Icarus 257 (2015) 396–405

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

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

Lewis R. Dartnell [a,*], Tom Andre Nordheim [b,c], Manish R. Patel [d,e], Jonathon P. Mason [d], Andrew J. Coates [b,c], Geraint H. Jones [b,c]

[a] Space Research Centre, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK
[b] Mullard Space Science Laboratory, University College London, Dorking, Surrey RH5 6NT, UK
[c] Centre for Planetary Sciences at UCL/Birkbeck, University College London, Gower Street, London WC1E 6BT, UK
[d] Department of Physical Sciences, The Open University, Milton Keynes, UK
[e] Space Science and Technology Department, STFC Rutherford Appleton Laboratory, Chilton, Oxfordshire OX11 0QX, UK

ARTICLE INFO

Article history:
Received 31 October 2014
Revised 10 April 2015
Accepted 7 May 2015
Available online 15 May 2015

Keywords:
Astrobiology
Cosmic rays
Exobiology
Venus
Venus, atmospheres

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

* Corresponding author.
E-mail address: lewis@lewisdartnell.com (L.R. Dartnell).

http://dx.doi.org/10.1016/j.icarus.2015.05.006
0019-1035/

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 ^{1}H, 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.