Web-based description of the space radiation environment using the Bethe–Bloch model

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Received 12 May 2015, revised 4 November 2015
Accepted for publication 10 November 2015
Published 10 December 2015

Abstract
Space weather is a rapidly growing area of research not only in scientific and engineering applications but also in physics education and in the interest of the public. We focus especially on space radiation and its impact on space exploration. The topic is highly interdisciplinary, bringing together fundamental concepts of nuclear physics with aspects of radiation protection and space science. We give a new approach to presenting the topic by developing a web-based application that combines some of the fundamental concepts from these two fields into a single tool that can be used in the context of advanced secondary or undergraduate university education. We present DREADCode, an outreach or teaching tool to rapidly assess the current conditions of the radiation field in space. DREADCode uses the available data feeds from a number of ongoing space missions (ACE, GOES-13, GOES-15) to produce a first order approximation of the radiation dose an astronaut would receive during a mission of exploration in deep space (i.e. far from the Earth’s shielding magnetic field and from the radiation belts). DREADCode is based on an easy-to-use GUI interface available online from the European Space Weather Portal (www.spaceweather.eu/dreadcode). The core of the radiation transport computation to produce the radiation dose from the observed fluence of radiation observed by the spacecraft fleet considered is based on a relatively simple approximation: the Bethe–Bloch equation. DREADCode also assumes a simplified geometry and material configuration for the shields used to compute the dose. The approach is approximate and sacrifices some important physics on the altar of rapid execution time, which allows a real-time operation scenario. There is no intention here to produce an operational tool for use in space science and engineering. Rather, we present an educational tool at undergraduate level that uses modern web-based and programming methods to learn some of the most important concepts in the application of radiation protection to space weather problems.
1. Introduction

Exploring space is no gala dinner.

The space environment is particularly rich in ionizing radiation and can be highly lethal (Schimmerling et al 2003).

Radiation encompasses all forms of energy emitted by a specific source moving through space by means of either particles or electromagnetic waves. More specifically, ionizing radiation refers to the strong interaction between high energetic charged particles and the material they travel into. In turn, the ionizing radiation is further split in two categories: directly and indirectly ionizing radiation. The former considers all the charged particles directly coming from the source and not changing its charge status on the way. The second group instead consists of the secondary ionizing particles produced after the interaction with a primary particle, which can be either charged or neutral, with the medium.

Two main sources of ionizing radiation are present in the interplanetary space: cosmic rays and solar energetic particles (SEP) (Bothmer and Daglis 2007). Both vary in time. Cosmic rays are always present at levels that when accumulated over time pose a serious risk of cancer to people and of damage to technology. SEP are sporadic but when they hit, the damage can be devastating.

Solar energetic particles are released during specific solar events, also called solar eruptions, including coronal mass ejections and solar flares, which are able to send out an enormous amount of highly energetic particles all over the heliosphere. SEP also include those particles eventually accelerated through the interaction with some specific event in space, such as shocks.

All these threats are part of the rapidly growing discipline named ‘space weather’, including all astrophysical and space processes impacting humans and technology in space or on Earth (see Schrijver (2015) for more information and a complete definition of space weather).

A strong solar eruption can produce dangerous doses of radiation, even at relatively low orbits where the geomagnetic field provides some shielding, and is definitely lethal for deep space missions. Manned missions of exploration have to be planned with careful attention to the space weather threat posed by radiation. For this task numerous statistical studies and computational tools have been developed so that a mission is planned under different scenarios and considering the plausible worst case scenario. Models include SEP produced by space weather events (King 1974, Feynman et al 1990, 1993, 2002, Xapsos et al 2004, 1999, 2000, Rosenqvist et al 2005, ISO TS 15391 2004), galactic cosmic rays (Nymmik et al 1992, 1996, ISO TS 15390 2004), as well as the radiation belt environment (Sawyer and Vette 1976, Vette 1991a, 1991b).

Many tools have been proposed in the literature in order to evaluate the radiation risks that astronauts face during space missions (SPENVIS 2012, SEPEM 2012, Singleterry et al 2011, Slaba et al 2010, Schwadron 2010, Tylka et al 1997, Peyrard 2003).

The focus is of course on the near Earth environment where for decades now human presence has been limited to. But the tools also include deeper space exploration. Once a deep space mission is ongoing, a task unfortunately not occurring since Apollo 17 in December...
1972, there is another need: to monitor space radiation in real time to assess the current conditions and make predictions of developing solar events. This task is not of immediate need because of the lack of manned missions since 1972, but is nevertheless a task to consider in planning a future return to manned exploration. World-wide space agencies and private ventures are now planning to undertake interplanetary journeys to celestial bodies, such as the Moon, Mars and asteroids (Reichert 2001, Stanley 2005, Hoffman et al 1997, NASA 2012).

Radiation risks during these missions will be extreme (Horneck et al 2003a, 2003b, 2003c, Crosby 2007, Durante and Cucinotta 2011, Reitz and Facius 2007).

The study of this topic requires fundamental concepts of nuclear physics that determine how radiation interacts with matter. But understanding the topic requires one to consider the different sources of high energy particles in space and aspects typical of radiation protection to assess the impact on technology or on astronauts.

We present here an educational project that uses the existing satellites monitoring space (and future as they will become available) to assess quickly, albeit approximately, the current risk of radiation dose exposure. The concept of dose and the related different ways to compute are described in section 2.1.

The goal is to develop a real time tool giving the current conditions available from the feeds of the existing monitoring satellites. The focus is only on deep space missions (i.e. we are not concerned here with radiation belts where other tools are already available (Sawyer and Vette 1976, Vette 1991a, 1991b)).

The idea of the present work is to develop a fast new tool able to assess doses received by human tissues taking into account particle datasets directly recorded by satellites, in order to provide the most realistic assessment of the present space situation. Furthermore, to reduce the computational effort, as the core of the computation, a first-order non-linear differential equation is considered in lieu of Monte Carlo simulations.

This design choice makes the computation faster and more general, although the final results will be less precise and less specific compared with those obtained from Monte Carlo simulations.

Nevertheless, this approach still maintains a good approximation in light of the physics carried by heavy charged particles. It is well established that a single charged particle behaves quite differently compared to a neutral particle when passing through matter. We know that the mean free path will be much shorter, and the interaction predominantly to due a long-range electromagnetic interaction with the target atoms, making the single collisions negligible. As result, the overall trajectory within the matter turns out to appear in first approximation straight, removing the necessity of using a Monte Carlo random walk. Moreover, a set of particles with the same properties will behave nearly in the same way, not being affected by the single point-to-point interaction.

Based upon these latter considerations, the macroscopic quantity stopping power is defined as the capability of a particular material to slow down an incoming particle through different types of interactions. The result is the loss of the initial particle energy along its path through the target material, so that the stopping power is related to the concept of linear energy transfer. The practical use of this quantity is provided in section 3.2, where the Bethe–Bloch equation is introduced.

Given the educational goal, at the undergraduate level, this approach, even with its limitations for real world professional applications, is preferable as a way to make students familiar with real-time monitoring of space radiation and the assessment of its dangerousness.

Additional educational endeavours can ask the students to replace the simple transport model used here with more advanced and accurate radiation transport methods.
The tool presented here, given the topic of application, has been named DREADCode. In summary its peculiarities are:

- data values directly taken from satellites, which leads to an almost real-time assessment and to a more realistic approach;
- fast computation of radiation transport thanks to the use of the Bethe–Bloch equation considering all the correction factors introduced over time;
- the opportunity to choose the material and composition of each layer that is supposed to shield the incoming particles;
- the opportunity to assess the dose situation at different distances from the Sun, which means considering the interplanetary space surrounding those planets closer to the Sun. Accuracy and precision at longer distances need further investigation, which are beyond the scope of this work and not yet well understood in the literature. Considering only the portion of the interplanetary space in which we are interested (i.e. at most up to the Mars distance) allows us to remove the constraint concerning its high spatial variability. Temporal variations are instead intrinsically well described by the input satellite dataset.

The code is written in MATLAB for its educational scope and has been recently made available online on the European Space Weather Portal website (ESWP, European Space Weather Portal website, www.spaceweather.eu, 2012), within the biological effects section (DREADCode, www.spaceweather.eu/biological_effects, 2012).

The paper is organized as follows. Given the highly interdisciplinary nature of the material presented, section 2 gives a brief description of the radiation sources of major importance in space, as well as an introduction to the main dosimetric quantities further used in the work. Section 3 describes the DREADCode structure, highlighting its modules and their integrations. Section 4 provides validation and verification results, while conclusions and future directions are provided in section 5, together with the educational potential of the tool.

2. Radiation sources and effects

During interplanetary missions, astronauts are going to face ionizing radiation coming from different sources: besides the aforementioned sources (i.e. SEP and cosmic rays), it is worth also mentioning solar wind and radiation belts.

The former represents the continuous stream of low energy charged particles from the Sun (predominantly protons at nearly 400 km s\(^{-1}\) through 800 km s\(^{-1}\), meaning few KeV or less) in a way similar to terrestrial wind. For our purposes, solar wind can be neglected as modern spacecraft are already equipped with properly designed shields against these particles.

Radiation belts are regions of relatively high energy particles trapped within the planetary magnetic fields, and surround those planets with a magnetosphere (e.g. Earth and Mercury). Similarly to solar wind, this source of radiation can also be neglected due to the short time spent by astronauts within them during the mission.

In contrast, we cannot neglect SEP at all, as they are very unpredictable, both in time and in magnitude, and are very problematic for interplanetary journeys. To date, it seems in fact to be impossible to properly design shields without dramatically increasing masses, volumes and, consequently, mission costs. These particles are directly originated in the Sun and released after the occurrence of extreme solar events, such coronal mass ejections (CMEs).

Finally, galactic cosmic rays (GCR) and anomalous cosmic rays (ACR) are fluxes of particles, ranging from proton to uranium nuclei, coming from galactic and extra-galactic
origins, whose path is undefined as they can undertake many deflections within the interplanetary magnetic field (IMF) before reaching the target. Consequently, the population of these particles inside the heliosphere is strictly function of the IMF strength, which in turn is a function of solar activity. Although we considered GCR and ACR as the same entity, the sources of these particles are very different (Durante and Cucinotta 2011). GCRs are basically charged particles coming from the deep space, flowing around the IMF lines and being accelerated when eventually encountering particular astrophysical events, such as shocks. ACRs are instead neutral particles coming from interstellar material, which happen to be weakly ionized through the interaction with solar wind as soon as they enter the heliosphere (Schrijver and Siscoe 2010). The latter are therefore mainly composed of weakly-ionized heavy nuclei which have lost only their outer atomic electrons, and as a result are influenced much less by the IMF than GCRs. Additionally, they show a significantly lower energy spectrum than GCRs.

### 2.1. Dose and biological effects

The main concern with radiation is the danger it can cause to devices and, mostly, to biological tissues. Historically, the main difficulty in assessing the dangerousness has always been in finding the best approach to link the macroscopic physical causes, such as the presence of a large scale radiation field, to the microscopic effects resulting at lower scales inside the matter. An ultimate common agreement on what is the best quantity to accomplish this task is still to come. Even though not being the solely suggested quantities, DREADCode takes into account the currently most used standard definitions for radiometry and dosimetry. These definitions are scientifically motivated and are incorporated into regulatory assessments (Valentin 2007, ICRP 2007, 2010).

#### 2.1.1. Effective dose and ambient dose equivalent

The main outputs of the code are the effective dose and the ambient dose equivalent.

The former is agreed to be the best approach to directly connect the microscopic biological effects to the macroscopic radiation fields in which the target is eventually found. In particular, it has been proved that different organs or tissues of the human body have different reactions to the same incoming radiation. This property is called radio-sensitivity, and is intimately related to both the cellular reparation capability of the single organ or tissue, and the cellular renovation rate (Shultis and Faw 2002). The effective dose gives an estimation of the different radio-sensitivities of biological tissues and is computed as

\[
E = \sum_T w_T \cdot H_T \text{ [Sv]}
\]

where \(H_T\) is the equivalent dose received by the tissue \(T\) and \(w_T\) are coefficients called the tissue weighting factors. The total sum of these coefficients is equal to 1 for whole body exposure. Recent values of \(w_T\) are given in table 1, together with the radiation weighting factors necessary to compute the equivalent dose. In analyzing these values, which are continuously updated through experimental and simulation campaigns, the relation between the greatest factors and those organs expected to have higher cellular renovation rates is noticable. Like the equivalent dose, the effective dose is expressed in Sv—Sievert.

Practically, the effective dose turns out to be very helpful when the exposure is well known and defined. However, when it comes to evaluating the ionizing effects in cases where
Figure 1. Spectra of data recorded by the satellites considered within DREADCode. The left panel represents a uniform and continuous spectrum for each ion, while the middle panel points out the more realistic average energy values measured for each energy bin and for each ion taken into account. The right panel gives an example of particles fluxes computed with Nymmik’s model.

Figure 2. Sketch representing the aligned (i.e. oriented) and expanded radiation field around the ICRU sphere, according to the definition in ICRP (2007, 2010).

Table 1. Radiation weighting factors $w_R$ and tissue weighting factors $w_T$ for the most common radiation types and organs. For neutrons, a specific continuous function is suggested in ICRP (2007).

| Radiation $R$                                       | $w_R$       |
|----------------------------------------------------|-------------|
| Photons                                            | 1           |
| Electrons and muons                                | 1           |
| Protons and charged pions                           | 2           |
| $\alpha$ particles, fission fragments and heavy ions| 20          |
| Neutrons $^{**}$                                   | specific function |

| Tissue $T$                                         | $w_T$       |
|----------------------------------------------------|-------------|
| Bone-marrow, colon, lung, stomach, breast, remainder tissues | 0.12        |
| Gonads                                             | 0.08        |
| Bladder, oesophagus, liver, thyroid                | 0.04        |
| Bone surface, brain, salivary glands, skin         | 0.01        |
| $\sum w_T$                                        | $\sim 1$    |
the exposure of the target is not totally clear, the latter becomes less useful. A glaring example is the variable position of astronauts during the different stages of a long-term mission.

A more suitable dose quantity has therefore been introduced, namely the ambient dose equivalent. According to the definition appointed in Valentin (2007) and ICRP (2007, 2010), this quantity represents the equivalent dose computed at 10 mm radially inside an ICRU sphere, when the radiation field is intended to be aligned (i.e. oriented), expanded and oppositely oriented with respect to the sphere, as indicated in figure 2. The ICRU sphere is a 30 cm-diameter sphere made of specific elements (76.2% O, 11.1% C, 10.1% H and 2.6% N), representing human tissue composition, with density equal to 1 g cc⁻¹ (ICRU 1980).

3. DREADCode: main features

DREADCode has a modular structure. Figure 3 shows a flowchart describing the main inputs, computational core and main outputs. Besides data sources, time period and shield properties, the user can also set up other features, including the exposure and the scaling factor, as well as the specific coefficients one prefers to use for each output assessment.

The main features of the DREADCode are listed in order.

First, as the input DREADCode receives particle flux data directly from satellite recordings. Only the true sources of radiation concern are considered: charged nuclei, from proton to uranium nuclei. Future versions will also consider neutral particles (neutrons, gamma rays), which are neglected for now.

This approach leads to an (almost) real-time assessment. A delay is still present due to the processing of the raw satellite data that is required before they are made available by the responsible agency (NOAA for the data sources used). Moreover, the user has to insert the shields or layers properties, such as thickness, material and elements composition.

Second, a radiation transport calculation is required to evaluate how many particles with a particular energy are able to penetrate the shields under consideration. For this task, a simplified model is used, instead of the more computationally demanding Monte Carlo method. This aspect will be subject to future evolution and improvement and is currently motivated by the need for computational speed to achieve real-time performance.

An example of what is stated above is given in figure 4, where snapshots taken from the on-line DREADCode are shown. In particular, after inserting the general necessary inputs, such as the time period, distance from the Sun and type of exposure of the analyzing object,
the user also has to define the layer properties. Firstly, knowledge of how many layers are present between the external radiation sources and the final target, i.e. human tissues, it is necessary. This figure represents the case with a single layer, e.g. an aluminium-based wall. Thereafter, for each layer one has to define its material, which may be single or multiple compounds, the relative weight fraction composition, as a percentage, and, finally, its thickness. 

Next, the user can select the type of particle data input considering, i.e. which satellite and/or model, as well as the desired output. In case of the effective dose, one has also to select the type of exposure and what conversion coefficients to use.

Finally, the results are represented with a graphics interface page. An example is given in figure 5 showing the case analyzed in section 4. This page gives a summary of the input parameters, as well as results for any requested output.
3.1. Inputs of the code

The code receives the following main inputs.

- The temporal period, i.e. the starting date and the ending date. These values should not exceed the ranges pointed out by the satellite’s websites.
- The satellite(s) data source, including ACE, GOES-13 and GOES-15. Nymmik’s models for GCR and ACR fluxes (ISO TS 15390, 2004, Nymmik et al 1992) have been also implemented to compare model and data-driven results, as well as use them when satellite data are not available, i.e. future periods or maintenance.
- The number, composition and weight fractions for each compound and thicknesses of layers (shields) between the incoming particles and the target.
- The total exposure surface of the target, such as the external spacecraft wall, the space suit surface or the human body surface. Examples of models used to compute the human body surface are pointed out in Verbraecken and Van de Heyning (2006) and Yu et al (2003).
- The angular exposure, in order to integrate the flux values overall the suitable solid angle.

Figure 5. Snapshot of the DREADCode on-line version showing the final page with results. This mask shows a summary of all input parameters inserted, together with results for those requested outputs.
The distance $R$ of the target from the Sun, expressed in AU.

- The exponent scaling factor $\beta$, which properly scales the flux/fluence values spatially from 1 AU (the location where these values are supposed to be recorded) to distance $R$ from the Sun, such that

$$F(R) = F(1\ AU) \cdot R^\beta.$$  

This value has been kept as a free parameter according to the uncertainty on the spatial scaling stated in Smart and Shea (2003).

- The output options and the suitable coefficients to use for the computation.

Concluding the main code features, it is remarkable that any time the user inserts an erroneous value inside the GUI, the code returns an output page indicating what the insertion error might be. This also occurs when the code itself is not able to link with the necessary websites or datasets. The most common fails derive from an incorrect date insertion, since any implemented satellite has a different temporal range to consider. Hence, the user should already be informed about the properties of the considered satellites. In particular, the necessary starting date limits have been pointed out in the GUI, while the limited ending dates obviously change as a function of the satellite. Further error indications have been configured for other common insertion mistakes and network connection failures.

### 3.2. Core of the code

The core of the code is the Bethe–Bloch equation, which returns the value of the stopping power for particles with a particular energy inside a prior-de fined medium. The stopping power $S$ is a useful physical quantity since heavy charged particles normally travel along straight lines within a medium, releasing great amounts of energy in a very short path, due to their great mass and charge.

The Bethe–Bloch equation is the following

$$S = -\frac{\Delta E}{dx} = K e^2 Z \sqrt{\frac{1}{A}} \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{T^2} \right) - \beta^2 - \frac{C}{Z} - \frac{\delta}{2} \right]$$

where

$$T_{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma \frac{m_e}{M} + \left( \frac{m_e}{M} \right)^2}$$

and

$$K = 4\pi N_A e^2 m_e c^2,$$

such that

$$\frac{4\pi N_A e^2 m_e c^2}{A} = 0.307075 \text{ MeV for } A = 1\ \text{g mol}^{-1}$$

- $N_A$ = the Avogadro number
- $e$ = electron radius
- $m_e$ = electron mass
- $Z$ = atomic number of the target
- $A$ = atomic mass of the target
- $Z$ = incident particle charge, in unit $e$
- $\beta = \frac{v}{c}$
- $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$
- $\delta$ = density effect correction parameter
- $C$ = shell correction parameter
$I =$ mean excitation potential of the target

$T_{\text{max}} =$ maximum transferable energy to an electron after a collision

The mean excitation potential $I$ is computed according to the model suggested by Sternheimer and Berger (1984), who charted these values for several elements.

When the incoming charged particles have high energies, the electric field associated to them also increases, which influences the stopping power (the $\beta \cdot \gamma$ term inside the logarithm would increase). Indeed, real media are already able to limit these effects, therefore the density effect correction $\delta$ has been introduced to correct the stopping power at high energies (Fermi 1940). In order to consider this effect we again use the model suggested by Sternheimer and Berger (1984).

Conversely, the shell correction $C$ corrects the error of the equation associated to low energies. The model used here is shown and explained in Barkas and Martin (1964).

Finally, notice that inside equation (1) there are terms related to the target material, such as $A$, $Z$, $\rho$ and $I$, and terms related to the incident particle properties, such as $z$ and, indirectly, $M$. The unit of the stopping power is MeV cm$^{-1}$, when the mass density of the medium is included, or MeV cm$^2$ g$^{-1}$ when one wants to remove the dependence of the target’s mass density from the computation.

To illustrate the performance of the Bethe–Bloch approach, figure 6 shows the stopping power variation as function of energy for incoming protons in different media. The minimum cut-off energy is 0.511 MeV, which is the value normally associated to electron bound energy. Results obtained from equation (1) have been compared with those obtained from other available tools both in the literature and on-line, such as Nucleonica (Nucleonica website, www.nucleonica.com, 2012), the ASTAR-PSTAR of the NIST databank (NIST, ASTAR-PSTAR website, www.nist.gov/pml/data/star, 2012) and SRIM (Ziegler 2003, Ziegler et al 2010). The results are shown in table 2. Clearly, while approximated, the approach is sufficiently accurate for a first order real time assessment.

### 3.2.1. The Bethe–Bloch equation for compounds.

Equation (1) can also be used when the target material is a mixture or multi-compound medium by using Bragg’s additivity rule (Bragg and Kleeman 1905, Seltzer and Berger 1982), which approximates the target as a sequence of mono-component layers by basically considering the whole stopping power as linearly proportional to each component’s stopping power, with mass fractions $w_j$ such that

$$
\left( \frac{dE}{dx} \right)_{\text{comp}} = \sum_j w_j \cdot \left( \frac{dE}{dx} \right)_j
$$

$$
w_j = \frac{n_j \cdot A_j}{\sum_k n_k \cdot A_k}
$$

### 3.3. Outputs of the code

The code allows the user to assess two different doses: the effective dose and the ambient dose equivalent.

#### 3.3.1. Effective dose assessment.

After evaluating the fluence of particles able to cross the shields configured, it is possible to obtain the effective dose by multiplying the fluence by specific coefficients. These coefficients, usually called fluence-to-effective-dose-coefficients, directly derive from experimental and accurate simulation campaigns aimed at evaluating
doses on human tissues inside specific radiation environments. They are normally looked up as function of energy and particle fluence, with the chance to interpolate when values do not match. Many coefficients can be found in the literature, but the code considers those published in Sato et al. (2009, 2010) and Petoussi-Henss et al. (2010).

Beside the computation speed, this solution turns out to be particularly reliable thanks to the wide studies devoted to computing these coefficients, which are continuously updated and published in the official radio-protection reports (Petoussi-Henss et al. 2010).

3.3.2. Ambient dose equivalent assessment. The user can also decide to evaluate the ambient dose equivalent $H_a$.

According to its definition, the code runs a further computation by following the particles inside a pre-fixed compound recalling the ICRU sphere, as long as they achieve 10 mm depth inside the sphere. Finally, the computed energy release is multiplied by the proper factors pointed out in table 1 to assess the ambient dose equivalent.

However, a computation of this kind would take more computational time than for the case of the effective dose assessment.

Table 2. Comparison of the stopping power computed with different tools, including the Bethe–Bloch model described in this manuscript.

| Energy (MeV) | Nucleonica | NIST | SRIM | DREAD | Code |
|--------------|------------|------|------|-------|------|
| 0.2          | $3.735 \cdot 10^2$ | $3.715 \cdot 10^2$ | $3.730 \cdot 10^2$ | $3.347 \cdot 10^2$ |
| 2            | $1.109 \cdot 10^2$ | $1.095 \cdot 10^2$ | $1.108 \cdot 10^2$ | $1.136 \cdot 10^2$ |
| 10           | $3.398 \cdot 10^1$ | $3.376 \cdot 10^1$ | $3.396 \cdot 10^1$ | $3.362 \cdot 10^1$ |
| 100          | 5.691      | 5.678 | 5.689 | 5.677 |

Figure 6. Stopping power profile as function of energy for an incoming proton and some target, computed from equation (1).
4. Results and discussion

To validate and verify the tool, DREADCode was tested in several scenarios and compared with established tools available online. In this section, some results are shown. Since DREADCode is a generic code to evaluate doses during interplanetary travels, we decided not to follow any strict mission schedule and test it for some different periods.

First of all, we are interested in comparing results between a period during which a solar event has been recorded and a period during which solar events did not occur. Table 3 compares these situations for the period 1–8 February (when no events were recorded) and the period 6–13 March (when a solar event was recorded). These periods have been selected according to the solar event list provided by NOAA (2012a).

Values obtained from GOES satellites seem to be coherent with the situation, since these satellites carry onboard devices able to record both $H^+$ and $\alpha$ high energy particles, even when solar events occur (NASA GOES Fact Sheet 2009). Unlike GOES, the ACE satellite turns out to be suitable for recording only GCR and high atomic number energetic particles, as well as solar wind. In fact, the most important device for our purpose is the CRIS instrument, which measures nucleons ranging $3 \leq Z \leq 28$, i.e. GCR. This device, however, does not properly cover periods of high solar activity, as it is usually switched off during solar events to prevent damage. This is the main reason why results from ACE are shown to be greater in the period 1–8 February than between 6–13 March.

Comparing the results from Nymmik’s model with those from ACE, it is possible to notice an agreement in the ambient dose equivalent. This model is a direct function of the IMF strength, which in turn is a function of the monthly sunspot number and solar activity. The number of sunspots is directly provided by the Solar Influences Data Analysis Center (SIDC) of the Royal Observatory of Belgium (ROB) (NOAA website http://sidc.oma.be, 2012b). This explains why the results are not influenced by the occurrence of solar events. On the other hand, a slight variation is noticed and explained by the different solar activity in the two periods.

As we expect, the second period, during which a solar event was recorded, shows a nearly ten times higher dose value than the case considering the GOES satellites.

Finally, we have compared DREADCode with similar tools already available online (namely SPENVIS (www.spenvis.oma.be, 2012) and SEPEM (http://dev.sepem.oma.be, 2012)) considering a mission to Mars according to the generic schedule pointed out in Horneck (2003b). Given the differences between the tools, the assessment conditions have

|                   | 1–8 February 2012 (no solar events recorded) | 6–13 March 2012 (solar event recorded) |
|-------------------|---------------------------------------------|---------------------------------------|
|                   | ACE  | GOES-13 | GOES-15 | Nymmik | ACE  | GOES-13 | GOES-15 | Nymmik |
| $E$ (mSv)         | 4.593 \cdot 10^{-1} | 8.7935 | 7.9255 | 5.0563 | 4.0685 \cdot 10^{-2} | 70.092 | 63.733 | 5.0400 |
| $H_a$ (mSv)       | 6.961 | 84.0432 | 78.5659 | 10.0971 | 4.1229 | 1785.0703 | 1644.9841 | 10.062 |

Table 3. Comparison between two different period results: the top table summarizes doses when no solar event has been recorded, while bottom table summarizes doses when solar event occurred.
been kept nearly as congruent as possible, even though some approximation to match these differences had to be done. The results are shown in table 4. We notice that the effective doses are shown to be in close agreement between all tools. Regarding the ambient dose equivalent, however, DREADCode appears to have a much more conservative approach than SPENVIS. SEPEM does not provide an assessment of this quantity. The two computing methods are radically different. While DREADCode runs once again the same transport method into a prefixed layer resembling the ICRU sphere, SPENVIS instead makes use of suited coefficients similar to those used to compute the effective dose. Despite the results having the same order of magnitude, DREADCode seems to give a more conservative outcome.

|                | SPENVIS | DREADCode | SEPEM |
|----------------|---------|-----------|-------|
| Effective dose (mSv) | 1459    | 1066.088  | 1125.4|
| Ambient dose equivalent (mSv) | 1170    | 3691.542  | —     |

5. Conclusions and future directions

In conclusion, we presented DREADCode, a handy tool to macroscopically assess the radiation doses on human tissues in a relatively short time, which considers a more realistic description of the existing radiation field by directly using satellite data. Conversely, similar and more advanced tools available to date only consider a generic view of the incoming radiation through statistical worst-case scenarios or semi-analytical models, which often turn out to be too generic and unrealistic. Instead, we believed that a significant improvement of this kind of assessment could be reached by exploiting the wide fleet of satellites currently at our disposal.

Moreover, unlike the statistical models based on past worst-case events which only consider protons, in DREADCode the dose from heavy nucleii is also taken into account.

Also, being directly connected with satellites allows us to consider an almost real time situation, with the only delay due to the time taken to process the data.

Parameter insertion is fast, easy and intuitive via a GUI, and the computational costs are relatively low when compared to more precise and accurate computations, such as those related to Monte Carlo simulations.

Finally, DREADCode is meant to introduce the basic concept in a modern web-based frame. DREADCode is not intended to address proper engineering shield design, given its highly conservative approach. The main goal here is to figure out what kind of particles are actually able to cross the shield configured by the user. No intention was given to the shield design itself. Its generic profile, however, allows the code to be used to assess the radiation shielding capacity for many general purposes, including spacecraft, spacesuits and outpost shielding ability.
DREADCode is highly modular and flexible, allowing for further spin off educational endeavours that can upgrade the code. The following examples can be taken into consideration.

- **Implementation of new satellite datasets or new particle data sources.** It could be interesting to implement new and different particle data sources, in order to improve the computation reliability on the long period, since satellites have limited life-time, comparable to few years, as well as to give more options to external users, such as different data sources.

- **Inserting new coefficients for specific organs or tissues.** So far, only whole body exposure has been taken into account. Nevertheless, the user could want to compute doses for specific organs, including the most problematic tissues. For this purpose, the literature offers specific coefficients, such as those suggested by Petoussi-Henss et al (2010), Sato et al (2009, 2010), Copeland et al (2010) and Ferrari et al (1997).

- **Considering secondary radiation.** The physics can also be complicated at will. When charged particles interact with the medium, they can also generate secondary radiation, including electrons and neutrons. While electrons are normally not a big concern, neutrons may reveal themselves to be problematic due to their high peak fluxes. This phenomenon turns out to be more important when energetic particles from space interact with the regolith of planetary surfaces, by increasing the neutron flux below the crust, whose magnitude should be considered when long-permanence outposts are planned to be built underneath the surface.

Additionally, the tool presents itself as a useful educational tool connecting several problematic aspects typical of interplanetary journeys.

We started addressing the idea of developing this tool after some experience acquired in covering the lectures on space weather recently proposed at KULeuven for undergraduate students. This broad subject is shown to be highly multi-disciplinary, including knowledge on astrophysics, material engineering and radioprotection. While traditional lectures dealing with established terrestrial applications can count on helpful hands-on sessions, courses on space weather rarely allow students to get in touch with the daily practical issues faced by technicains in this field.

In particular, we noticed the absence of a direct interconnection between the theoretical and observational approach of the study of astrophysical events and the effective causes led by them on the human environment, with a particular gap noticed in the field of radioprotection in space. The latter is thought to be mainly caused by the absence of manned space missions over the recent decades, which lead education to head in different directions, such as the impact of radiation on human technologies instead of biological materials. DREADCode has therefore been devised to fill this educational gap.

By using the Bethe–Bloch equation, undergraduate students additionally learn more about the radiation–matter interaction with highly energetic charged particles, as well as the difficulty in finding proper materials suitable for shielding radiation without increasing masses and costs. Moreover, they are going to tackle the high uncertainty in realistically setting the target conditions, given the wide variability of the possible scenarios during such long missions.

Finally, students become familiar with the elevated order of magnitude of doses reached in space, which are very rarely met in terrestrial conditions, and only likely in accidental situations. These values pose further issues in evaluating the macroscopic biological effects on human tissues. In fact, though the typical concerns of terrestrial radiation fields are mainly focused on long-term low-dose cancer-risk expositions, radiation in space brings out a new
synergistic combination of constant low-level doses from GCR and sudden acute exposure in case of solar events, leading to a multi-scale phenomenon rarely found in terrestrial applications.

Acknowledgments

The research leading to these results has received funding from the European Commission under the grant agreement eHeroes (project no. 284461, www.eheroes.eu).

References

NASA (National Aeronautics and Space Administration) 2012 NASA lunar exploration objectives www.nasa.gov/externalflash/human_space
Barkas W H and Berger J M 1964 Tables of energy losses and ranges of heavy charged particles Studies in Penetration of Charged Particles in Matter (National Academy of Sciences–National Research Council, Publication 1133) p 103
Bothmer V and Daglis I A 2007 Space Weather: Physics and Effects (Berlin: Springer)
Bragg W H and Kleeman R 1905 XXXIX. On the a particles of radium, and their loss of range in passing through various atoms and molecules Phil. Mag. Ser. 6 10 318–40
Copeland K, Parker D E and Friedberg W 2010 Alpha particles at energies of 10 MeV to 1 TeV: conversion coefficients for fluence-to-absorbed dose, effective dose, and gray equivalent, calculated using monte carlo radiation transport code MCNPX 2.7.A Radiat. Prot. Dosim. 138 310–9
Crosby N B 2007 Major radiation environments in the heliosphere and their implications for interplanetary travel Space Weather—Physics and Effects (Berlin: Springer) pp 131–71
DREADCode 2012 DREADCode website www.spaceweather.eu/biological_effect
Durante M and Cucinotta F A 2011 Physical basis of radiation protection in space travel Rev. Mod. Phys. 83 1245
ESPW 2012 European Space Weather Portal (ESPW) website www.spaceweather.eu.
Fermi E 1940 The ionization loss of energy in gases and in condensed materials Phys. Rev. 57 485
Ferrari A, Pelliccioni M and Pillon M 1997 Fluence to effective dose conversion coefficients for protons from 5 MeV to 10 TeV Radiat. Prot. Dosim. 71 85–91
Feynman J, Armstrong T P, Dao-Gibner L and Silverman S 1990 New interplanetary proton fluence model J. Spacecr. Rockets 27 403–10
Feynman J, Spitale G, Wang J and Gabriel S 1993 Interplanetary proton fluence model: JPL 1991 J. Geophys. Res. 98 13–13
Feynman J, Ruzmaikin A and Berdichevsky V 2002 The JPL proton fluence model: an update J. Atmos. Solar-Terrest. Phys. 64 1679–86
Hoffman S J and Kaplan D I 1997 Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team NASA Special Publication 6107 (Houston, TX: Lyndon B Johnson Space Center)
Horneck G, Fiacus R, Reitz G, Retterberg P, Baumstark-Khan C and Gerzer R 2003a Critical issues in connection with human missions to Mars: protection of and from the Martian environment Adv. Space Res. 31 87–95
Horneck G et al 2003b HUMEX, a study on the survivability and adaptation of humans to long-duration exploratory missions Technical Report ESA SP-1264
Horneck G et al 2003c HUMEX, a study on the survivability and adaptation of humans to long-duration exploratory missions, part I: lunar missions Adv. Space Res. 31 2389–401
ICRP 2007 The 2007 recommendations of the International Commission on Radiological Protection Ann. ICRP 37 (ICRP Publication 103) (Ottawa: ICRP)
ICRP 2010 Conversion coefficients for radiological protection quantities for external radiation exposures Ann. ICRP 40 (ICRP Publication 116) (Ottawa: ICRP)
ICRU 1980 Radiation Quantities and Units (ICRU Report 33) (Bethesda, MD: International Commission on Radiation Units and Measurements)
ISO TS 15390 2004 Space environment (natural and artificial)—galactic cosmic ray model ISO 15390:2004(E)
ISO TS 15391 2004 Space environment (natural and artificial)—probabilistic model for fluences and peak fluxes of solar energetic particles ISO 15391:2004(E)

King J H 1974 Solar proton fluences for 1977–1988 space missions J. Spacecr. Rockets 11 401–8

NASA 2009 NASA GOES Fact Sheet. GOES N series data book—revision D (CDRL PM-1-1-03, Contract NASS-98069)

NIST 2012 NIST, ASTAR-PSTAR website www.nist.gov/pml/data/star

NOAA 2012a NOAA website www.swpc.noaa.gov/ftpdir/indices/SPE.txt

NOAA 2012b NOAA website http://sidc.oma.be

Nucleonica 2012 Nucleonica website www.nucleonica.com

Nymmik R A, Panasyuk M I, Pervaja T I and Suslov A A 1992 A model of galactic cosmic ray fluxes Int. J. Radiat. Appl. Instrum. 20 427–9

Nymmik R A, Panasyuk M I and Suslov A A 1996 Galactic cosmic ray flux simulation and prediction Adv. Space Res. 17 19–30

Petoussi-Henss N et al 2010 Conversion coefficients for radiological protection quantities for external radiation exposures Ann. ICRP 40 1

Peyrard P F et al 2003 A toolkit for space environment RADECS 2003: Proc. 7th Eur. Conf. on Radiation and its Effects on Components and Systems

Reichert M 2001 The future of human spaceflight Acta Astronaut. 49 495–522

Reitz G and Facius R 2007 Space weather impacts on space radiation protection Space Weather—Physics and Effects (Berlin: Springer) pp 289–352

Rosswog S, Langer N, Hilgers A, Evans H, Daly E, Hapgood M, Stamper R, Zwickl R, Bourdarie S and Boscher D 2005 Toolkit for updating interplanetary proton-cumulated fluence models J. Spacecr. Rockets 42 1077–90

Sato T, Endo A, Zankl M, Petoussi-Henss N and Niita K 2009 Fluence-to-dose conversion coefficients for neutrons and protons calculated using the PHITS code and ICRP/ICRU adult reference computational phantoms Phys. Med. Biol. 54 1997

Sato T, Endo A and Niita K 2010 Fluence-to-dose conversion coefficients for heavy ions calculated using the PHITS code and the ICRP/ICRU adult reference computational phantoms Phys. Med. Biol. 55 2235

Sawyer D M and Vette J I 1976 AP-8 trapped proton environment for solar maximum and solar minimum NASA STI/Recon Technical Report

Schimmerling W, Cucinotta F A and Wilson J W 2003 Radiation risk and human space exploration Adv. Space Res. 31 27–34

Schrijver C J and Siscoe G L 2010 Heliophysics: Space Storms and Radiation: Causes and Effects (Cambridge: Cambridge University Press)

Schrijver C J et al 2015 Understanding space weather to shield society: a global road map for 2015–2025 commissioned by COSPAR and ILWS Adv. Space Res. 55 2745–807

Schwarzdon N A et al 2010 Earth-Moon-Mars radiation environment module framework Space Weather 8 S00E02

Seltzer S M and Berger M J 1982 Evaluation of the collision stopping power of elements and compounds for electrons and positrons Int. J. Appl. Radiat. Isotopes 33 1189–218

SEPEM 2012 SEPEM website http://dev.sepem.oma.be

Shultis J K and Faw R E 2002 Fundamentals of Nuclear Science and Engineering (New York: Marcel Dekker) chapter 2

Singleterry R C Jr et al 2011 Oltaris: on-line tool for the assessment of radiation in space Acta Astronaut. 68 1086–97

Slaba T C, Blattning S R and Badavi F F 2010 Faster and more accurate transport procedures for heavy ions J. Comput. Phys. 229 9397–417

Smart D F and Shea M A 2003 Comment on estimating the solar proton environment that may affect Mars missions Adv. Space Res. 31 45–50

SPENVIS 2012 SPENVIS website www.spenvis.oma.be

Stanley D 2005 NASA exploration systems architecture study NASA Final Report, TM-2005-214062

Sternheimer R M, Berger M J and Seltzer S M 1984 Density effect for the ionization loss of charged particles in various substances At. Data Nucl. Data Tables 30 261–71

Tykta A J, Adams J H Jr, Boberg P R, Brownstein B, Dietrich W F, Flueckiger E O, Petersen E L, Shea M A, Smart D F and Smith E C 1997 Creme96: a revision of the cosmic ray effects on microelectronics code IEEE Trans. Nucl. Sci. 44 2150–60
Valentin J 2007 The 2007 Recommendations of the International Commission on Radiological Protection (Amsterdam: Elsevier)
Verbraecken J, Van de Heyning P, Backer W D and Van Gaal L 2006 Body surface area in normal-weight, overweight, and obese adults. A comparison study Metabolism 55 515–24
Vette J I 1991a The AE-8 trapped electron model environment NASA STI/Recon Technical Report
Vette J I 1991b The NASA/National Space Science Data Center trapped radiation environment model program, 1964-1991 Technical Report (Greenbelt, MD: Goddard Space Flight Center, National Aeronautics and Space Administration)
Xapsos M A, Summers G P, Barth J L, Stassinopoulos E G and Burke E A 1999 Probability model for worst case solar proton event fluences IEEE Trans. Nucl. Sci. 46 1481–5
Xapsos M A, Summers G P, Barth J L, Stassinopoulos E G and Burke E A 2000 Probability model for cumulative solar proton event fluences IEEE Trans. Nucl. Sci. 47 486–90
Xapsos M A, Stauffer C, Gee G B, Barth J L, Stassinopoulos E G and McGuire R E 2004 Model for solar proton risk assessment IEEE Trans. Nucl. Sci. 51 3394–8
Yu C-Y, Lo Y-H and Chiou W-K 2003 The 3 d scanner for measuring body surface area: a simplified calculation in the chinese adult Appl. Ergonom. 34 273–8
Ziegler J F 2003 Stopping and Range of Ions in Matter SRIM-2003
Ziegler J F, Ziegler M D and Biersack J P 2010 SRIM—the stopping and range of ions in matter Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. Atoms 268 1818–23