm^{-2} of atmospheric depth [12]. Since the average atmospheric thickness on Mars is ~16 g cm^{-2}, it is reasonable to expect the Pfotzer maximum to occur within the Martian regolith; despite this, no such peak is observed in the McKeever et al. results.

5. GEANT4 results

We have made use of GEANT4, a Monte Carlo simulation toolkit for particle physics [13] to model the transport of GCR through the Martian regolith. Our model consists of a 70 km atmospheric column on top of 20 m of regolith. The atmosphere is composed of a stack of 20 layers of equal thickness, each with the appropriate composition, temperature, density and pressure attributes, to simulate the atmospheric profile. The atmospheric description was taken from the Mars Climate Database [14], and represents summer at Arabia Terra, with a surface pressure of 6 mbar [15]. The regolith is taken to be spatially homogenous, with an elemental composition based on Pathfinder measurements [16]. Two scenarios are tested: a dry regolith (density 1.6 g cm^{-3}); and one containing 10% water as permafrost (density 1.76 g cm^{-3}). GCR (100 MeV to 20 GeV per nucleon) were extracted from the SPENVIS database [17] for Martian orbit (1.5 astronomical unit) under both solar quiet and solar maximum conditions, and extrapolated to 1 TeV per nucleon for primary particles with $Z = 1$–26 (H–Fe). Primary particles are generated at the top of the atmosphere to create an isotropic angular distribution. The interactions of protons, and resulting secondary cascades, are followed explicitly by the GEANT4 code. Energy deposition events in the regolith are logged and binned into 5 cm depth intervals to produce a depth profile of absorbed dose.

Fig. 2 shows the variation in annual dose rate with depth from GCR protons. The thick line is the result of the PLANETOCOSMICS code [18] and the dotted line is the result of this model. The surface dose rates agree within

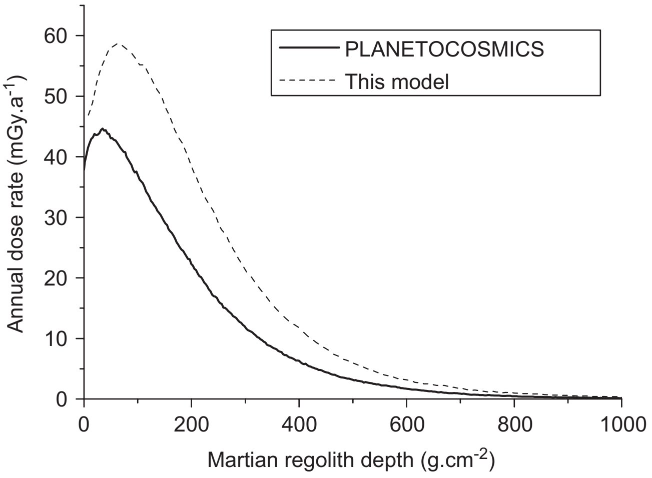

Fig. 2. Annual dose rate from GCR protons during solar minimum.

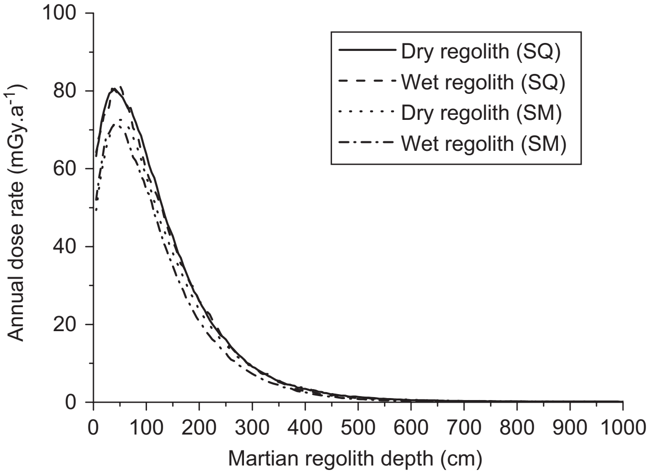

Fig. 3. Dose-rate variation with depth for dry and wet regolith, during solar maximum (SM) and solar quiet (SQ) activity.

20%. The maximum occurs at a slightly shallower depth in the PLANETOCOSMICS result. This difference is likely to be due to the fact that PLANETOCOSMICS used a different GCR spectrum (CREME96) than the one used in our model, i.e. SPENVIS. Moreover, in PLANETOCOSMICS code the GCR proton energy spectra was in the range of 100 MeV–1 TeV per nucleon, the atmospheric variables were taken from the Mars-GRAM2001 model [19] and the regolith density was taken as 2.81 g cm^{-3}. Apart from the agreement in surface dose rates, the occurrence of the Pfotzer maximum in both simulations helps to give confidence in the results.

The total annual GCR dose rate has been derived by assuming that the remaining nucleons in the spectra (i.e. He–Fe) deposit energy in a similar manner to protons. This assumption significantly reduces the computation time. Thus, the total dose rate from the GCR can be derived by scaling the proton dose rate by a factor of 1.37 at each depth in the regolith. The scaling factor of 1.37 is based on the ratio between the number of total nucleons and the total number of protons in the derived GCR flux from CREME96. These total dose rates for dry and wet soil (i.e. 10% water as permafrost) are shown in Fig. 3.

6. Discussion

Our estimate of the annual surface GCR dose rate during solar minimum conditions is 63 mGy a^{-1}. It increases to a maximum of 80 mGy a^{-1} at a depth of about 40 cm into the Martian regolith. Subsequently, the dose rate decreases monotonously to less than 2% of the initial value in the next 5 m interval. Our results on proton dose-rate variation with depth broadly agree with the simulation using PLANETOCOSMICS, which has, in turn, been successfully tested with the actual dose-rate variations in the Earth's atmosphere. Our results on total GCR dose rate can be compared to the published results of the HZETRN model [5–8,11], as discussed below.

Various HZETRN simulations, except [11], show the existence of the Pfotzer maximum in about first 10 cm depth in the Martian regolith (density 3 g cm^{-3}). We also observe the Pfotzer maximum in our results, however, at a depth of about 40 cm (density 1.6 g cm^{-3}).

The other significant difference exists in the magnitude of the surface dose rate. The simulations results from the HZETRN model itself differ by about three times. For example, McKeever et al. [11] calculate a value of 78 mGy a^{-1} for solar minimum conditions, while Kim et al. [6] and Mileikowsky et al. [7] quote a value of about 194 mGy a^{-1}. The reasons for such a discrepancy are unknown; minor possible variations in the input parameters (atmospheric thickness, GCR spectrum, magnetic field etc.) cannot explain such large variations in the surface dose-rate results using the same transport code. Unfortunately, these papers do not give enough details of their simulation so as to be able to address this problem. Nonetheless, it is encouraging to note that our result on the surface dose rate is within 20% of the actual measured surface dose rate from MARIE [5] of 76 mGy a^{-1}. These results also happen to be close to the results obtained by McKeever et al. [11] using HZETRN.

Further work will expand the GEANT4 simulation to cover realistic variations in atmospheric thickness and composition, and to include the spatial and temporal variations in cosmic ray flux. Also, the variation of dose rate with depth into the regolith must be weighted by including the effects of the LET dependence of luminescence efficiency [20]. Only then will it be practical to derive accurate luminescence ages from in situ measurements of burial dose from arbitrary locations on the Martian surface.

7. Summary

The variation with depth of the dose rate into the Martian regolith has been simulated for realistic GCR spectra. The form of the model results is consistent with published experimental observations of the depth dependence in the Earth's atmosphere. The total Martian surface dose rate is predicted to be about 63 mGy a^{-1}. The dose rate reaches a maximum at a depth of 40 cm in the regolith (density 1.6 g cm^{-3}). The dose rate due to GCR is less than 2% of the initial value below about 5 m.

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References

[1] M. Jain, C.E. Anderson, L. Bøtter-Jensen, A.S. Murray, H. Haack, J.C. Bridges, Radiat. Meas. 41 (2006) 755.

[2] M.J. Aitken, An Introduction to Optical Dating, Oxford University Press, New York, 1998.
[3] A.J. Tylka, J.H. Adams Jr., P.R. Boberg, B. Brownstein, W.F. Dietrich, E.O. Flueckiger, E.L. Petersen, M.A. Shea, D.F. Smart, E.C. Smith, IEEE Trans. Nucl. Sci. NS-44 (6) (1997) 2150.
[4] S.C. Solomon, et al., Science 307 (2005) 1214.
[5] C. Zeitlin, et al., Adv. Space Res. 33 (2004) 2204.
[6] M.Y. Kim, S.A. Thibeault, L.C. Simonsen, J.W. Wilson, Comparison of martian meteorites and martian regolith as shield materials for galactic cosmic rays, NASA TP-208724, 1998.
[7] C. Mileikowsky, et al., Icarus 145 (2000) 391.
[8] A.K. Pavlov, A.V. Blinov, A.N. Konstantinov, Planet Space Sci. 50 (2002) 669.
[9] J.W. Wilson, F. Cucinotta, F. Badavi, HZETRN: description of a free space ion and nucleon transport and shielding computer program, NASA TP-3495, 1995.
[10] G. Jeffrey Taylor, et al., in: Sixth International Conference on Mars, 2003.
[11] S.W.S. McKeever, et al., Radiat. Meas. 37 (2003) 527.
[12] I.S. Bowen, R.A. Millikan, H. Victor Neher, Phys. Rev. 53 (1938) 855.
[13] S. Agostinelli, et al., Nucl. Instr. and Meth. A 506 (2003) 250.
[14] ⟨http://www-mars.lmd.jussieu.fr/⟩.
[15] S.R. Lewis, et al., JGR-Planet 104 (E10) (1999) 24177.
[16] H. Wanke, et al., Space Sci. Rev. 96 (2001) 317.
[17] ⟨http://www.spenvis.oma.be/⟩.
[18] http://cosray.unibe.ch/~laurent/planetocosmics/.
[19] C.G. Justus, D.L. Johnson, Mars Global Reference Atmospheric Model 2001 version (Mars-GRAM 2001): User's guide, George C. Marshal Space Flight Center Marshall Space Flight Center, AL.
[20] M. Jain, C.E. Andersen, W. Hajdas, J.M. Edmund, L. Bøtter-Jensen, doi:10.1016/j.nima.2007.05.112.