MODELLING PLANETARY RADIATION ENVIRONMENTS: ASTROBIOLOGICAL PERSPECTIVES

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ABSTRACT

The damaging effect of ionizing radiation on cellular structure is one of the major limiting factors on the survival of life in potential extraterrestrial habitats. Here we describe in detail the programme architecture and functionality of a computer model created to simulate radiation propagation in planetary environments. Versatility of the data produced and easy reconfiguration of the simulation parameters to many different scenarios are prime features of the model design. We also report on the application of the model to calculate the subsurface radiation field on Mars. Bacteria or spores held dormant by freezing conditions cannot metabolise and become inactivated by accumulating radiation damage. A large energy range of solar energetic protons and galactic cosmic rays and their resultant secondary cascades have been simulated through the martian atmosphere and subsurface. Particle energy spectra, flux profiles, and cellular absorbed radiation dose are determined for the surface and at regular depth intervals underground, allowing the calculation of microbial survival times. Implications of the results to directing the search for extant life are discussed, as are numerous other applications for this flexible model.

KEYWORDS: Mars, astrobiology, ionizing radiation, model

INTRODUCTION

Astrobiology is the scientific discipline concerned with assessing the possibility of life in extraterrestrial settings. Mars is considered to be one of the prime astrobiological targets. Extensive evidence suggests a warm wet early Mars, similar to primordial Earth's climate, and the presence of organic molecules; an environment thought compatible with the development and survival of life (Clark 1998).

The martian surface today, however, is a cold barren desert. Low surface temperatures and atmospheric pressure mean that surface water is unstable as a liquid. Further hazards include the unshielded flux of solar ultraviolet (UV) light and the extremely chemically oxidising conditions it is thought to create in the topsoil. Consequently, the very surface of the planet is likely almost entirely sterile. Although an inconclusive biosignature of deep subsurface life has been detected (short-lived methane plumes in the atmosphere suggestive of methanogenic metabolism; Krasnopolsky 2006), the hypothesis of a deep hot biosphere on Mars is likely to remain untestable for the foreseeable future. Technological constraints mean our lander or rover probes will be restricted to access of only the top meter or two of the regolith. The major survival hazard in this near-subsurface region, beneath the oxidising layer and penetration of UV, is the flux of exogenous ionizing radiation. This study constitutes the most accurate model to date of the subsurface ionizing radiation environment, as a function of both depth and surface composition, and its influence on the survival of different microbes.

The near-surface ionizing radiation field is dominated by solar energetic protons (SEP) and galactic cosmic rays (GCR). SEP, accelerated by flares and coronal mass ejections, are of a relatively low energy but high flux, whereas GCR originate beyond the solar system with a very hard energy spectrum, but have orders of magnitude lower flux. The GCR spectrum is composed of 85% protons, 14% alpha, and a small fraction of heavy ions (fully ionised atomic nuclei), and is thought to be mainly accelerated by Type II supernovae.

SEP are deflected by the geomagnetosphere and attenuated by Earth's atmosphere, but the Martian surface is unprotected by a global dipole magnetic field or significant atmospheric shielding. The more energetic GCR primary particles produce extensive showers of secondaries in the terrestrial atmospheric column. When a GCR strikes an atmospheric nucleus energetic secondary mesons (pions and kaons), nucleons, gammas and nuclear fragments are produced, which then themselves interact with other nuclei. Secondary mesons decay over a short timescale to produce muons, gamma rays and electrons. Thus the air shower is composed of a central 'hard component' core of nuclear fragments within a spreading 'soft component' cone of the electromagnetic cascade (Eidelman and Hayes 2004). The radiation field produced by SEP and GCR is harmful to life (Nelson 2003) through both direct ionisation of biomolecules and radiolytic generation of highly reactive diffusible chemical species such as free radicals and hydrogen peroxide (Baumstark-Khan and Facius 2001).

Radiation dose is defined as the amount of energy deposited per unit mass, and takes units of Grays, Gy ($J.kg^{-1}$). However, different ionizing species are not equally harmful to cells. The highly ionizing particles of hadronic cascades, the protons and high-charge/high-energy (HZE) ions, are much more devastating than other secondaries such as muons, gammas and electrons. Furthermore, the response to radiation damage varies greatly between cells: radiosensitive bacteria are inactivated by absorbed doses more than an order of magnitude less than the lethal dose for resistant species, which are protected by highly efficient DNA repair mechanisms or by formation of a desiccated spore. On Mars, however, the freezing climatic conditions imply that any near subsurface life is forced to remain dormant for long periods and so unable to repair radiaiton damage. Thus ionisation effects accumulate until the cell becomes inactivated. Crucial to the hope of sampling viable cells from the martian subsurface is a gauge on their survival time under exposure to cosmic radiation, as a function of their shielding depth. No particle detector has been landed on the martian surface and so computer modelling is crucial in determining the radiation environment both on the ground and beneath, in order to estimate microbial survival.

METHODS

The majority of previous work on space radiation biology has used analytic approximations to particle propagation based on the integrodifferential Boltzmann transport equations. These necessitate simplifications including target homogeneity, normally incident particles, disregarding the cascade angular spread, and neglecting the generation and propagation of certain secondary particle types (including the extensive showers of gamma, electrons and pions). Instead, our study employs Geant4, a toolkit for the explicit Monte Carlo (MC) simulation of the propagation of particles through matter (Agostinelli et al. 2003).

Geant4 has been created by a large consortium of collaborating researchers and exploits the object-orientated capabilities of C++. The class structure provides a broad range of functionality, and our Geant4 model of the Martian subsurface radiation environment represents a distinct improvement on previous work, supporting simulation of the entire secondary cascades within a full 3D environment, precise specification of the geometry, atmospheric and regolithic spatial heterogeneity, reproduction of particle scattering and the actual isotropic angular distribution of incoming primary particles.

Model specifics

Detailed descriptions of the parameters and rationale used to simulate microbial survival in the current martian subsurface environment have been given previously (Dartnell et al. 2006). What follows here is a more complete treatment of the model architecture itself. The model was designed from the outset to output a broad range of astrobiologically-relevant data and to be rapidly reconfigured to simulate any planetary environment in terms of atmospheric and surface composition, as well as particle deflection by local magnetic fields, such as the martian crustal anomalies.

Following the Geant4 framework, the coding architecture of our model is modular. Within Geant4 three user-defined classes are mandatory: Detector Construction, Physics List, and Primary Generator. Respectively, these specify the dimensions, material compositions, active fields and position of all daughter volumes within the model; all particles and the physical processes to which they are subject, and the energy range that each physics model is set to operate over; the type and energy spectra of all primary particles input into the model, as well as position and vector of origination. Additional classes specify sensitive volumes and appropriate triggers to capture the desired information on particle fluxes, energy spectra, and ionisation distributions, all as a function of depth. Others handle arrays to pre-process generated data and dump regularly to an external file, kill irrelevant particle tracks, handle visual output, and so on.

Figure 1 shows a visualisation of the model design, as well as a schematic of the major inputs and data streams produced. The model is composed of an atmospheric column atop a block of surface material, with an angular distribution of primary particles generated above. The atmosphere is built-up of stacked layers so that density, temperature and gaseous composition profiles can be accurately reproduced. The planetary surface is by default an homogenous slab, with user-defined composition and density, but can also be layered arbitrarily finely, although with a cost to processing efficiency of particle propagation.

For the martian simulation, three distinct surface scenarios were created. Model (1), 'Dry Homogenous' or DH, is a simple spatially homogenous block of regolith devoid of water, constructed to allow comparison of results with previous publications. Model (2), 'Pure Ice' or PI, is a spatially homogenous block of water ice used to emulate environments such as the north polar ice cap, frozen crater lakes or the putative Cerberus pack-ice. Model (3), 'Wet Heterogeneous' or WH, was designed

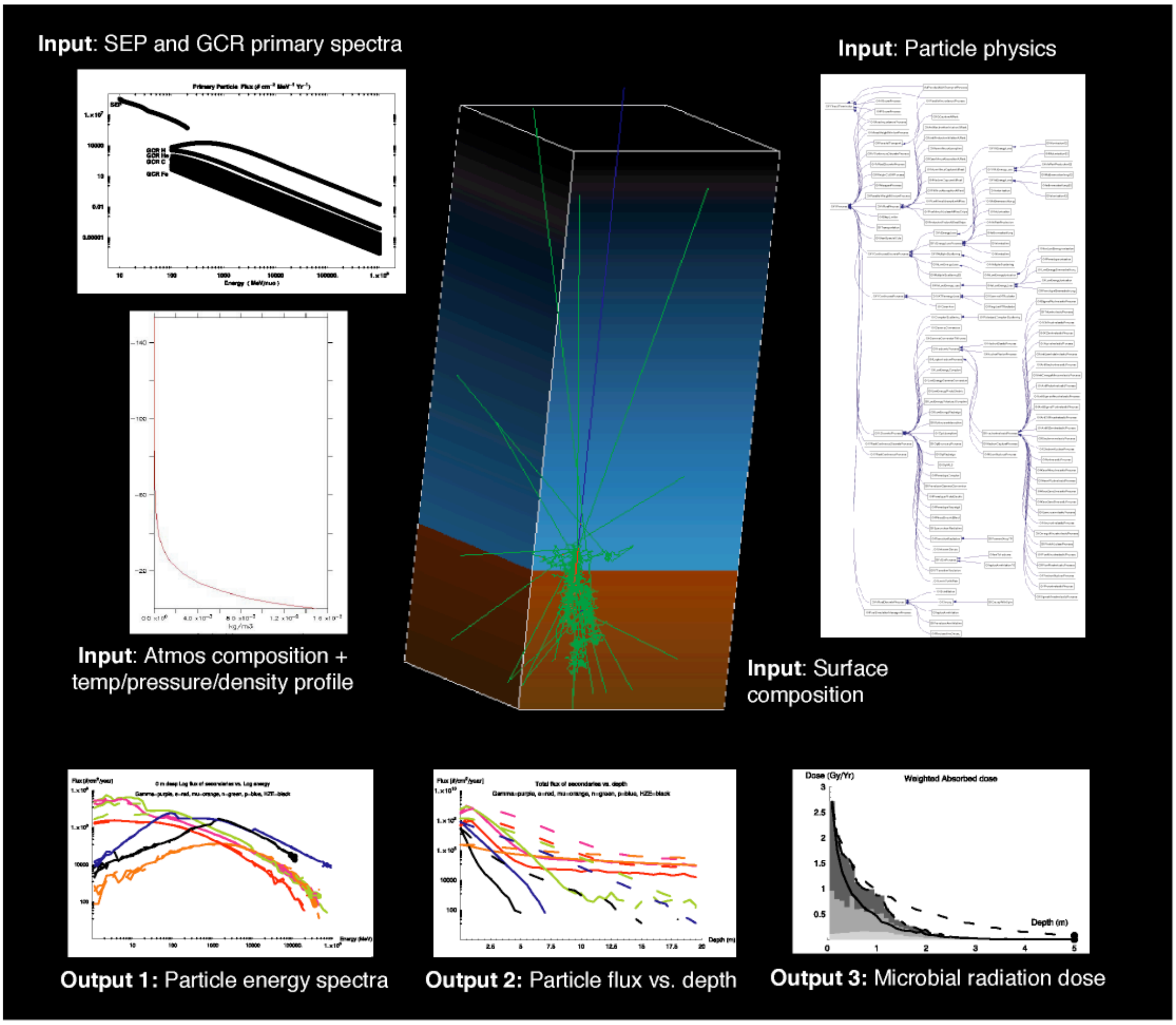

Figure 1: Schematic of the major inputs to the model and three streams of data produced. The centre shows a visualisation of the extensive subsurface secondary cascade produced from a single energetic GCR proton.

as a more realistic reproduction of the martian regolith, built up of layers of permafrost.

By default, a total surface depth of 20m is used, although the vast majority of particle interactions occur in the top few meters of regolith. This is subdivided into 200 layers, and at the top surface of each of these volumes is positioned a micron-thick film of water, taken to physically approximate a bacterial cell. These volumes are designated as detectors and are triggered by specific conditions. Every fifth layer is sensitive to certain particles propagating across its top surface, and records their type and kinetic energy. Five particle species are of interest: HZE, protons, neutrons, muons (+/-), electrons/positrons and gammas. The data collected by the detectors thus gives energy spectra for these important particles at 0.5m depth resolution (output 1). These are not specific to microbial targets and so can also be used to calculate the dose absorbed by astronauts within habitats protected by regolith-derived shielding. Integrating across the energy range for each particle type reveals the flux as a depth profile (output 2). Furthermore, all detector volumes are triggered by ionisation energy deposited within them by any propagating particles. The particle type responsible and its energy is noted and used to weight the deposited energy to take account of differing biological effectiveness. These data yield the microbial radiation dose rate as a function of depth (output 3). Experimental data gives the kill-curves of bacterial species with different radioresistant properties as a function of dose, and so population survival times can be estimated from the model.

The model sequentially processes one primary at a time, each of a specified particle type and drawn from a given energy spectrum (across five orders of magnitude: 10 MeV – 1 TeV), and tracks the complete propagation of its generated secondary cascade through the atmosphere and subsurface. The treatment of all physical processes is taken from the open source software PLANETOCOSMICS (http://cosray.unibe.ch/~laurent/

planetocosmics/). To pool data from statistically significant numbers of primaries the simulation is run simultaneously across a computer network.

RESULTS & DISCUSSION

As described above, the model has been designed to simulate any planetary radiation environment desired. The first study was into the subsurface radiation field on Mars. The calculated energy spectra, flux profiles, and calculated microbial survival times have been reported in detail previously (Dartnell et al. 2006), but the major results can be summarised as follows.

With a peak dose rate of 2.65 Gy/year at no point is the ionizing radiation environment on or beneath the martian surface lethal to even radiosensitive terrestrial bacteria. Only metabolically active cells, however, are able to repair radiation damage and reproduce. Current martian near-surface conditions imply any extant life will be held dormant, and survival will be determined by dose accumulated over long time periods.

In terms of planetary protection, a contaminant population of terrestrial cells or spores deposited onto the martian surface by a lander probe need only be blown under a thin layer of dust for protection from rapid deactivation by UV and they will survive the SEP and GCR flux for several millennia. Over geological time-scales though, even the most radioresistant populations are inactivated. At 2m depth, for example, the ExoMars drill length, a population dormant in regolith permafrost suffers a million-fold cull in under 140,000 years. For the prospects of finding viable martian microbes then, cells must either have been brought to the surface only recently, by outflow of deeper meltwater or exposure by impact excavation, for example, or else be able to periodically revive to repair radiation damage and reproduce, and so reset the inactivation clock.

One site of particular astrobiological interest is the putative frozen sea observed on the plains of Elysium. This is believed to have been disgorged by the Cerberus Fossae only 5 million years ago, rapidly freezing in the current climate, and presents an opportunity for our landers to sample water from much greater depths than they could otherwise access. Assuming cellular dormancy since soon after this discharge event, the PI model predicts a bore hole of at least 9.5m would be needed for any hope of retrieving culturable radioresistant bacteria.

Ionizing radiation is also produced by radionuclide decay, and it has been calculated that the intrinsic radioactivity of martian regolith produces a dose of 4×10^{-4} Gy/year (Mileikowsky et al. 2000). Within the WH regolith model this corresponds to a depth of ~5.5m at which the background activity begins to dominate over GCR penetration. Beneath this depth dormant cells receive no further benefit of shielding, and radio-resistant cells can be inactivated by radioactivity of the regolith alone in under 40 million years. The near-zero radionuclide content of pure ice implies that frozen crater lakes or the polar caps are the most favourable environments for finding viable cells after long periods of dormancy.

Further applications

The radiation model can also be applied to a broad range of other astrobiological questions. Beyond finding extant life, evidence of extinct life on Mars would also be profoundly important. Potentially detectable biosignatures include complex macromolecules, distinct from abiotic organics such as unpolymerised amino acids or nucleobases. Large molecules are degraded and broken apart by ionizing radiation and so the persistence time of such biomarkers in the surface is of great interest.

Another biosignature, also used in dating the emergence presence of life on Earth, is the isotopic ratio $^{13}C/^{12}C$ in sediments. Carbon fixation by life favours the lighter isotope and produces a tell-tale fractionation of several percent in biotic deposits. However, the nuclear reactions induced by energetic cosmic rays also create an isotopic shift. Calculating the period before possible biogenic fractionation becomes masked by accumulating cosmic-ray-produced ^{13}C is thus also crucial to designing life-detection packages for future probes.

Mars is not the only astrobiological target in the solar system, and the model can also be used to simulate these environments, as well as more hypothetical situations with extrasolar planets. The Jovian moon Europa is believed to possess a water ocean beneath its icy crust that may provide many of the prerequisites for life. Europan life may be limited by the availability of redox gradients from which to extract energy. One proposed source is the production of both oxidants and organics in the surface ice by radiolysis and recombination of water and carbon dioxide molecules. Simulating the interaction of the Europan radiation environment with the surface ice could estimate production rates from this radiation-driven chemistry.

Another proposed extraterrestrial habitat is a cloud layer in the Venusian atmosphere where the temperature and pressure regime is suitable for suspended water droplets. Here again the radiation field may be an important constraint on life.

One further important area of space radiation research within the context of astrobiology is addressing the theory of panspermia. This hypothesis states that cells can be transported between worlds within meteorites.

Theoretical and experimental studies show that rock can be excavated off a planetary surface by nearby impact without sterilising heat or pressure shock, and several such meteorites are known to have reached Earth from Mars. The possibility exists of cross-fertilisation within the solar system, especially during the primordial era. Dormant bacteria within such rock fragments are only partially shielded from the space radiation environment and it is the accumulated damage from SEP and GCR exposure that is thought likely to be limiting to survival during orbital transit.

All of these aforementioned scenarios can be modelled with simple reconfigurations to our radiation model.

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