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Radiation Dosimetry Estimations in the Venusian Atmosphere during Different Periods of Solar Activity

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Abstract: The new space era has expanded the exploration of other planets of our solar system. In this work, radiation quantities are estimated in the Venusian atmosphere using the software tool DYASTIMA/DYASTIMA-R, such as the energy deposit and the ambient dose equivalent rate. Monte Carlo simulations of the secondary particle cascades for different atmospheric layers were performed during solar minimum and solar maximum conditions, as well as during the extreme solar particle event that took place in October 1989, with a focus on the so-called Venusian zone of habitability.

Keywords: radiation dosimetry; simulation; habitability

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1. Introduction

Space exploration is developing rapidly, with a strong focus on the Moon and Mars. In this scope, the twin sister of Earth, Venus, could also constitute an important scientific challenge [1,2], especially because some of the possible mission trajectories towards Mars may include some flybys of Venus [3]. Although Venus is quite similar to Earth, in terms of diameter and mass, it seems that a completely different evolutionary process has taken place, resulting in a very different atmospheric composition [4,5].

Venus presents a very strong greenhouse effect, due to its high atmospheric composition of CO_2 [6]. The planet is totally covered with clouds, which results in an increased planetary albedo (0.8 to 0.9) [7], making Venus the second brightest object in the night sky. The runaway greenhouse effect is responsible for some of the main differences observed between Earth and Venus, and for what made Venus the hostile environment that is now [1,5]. Other important differences include the inner magnetic field, plate tectonics, volcanism, etc. The atmosphere of Venus is characterized by high temperature and strong winds, and it is very hot (the average surface temperature is ~740 K [8]), dense, and corrosive, mostly consisting of carbon dioxide with clouds of sulfuric acid. These clouds extend from about 45 km to 65–70 km of altitude [9,10]. However, recent studies and observations indicate the existence of possible habitable conditions [11–16] inside the aerial biosphere surrounding Venus, which may be compatible with life, extending from 43 km (393 K) to 63 km above the surface. Unlike Earth, Venus does not possess a significant magnetic field. This, alongside the lower distance from the Sun, leads to greater solar ultraviolet radiation and a higher flux of charged particles, such as galactic cosmic rays (GCR) and solar energetic particles (SEP) [5,17]. GCR constitute a permanent radiation background, whereas the sporadic SEP may be very efficient at stimulating prebiotic chemistry and may have therefore aided in the origin of life [18].

On Earth, the possible biological effects of radiation, and more specifically those of cosmic radiation [19], as well as the necessity to protect aviation crews were acknowledged by the European Commission in 1996 with Directive 96/29/EURATOM [20]. Since then, concerted efforts have been made globally regarding radiation protection issues by various stakeholders in this direction, with the development of many protocols, models, and tools. In the dawn of the new space exploration and colonization era, the calculation of the radiation dose received by space crews is crucial. Venus, being the closest neighbor of our terrestrial home, may provide an exciting opportunity for such studies.

In order to perform radiation dosimetry studies regarding the exposure to cosmic radiation, a software application called Dynamic Atmospheric Shower Tracking Interactive Model Application (DYASTIMA) was developed by the Athens Cosmic Ray Group [21]. DYASTIMA is based on Geant4 [22–24] performing Monte Carlo simulations of secondary cosmic ray cascades in any planet with an atmosphere, providing all the necessary information of the air showers' characteristics, i.e., number, energy, energy deposition, direction and time of arrival of the secondary particles at the desired atmospheric layers as a function of several parameters, such as different solar activity conditions, location, and altitude. Moreover, its embedded feature DYASTIMA-R allows [25] the estimation of radiobiological quantities, which are crucial for the assessment of the radiation exposure of aircrews and space crews.

DYASTIMA/DYASTIMA-R is a validated tool [26] according to international standards provided by the International Committee on Radiological Protection (ICRP) and International Commission on Radiation Units and Measurements (ICRU) [27,28]. So far, DYASTIMA has been used successfully for air shower studies during periods of quiet and disturbed solar activity [21,29] as well as for the calculation of the operational radiological quantity ambient dose equivalent rate (dH*(10)/dt) inside Earth's atmosphere [25,30–32]. In a first attempt to perform a simulation, the ionization rate inside the Venusian atmosphere was also estimated [31]. The DYASTIMA software application can be easily accessed through the Athens Neutron Monitor Station (A.Ne.Mo.S.) portal (http://cosray.phys.uoa.gr/index.php/dyastima, accessed on 15 September 2022). In addition, a database of selected scenarios performed with DYASTIMA/DYASTIMA-R is available on the portal of the European Space Agency (ESA) Space Weather (SWE) (https://swe.ssa.esa.int/dyastima-federated, accessed on 15 September 2022) as a federated product.

In this work, the energy deposit and the ambient dose equivalent rate at the different atmospheric layers of Venus will be estimated by simulation performed with the DYASTIMA software. The necessary simulation input parameters are adequately analyzed, and results and future steps are also thoroughly discussed.

2. Technical Analysis and Data Selection

DYASTIMA/DYASTIMA-R allows for the possibility of extensive parameterization; therefore, the performance of simulations requires the input of several parameters by the user via the user-friendly graphical interface of DYASTIMA, as described in the available software user's manual [33]. These include the characteristics of the planet, the atmospheric composition and profile, the primary cosmic ray spectrum, the appropriate physics list to describe the physical interactions taking place, the simulation geometry, the tracking layers, the characteristics of the phantom, and the number of events and iterations [21].

The characteristics of Venus, i.e., radius, gravity acceleration, and surface pressure used in this work can be easily found in the bibliography, for example, in the NASA Venus Fact Sheet available at https://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html (accessed on 15 September 2022). The atmospheric composition is also defined as 97% CO_2 and 3% N_2. The atmospheric profile, i.e., the temperature versus the atmospheric altitude, used for the simulations presented in this work is based on the Venus International

Reference Atmosphere [34]. Estimated parameters for the lower and middle atmospheric layers (0 km to 100 km) at low latitudes, φ (φ < 30°) [35] and for the upper atmospheric layers (100 km to 150 km) at low latitudes (φ < 16°) for daytime [36] have also been taken under consideration. The complete Venusian atmospheric profile is illustrated in Figure 1 (data from [26–28]), where the possible habitability zone is outlined in grey color. It should be noted that the specific atmospheric composition and profile have been used in previous work [31,37].

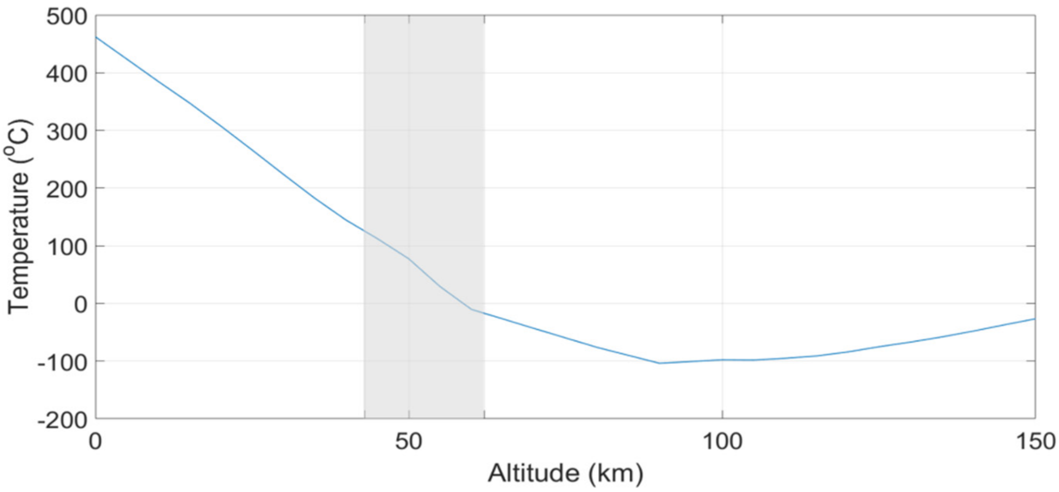

Figure 1. Temperature profile of Venus (data from [26–28]).

Another cornerstone for the simulation performance is the definition of the incoming primary cosmic ray particle's differential spectrum at the top of the Venusian atmosphere (corresponding to 150 km in this work). The primary spectra used in this work are based on the CRÈME 2009 model [38–41]. CRÈME 2009 provides the flux of ions with atomic number 1 to 28, for energies ranging from 1 MeV/nucleon up to 100 GeV/nucleon at 1 AU (Sun–Earth distance) in interplanetary space. More specifically, the GCR spectrum was considered for solar maximum and solar minimum activity, for quiet conditions, i.e., without taking into account any solar energetic particle (SEP) events. As the gradient of the flux of the galactic component is quite low in the inner solar system [31,37,42], there was no need to rescale the GCR in order to use it for Venus.

To simulate a strong SEP event, the CRÈME 2009 "Worst Week" scenario was used, corresponding to the series of strong SEP events that took place during October 1989. In this case, it is necessary to rescale the SEP flux, as it depends significantly on the orbital distance. The scaling is according to the geometric factor $1/R^2$, where R corresponds to the Sun–Venus distance (0.72 AU).

For both GCR and SEP spectra, six dominant ion species have been used (H, He, C, O, Si, and Fe) in order to achieve high accuracy, as these ions are mostly abundant in cosmic radiation, representing almost 97% of the energy in the cosmic ray energy spectrum. In addition, the spectra have been extrapolated up to 1 TeV/nucleon by fitting a power law tail [31,37]. The primary spectra for solar minimum and solar maximum conditions, as well as for flare conditions (Worst Week scenario) are presented in Figure 2.

Finally, it is noted that, as Venus does not have a significant intrinsic magnetic field, the magnetic field components at the interface were given the value of 0.

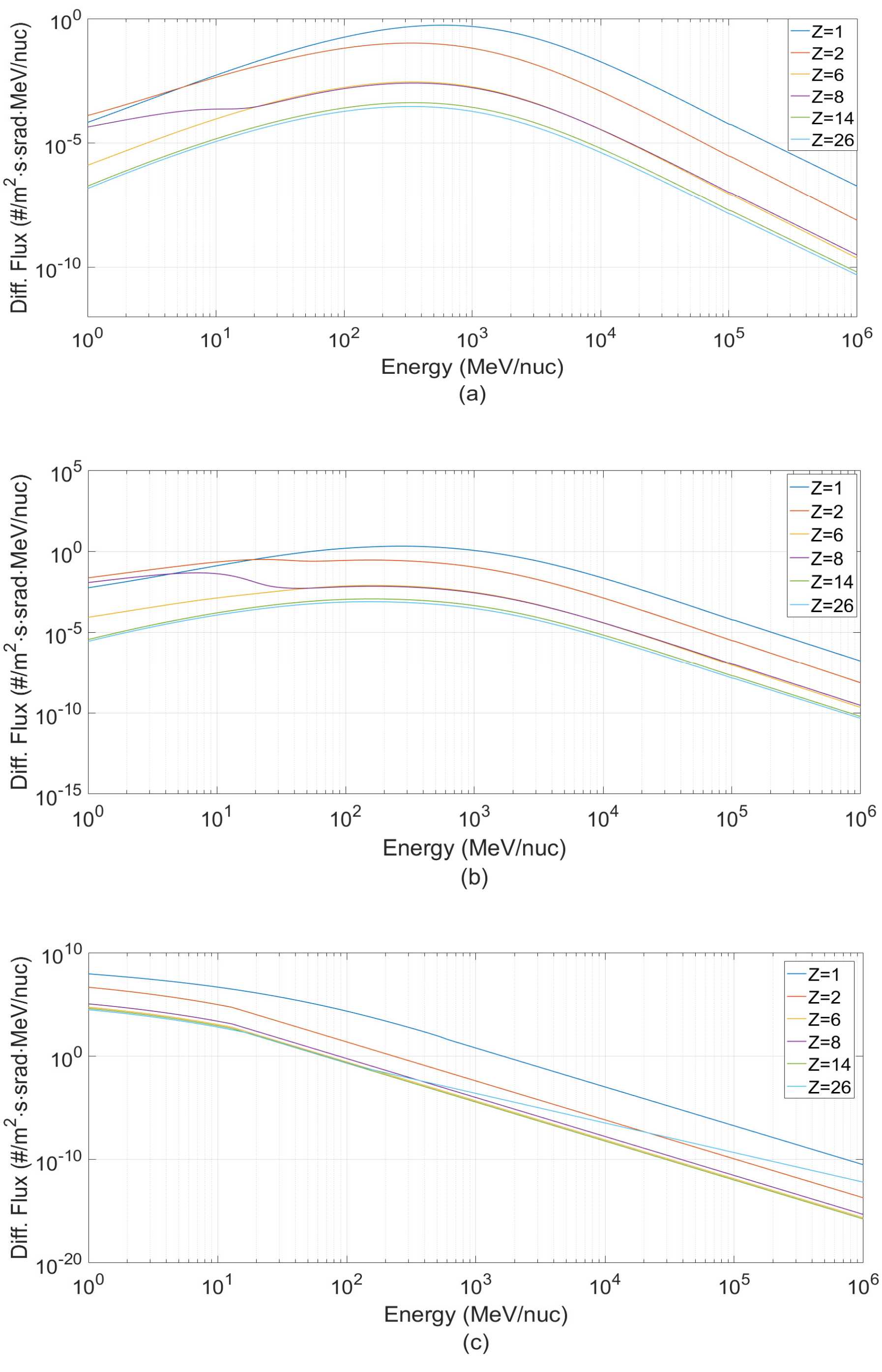

Figure 2. Differential flux of the incoming primary cosmic ray particles as a function of energy for various elements for solar maximum (**a**), solar minimum (**b**), and for solar flare conditions ("Worst Week" scenario) (**c**).

3. Results

In the last decade, several studies have been performed in order to fully understand the physicochemical properties of the Venusian atmosphere, as well as to provide estimations about the energy deposition, the ionization rate, and the assessment of the possible radiation exposure [5,31,43,44], using several Monte Carlo simulation packages and models of cosmic radiation particle propagation in the atmosphere. In this work, Monte Carlo simulations of the secondary particle cascades generated inside the atmosphere of Venus were performed with the software tool DYASTIMA/DYASTIMA-R. These concern the calculation of the energy deposition and the ambient dose equivalent rate for different altitudes (0 km to

150 km) and phases of solar activity (solar maxima, solar minima, flare conditions). Each simulation was performed for 50,000 events.

The ionizing energy deposit as a function of altitude is depicted for solar minimum, solar maximum, and the Worst Week scenario in Figure 3. The habitability zone of Venus is indicated in grey. Specifically, the ionizing energy deposit is observed in the zone of 30–90 km, presenting a peak value at 63 km (top of the zone) in both solar minimum and solar maximum cases. Because the atmosphere of Venus is really thick (the air pressure on the surface is about 90 atmospheres), all particles deposit their energy on the top and middle atmospheric layers without reaching the surface.

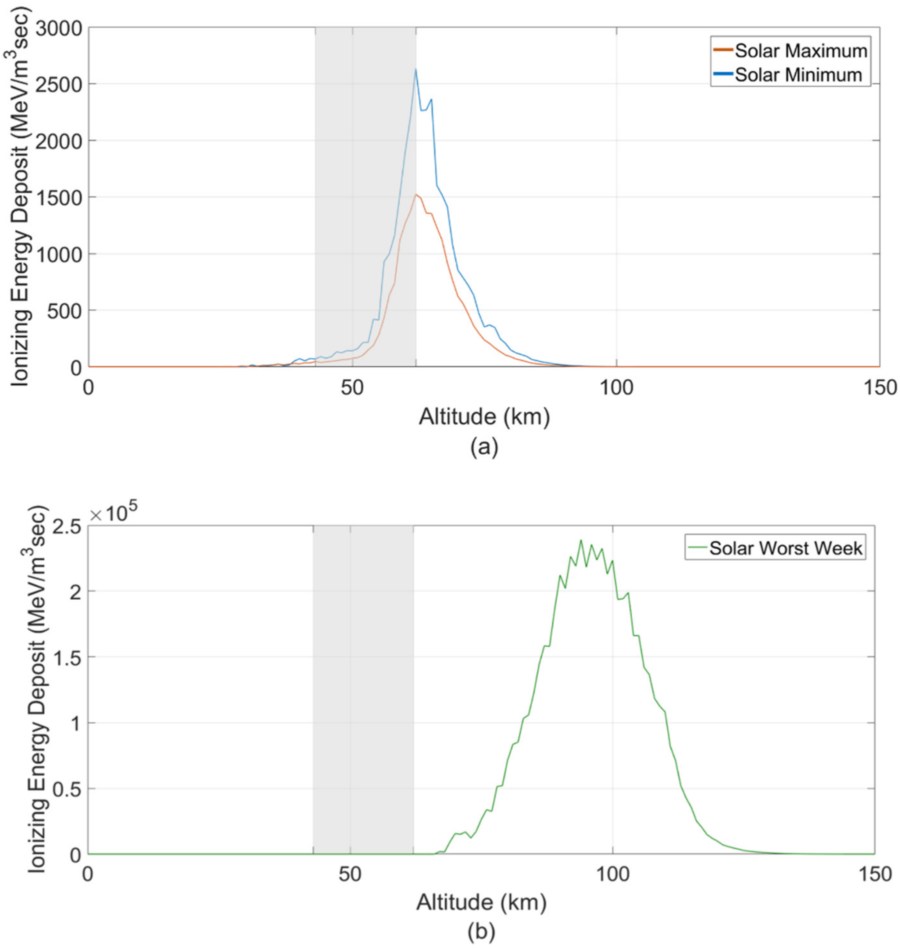

Figure 3. Energy deposition in the Venusian atmosphere for solar minimum and solar maximum conditions (**a**) and for the Worst Week scenario (**b**).

It is also clear that the energy deposit is higher during minimum solar activity, due to the anticorrelation of solar activity with the cosmic ray intensity. Similar behavior is also observed on Earth [30,32]. Furthermore, in the zone of 43 km to 63 km, where the conditions are similar to Earth, the energy deposit decreases almost exponentially towards the Venusian surface. As far as the Worst Week scenario is concerned, the energy deposit peak value shifts roughly 30 km higher in the atmosphere, to an altitude of 90 km according to Figure 3b, with no effect on this zone, while it is also two orders of magnitude greater than the one due to the background GCR.

Moreover, radiation dosimetry calculations were performed with DYASTIMA-R for the aforementioned conditions. DYASTIMA-R features provide the possibility to perform radiation dosimetry calculations via Monte Carlo simulations inside the atmosphere of a planet, using as input the output provided by DYASTIMA. More specifically, a human phantom is irradiated with the particles collected at each atmospheric layer (via the simulations performed with DYASTIMA), and, in this way, the dose as well as the equivalent dose rates can be calculated for different altitudes inside the Venusian atmosphere, as well as for different phases of solar activity. The user can choose the dimensions and the material of the human phantom. In our case, the simulations were performed assuming an ICRU sphere phantom made of tissue-equivalent material [45], placed at different atmospheric layers, following the same procedure that has been previously applied for radiation dosimetry calculations inside Earth's atmosphere [30,32]. Each simulation scenario was performed for 20 iterations (interactions of the collected particles with the phantom matter). The weighting factors for each radiation type, which are necessary for the reflection of the relative biological effectiveness and the quality of each radiation type and therefore for the determinations of the ambient dose equivalent rate, are based on [45]. Ambient dose equivalent rate dH*(10)/dt corresponds to the equivalent dose (energy deposit per mass, multiplied by the radiation weighting factor) at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius vector opposing the direction of the aligned field [28,29,46].

The ambient dose equivalent rate dH*(10)/dt for solar minimum, maximum, and during the Worst Week scenario are presented in Figure 4. It can be observed that during solar minimum activity, dH*(10)/dt is higher due to the previously mentioned anticorrelation of the solar activity and the cosmic ray intensity. During the solar minimum conditions, some fluctuations are observed as the altitude rises, but high above the possible habitability zone, whereas all radiation dose profiles are relatively flat in the higher atmospheric layers. During the Worst Week scenario, the radiation dose value is higher, almost three orders of magnitude than the one of solar minimum, and has a significant value above 75 km with a peak value observed at 100 km. These results are in accordance with previous studies, where a similar qualitative behavior is identified for the radiation exposure [43].

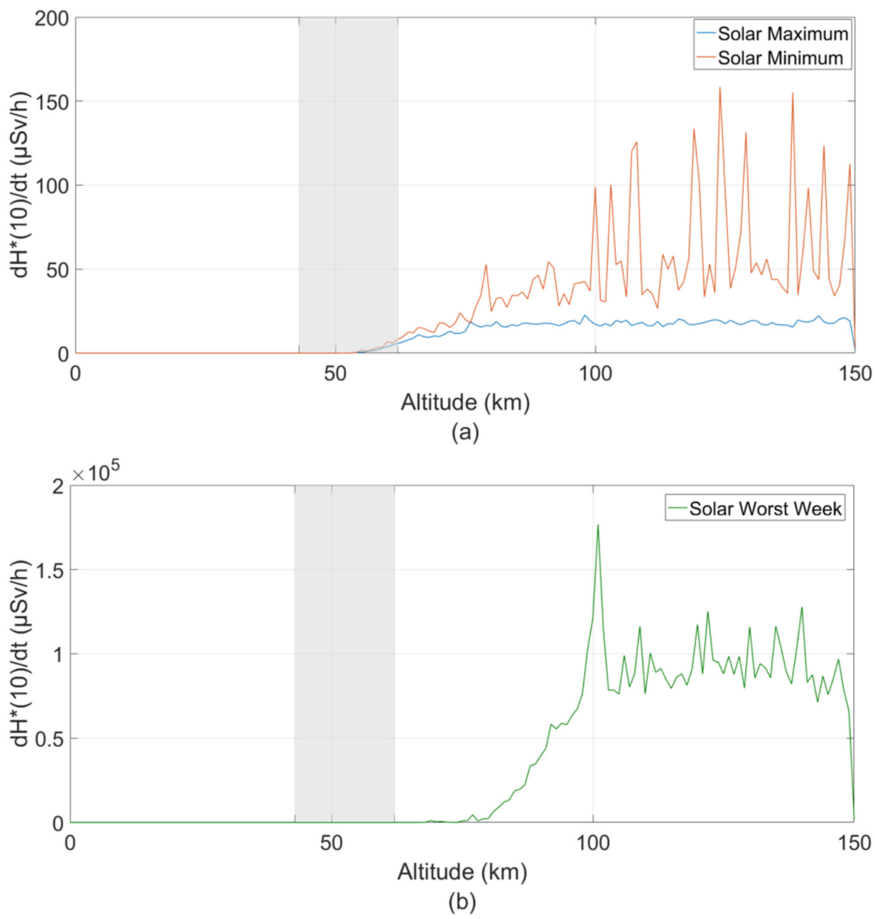

Figure 4. The ambient dose equivalent rate for different altitudes in the atmosphere of Venus during solar minimum and solar maximum conditions (**a**) and the Worst Week scenario (**b**).

4. Discussion and Conclusions

Venus is known as the twin sister planet of Earth. However, a completely different evolutionary path led to the formation of a hostile for life environment on the surface and inside the atmosphere of Venus. The upper atmospheric layers are more susceptible to a higher radiation flux (cosmic radiation and ultraviolet radiation) [5,17], as Venus is closer to the Sun (0.75 AU). However, in the middle atmospheric layers, 43 km to 63 km higher from the surface, there is the so-called "habitability zone" of Venus, a region with similar temperature and pressure to Earth's atmospheric conditions at ground level [43]. This fact has led many scientists to suggest the re-visiting of Venus in a new scope, as it may offer many possibilities regarding habitability studies towards our future steps on Mars, or even colonization of Venus with a floating manned space mission [43,47]. Furthermore, several astrobiological missions to Venus have also been proposed to probe its clouds [48].

In this work, the energy deposit and the ambient dose equivalent rate in the atmospheric layers of Venus were studied by performing simulations of the cosmic radiation secondary particles' cascades with the DYASTIMA/DYASTIMA-R software. DYASTIMA has been used previously for the calculation of the ionization rate inside the Venusian atmosphere [30]. This investigation led to results with great impact concerning periods of solar maximum and solar minimum activity, and, in addition, flare conditions, by examining the events of October 1989 (Worst Week scenario). As expected, the radiation exposure is higher at the top atmospheric layers during solar minimum conditions (compared to solar maximum conditions) and higher by two orders of magnitude during a strong SEP event. However, in this zone, an increased degree of radiation protection is observed due to the thick Venusian atmospheric shielding, with the ambient dose equivalent rate values being similar to the ones we experience on Earth, if compared with studies performed regarding the exposure inside Earth's atmosphere [25,30,32]. These results are also in accordance with other studies [43], where the exposure to cosmic radiation exhibits a very similar qualitative behavior. However, a quantitative analysis is not performed at this point due to the fact that different radiobiological quantities are used in each study.

The aforementioned results are provided as a federated product through the ESA SWE portal (https://swe.ssa.esa.int/dyastima-federated, accessed on 15 September 2022). Future steps include the performance of simulation with the DYASTIMA/DYASTIMA-R software of the atmospheres of other planets, such as Mars.

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