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Constraints on a potential aerial biosphere on Venus: I. Cosmic rays

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ABSTRACT

While the present-day surface of Venus is certainly incompatible with terrestrial biology, the planet may have possessed oceans in the past and provided conditions suitable for the origin of life. Venusian life may persist today high in the atmosphere where the temperature and pH regime is tolerable to terrestrial extremophile microbes: an aerial habitable zone. Here we argue that on the basis of the combined biological hazard of high temperature and high acidity this habitable zone lies between 51 km (65 °C) and 62 km (−20 °C) altitude. Compared to Earth, this potential venusian biosphere may be exposed to substantially more comic ionising radiation: Venus has no protective magnetic field, orbits closer to the Sun, and the entire habitable region lies high in the atmosphere – if this narrow band is sterilised there is no reservoir of deeper life that can recolonise afterwards. Here we model the propagation of particle radiation through the venusian atmosphere, considering both the background flux of high-energy galactic cosmic rays and the transient but exceptionally high-fluence bursts of extreme solar particle events (SPE), such as the Carrington Event of 1859 and that inferred for AD 775. We calculate the altitude profiles of both energy deposition into the atmosphere and the absorbed radiation dose to assess this astrophysical threat to the potential high-altitude venusian biosphere. We find that at the top of the habitable zone (62 km altitude; 190 g/cm^2 shielding depth) the radiation dose from the modelled Carrington Event with a hard spectrum (matched to the February 1956 SPE) is over 18,000 times higher than the background from GCR, and 50,000 times higher for the modelled 775 AD event. However, even though the flux of ionising radiation can be sterilizing high in the atmosphere, the total dose delivered at the top of the habitable zone by a worst-case SPE like the 775 AD event is 0.09 Gy, which is not likely to present a significant survival challenge. Nonetheless, the extreme ionisation could force atmospheric chemistry that may perturb a venusian biosphere in other ways. The energy deposition profiles presented here are also applicable to modelling efforts to understand how fundamental planetary atmospheric processes such as atmospheric chemistry, cloud microphysics and atmospheric electrical systems are affected by extreme solar particle events. The companion paper to this study, *Constraints on a potential aerial biosphere on Venus: II. Solar ultraviolet radiation* (Patel et al., in preparation), considers the threat posed by penetration of solar UV radiation. The results of these twin studies are based on Venus but are also applicable to extrasolar terrestrial planets near the inner edge of the circumstellar habitable zone.

1. Introduction

1.1. Venus and Earth

Venus is the Earth's nearest planetary neighbour, and in some respects the two worlds are much alike. Venus is very similar to the Earth in both diameter (95%) and mass (82%): both are small rocky terrestrial planets in the inner Solar System that presumably formed with similar compositions, and today both have appreciable atmospheres. But for habitability and the possibility of life, the devil is in the detail. Venus and Earth may be like twins in their formation and early lives, but have followed starkly contrasting planetary evolutionary trajectories over the history of the Solar System to two very different environmental end-points (Svedhem et al., 2007; Driscoll and Bercovici, 2013). The current

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venusian surface, blanketed by a ~90 bar atmosphere of carbon dioxide and the powerful greenhouse effect this generates, experiences an average temperature of over 450 °C. These surface conditions are not compatible with the fundamental prerequisites of life as we know it: liquid water and organic chemistry.

Venus is at the inner edge of the circumstellar habitable zone and has undergone a runaway greenhouse effect (Walker, 1975; Kasting, 1988). There is the possibility, though, that the venusian surface once presented habitable conditions for the emergence of life. Venus likely received a similar volatile inventory to Earth during its formation and early history, including that of water (Kasting, 1988). These early venusian oceans would have been lost when the increasing solar output triggered a runaway moist greenhouse process, evaporating the basins dry. Water vapour high in the atmosphere would then have dissociated by solar UV photolysis, the hydrogen lost readily to space, and the oxygen ions either also lost to space though pick-up by the solar wind or by the oxidation of minerals in the crust. The hundred-fold enrichment of deuterium in the venusian atmosphere, relative to the light hydrogen isotope ^1H, implies the escape of a large amount of the initial hydrogen inventory of Venus, and thus likely water (Donahue et al., 1982; Donahue and Hodges, 1992). Recent measurements of the escape rate of atmospheric ions find the ratio of hydrogen to oxygen to be almost 2:1, the stoichiometry of water (Barabash et al., 2007), and over the planet's history Venus could have lost at least one terrestrial ocean of water (Kulikov et al., 2006). Alternatively, Venus may have lost its water inventory before the magma ocean cooled and thus without the subsequent formation of a temporary water-size ocean (Gillmann et al., 2009; Chassefière et al., 2012).

It is not known when this runaway moist greenhouse process occurred, and therefore for what period of its history the venusian surface may have been wet and habitable to provide a window of opportunity for life to emerge. What's more, the global resurfacing event that occurred 300–600 Mya (Strom et al., 1994; Nimmo and McKenzie, 1998) has likely destroyed (or at least very deeply buried) any ancient ocean basins or other markers or evidence of this pre-hothouse history, although the observation of what may be felsic rocks in the highlands imply the existence of a past ocean (Hashimoto et al., 2008; Basilevsky et al., 2012). In any case, oceans may have persisted on early Venus for 600 myr (Kasting, 1988) to as long as several billion years (Grinspoon and Bullock, 2003) and thus the planet possibly provided an early environment sufficiently clement, and for long enough, for an indigenous origin of life (or perhaps inoculation through lithopanspermia by microbes transferred from Earth by meteorite during the Late Heavy Bombardment).

Any biosphere that potentially developed on early Venus may have been driven to extinction as the planet warmed and the oceans were lost and the surface subsequently became thermally sterilised. Alternatively, some venusian life may have survived by migrating to follow still-habitable conditions: migrating either far below or high above the surface. Schulze-Makuch and Irwin (2002) point out that if sufficient water remains in the venusian subsurface, it may remain in a liquid state due to the pressure of overbearing rock layers and they speculate that this supercritical water, or perhaps supercritical carbon dioxide (Budisa and Schulze-Makuch, 2014), may be able to support a deep subsurface chemoautotrophic ecosystem. A more plausible potential habitable zone on current-day Venus is in the clouds.

1.2. Life in the clouds

Venus is totally covered in clouds, resulting in a very high planetary albedo of around 0.8 (Marov and Grinspoon, 1998). The base of this thick cloud cover lies at about 47 km above the surface (at a temperature around 100 °C) and extends up to over 70 km in altitude. In equatorial and mid-latitudes the cloud top is located at 74 km, but decreases towards the poles to 63–69 km (Ignatiev et al., 2009). These clouds can be subdivided into three layers – upper (56.5–70 km altitude), middle (50.5–56.5 km) and lower (47.5–50.5 km) – based on the size distribution of aerosol particles present (Knollenberg and Hunten, 1980; Donahue and Russell, 1997). The smallest, Mode 1 droplets, around 0.4 μm in diameter, and Mode 2 droplets, sized around 2–2.5 μm, occur in all three cloud layers. The largest aerosol particles, Mode 3, occur only in the middle and lower cloud decks, and are around 8 μm in size (Knollenberg and Hunten, 1980).

The particles composing the clouds are mostly H_2SO_4 aerosols, ranging from 80% in the upper clouds to around 98% acid concentration in the lower layer. Although it has been pointed out that these Mode 3 particles are around the same size as terrestrial cloud droplets (Grinspoon, 1997), it is still unresolved as to whether these aerosol particles are large and spherical, or elongated and crystalline, in nature (Krasnopolsky, 2006), or have a mixed composition: radio occultation measurements are consistent with a solid core coated by a shell of liquid sulphuric acid (Cimino, 1982).

At the very least, then, the cloud decks of Venus offer an aqueous environment for colonisation by life. Such life may have arisen in a benign surface environment of Venus, potentially in a primordial ocean, before the planet suffered a runaway greenhouse, and these microorganisms lofted into the clouds by the same mechanisms as terrestrial high-altitude cells discussed below. The venusian clouds are composed of water that is very low pH with sulphuric acid and dispersed as a fine aerosol. This potentially habitable environment has lead a number of researchers to discuss the possibility of aerial venusian life: Sagan (1961), Morowitz and Sagan (1967), Grinspoon (1997), Cockell (1999), and Schulze-Makuch and Irwin (2002). Available sources of metabolic energy for life include photosynthesis, possibly absorbing ultraviolet wavelengths, employing the oxidation of hydrogen sulphide or carbonyl sulphide (Schulze-Makuch et al., 2004); or chemotrophic reduction of sulphate (Cockell, 1999). Schulze-Makuch et al. (2013) posit a venusian cloud ecosystem that couples sulphur-oxidising photoautotrophs and sulphur-reducing chemotrophs: photosynthetic cells employing a photosystem-I-like pathway to reduce carbon by oxidising hydrogen sulphide, and a lower layer of chemosynthetic organisms that complete the cycle by reducing sulphur again.

To a first approximation, the potential habitable zone for a venusian aerial biosphere would be the vertical extent corresponding to the temperature range for growth demonstrated by known terrestrial extremophile microorganisms: between about 120 °C and −20 °C (Cavicchioli, 2002). Fig. 1 plots the temperature and pressure profiles through the venusian atmosphere (data from Venus International Reference Atmosphere: Kliore et al., 1985; Seiff et al., 1985; Keating et al., 1985), and so shows that these temperature limits would place the habitable region between 43 km (120 °C) and 62 km (−20 °C) above the surface, overlapping the cloud layers. Fig. 1 also shows the pressure regime to be benign to life over this altitude range. Such a temperature basis has been used in the past to define the venusian habitable zone: Cockell (1999), for example, argues for an even deeper thermal floor at 150 °C as a generic limit for life based on the stability of complex organic molecules. However, here we argue in Section 4 that the survival limits of terrestrial polyextremophile organisms able to tolerate the combined environmental challenges of both very high temperatures and acidities (thermophilic hyperacidophiles) indicate a more appropriate floor for the putative venusian aerial biosphere to be at 65 °C, equating to around 51 km altitude. This more constrained temperature limit is shown in Fig. 1 (and results Figs. 5 and 6) as a horizontal red line.

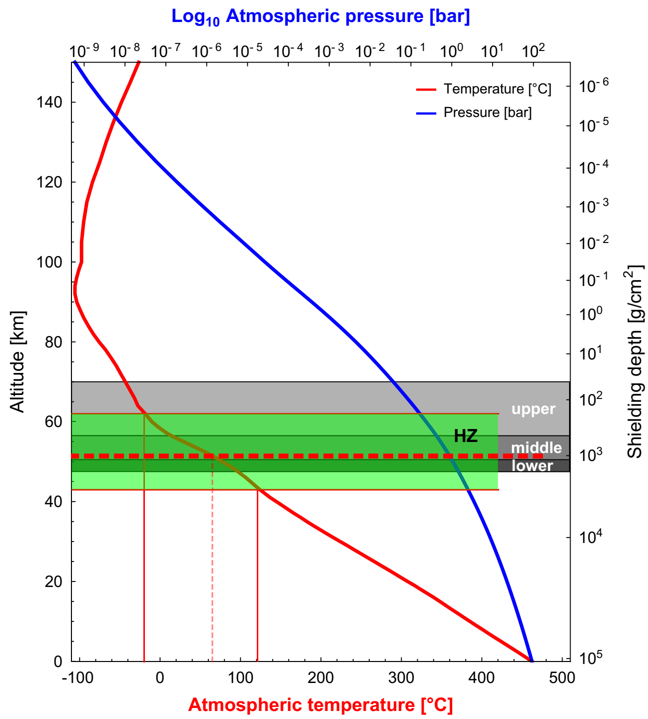

Fig. 1. The habitable zone high in the venusian atmosphere. Temperature (red) and pressure (blue) are plotted as a function of altitude. The three cloud layers are shown in shades of grey and the conventional habitable zone, at temperatures between −20 °C and 120 °C, is shown by the green region (labeled HZ). As discussed, however, no terrestrial thermophilic-hyperacidophiles can tolerate pH 0 at temperatures above 65 °C and so here we argue that this represents the true floor to the venusian aerial habitable zone, as indicated by the dashed red line at 51 km altitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

While analogue sites on Earth (see review in Preston and Dartnell, 2014) do not offer long-lived aerosols with temperatures or acidities comparable to Venus, the presence of life at high altitudes in the terrestrial atmosphere is well-known (Rothschild and Mancinelli, 2001). Womack et al. (2010) summarizes the argument that the atmosphere is not simply a transient transport phase between terrestrial surface locations but represents a genuine niche where bacteria are actively metabolizing to drive biogeochemical cycling, as well as reproducing. Sattler et al. (2001), for example, demonstrate growth of bacteria in super-cooled cloud droplets sampled from a meteorological station on a mountain top in the Alps. The limiting factor on a terrestrial aerial biosphere is likely to not be nutrient availability or environmental extremes, but residence time in the atmosphere before precipitating back down (see review in Womack et al., 2010). In contrast to the Earth, venusian clouds are not transient entities but represent a global, continuous feature, with aerosol particles sustained for at least several months, rather than just a few days in the terrestrial atmosphere, and so represent a stable potential niche if microorganisms remain lofted in this aerial HZ (Grinspoon, 1997; Schulze-Makuch et al., 2013).

1.3. Radiation environment

Alongside the extreme acidity of the clouds another environmental hazard to putative venusian life, and one that has received much less discussion thus far, is the nature of the radiation environment that an aerial biosphere would be exposed to. Both cosmic radiation and solar ultraviolet radiation will penetrate the upper atmosphere and are considered here in these twin papers.

The ionising radiation field created by the penetration of cosmic rays is hazardous to life through a number of direct and indirect mechanisms (see review in Dartnell, 2011a and references therein). The space particle radiation environment is composed of two populations of particles: galactic cosmic rays (GCR) and solar energetic protons (SEP), the more energetic of which generate extensive cascades of secondary particles when they interact with shielding matter. GCR particles show a peak in flux at around 500 MeV/nucleon but the power law tail of the spectra extends up to 10^{20} eV at low fluxes. The GCR spectrum is composed of 85% protons, 14% alpha (helium nuclei), and a small fraction of heavy ions (fully ionised atomic nuclei) and electrons, and is thought to be mainly accelerated by Type II supernovae. GCR below about 1 GeV/nucleon are modulated by the heliosphere (Klapdor-Kleingrothaus and Zuber, 2000) so their flux is anticorrelated with the solar activity cycle (solar minimum and maximum proton spectra are shown in Fig. 3). SEP are accelerated at the shock front of flares and coronal mass ejections typically up to several hundred MeV. At lower energies, SEP flux is orders of magnitude greater than the background GCR but these events are transient and sporadic, their occurrence varying with the 11-year solar activity cycle.

Whilst GCR form a relatively uniform background flux of particle radiation, there is a great deal of variability in the energy spectrum and total fluence of solar particle events (SPEs). The solar flare of 1st September 1859, reported by both Richard Carrington and Richard Hodgson, was one of the most intense white-light flares ever observed, and the resultant geomagnetic storm resulted in wildfires across continental US and Europe ignited by arcing telegraph wires and produced aurorae visible as far south as Cuba and Jamaica (Tsurutani et al., 2003; Cliver, 2006). Attempts have been made to use ice core nitrate levels to estimate the energetic particle fluence of the 'Carrington Event' (McCracken et al., 2001a,b; Shea et al., 2006) but this is now deemed to represent an unreliable index of fluence into the upper atmosphere (Wolff et al., 2012; Cliver and Dietrich, 2013). More robustly, cosmogenic isotopes, such as ice core Be-10 deposits or tree-ring records of C-14, have been used to infer the intensities of pre-space-age SPEs. This tree-ring C-14 data reveals that the most extreme SPE of the Holocene (the past ~10,000 years of the current climatic epoch) occurred in 775 AD, with an F200 (the integral proton fluence above 200 MeV) of around 8×10^9 cm^{-2} – over fifty times more intense than the recorded event of February 1956 (Kovaltsov et al., 2014). Here, we model both the 1859 Carrington Event and the 775 AD SPE.

The total shielding thickness of the venusian atmosphere, around 10^5 g/cm^2 (Borucki et al., 1982), is two orders of magnitude greater than the terrestrial shield of 1033 g/cm^2 (United States Committee on Extension to the Standard Atmosphere NOAA, 1976), so even the most energetic primary cosmic rays produce negligible radiation at the surface. The high-altitude region offering conditions compatible with life, however, is much less shielded and the peak in cosmic ray ionisation occurs at an altitude of ~63 km in the venusian atmosphere (Dubach et al., 1974; Borucki et al., 1982; Upadhyay et al., 1994; Nordheim et al., 2015), overlapping this potential habitable zone shown in Fig. 1. It is thus possible that this peak radiation environment may represent a survival threat to venusian life already stressed by the other environmental hazards such as acidity, temperature and solar UV. Additionally, in contrast to the Earth, Venus receives no protection against charged particle radiation from a global magnetic field and also orbits 30% closer to the Sun and so is exposed to a greater flux of SEP, of particular concern during an extreme SPE such as the Carrington Event or that of 775 AD.

Cosmic ray-induced ionisation deep within the venusian atmosphere has been previously studied by Dubach et al. (1974), Borucki et al. (1982), and Upadhyay et al. (1994), using approximate transport equations to calculate particle flux through the atmosphere. A more sophisticated model was presented by Nordheim et al. (2015), employing a full 3D Monte Carlo model of cosmic ray particle propagation and interactions with the venusian atmosphere to calculate the ionisation profile.

Here we use that model to address the threat posed to life in the high-altitude habitable zone of the venusian atmosphere from the ionising radiation environment created by both galactic cosmic rays and the rare but intense pulses of energetic particle radiation from solar particle episodes like the Carrington Event. This present study extends modelling work conducted on the astrobiological effects of cosmic radiation penetrating the top subsurface of Mars (Dartnell et al., 2007a,b).

2. Method

2.1. Cosmic ray modelling

For modelling the propagation of energetic charged particle radiation through the venusian atmosphere we used the PLANETOCOSMICS (http://cosray.unibe.ch/~laurent/planetocosmics/) software application (Desorgher et al., 2005). This code is based on the Geant4 Monte Carlo simulation toolkit for particle interactions with matter (Agostinelli et al., 2003) and was developed at the University of Bern for the European Space Agency. PLANETOCOSMICS simulates discrete electromagnetic and hadronic particle interactions in planetary atmospheres, including a full treatment of secondary particle cascades, and the normalization to the incident flux, and has been validated against terrestrial balloon measurements (Desorgher et al., 2005; Vainio et al., 2009).

The modelling geometry was constructed as an atmospheric column 150 km high, subdivided into 93 layers to recreate the density, pressure and temperature profiles within the venusian atmosphere. This atmospheric description is based on the Venus International Reference Atmosphere (Kliore et al., 1985), using tabulated parameters provided by Seiff et al. (1985) for the lower and middle atmosphere (0–100 km) and those of Keating et al. (1985) for the daytime upper atmosphere between 100 and 150 km. An atmospheric composition of 96.5% CO_2 and 3.5% N_2 was used. The shielding depth (g/cm^2) scale shown in Figs. 1, 5 and 6 was derived by integrating the atmospheric density (g/cm^3) profile above any given altitude, as shown in Nordheim et al. (2015). The atmospheric layers report on the energy deposited within them by the propagating primary and secondary particles, predominantly by ionisation, which allows calculation of the profiles of ionisation per both unit volume and unit mass (i.e. absorbed radiation dose), as a function of altitude.

The irradiation geometry of an isotropic hemispherical source above the planetary atmosphere is recreated by a point source at the top of the modelled atmospheric column delivering primary cosmic ray particles according to a cosine law angular distribution (where the intensity is proportional to the cosine of the angle from the vertical). All primary and secondary particles are tracked until they either come to rest within the atmospheric column or are absorbed by the planetary surface. Galactic cosmic ray primaries are modelled from $Z = 1–28$ and from 1 MeV/nucleon to 1 TeV/nucleon, given by the CREME2009 model during 'solar quiet' conditions during both solar minimum and solar maximum. Further details on the modelling approach employed here are provided in Nordheim et al. (2015).

2.2. Extreme solar particle event spectra

While the particle energy distribution of the 1859 Carrington or 775 AD SEP events are unknown, their spectral shape can be modelled on more recent large SEP events that have been recorded. The spectral shapes of large SEP events were modelled using the fitted Weibull distribution parameters provided by Kim et al. (2009) for the February 1956 event and Xapsos et al. (2000) for the August 1972 and October 1989 events. The integral fluence, Φ, above a threshold energy, E (in MeV), is described by the Weibull distribution using the exponential function $\Phi(>E) = \Phi_0 e^{-kE^\wedge\alpha}$ (taking units of cm^{-2}), which can be simply differentiated to $d\Phi/dE = \Phi_0 k\alpha E^{\alpha-1} e^{-kE^\wedge\alpha}$ (with units cm^{-2} MeV^{-1}). The parameters k and α define the spectral shape (the spectrum hardness) and Φ_0 determines the overall magnitude of the event. The parameters used here are listed in Table 1.

These three spectral shapes were selected because August 1972 was the highest fluence event of the space age, but has a relatively soft spectrum (low fluence of higher energy particles); February 1956 had a particularly hard spectrum; and October 1989 is intermediate between these but with high flux at low energies. The integral and differential fluence spectra of these selected representative spectra are plotted for comparison in Fig. 2 (left column).

Previous modelling efforts (Townsend et al., 2003, 2006, 2013; Stephens et al., 2005; Thomas et al., 2007, 2011; Rodger et al., 2008; Calisto et al., 2012, 2013; Norman et al., 2014) on the effects of an extreme, Carrington-like, SPE fitted their primary spectrum to the $E > 30$ MeV fluence (F30) estimated by McCracken et al. (2001a,b) from ice-core nitrate data. Ice core nitrate deposits have, however, now been shown to not offer a reliable index of energetic particle fluence hitting the upper atmosphere, and the nitrate spike seen in the ice core data presented by McCracken et al. (2001a,b) is most likely mis-dated and due to biomass burning plumes rather than SEP. (Wolff et al., 2012; Cliver and Dietrich, 2013; Kovaltsov et al., 2014). Instead, here we take more recent estimates on the energetic particle fluence of the Carrington and 775 AD events. Usoskin and Kovaltsov (2012) conclude that a F30 of $\sim 2 \times 10^{10}$ cm^{-2} is possible for the Carrington Event, but only if it had a soft spectrum like August 1972 rather than the February 1956 event, as otherwise it would have been evident in the Be-10 record. Cliver and Dietrich (2013) estimate an F30 for the Carrington Event of $\sim 1.1 \times 10^{10}$ cm^{-2}, with the $\pm 1\sigma$ uncertainty spanning a range of $\sim 10^9–10^{11}$ cm^{-2}. Thus we take a proton F30 of 2×10^{10} cm^{-2} as a reasonable worst-case fluence for a Carrington-like extreme SEP event. For the 775 AD event, the most extreme SPE recorded by cosmogenic C-14 in tree rings, Kovaltsov et al. (2014) give an estimated F200 of 8×10^9 cm^{-2}, and probably with a hard spectral shape like February 1956 (Usoskin et al., 2013). In this way, the soft August 1972 spectral shape is most likely for the 1859 Carrington Event and the hard February 1956 spectral shape for the 775 AD event, but for completeness here we model all three representative spectral shapes for both events as potential scenarios of a worst-case SEP event.

Table 1
Weibull parameters used to model the spectral shapes of the February 1956 (Kim et al., 2009), August 1972 and October 1989 (Xapsos et al., 2000) solar particle events (SPE), and the Φ_0 parameter after scaling each of these representative spectra to the estimated $E > 30$ MeV integral fluence of the Carrington Event (Usoskin and Kovaltsov, 2012; Cliver and Dietrich, 2013) and estimated $E > 200$ MeV integral fluence of the 775 AD extreme SPE (Kovaltsov et al., 2014).

SPE	k	α	Φ_0	Carrington model Φ_0	775 AD model Φ_0
23 February 1956	0.3758	0.4227	4.87×10^9	9.74×10^{10}	2.73×10^{11}
4 August 1972	0.0236	1.108	2.46×10^{10}	5.56×10^{10}	3.44×10^{13}
19 October 1989	2.115	0.2815	1.23×10^{12}	4.94×10^{12}	9.66×10^{13}

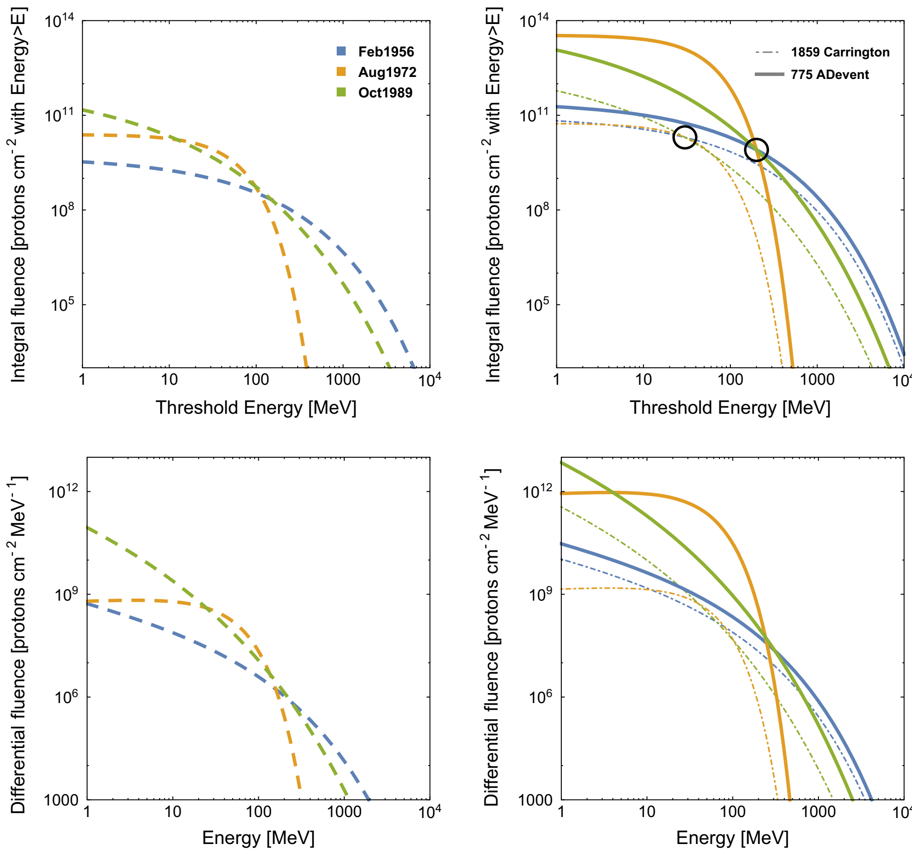

Fig. 2. Integral (top left panel) and differential (bottom left) fluence spectra for the three selected extreme solar energetic particle events of February 1956, August 1972 and October 1989, modelled using Weibull distributions (Xapsos et al., 2000; Kim et al., 2009). These representative spectral shapes are scaled-up (top right) to recreate the maximum estimated Carrington Event fluence (thin dot-dashed lines) of 2×10^{10} protons/cm^2 with energy >30 MeV (Usoskin and Kovaltsov, 2012; Cliver and Dietrich, 2013), and the 775 AD event (thick lines) of 8×10^9 protons/cm^2 with energy >200 MeV (Kovaltsov et al., 2014). The congruence of these scaled-up integral fluence spectra at F30 for the Carrington Event and F200 for the 775 AD SPE are indicated with black circles. The bottom right panel shows the differential spectra of the scaled-up solar particle events.

The three representative spectral shapes, February 1956, August 1972, and October 1989, are each scaled-up to fit the estimated fluences of the 1859 Carrington Event and 775 AD extreme SEP events; F30 = 2×10^{10} protons cm^{-2} and F200 = 8×10^9 protons cm^{-2}, respectively. The Φ_0 Weibull distribution parameters of these scaled-up model spectra are listed in the final two columns of Table 1.

The scaled-up integral spectra displayed in Fig. 2 (top right panel) shows the three spectral shapes used to model the 1859 Carrington Event and 775 AD event to intersect at a threshold energy of 30 MeV and 200 MeV, respectively, as indicated by black circles. This method of scaling-up specific recorded events of the past 60 years to attempt to reconstruct the spectrum of older, extreme SPEs such as the Carrington Event, has been employed by previous studies to determine the forcing of atmospheric chemistry and destruction of the stratospheric ozone shield (Rodger et al., 2008; Thomas et al., 2007, 2011; Calisto et al., 2012, 2013); for studying a worst-case scenario for solar particle events and irradiation of human crews or spacecraft components (Townsend et al., 2003, 2006, 2013; Stephens et al., 2005); or for calculating the dose delivered in the martian atmosphere and surface (Norman et al., 2014).

Finally, the modelled Carrington Event spectra at the Earth are scaled to the orbital distance (R) of Venus. Lario et al. (2006) report that the prior consensus for radial extrapolation from 1 AU of solar particle fluences was scaling by a factor of $R^{-2.5}$, and updated this on the basis of simultaneous observational data from multiple spacecraft on 72 SEP events to the range of $R^{-2.1}$ to $R^{-1.0}$. Here, we adopt an upper estimate to provide a worst-case scenario and scale the modelled Carrington Event spectra by $1/R^2$ to account for the higher solar particle fluence at 0.72 AU of Venus. Fig. 3 displays the differential fluence spectra (in units of protons cm^{-2} sr^{-1} MeV^{-1}) for the extreme SPEs, constructed as above, as they were passed to the venusian atmosphere particle transport model.

The flux profile of the Carrington Event has been modelled by Smart et al. (2006). In Fig. 4 we replot their results with a linear scale for the proton flux >30 MeV and as a function of time after the initial coronal mass ejection, showing the peak flux to arrive with the interplanetary shock around 17.5 h after the CME occurred. We integrated beneath this modelled flux profile to plot the cumulative flux (Fig. 4, inset) and thus calculate that 80% of the total SPE fluence is delivered in the time window ±10 h around the peak flux. We take this estimated 20 h window for the delivery of the majority of the Carrington Event fluence as a representative timescale for extreme SEP events for the sake of comparison with other fluences. Fig. 3 also shows the GCR fluence over 20 h, under both solar minimum and maximum conditions, as well as the CREME2009 'worst week' model for solar energetic protons over the same duration, all compared against the modelled extreme SPE spectra.

3. Results

Fig. 5 displays the calculated profiles of energy deposited into the venusian atmosphere (eV/cm^3) as a function of altitude for the three representative spectral shapes (February 1956: blue; August 1972: orange; October 1989: green) of the modelled 1859 Carrington Event (thin dot-dashed lines) and 775 AD extreme

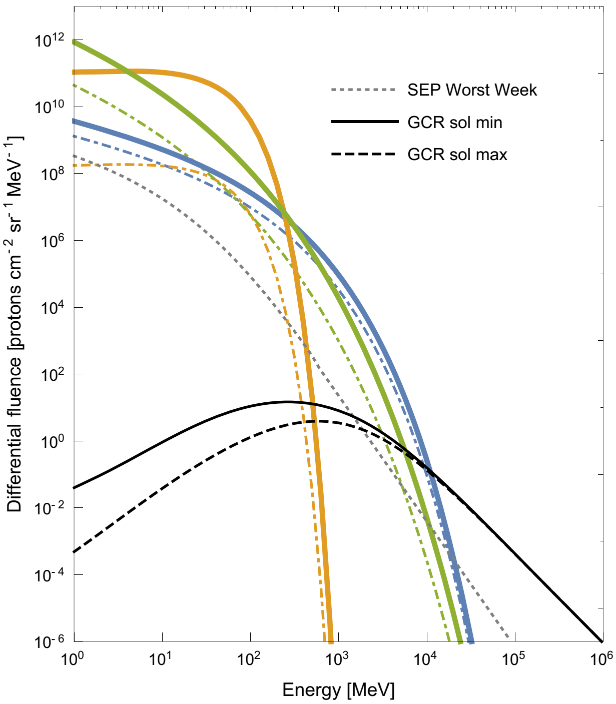

Fig. 3. Differential fluence spectra of the 1859 Carrington (thin dot-dashed lines) and 775 AD (thick lines) extreme SEP events, modelled with the three spectral shapes colour-coded as in Fig. 2 (purple: February 1956; orange: August 1972; green: October 1989), compared against the background proton fluence from galactic cosmic rays under both solar minimum (black solid) and maximum (black dashed) conditions, and the CREME2009 'worst week' solar energetic proton model (grey dotted), all over a 20 h duration. Although only proton spectra are shown in this figure for GCR, the full *Z* range of primary particles were modelled in Nordheim et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

SEP event (thick lines). The vertical extent of the potential habitable zone as we argue it here is shown by the light green region, with the thermal floor of the habitable zone at 65 °C (51 km altitude).

To compare against the total fluence of these extreme SPE models, the ionising radiation profile resulting from 20 h of flux – the estimated duration of the major flux of the Carrington Event (Fig. 4) – of the CREME2009 worst week SEP model (dashed grey) and galactic cosmic rays during both solar maximum (dashed black line) and solar minimum (solid black) are also shown from Nordheim et al. (2015). It is noted that extreme SPEs would be expected during solar maximum rather than solar minimum, and that the occurrence of a coronal mass ejection would cause a transient Forbush decrease in GCR flux, but the average solar maximum and minimum conditions are shown for comparison.

Colour-coded rings overlain onto the profiles indicate the peak energy deposition from each of these sources of primary particle radiation into the venusian atmosphere.

Fig. 6 plots the absorbed dose (Gray) as a function of altitude for the cosmic ray sources considered here. The same colour-coding system as Figs. 2, 3 and 5 is used for the extreme SPE models, and the CREME2009 worst week SEP model and GCR solar minimum and solar maximum fluxes summed over the estimated 20 h duration of the event major flux.

The radiation dose profiles in Fig. 6 will be examined closely in Section 4, but these calculated values can be used here to validate this modelling approach against previous studies. The GCR profiles plotted in Fig. 6 are for the estimated 20 h duration of the transient burst of the Carrington Event, but if scaled up to an entire year this model predicts a dose deposition of 0.065 Gy/year for GCR solar minimum conditions and 0.039 Gy/year for GCR solar maximum at a shielding depth of 16 g/cm^2 (74.85 km altitude in the venusian atmosphere). These figures compare well with unrelated studies modelling the GCR absorbed dose rate during solar minimum and maximum on the martian surface also beneath a shielding depth of 16 g/cm^2 of atmosphere (McKeever et al., 2003; Dartnell et al., 2007b; Banerjee and Dewangan, 2008) and subsequently corroborated by Mars Science Laboratory surface measurements (Hassler et al., 2014).

4. Discussion

The ionising radiation field created by cosmic rays is deleterious to the complex organic molecules of life (Baumstark-Khan and Facius, 2001; Dartnell, 2011a) and previous modelling studies have examined the implications of cosmic ray irradiation for life near the martian surface (Pavlov et al., 2002; Kminek et al., 2003; Dartnell et al., 2007a,b) or the natural transfer of viable microorganisms between planetary bodies by lithopanspermia within ejected meteorites (Clark et al., 1999; Mileikowsky et al., 2000). The current environmental conditions on Venus, created by a runaway greenhouse process, ensure that the surface is certainly incompatible with life, but there remains the possibility of a habitable zone within the cloud layers. This habitable zone is high within the atmosphere, with the top of the region at 62 km altitude receiving less than 200 g/cm^2 shielding depth, far less than the biosphere on the surface of the Earth beneath 1033 g/cm^2 (United States Committee on Extension to the Standard Atmosphere NOAA, 1976). Also, unlike Earth, Venus possesses no significant global magnetic field to provide protection against the charged

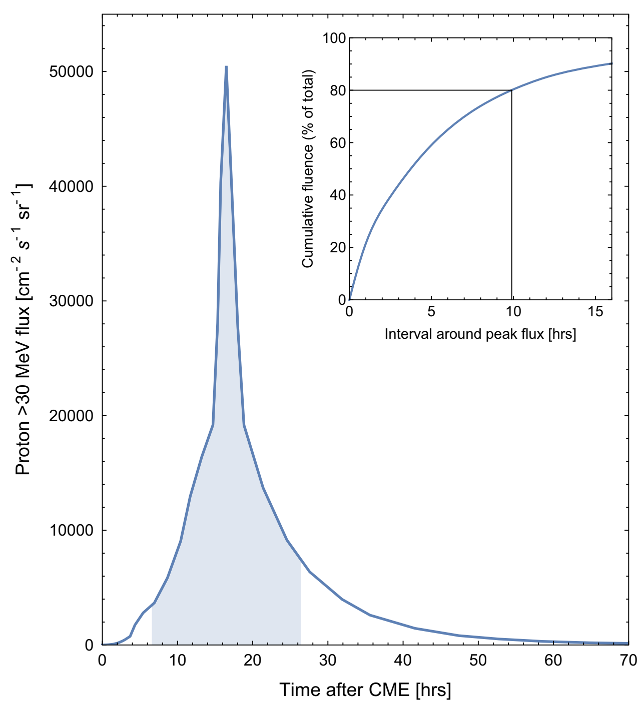

Fig. 4. The estimated flux profile of the Carrington Event for protons with energy greater than 30 MeV (Smart et al., 2006), replotted here with linear proton flux scale and as a function of time since the initial coronal mass ejection. The inset plot shows that 80% of the cumulative fluence is delivered ±10 h around the time of peak flux, as indicated with the light blue shading in the flux profile of the main figure, and so a 20 h duration for the delivery of the majority fluence of the Carrington Event is used here. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

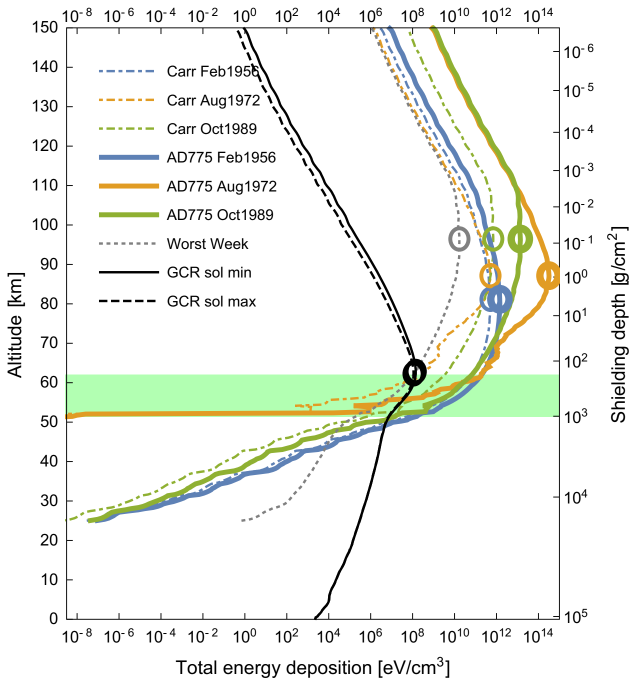

Fig. 5. Energy deposition from secondary particle cascades in the venusian atmosphere as a function of altitude. Profiles are shown for the 1859 Carrington (thin dot-dashed lines) and 775 AD (thick lines) extreme SEP events, modelled with the three spectral shapes colour-coded as in Figs. 2 and 3 (purple: February 1956; orange: August 1972; green: October 1989), along with the CREME2009 worst week SEP model (dashed grey) and GCR spectra during solar minimum (solid black) and solar maximum (dashed black) summed over the approximately 20 h duration of the major flux of extreme SPEs like the Carrington Event (Fig. 4). Peak energy deposition for each cosmic ray source is indicated with a colour-coded ring. The extent of the potential venusian habitable zone as we argue it is shown as the light green region, with the thermal floor at 65 °C (51 km altitude). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

particle radiation of GCR or SEP, and its orbit is closer to the source of the very high flux but transient solar particle events.

Furthermore, the powerful greenhouse effect of the dense venusian atmosphere means that the putative biosphere is tightly bounded by a thermal floor below which it cannot descend without being sterilized. The Earth's biosphere penetrates many kilometers into the oceans, or even rocky subsurface before the temperature gradient becomes limiting, and if any event were to sterilize the surface then deep life can subsequently reestablish surface ecosystems. The entirety of the potential venusian habitable zone may be exposed to astrophysical hazards, however, and there is no reservoir of life elsewhere that can recolonise afterwards.

Thus, the circumstances of the potential biosphere on Venus make it reasonable to ask whether cosmic radiation poses a hazard to life here. Here, we model the penetration of galactic cosmic rays through the venusian atmosphere to the potential aerial habitable zone, as well as episodic but extremely intense solar particle events that accelerate very large fluxes of charged particle radiation.

4.1. Defining the venusian aerial habitable zone

Before discussing these radiation modelling results, it is necessary to justify what we mean by the aerial habitable zone on Venus. Most simply, the potential habitable zone could be defined on the basis of the temperature limit alone for the survival of known terrestrial life or stability of organic molecules, defining upper and lower bounds by the thermal atmospheric profile. This is the approach taken by Cockell (1999), who argues for a thermal range of 0–150 °C. However, this is considering only one environmental extreme. Life in the clouds of Venus would need to tolerate not only the high temperatures, but also extremely low pH at the same time.

Thermoacidophiles, terrestrial organisms able to tolerate a combination of both high temperatures and low pH, are exclusively archaea, clustering into two phylogenetic groups: the Crenarchaeota (*Acidianus* and *Sulfolobus* genera) and the Euryarchaeota (*Thermoplasma*, *Picrophilus*, and *Ferroplasma* genera) (Angelov and Liebl, 2006). *Acidianus infernus* shows optimal growth at around 90 °C and grows anaerobically by sulphur-reduction with H_2, but will not grow below pH 0.5. (Segerer et al., 1986). On the other hand, *Ferroplasma acidarmanus*, isolated from acid main drainage, is capable of growth at pH 0, but not at temperatures much higher than 40 °C (Edwards et al., 2000). The concurrent challenges of high temperature and high acidity are especially aggressive to the stability of organic molecules and the survival of life, and thermoacidophiles appear to be constrained in what they can adapt to: the survival envelope of terrestrial extremophiles does not protrude far into the parameter space of high temperatures and high acidity (Dartnell, 2011b; Harrison et al., 2013).

The most extreme thermophilic hyperacidophilic organisms known are species of the *Picrophilus* genus. These archaea grow at pH 0 or even negative pH values, and indeed adaptation to conditions of 1.2 M sulphuric acid has been reported, but they are only moderately thermophilic and can tolerate pH 0 at a temperature no higher than 65 °C (Schleper et al., 1995, 1996; Fütterer et al., 2004; Thürmer et al., 2011). Survival at such low environmental pH,

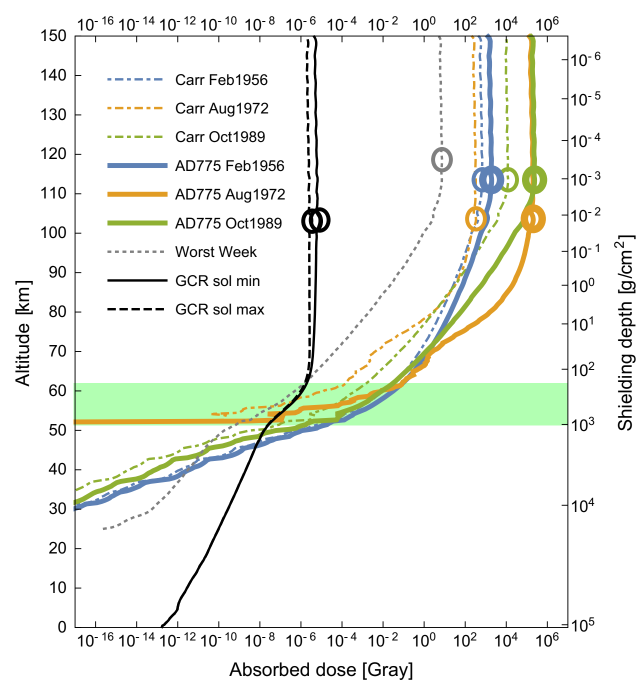

Fig. 6. Absorbed dose (Gray) as a function of altitude in the venusian atmosphere. Profiles are shown for the 1859 Carrington (thin dot-dashed lines) and 775 AD (thick lines) extreme SEP events, modelled with the three spectral shapes colour-coded as in Figs. 2 and 3 (purple: February 1956; orange: August 1972; green: October 1989), along with the CREME2009 worst week SEP model (dashed grey) and GCR spectra during solar minimum (solid black) and solar maximum (dashed black) summed over the approximately 20 h duration of the major flux of extreme SPEs like the Carrington Event (Fig. 4). Peak energy deposition for each cosmic ray source is indicated with a colour-coded ring. The extent of the potential venusian habitable zone as we argue it is shown as the light green region, with the thermal floor at 65 °C (51 km altitude). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

however, carries substantial energetic costs as the intracellular conditions must be maintained at a relatively more clement pH 4.6 by active proton pumping (Fütterer et al., 2004). *Picrophilus* is an obligately aerobic heterotroph, and so sulphur-metabolising chemoautotrophs relevant to the venusian atmosphere may struggle to harvest energy at a high enough rate to maintain internal cellular homeostasis and survive. Whilst photosynthesis is an option for biological energy in the clouds (perhaps employing sulphur: Schulze-Makuch et al., 2004, 2013), the maximum temperature for terrestrial photoautotrophs is around 75°, limited by the thermal degradation of chlorophyll (Rothschild and Mancinelli, 2001). For hyperacidophiles, there is no evidence for photosynthesis at ~pH 2 above 45 °C (Cox et al., 2011). It seems reasonable, then, to take the 65 °C survival maximum for hyperacidophilic terrestrial life as a conservative level for the thermal floor of the venusian aerial habitable zone. Thus, we define the potential venusian niche as between 62 km (−20 °C) and 51 km (65 °C) above the surface.

4.2. Ionising radiation environment of the aerial habitable zone

Fig. 5 shows that both solar minimum and solar maximum radiation profiles peak at around 62.5 km altitude (~175 g/cm^2 shielding depth): coinciding with the top of the potential venusian aerial habitable zone. Over the duration of the peak flux of an extreme SEP event, estimated here from the Carrington Event to be 20 h (Fig. 4), this equates to a total energy deposition of 1.1×10^8 eV/cm^3 of atmosphere at solar maximum, and slightly higher at 1.4×10^8 eV/cm^3 during solar minimum, due to the reduced modulation of the primary GCR spectra below around 1 GeV (Fig. 3).

As would be expected from their respective spectral hardness, Fig. 5 shows clearly that the extreme SEP events modelled on the hard-spectrum (appreciable flux at high energies) February 1956 SPE exhibits a peak in energy deposition deepest in the atmosphere (blue; 81 km; ~4 g/cm^2), with the peak resulting from the August 1972 spectral shape model occurring above that (orange; 87 km; ~0.9 g/cm^2), and the October 1989 spectral shape with the greatest flux at lower proton energies results in a peak highest above the venusian surface (green; 97 km; ~0.08 g/cm^2). As explained above, the soft August 1972 spectral shape is most likely for the 1859 Carrington Event (Usoskin and Kovaltsov, 2012) and the hard February 1956 spectral shape for the 775 AD event (Usoskin et al., 2013), but for completeness all three spectral shapes are shown for both events to account for the worst-case possible SEP event. Although the altitude of the peak varies between these three spectral shapes, for the modelled Carrington Event the energy deposition at these peaks is approximately the same: between 5.2×10^{11} eV/cm^3 (August 1972) and 7.0×10^{11} eV/cm^3 (October 1989). For the 775 AD extreme SEP event, the August 1972 spectral shape produces a peak energy deposition of 3.2×10^{14} eV/cm^3, the October 1989 spectral shape yields a maximum of 1.4×10^{13} eV/cm^3, and the February 1956 model a peak of 1.5×10^{12} but occurring deepest in the atmosphere due to the spectral hardness. Thus, the peak energy deposition from extreme solar particle events is three to six orders of magnitude greater than the peak background atmospheric ionisation from galactic cosmic rays, and occurs roughly 20–30 km higher in the atmosphere. For comparison, the peak energy deposition from 20 h of the CREME2009 worst week SEP model, occurs at approximately the same altitude (97 km) as the October 1989 models of extreme SEP event, but 40 times lower in energy deposition than the modelled Carrington Event, and 800 times lower than the AD 775 event.

While the modelled atmospheric energy deposition from galactic cosmic rays and typical (worst week) SEP as a function of altitude used here is from Nordheim et al. (2015), the energy deposition profiles produced from the modelled 1859 Carrington and 775 AD event spectra here are novel. Such modelling results provide crucial input for efforts to understand fundamental planetary atmospheric processes such as atmospheric chemistry, cloud microphysics and atmospheric electrical processes, as discussed more fully in Nordheim et al. (2015). For radiobiology studies, however, the more important metric for an ionising radiation field is the energy deposited per mass: the absorbed radiation dose in Grays, shown in Fig. 6.

Fig. 6 reveals the radiation dose profiles to be relatively flat high in the atmosphere. The thin upper atmosphere down to an altitude of 100 km provides a shielding depth of only 0.03 g/cm^2: equivalent to aluminium foil 0.1 mm thick. The peak dose occurs at an altitude of between 104 km and 114 km (0.0125–0.001 g/cm^2) for all of the extreme SPE models, due to the very high flux of low energy protons produced by these solar energetic particle events. The greatest dose delivered by the modelled Carrington Event is over 12 kGy, and 240 kGy for the 775 AD event, both at an altitude of 114 km with the October 1989 spectral shape, which has the greatest flux of lower energy protons (see Fig. 2). By comparison, during the 20 h approximate duration of an extreme SPE (Fig. 4) galactic cosmic rays would have delivered less than 1×10^{-5} Gy, but at a slightly lower altitude of around 100 km from the flux of higher energy primaries. The radiation dose profiles from galactic cosmic rays are flat above about 60 km because these more energetic particles penetrate with minimum energy losses (mainly to electronic ionisation) before nuclear interactions and fragmentation of the primary particles become more significant.

These peaks in cosmic radiation dose from extreme SPEs all occur high in the venusian atmosphere, where the conditions are too cold for life (and the ultraviolet environment is also limiting; see the companion paper *Constraints on a potential aerial biosphere on Venus: II. Solar ultraviolet radiation*; Patel et al., in preparation), and it is the radiation environment within the potential habitable zone (also indicated in Figs. 5 and 6) that is relevant.

Although the absorbed dose profile from an extreme SPE declines rapidly with increasing atmospheric density, the radiation threat is still much greater than the background GCR flux in the altitude range of the aerial habitable zone. The dose profile from the soft spectrum of the August 1972 model declines most substantially, but the enhanced radiation environment caused by the hard spectrum of the February 1956 event penetrates deep into the atmosphere. At the top of the potential venusian habitable zone, at 62 km altitude, the radiation dose from the February 1956 model of the Carrington Event delivers over 18,000 times greater radiation dose than the background from GCR, and around 50,000 times higher for the February 1956 and August 1979 spectral models of the 775 AD event. By the altitude of 51 km, the bottom of the aerial habitable zone that we argue on the basis of the 65 °C temperature limit, the February 1956 model of the Carrington Event still causes a 170-fold increase in ionising radiation relative to the GCR background, and a 470-fold increase for the same hard-spectrum model of the 775 AD event.

A Carrington-type event would clearly cause a transient but very substantial increase in the ionising radiation environment, relative to the background ionisation from the steady but low flux of galactic cosmic rays. But would this radiation pulse high in the venusian atmosphere pose a significant hazard to micro-organisms inhabiting the aerial biosphere?

Even at the top of the putative habitable zone (62 km altitude; 190 g/cm^2 shielding depth) and assuming the worst-case spectral shape (the February 1956 model) of the 775 AD extreme event, the total radiation dose delivered by an extreme sporadic SPE is 0.09 Gy. This absorbed dose calculation does not take into account that different types of ionising radiation (such as gamma rays or recoiling nuclear fragments) produce patterns of bimolecular damage more difficult for terrestrial cells to repair, and therefore more lethal. Human radiobiology studies often attempt to account for this variation by weighting the absorbed dose by an empirically-derived quality factor for different radiation types. These factors are dependent on aspects such as the organism, dose rate and irradiation conditions (Nelson, 2003), and so are not included here: the likely response of potential venusian cells is unknown. For an idea of the order of scale involved, however, the average quality factor measured for the Mars Science Laboratory landing site on the martian surface ($22\,g/cm^2$) is around 3 (Hassler et al., 2014), and will be less than this at $190\,g/cm^2$ depth in the venusian atmosphere. Thus, a worst-case scenario of an extreme SPE delivering an absorbed dose of 0.09 Gy at the top of the venusian habitable zone is reasonable.

This would not pose a significant survival hazard for even radiation-sensitive microorganisms. For example, *Shewanella oneidensis* accumulates high intracellular iron concentrations and is radiation-sensitive, but still exhibits 10% population survival after a dose of 70 Gy (the D_{10} value). Sterilising doses are approached higher up in the venusian atmosphere: the August 1972 modelled 775 AD event delivers a radiation dose of over 2 kGy at 80 km altitude, but if any cells were to have been lofted this high they would already be dormant due to the surrounding environmental conditions. Furthermore, terrestrial radiation-resistant microbes such as the mesophilic *Deinococcus radiodurans* have a D_{10} survival value of over 10 kGy (Daly et al., 2004), and the most radiation resistant hyperthermophilic archaeon known, *Thermococcus gammatolerans*, has optimum growth at 88 °C and can resist 3 kGy without loss of population viability (Jolivet et al., 2003; Tapias et al., 2009; Zivanovic et al., 2009).

Whilst the greatly enhanced radiation flux from an extreme SPE may not pose a direct radiological hazard to potential life it does nonetheless create a severe ionisation of the upper atmosphere of Venus, and this could force atmospheric chemistry that may perturb a venusian high-altitude biosphere in other ways. Nordheim et al. (2015) offer results on the atmospheric ionisation from background GCR and transient SEP events, and the data provided in this present study can similarly be used in models on the atmospheric effects of an extreme solar particle event in terms of atmospheric chemistry, cloud microphysics or atmospheric electrical processes, in the same way the effects of a Carrington-type event on the terrestrial atmosphere have been considered (Reid et al., 1978; Jackman et al., 2000; Thomas et al., 2007; Rodger et al., 2008; Calisto et al., 2012, 2013).

4.3. Conclusions

In summary, we argue here for a more limited altitude range for the potential aerial ecosystem in the venusian atmosphere; the bottom of the habitable zone occurring at 51 km (65 °C) as defined by thermophilic-hyperacidophile organisms able to tolerate the combined hazards of high temperature and high acidity. This high-altitude thermal floor means that, unlike habitable rocky planets like Earth or Mars, the entirety of the potential venusian habitable zone may be exposed to astrophysical hazards, and if this narrow band is sterilised there is no reservoir of deeper life that can recolonise afterwards. We find here that, although sterilizing doses are delivered higher in the atmosphere, the direct ionising radiation flux from galactic cosmic rays or extreme solar particle events, such as the 1859 Carrington Event or 775 AD event, is unlikely to pose a significant hazard to potential venusian life, even at the top of the high altitude habitable zone. The companion paper to this, *Constraints on a potential aerial biosphere on Venus: II. Solar ultraviolet radiation*, models the penetration and scattering of solar UV through the venusian atmosphere to the cloud layers to assess the threat that it may pose to microbial life. Beyond explicitly modelling Venus, these twin papers are also applicable to terrestrial exoplanets on the inside edge of the circumstellar habitable zone, where the only ecological niche is high in the atmosphere.

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