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The COSPAR planetary protection requirements for space missions to Venus

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A B S T R A C T

The Committee on Space Research's (COSPAR) Planetary Protection Policy states that all types of missions to Venus are classified as Category II, as the planet has significant research interest relative to the processes of chemical evolution and the origin of life, but there is only a remote chance that terrestrial contamination can proliferate and compromise future investigations. "Remote chance" essentially implies the absence of environments where terrestrial organisms could survive and replicate. Hence, Category II missions only require simplified planetary protection documentation, including a planetary protection plan that outlines the intended or potential impact targets, brief Pre- and Post-launch analyses detailing impact strategies, and a Post-encounter and End-of-Mission Report. These requirements were applied in previous missions and are foreseen for the numerous new international missions planned for the exploration of Venus, which include NASA's VERITAS and DAVINCI missions, and ESA's EnVision mission. There are also several proposed missions including India's Shukrayaan-1, and Russia's Venera-D. These multiple plans for spacecraft coincide with a recent interest within the scientific community regarding the cloud layers of Venus, which have been suggested by some to be habitable environments. The proposed, privately funded, MIT/Rocket Lab Venus Life Finder mission is specifically designed to assess the habitability of the Venusian clouds and to search for signs of life. It includes up to three atmospheric probes, the first one targeting a launch in 2023.

The COSPAR Panel on Planetary Protection evaluated scientific data that underpins the planetary protection requirements for Venus and the implications of this on the current policy. The Panel has done a thorough review of the current knowledge of the planet's conditions prevailing in the clouds. Based on the existing literature, we conclude that the environmental conditions within the Venusian clouds are orders of magnitude drier and more acidic than the tolerated survival limits of any

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known terrestrial extremophile organism. Because of this future orbital, landed or entry probe missions to Venus do not require extra planetary protection measures. This recommendation may be revised in the future if new observations or reanalysis of past data show any significant increment, of orders of magnitude, in the water content and the pH of the cloud layer.

1. Introduction

1.1. Historical perspective of Venus exploration

The exploration of Venus began in 1962 when the National Aeronautics and Space Administration (NASA) Mariner 2 spacecraft flew by the planet, providing a remote, 42-minute scan of the atmosphere and surface (Fig. 1- left) (Sonett 1963). Since this initial fly-by, there have been several missions, such as the Soviet Union's Venera 7 and 8 landers, in 1970 and 1972, respectively, demonstrating the first successful landings on another planet (Avduevsky et al., 1971; Marov et al., 1973). This was followed in 1975 by Venera 9, an orbiter and a lander that provided the first surface images of Venus. In 1981, the Venera 13 probe returned the first coloured images of the surface of Venus. The last landed spacecraft on Venus was the Soviet Vega 2 mission in 1985, which, due to the extremely high surface temperatures and pressures, survived only 52 min (Bertaux et al., 1996).

In 1990, NASA's Magellan spacecraft used radar to provide a detailed view of the planet's surface (Pettengill et al., 1991). Venus Express, a European Space Agency (ESA) mission, studied the planet from 2006 to 2014 (Svedhem et al., 2009), and the Akatsuki Venus Climate orbiter, a Japan Aerospace Exploration Agency (JAXA) mission, has successfully orbited Venus since 2016 (Fukuya et al., 2021; Fig. 1- right). NASA's Parker Solar Probe has recently made multiple flybys of Venus, including the closest approach in July 2020, passing just 833 km above the surface (Wood et al., 2022). During this close encounter, Parker flew through the upper atmosphere and detected a natural radio signal providing the first direct measurement of the atmosphere in almost 30 years. These observations demonstrated that Venus' upper atmosphere (the ionosphere) changes its density over the 11-year solar cycle (Collinson et al., 2018).

More recently, three new missions were approved and are currently being developed for launch towards the end of the current decade to operate in the early 2030s:

1) NASA's VERITAS orbiter mission (Smrekar et al., 2020) will study Venus' geologic evolution and processes such as tectonic style and ongoing volcanism. This Discovery class mission is a partnership between scientists and engineers at NASA/JPL with the German (DLR), Italian (ASI) and French Space Agencies (CNES). VERITAS is expected to launch and reach Venus as early as 2031. The mission will acquire radar and infrared measurements, combined with the gravity science data from telecom tracking, all within a low altitude orbit of less than 250 km, passing over the poles and allowing global observations. VERITAS also will create the first near-global map of rock types, making it the first mission to reveal the composition and distribution of Venus' surface materials. The nominal mission is expected to be four Venus days long, i.e., 2.7 Earth years (Hensley et al., 2022).
2) NASA's DAVINCI is expected to launch in 2029, have two flybys in 2030 and drop a probe down to the surface in 2031, which will take an hour to descend, making thousands of measurements and eventually taking close-up images of the surface (Arney et al., 2021). The *in-situ* measurements during the descent phase will focus on characterizing the chemical and isotopic composition of the Venus atmosphere. The near-infrared (NIR) descent imaging of the surface will complement the remote flyby observations of the dynamic atmosphere, cloud deck, and surface NIR emissivity (Garvin et al., 2022). With its entry probe, the mission will provide the first unique characterization of the deep atmosphere environment and chemistry, including trace gases, key stable isotopes, oxygen fugacity, constraints on local rock compositions, and topography of a tessera.

Fig. 1. (Left) Image Credit: NASA/Mariner 10 1974. Mosaic image of the thick cloud coverage of Venus. Only through radar mapping is the surface revealed. (Right) Image Credit: JAXA, ISAS, DARTS; Processing & Copyright: Damia Bouic. Cloud layer of Venus at night in the infrared as seen by Venus Climate Orbiter, Akatsuki in 2015.

DAVINCI aims to make improved measurements of the D/H ratio to resolve the different hypotheses of the past water cycles and the history of water loss.

3) ESA will launch the orbiter EnVision in 2031 (Ghail et al., 2019) and will acquire high-resolution optical, spectral (in the ultraviolet and near and shortwave infrared), and radar images of the planet's surface and subsurface (the radar will penetrate the upper 100 m to 1 km of the planet's surface) to determine the nature and current state of geological activity, the evolution of the surface topography, and its relationship with the atmosphere. In addition, the Radio Science investigation will allow for the sounding of the structure and composition of the middle atmosphere, and the cloud layer, in occultation. The spacecraft telemetry tracking will observe the planet's gravity field with a spatial resolution of ~170 km (Rosenblatt et al., 2021). EnVision will operate at about 500 km above Venus' surface, in a polar orbit, making thousands of passes over a period of six Venus sidereal days (four Earth years).

Other space agencies have also announced new possible missions to Venus: Venera-D is a proposed Roscosmos Russian orbiter and lander mission that includes a long-duration lander to be launched in 2029 (Zasova et al., 2019). The India Space Research Organization (ISRO) is planning the first mission to Venus: Shukrayaan orbiter -with two possible launch windows, one in December of 2024 and the next similar launch window in 2031- to study the surface and the atmosphere of Venus over four years (Sundarajan 2021). The spacecraft will carry both Indian and international science instruments.

Other mission concepts are being considered, such as the Venus Life Finder (VLF). This mission consists of a series of up to three atmospheric probes designed to assess the habitability of the Venusian clouds and to search for signs of life there (Seager et al., 2022). The first mission is targeted for launch as early as 2023 as VLF's team has contracted with Rocketlab to send a probe to the Venusian atmosphere using a 2023 launch window. This first mission will place a probe to collect data in the upper atmosphere of the clouds, where the climate is most hospitable, for approximately three minutes. A backup launch window is available in January 2025 (French et al., 2022). The main mission, which targets a 2026 launch opportunity, would consist of a super-pressure variable float altitude balloon to operate within the cloud layers throughout the altitudes of 48 to 60 km (Agrawal et al., 2022). The proposed mission could help elucidate the limits of habitability and the role of unknown chemistry or possibly life itself in the Venus atmosphere. The instrumentation within the balloon would be designed to -among others- determine certain parameters that are critical for habitability such as the amount of water vapor in the cloud layers, the acidity of the cloud droplets, the temperature and pressure (Agrawal et al., 2022; Buchanan et al., 2022). This mission has been proposed by a consortium led by the Massachusetts Institute of Technology (MIT), including private sponsors, which demonstrates the potential future interest of Venus exploration for commercial and privately funded initiatives.

The whole suite of near-term missions to Venus demonstrates the increasing, international, interest in the study of our sister planet and therefore the need to ensure that this exploration does not jeopardise future scientific investigations.

1.2. Current understanding of the Venus environment

The atmosphere of Venus consists mostly of carbon dioxide (CO_2) with opaque clouds of sulfuric acid aerosols, making optical orbital or Earth based observations of the surface impossible. The Venus International Reference Atmosphere (VIRA) or COSPAR model was compiled in 1982–1983 and was based on data from the Pioneer Venus Orbiter and Probe, as well as the Venera probe (Kliore et al., 1985). Since then, the model has been updated using space missions' data and Earth-based observations (Moroz and Zasova 1997). *In-situ* and observational data have been used to estimate the average composition of the Venus's atmosphere as 96.5% CO_2, 3.5% N_2, 150 ppm SO_2, 70 ppm Ar, 20 ppm H_2O, 17 ppm CO, 12 ppm He and 7 ppm Ne (Williams 2022).

However, at the surface there are some of the most extreme conditions observed in the Solar System, with a surface pressure of 93 bar that renders its CO_2-dominated atmosphere in a supercritical fluid state. Recent experiments on supercritical fluids suggest that with this high pressure and density, a density-driven separation of N_2 from CO_2 should occur at the near surface (Lebonnois and Schubert, 2017). The atmosphere is hottest at the surface, with an averaged surface temperature of 723 K (450 °C), above which temperature decreases with altitude at nearly the dry adiabatic lapse rate of ~10 K/km. In the region of roughly 48 to 70 km there are three cloud layers formed by aerosols of sulfuric acid (Zhang et al., 2012; Arney et al., 2014; Krasnopolsky et al. 2015). The clouds are rather featureless in visible light, but show structure in other wavelengths such as infrared or ultraviolet, see Fig. 2.

From an altitude of 120–150 km, in the thermosphere, the temperature increases with altitude, due to ionization and dissociation caused by solar radiation (Taylor et al., 2018). Venus lacks a magnetic field, but the ionosphere (formed by ionized molecules produced by interaction with the ultraviolet radiation from the Sun) interacts with the magnetic field of the Sun. This field, which is carried by the solar wind, induces a weak magnetic field that envelops the planet and extends from Venus, outward, into the solar system. Lighter gases, such as water vapour, are continuously blown away by the solar wind through the induced magnetotail. In the water vapor of the Venusian atmosphere, the ratio of deuterium to hydrogen (D/H) is ~157 times larger than D/H ~ 1.5×10^{-4} for Earth (Donahue et al., 1982; Bézard and de Bergh 2007) which may imply that large amounts of water vapor have escaped from the atmosphere.

A Venus year takes only 225 Earth days, whereas a Venus day is

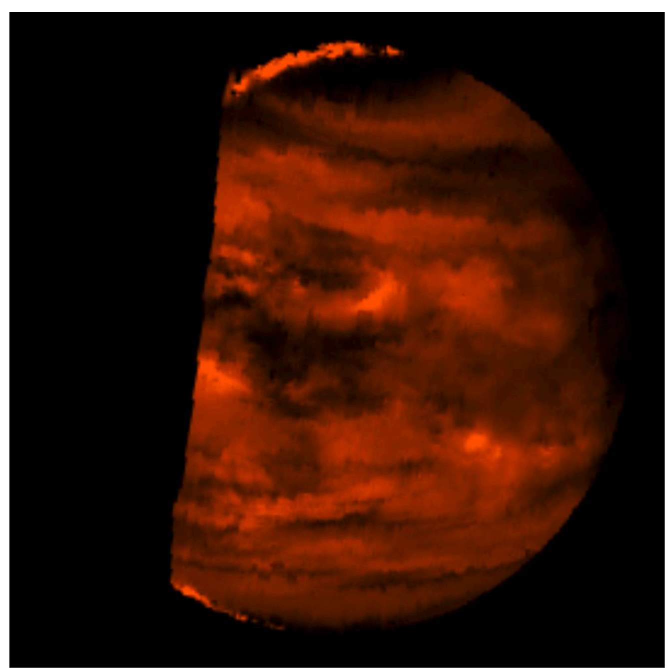

Fig. 2. This false-color image is a near-infrared (2.3 μm) map of lower-level clouds on the night side of Venus, obtained by the Near Infrared Mapping Spectrometer aboard the Galileo spacecraft as it approached the planet's night side on February 10, 1990. Bright slivers of sunlit high clouds are visible on the limb at top and bottom. The map shows the turbulent, cloudy middle atmosphere some 50 to 55 km above the surface, 10 to 16 km below the visible cloud tops. The red color represents the radiant heat from the lower atmosphere (about 200 °C) shining through the sulfuric acid clouds, which appear as much as 10 times darker than the bright gaps between clouds. This cloud layer is at about −30 °C, at a pressure of about one-half Earth's surface atmospheric pressure. Credit: NASA/JPL Galileo.

about 243 days long making the atmospheric dynamics very different from that of Earth. The upper layer of the troposphere exhibits a phenomenon of super-rotation, in which the atmosphere circles the planet in just four Earth days with winds blowing at 350 km/h or more (Svedhem et al., 2007). The gases of the thermosphere also show strong circulation as they are heated and partially ionized by sunlight, in the sunlit hemisphere, and migrate to the dark hemisphere where they recombine and descend (Bertaux et al., 2007a).

1.3. Astrobiological interest in Venus

Some models suggest that Venus may have been habitable in the distant past, containing liquid water at the surface (Donahue and Hodges 1992; Way and Del Genio 2020). However, other models suggest that evolution without liquid water could have existed (Krissansen-Totton et al., 2021). While the present-day surface of Venus is too hot to be habitable, it has been postulated that the cloud layer with lower temperatures may be favourable to life, as initially hypothesized by Morowitz and Sagan (1967). This subject has been extensively explored over the years (Cockell 1999; Grinspoon 1997; Limaye et al., 2018; Schulze-Makuch and Irwin 2002; Schulze-Makuch et al., 2004; Way et al., 2016).

This has recently been further debated by the claim of potential phosphine detection within the cloud layer, which on Earth is produced as a byproduct of life or by industrial processes (Greaves et al., 2021). These observations have been controversial, and several rebuttals and reanalysis have been published since this initial discovery (Akins et al., 2021; Cordiner et al., 2022; Encrenaz et al., 2020; Greaves et al., 2022; Villanueva et al., 2021).

Although the average composition has been estimated (as discussed in Section 1.2) the details of the specific composition of the clouds are still under debate. Some recent models have postulated that ammonia salts are present (possibly produced by biological activity), which could render the clouds less acid and thus more habitable (Bains et al., 2021). As a result, the astrobiological interest of Venus and the diversity of open research questions has been reassessed by the scientific community (Limaye et al., 2021).

In view of this renewed interest, the COSPAR Panel on Planetary Protection has re-evaluated the scientific data that underpins the planetary protection requirements for Venus. Here, we discuss the present-day COSPAR Planetary Protection Policy (Section 2); the environmental constraints, as summarized in refereed publications that are based on actual observations and well validated models (Section 3) and the recommendation of the Panel (Section 4).

2. Current COSPAR planetary policy categorization for Venus

The international standards for planetary protection have been developed through consultation and discussion between the Committee on Space Research's (COSPAR) Panel on Planetary Protection (hereafter referred to as the Panel) and the scientific community and the national space agencies (COSPAR 2018). The resulting COSPAR Planetary Protection Policy (hereafter referred to as "the Policy") has a voluntary non-legally binding status, which allows for the Policy to be updated as scientific understanding in peer-reviewed studies develops. It is the only international standard on planetary protection for reference of space-faring nations to guide compliance with Article IX of the United Nations Outer Space Treaty of 1967 that stipulates against harmful contamination (Coustenis et al., 2019a, b). Under Article VI, States Parties to the Outer Space Treaty bear international responsibility for national activities (both governmental agencies and non-governmental entities) in outer space, including the moon and other celestial bodies (UNOOSA, 2002). It is the prerogative of governments to determine how to implement the rights and obligations under the Treaty and how to authorize and supervise activities of non-governmental entities under their jurisdiction.

The primary aim of the COSPAR Planetary Protection Policy is twofold (COSPAR 2021), to ensure that:

1) For outbound missions, future scientific investigations of possible extra-terrestrial life forms, precursors, and remnants are not jeopardised (i.e. avoidance of forward contamination).
2) For sample return missions, Earth is protected from the potential hazard posed by extra-terrestrial matter carried by spacecraft returning from an interplanetary mission (i.e. avoidance of backward contamination).

The Policy provides guidance on how to minimize the risk of terrestrial microorganisms surviving and replicating on the target body, which may compromise future astrobiological research (see Fisk et al., 2021 for details). Venus is currently listed as a Category II body with regards to forward contamination, which applies to all types of missions (gravity assist, orbiter, lander), where there is significant interest in the target body relative to the process of chemical evolution and the origin of life but where there is only a remote chance that contamination could compromise future investigations. "Remote chance" implies, in this context, the absence of environments where terrestrial organisms could survive and replicate, or a very low likelihood of transfer to environments where terrestrial organisms could survive and replicate.

For sample return missions, Venus is classified as Category V unrestricted Earth return, with the outbound part of the mission being in Category II. In this paper, we focus only on revisiting the assignment as Category II for forward contamination as there is no currently foreseen mission planning a sample return.

3. New considerations of the planetary protection requirements for Venus

The Panel has evaluated published research relating to the Venus atmospheric and surface environment. Focus has been placed on temperature (T) and water activity (Aw), as these two parameters have been shown to be key limits to survival and replication of Earth life (Rummel et al., 2014; Kminek et al., 2010). The Panel has also considered the existing atmospheric models for ionizing and UV radiation, and acidity.

3.1. Water activity and temperature

Through an extensive literature review (Kminek et al., 2010; Rummel et al., 2014 and references within), limits of life on Earth with regards to temperature and water activity have been established (with appropriate buffer). Studies were performed specifically for the establishment of "special regions" on Mars (areas that have a higher probability of being habitable). No evidence of either cell division or metabolism in terrestrial organisms at water activity (Aw) less than 0.60 was found in the scientific literature in the COSPAR planetary protection review performed in 2014 (Rummel et al., 2014). An extra safety margin of 0.1 was added, and the special regions limits were set at 0.5. It should be noted that, more recently, Stevenson et al. (2017b) reported a record for replication (i.e., cell proliferation or division), which is the germination of the fungus *Aspergillus penicillioides* at an Aw of 0.585, which lies within the established limits provided by Rummel et al. (2014). The present lower temperature limit for cell division is -18 °C as reported by Collins and Buick (1989) in experiments with the psychrotrophic pink yeast *Rhodotorula glutinis.* Therefore, for Special Regions on Mars, the lower limit for water activity was set to 0.5 and for temperature: -28 °C (Olsson-Francis et al. 2022; Benison et al. 2021; Hallsworth et al. 2021a, Stevenson et al., 2017a). If either of these limits is not met, a region is deemed uninhabitable for terrestrial microbes, regardless of other environmental parameters (radiation, nutrients, pH, etc.). These numbers have also recently been included in the Policy as general limits for replication of terrestrial organisms that can be applied to other Solar System bodies (see subsection 5 "Environmental conditions for replication” in the Annex “Implementation guidelines and category specifications for individual target bodies” of COSPAR 2020). The Panel regularly reviews the literature to evaluate whether these limits need to be revisited.

Note that we focus on replication and survival rather than just survival because cell replication would be required to cause measurable contamination on another Solar System body. There can be no replication without survival, and no contamination without replication. It must be clarified that the tolerated temperature and water activity ranges for cell survival, which can happen in a dormant or anhydrobiosis state, are much broader (T within −263 °C to +122 °C and Aw within 0 to 1) than the limits for active metabolism and replication (see Table 4 in Rettberg et al., 2019). However, within this work we focus on the environmental limits for replication, which are narrower and pose a harder limit for life.

The surface of present-day Venus is inhospitable with surface temperatures approaching 450 °C (Dartnell et al., 2015), whereas the upper temperature limit for life on Earth is between 120–130 °C (Merino et al., 2019). Only the cloud layer has temperatures that are acceptable for terrestrial replication. A thermal habitable zone is predicted to exist at an altitude range of 62 to 48 km, above which temperatures drop below the lower thermal limit of cell replication and below which temperatures exceed the evaporation temperature (Patel et al., 2022) and the water in the Venusian clouds is primarily within H_2SO_4-bearing aerosol droplets (Young, 1974).

Hallsworth et al. (2021b) computed the water activity within the clouds of Venus from observations of temperature and water-vapour abundance and found Aw<0.004 for the sulfuric acid droplets which constitute the bulk of Venus clouds. Pressure and temperature values were based on Venus’s entry probe measurements. The water-vapour mixing ratio was obtained from the parametrization of Gao et al. (2014), which is based on observations from Bertaux et al. (2007b) using the SPICAM on Venus Express (2007) and the Venera 11 (1978), 13 and 14 missions (1982) (Ignatiev et al., 1997). The derived sulfuric acid concentration that corresponds to this water activity according to models of H_2SO_4—H_2O mixtures are consistent with published observations and models of acid content on the clouds of Venus (Zhang et al., 2012; Arney et al., 2014; Krasnopolsky et al. 2015). Fig. 3 shows a summary of the environmental conditions of the cloud layer as described by Hallsworth et al. (2021b).

Our review shows that although the temperature range may be adequate for life, the water activity level of the cloud layer (Aw<0.004) is two orders of magnitude lower than the most extreme value for replication tolerated by life on Earth (Aw = 0.585) (Hallsworth et al., 2021b).

3.2. Cloud layer acidity

Earlier theoretical assessments of the pH level in Venus’s cloud droplets indicated that it could range between pH 0.5 in the upper clouds and pH −1.3 in the lower cloud region (Grinspoon and Bullock, 2007), which compared favourably with the known survivability of terrestrial acidophiles. For instance, *Picrophilus torridus* can replicate at pH −0.06 at 60 °C (Schleper et al., 1995). However, more recently, when employing the Hammett acidity value, appropriate for very concentrated solutions of sulphuric acid, Seager et al. (2021) calculated the Hammet Acidity of the Venusian clouds to be about −11.5, which is far below the tolerated pH limit for life. Seager et al. explain that the conventional scale of “pH” ($-\log_{10}[H^+]$) only applies to dilute aqueous solutions. In the case of concentrated acids such as sulfuric acid, then the Hammett Acidity must be used. For instance, a concentration of 85%

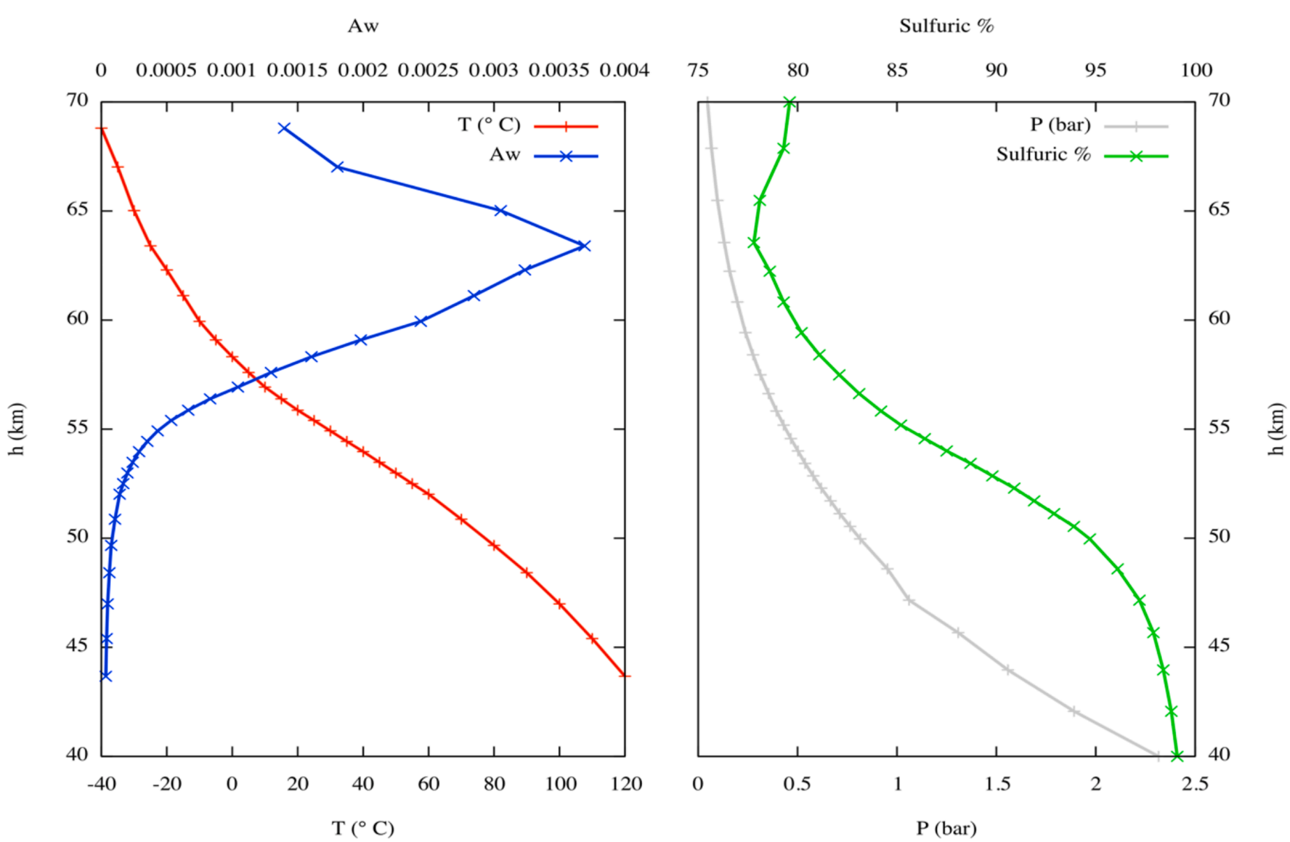

Fig. 3. Representative Venus vertical profile of the temperature (T), water activity (Aw), pressure (P) and sulfuric acid concentration in% from 40 to 70 km above the surface. The cloud layer has a temperature range below the upper-temperature limit for life on Earth, around 120–130 °C, and above the lower limit, with buffer, for temperature: −28 °C. However, the water activity remains Aw<0.004, which is well below the lower limit for life of 0.5. Data was taken from Hallsworth et al. (2021b).

sulfuric acid such as the one of the cloud layers, see Fig. 3, has a Hammett Acidity of about −11.5 (Yates et al., 1964).

Since acidity is expressed in a log scale, the clouds of Venus are $>10^{11}$ times as acidic as the Dallol geothermal area, which are deemed one of the most extreme environments on Earth (Kotopoulou et al., 2019; Cavalazzi et al., 2019). In the words of Seager et al. (2021) "*There is no Earth-based analogy of life adapting to or living in sulfuric acid concentrations as high as those in Venusian cloud droplets.*" However, Bains et al. (2021), have postulated that ammonia, a component that has been tentatively detected in the clouds by Venera 8 and Pioneer Venus probes, may effectively neutralize locally the acid in pockets of cloud droplets to approximately pH 1, which is plausible for terrestrial acidophilic microorganisms to grow. However, future data would be required to confirm the detection of ammonia and verify the hypothesized presence of ammonium sulfite salts in the clouds.

In summary, according to the recent literature, our review concludes that the environmental conditions within the Venusian clouds are orders of magnitude more acidic than any natural environment on Earth, and beyond the survival limits of any known terrestrial extremophile organism (Seager et al., 2021).

3.3. Radiation environment at the cloud layer

Even though the flux of ionizing radiation can be sterilizing high in the Venusian atmosphere, the total dose delivered at the top of the cloud layer by a worst-case solar particle event is 0.09 Gy, which is not likely to present a significant survival challenge for life (Dartnell et al., 2015). However, the extreme ionization could force atmospheric chemistry in ways that are not familiar to us on Earth (Dartnell et al., 2015). At the top of the thermal aerial habitable zone (62 km) the incoming solar irradiance creates a severely challenging UV environment, with extremophiles such as *Deinococcus radiodurans* expected to be able to endure these UV conditions for approximately 80 s. A potential thermal and UV and VIS radiation habitable zone extends from 59 to 48 km on Venus (Patel et al., 2022).

In summary, according to the recent literature, our review concludes that the environmental radiation at the cloud layer does not pose a hard limit for life as we know on Earth.

4. Conclusions and COSPAR assessment

Based on the existing measurements reported in the literature, we can conceive of no realistic environment within the Venusian clouds where terrestrial life could replicate. Even where the atmospheric temperatures are mild enough to support terrestrial life, the extremely low water activity would prevent replication. In addition, the high concentration of sulfuric acid creates an environment that is 11 orders of magnitude more acid than the most extreme case of acid tolerance known from terrestrial life forms.

The most recent publications suggest that the environmental conditions within the Venusian clouds are orders of magnitude more acidic and arid than the most extreme conditions tolerated by terrestrial extremophiles. Therefore, the COSPAR Panel on Planetary Protection concludes that without new measurements demonstrating water activity > 0.5, Venus clouds are not a concern for planetary protection. They are, of course extremely interesting for planetary science relative to the process of chemical evolution and the origin of life, but, based on our current understanding of life on Earth, there is only an extremely remote chance that terrestrial contamination carried by spacecraft could compromise future investigations. This implies that any mission to Venus should remain as Category II.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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