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Interactive comment on "Martian sub-surface ionising radiation: biosignatures and geology" *by* L. R. Dartnell et al.

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Authors' Comments in response to Anonymous Referee 2:

p. 459, P1, l 3. I don't know what the authors mean by "typically," but there are 70 ground-level enhancements, or GLEs, since 1942. A GLE cannot be produced unless there are a considerable number of incoming protons with energies above 100 MeV.

The word 'typically' was used here to explain that most protons ejected by a solar particle event are accelerated to an energy of less than several hundred MeV. Although it is true that a small proportion of protons are accelerated even into the GeV energy range, there is a sharp knee in the spectrum and these particles are many orders of magnitude less frequent than those at 100 MeV [Reames, D. V. (2004) "Solar energetic particle variations." Advances in Space Research 34(2): 381-390]. In addition, such hard SEP spectra are very rare (the reviewer cites 70 GLEs since 1942), and so contribute a negligible fraction of the total SEP flux averaged over years and are greatly dominated by GCR at this energy. So for this reason we decided not to simulate the subsurface dose effect of SEP flux. There is further discussion on a related matter in response to the reviewer's comment on p.460 para.2.

p. 459, P1, l 9. Replace "complimentary" with "complementary."

Well spotted - thank you!

p. 459, P2. At this depth, electrons result from neutral pion decay into two high-energy photons, producing electromagnetic showers, a very local phenomenon, and the neutral pions are produced by high-energy nucleon-nucleus collisions. This will take place inside the crustal magnetic fields, some of them in the sub-surface soil and make their way up as albedo. Hence it is correct to say, but for different reasons, as the authors do in the same paragraph on the following page that "these crustal fields can be ignored in modelling the subsurface radiation environment on Mars.

The mapping simulation was run to test the deflection of primary protons and electrons propagating down towards the surface, and found that indeed the crustal magnetic anomalies can be discounted as insignificant deflection. The reviewer makes a fair point that electrons are also generated within the secondary cascades through neutron pion decay, although this source will be minimal within the thin martian atmosphere. The deflection of backscattering electrons by the magnetic anomalies is ignored as they play no part in the subsurface radiation dose.

p. 460, P2. Since a GLE has to penetrate the earth's atmosphere of 1000 g/cm2, this statement must be wrong. If the density of Martian soil is roughly the same as terrestrial soil, a GLE can penetrate 600 g/cm2 or more.

The reviewer is absolutely correct here that Ground Level Events, by definition, require SEP-generated particles to penetrate at least 1,000 g/cm2 to reach the Earth's surface and be observed. As discussed above, however, such events are short-lived and rare and averaged over long time-scales the SEP spectrum contributes insignificant dose beneath the surface relative to GCR cascades. The mean annual SEP flux provided by Usoskin et al (2006) has been processed through our model and supports this assertion. Two previous papers on aspects of the martian subsurface radiation dose cited by our work also do not consider the sub-surface dose contribution from SEP. Pavlov et al (2002) treat only GCR nuclei and Mileikowski et al (2000) also argue that sufficient protection against solar particles is given by about 30 g/cm2. If a hard SEP event were to coincide with human astronauts on the Martian surface, the dose rates would probably be disastrous, but considering geological timescales for astrobiology and OSL dating these anomalous events are not significant. Section 1.2 has been modified to clarify these points.

p. 464, P2, l 3. Isn't 2.65 too steep? Gaisser and Stanev (revised by Sokolsky and Streitmatter) [J. Phys G, Review of Par ticle Physics 33, 245(2006)] give 2.7. That may not seem like much, but over several decades of energy, the difference may be considerable. The top energy is only 1 GeV. How was this determined to be sufficient? Are these energy bins step functions?

My literature review found a range of estimates for the power law exponent of GCR spectra, in addition to the variation of this fitted parameter between different ions. Naganot et al (1992) [Energy spectrum of primary cosmic rays above 10^{17} eV determined from extensive air shower experiments at Akeno, J. Phys. G. Nucl. Part. Phys. 18. 423-442.] give 2.62 $\pm$0.12 below 10^{15} eV whereas Klapdor-Kleingrothaus and Zuber (2000) [Chapter 8: Cosmic Radiation. Particle astrophysics. 223 - 247] give a value of 2.7 below 10^{15} eV. I decided to select the more conservative value for this work (i.e. to over-estimate rather than under-estimate the dose delivered by high-energy GCR ions). Perhaps in future studies it might be worth considering to use 2.7 as this seems to be the more recent consensus. In any case, the difference in energy delivered between the two extrapolations is negligible. Taking the CREME96 model for primary spectra, we calculate the total energy for the GCR spectra (Z=1-26, E=100 MeV - 1 TeV) after extrapolating with different power-law exponents:

Solar minimum conditions:

gamma=-2.65 Total annual GCR energy delivered to top of martian atmosphere = 1.33448E11 MeV/cm2

gamma=-2.70 Total annual GCR energy delivered to top of martian atmosphere = 1.33053E10 MeV/cm2

(a difference of only 0.30%.)

Solar maximum conditions:

gamma=-2.65 Total annual GCR energy delivered to top of martian atmosphere = 9.33873E10 MeV/cm2

gamma=-2.70 Total annual GCR energy delivered to top of martian atmosphere = 9.3001 E10 MeV/cm2

(a difference of only 0.41%.)

The difference amounts to less than 0.4% and so we do not consider there to be significant variation under either solar minimum or maximum conditions.

The top energy is stated as 1 TeV/nuc and not 1 GeV/nuc. Above this primary energy limit the particles have such low flux as to contribute negligible dose - the CREME96 primary GCR model shows primaries at 1 TeV/nuc to have an annual flux more than seven orders of magnitude lower than the peak flux at several hundred MeV.

p. 465, item 4. Please give the Martian atmospheric depth in g/cm2.

This has been done.

p. 466, Eq. 1. z1 is the scale height and should be about 10.8 km for the current Martian atmosphere. Please give the value or values you used. The scale-height governs the rate at which pions and muons decay. In a thick early Martian atmosphere, this process will dominate at the surface as it does on the terrestrial surface.

The calculated scale height is now specified.

p. 466, penultimate line. Fig. 4 should be in semi-logarithmic format. In that fashion, the scale-height would be clearly evident as the inverse of the slope of the lines.

Figure replotted as requested.

p. 467, P1. After rereading several times, I realized that 1017 g/cm2 referred to an early (the earliest considered?) atmosphere. It is not clear from the text. However, the terrestrial atmosphere is not 1017 g/cm2 deep but 1033.227 g/cm2 deep.

The sentence explaining the selection of a 0.385 bar atmosphere has been moved and expanded to make this point more clear.

The terrestrial atmospheric thickness of 1019 g/cm2 is the one given by the model NRLMSISE at the equator on January 2000, and taken in this study as a representative figure. The shielding depth at any one time varies depending on weather conditions and altitude. In any case, for such a thick atmosphere, slight variation in depth will not impact the surface radiation doses. However, we accept the reviewer's remark that 1033 g/cm2 is a more representative figure than 1017 g/cm2 to use for the terrestrial atmosphere, and so we have rerun the atmospheric calculation and radiation model to this effect, and thank the reviewer for his/her helpful suggestion. The manuscript has been corrected in several places, including Figure 4, to reflect this requested change, although the results don't differ from this slight modification.

p. 467, P2, last line and p. 468, first line. I must say that I am uncomfortable with this. Neglecting nucleus-nucleus collisions, which produce secondary nucleons and nuclei, and replacing these complex processes with a single weight sweeps a lot of physics under the rug. The nuclear flux is attenuated much faster than the nucleonic flux because of the larger nucleus-nucleus cross sections. Energy deposition which depends finally on ionization is somewhat different. The ionization due to an iron nucleus is 26 times that of 26 protons of the same energy per nucleon because of the Z^2 term in the stopping power.

We agree absolutely with the reviewer: it is indeed a simplification to treat, for example, an Fe^{26+} ion as 26 protons. However, in any computer model approximations must be made to make the problem tractable, and in this particular case two important approximations must be made. Firstly, it is not feasible in terms of the computer processing time required to explicitly simulate all 26 primary ions from protons (Z=1) to iron nuclei (Z=26) with a Monte Carlo transport code, and so some degree of using appropriately-weighted data to fill-in for the input from other ions is necessary. Secondly, the particle transport code used in this study, Geant4, is a Monte Carlo code which explicitly simulates the propagation, electromagnetic interaction, ionisation, nuclear fragmentation, and attenuation of every single primary particle and its entire secondary cascade. Despite being enormously computationally demanding, such MC codes are claimed to yield a more faithful treatment of energetic particle physics than other approximations used, such as the HZETRN code based on the solution of the integrodifferential Boltzmann transport equation. This is obviously only possible as far as detailed descriptions of the particle interactions are available, and in the case of Geant4 the ion interaction physics has been implemented up to Z=6 (carbon) and E=10 GeV/nuc. So the use of the Geant4 Monte Carlo code for the calculation of the Martian subsurface radiation distribution is restricted to using weighted proton data for ions heavier than carbon and energies above 10 GeV/nuc. Nonetheless, despite these Z and E limitations, the Geant4 physics descriptions can still handle 87% of the complete GCR spectra, as calculated by spectral integration of the CREME96 primary model (Z=1-6 and E$<$10GeV/nuc for ions), and Geant4 is used extensively for modelling within the space weather community, as well as in particle accelerator and medical physics studies [http://geant4.web.cern.ch/geant4/]. Furthermore, we have run test simulations to demonstrate the validity of a weighted proton approximation, as explained below.

We have used Geant4 to run a test simulation to compare the dose-depth profile produced by modelling C-12 primary ions up to 10 GeV/nuc (the upper limit in energy imposed by Geant4 physics implementation) against that of proton primaries. As can be predicted, the profile of dose deposition by the C-12 ions is different from that of protons: more energy is deposited at a shallower depth due to the greater Z^2 value. This is the concern that the reviewer raises about the more rapid attenuation of flux from larger nucleus-nucleus cross-sections. It is also true, however, that heavy ions constitute a relatively small proportion of the GCR spectrum relative to protons (in the CREME96 solar minimum model, protons alone contribute 73% of the total energy, and alpha particles another 19%). To demonstrate that the complete GCR spectra can be justifiably approximated with proton-weighted data, we have modelled the GCR spectra firstly using only weighted proton data and secondly using appropriately-energy-weighted data from proton, helium and carbon primaries, as shown in Figure 5 of the paper. It should be stressed that our Geant4 particle modelling does not neglect nucleus-nucleus interactions (recoil nuclei and nuclear fragments in the target are treated fully within the Z and E constraints of the available physics descriptions), but only proton primaries are used to emulate the full incoming GCR particle spectra.

The two plots can be seen to differ only marginally, with the proton-only calculation yielding a peak dose differing by only 3% in the top 500g/cm2 from the much more computationally-expensive model incorporating data from proton, alpha and carbon primaries. This difference is negligible considering the greater sources of variation inherent in such radiation modelling, such as differing GCR primary spectra models and particle interaction models. Furthermore, it should be noted that below 200 g/cm2 (67 cm of Martian regolith) the scaling approximation becomes increasingly accurate because the primary ions will have undergone extensive hadronic interactions and the flux transformed from highly-ionizing ions (with large Z^2 values) into unbound nucleons. We are confident that the finding that the proton-only model calculates a slightly higher total dose deposited in the regolith is a real effect and not an artefact of the weighting of data from several primary ions. One possible explanation is that the more extensive nuclear reactions triggered by the relatively small flux of heavier ions produces more albedo particles, with slightly more of the incoming energy thus 'leaking' back out of the regolith.

Our collaborator, Laurent Desorgher, has run a similar test simulation of the ionisation rate through the terrestrial atmosphere with his freely-available PLANETOCOSMICS software, which uses the same physics lists as this study. In this case a broader range of heavy ion primaries were simulated: He-4, C-12, N-14, O-16 and Fe-56 (although the published maximum for the Geant4 ion physics is Z=6, it has been as-yet-unofficially verified on Ar-Ar collisions, and is probably not wildly wrong even for Fe nuclei, and so was worth pushing the limits for this test). This more complete test, comparing the results from reconstructing the complete GCR spectra using all these heavy ions alongside the approximation of using only weighted-proton data shows an identical result to the Mars regolith test simulation: there is negligible difference between the proton-only approximation and the much more computationally-expensive model built up from explicitly simulating five separate ion spectra.

It should be stressed that were data such as ion flux rates required, than the explicit simulation of HZE primaries would obviously be necessary, but we have convincingly shown here that the data of interest for this current paper, dose rate as a function of depth, is not sensitive to approximating the full GCR spectra from accurately-weighted proton-only model data.

This paper is not intended as a comprehensive treatment of alternative particle transport codes, going into detail on the relative merits of Monte Carlo and Boltzmann equation methodologies, but as a presentation of the interdisciplinary interest of modelled Martian subsurface dose rates; from astrobiology to geological dating. The manuscript has thus been modified to include the data comparison of proton-only and H-He-C models, demonstrating the validity of our methodology, but the lengthy discussion reserved for this letter.

p. 471, P2. Depths in g/cm2 please, and accompanying scale height or scale heights.

Shielding depths have been added. The scale heights are used in calculation of the atmospheric density profiles, but not in the Monte Carlo radiation transport methodology. As such they are explained in (4) of the Method, but not in presentation of the results.

p. 471, P3. Exactly. That’s the problem with that form of representation.

This paper has been written for an interdisciplinary audience, demonstrating the relevance of radiation modelling to biologists and geologists, to whom the conventions of radiation physics may not be familiar. Throughout the paper, such concepts are explained at a fundamental level and parameters have been given, for example, in terms of both surface pressure (bar) and shielding thickness (g/cm2).

p. 471, P4. No, see my comment on p. 467, P1.

Please see earlier response.

p. 473, P1, l 5. See my comment on p. 467, P2,

Please see earlier response.

Interactive comment on Biogeosciences Discuss., 4, 455, 2007.