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How Habitable are the Clouds of Venus?
The Ultraviolet Habitable Zone over Time

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Abstract

The surface of Venus can be counted as one of the most inhospitable environments found among any of the terrestrial planets due to its extreme temperatures (737 K) and high pressures (92 bars). Not every environment on Earth's sister planet is as hostile as the surface however. The lower and middle cloud layers (~ 47.5 km to ~ 56.5 km) offer significantly more clement conditions with pressures around 1 bar and temperatures ranging from 80 °C to -20 °C - both well within the tolerable limits of life on Earth. To further investigate the potential habitability of these cloud layers both in the present day and in the past I analyse the fluxes of UV-A, -B and -C radiation arriving at the top of the cloud layers at 65 km and compare them to the lethal UV dosage of various species of bacteria, as UV (especially UV-C and to a lesser extent UV-B) radiation is highly adept at damaging DNA. I do this by conducting a set of simulations with the Kompot code with varying solar spectra corresponding to different points in time between the present day and 3.2 Gyr in the past. To make sure that these simulations are accurate I first conduct a parametric study to find the best fitting values for the three free eddy diffusion parameters and compare the outcomes to measurements from the SOIR instrument of the Venus Express spacecraft, resulting in $K_{eddy,max} = 6.0 \times 10^9 \text{ cm}^2\text{s}^{-1}$, $A = 1.0 \times 10^7$ and $B = -0.1$ being chosen as the best fitting values. My results show that Venus exobase height increases the further back in time the simulations go, which is a consequence of the higher solar XUV (X-ray and ultraviolet) flux in the past. The incident UV-A, -B and -C fluxes on Venus all exhibit similar temporal behaviour to each other as they each steadily increase from their lowest values 3.2 Gyr ago to their highest values in the present day. The fluxes of UV-A and UV-B show no significant decrease between the top of the atmosphere and the top of the cloud layers at 65 km. UV-C meanwhile exhibits a moderate reduction by $\sim 10\%$ between the two heights. None of the three spectral ranges show a significant temporal dependence of their respective flux-difference (or lack thereof) between the top of the atmosphere and 65 km, indicating that Venus does not currently possess and in all likelihood has not at any point in the past 3.2 Gyr possessed an ozone layer (or similar shielding mechanism) that could have mitigated the incoming UV radiation. As such the high UV-C flux at 65 km makes the existence of a biosphere at these altitudes rather unlikely. *Deinococcus radiodurans*, a model organism for high radiation tolerance, for example would experience a 99% reduction in population after only 227 seconds under present-day levels of UV-C radiation. It has to be noted, however, that Venus does possess a mechanism that significantly mitigates the incoming UV flux in the form of the "mysterious UV-blue absorber" (MUBA). The MUBA is located within the upper cloud layer of Venus and thus not accounted for in my simulations. As such my results are not conclusive enough as to eliminate the possibility of Venusian life in the lower and middle cloud layers.

Kurzfassung

Die Oberfläche der Venus stellt aufgrund ihrer extremen Temperaturen (737 K) und ihres hohen Drucks (92 bar) eine extrem lebensfeindliche Umgebung dar. Allerdings sind die Bedingungen auf ihr nicht überall so unwirtlich wie auf der Oberfläche. Mit Druckwerten von etwa 1 bar und Temperaturen zwischen 80 °C und −20 °C herrschen in den unteren und mittleren Wolkenschichten ($\sim 47,5$ km bis $\sim 56,5$ km) deutlich mildere Bedingungen vor, welche innerhalb der für Leben auf der Erde tolerierbaren Grenzen liegen. Da UV-Strahlung (insbesondere UV-C und in geringerem Maße UV-B) DNA besonders effektiv schädigen kann, analysiere ich die Flüsse von UV-A-, UV-B- und UV-C-Strahlung, die das obere Ende der Wolkenschichten in einer Höhe von 65 km aktuell erreichen und in der Vergangenheit erreicht haben. Um die potenzielle Habitabilität dieser Wolkenschichten näher zu untersuchen vergleiche ich diese Strahlungsflüsse mit den tödlichen Strahlungsdosen mehrerer Bakterienspezies. Hierzu führe ich mit dem Code Kompot eine Reihe von Simulationen durch, wobei unterschiedliche Sonnenspektren verwendet werden, die verschiedenen Zeitpunkten zwischen der Gegenwart und 3,2 Ga in der Vergangenheit entsprechen. Um sicherzustellen, dass diese Simulationen möglichst genau sind, führe ich zunächst eine parametrische Studie durch, um die bestpassenden Werte für die drei freien Parameter der turbulenten Diffusion (Eddy-Diffusion) zu bestimmen. Anschließend vergleiche ich die Ergebnisse mit Messungen des SOIR-Instruments der Raumsonde Venus Express. Daraus ergeben sich $K_{\text{eddy,max}} = 6,0 \times 10^9 \text{ cm}^2\text{s}^{-1}$, $A = 1,0 \times 10^7$ und $B = -0,1$ als die am besten passenden Parameterwerte.

Meine Ergebnisse zeigen, dass die Exobasenhöhe der Venus zunimmt, je weiter die Simulationen in die Vergangenheit zurückreichen. Dies ist eine Folge des höheren solaren XUV-Flusses (Röntgen- und Ultraviolettstrahlung) in der Vergangenheit. Die einfallenden UV-A-, UV-B- und UV-C-Flüsse auf der Venus weisen alle ein ähnliches zeitliches Verhalten auf: Sie steigen jeweils stetig von ihren niedrigsten Werten vor 3,2Ga auf ihre höchsten Werte in der Gegenwart an. Die Strahlungsflüsse von UV-A und UV-B zeigen zwischen der Obergrenze der Atmosphäre und der Obergrenze der Wolkenschichten in 65 km Höhe keine signifikante Abnahme. UV-C hingegen weist zwischen diesen beiden Höhen einen moderaten Rückgang von etwa 10% auf. Keiner der drei Spektralbereiche zeigt eine signifikante zeitliche Abhängigkeit der jeweiligen Flussdifferenz zwischen der Obergrenze der Atmosphäre und dem Erreichen der oberen Wolkenschichten. Dies deutet darauf hin, dass die Venus gegenwärtig keine Ozonschicht (oder einen vergleichbaren Abschirmmechanismus) besitzt und mit hoher Wahrscheinlichkeit auch zu keinem Zeitpunkt in den vergangenen 3,2 Ga besessen hat. Daher erscheint die Existenz von Leben in diesen Höhenlagen aufgrund des immernoch sehr hohen UV-C-Strahlungsflusses in 65 km Höhe eher unwahrscheinlich. *Deinococcus radiodurans*, ein Modellorganismus für hohe Strahlung-

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sresistenz, würde beispielsweise unter den heutigen UV-C-Strahlungsbedingungen bereits nach nur 227 Sekunden eine Populationsreduktion um 99% erfahren. Es ist jedoch anzumerken, dass die Venus über einen Mechanismus verfügt, der den einfallenden UV-Fluss erheblich abschwächt: den sogenannten „mysteriösen UV-blau-Absorber“ (MUBA). Der MUBA befindet sich innerhalb der oberen Wolkenschicht der Venus und wird daher in meinen Simulationen nicht berücksichtigt. Folglich reichen meine Ergebnisse nicht aus, um die Möglichkeit von Leben in den unteren und mittleren Wolkenschichten der Venus vollständig auszuschließen.

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1. Introduction

As the second-brightest object in the night sky, Venus has likely been observed by various ancient cultures all around the world, with its earliest documented observations dating back to the second millennium B.C.E. (Evans, 1998). Ever since then the planet has inspired human fascination. This was only exacerbated by the discovery of Venus' atmosphere in 1761 by Mikhail Lomonosov, which stoked contemporary and later scientists' imagination until well into the 20th century. Svante Arrhenius, Nobel laureate and one of the pioneers of modern climate science, for example wrote in 1918 that "A very great part of the surface of Venus is no doubt covered with swamps [...]", arguing that "low forms of life [...] belonging to the vegetable kingdom" existed in abundance, while organisms living in Venus' polar regions "should have developed into higher forms than elsewhere, and progress and culture, if we may so express it, will gradually spread from the poles toward the equator." (Arrhenius, 1918).

The image of Venus as a lush and humid world with dense vegetation gradually began to change around the mid-20th century as new spectroscopic measurements failed to find signs of oxygen and water vapor, while simultaneously showing an abundance of carbon dioxide. Even though these findings still underestimated the amount of CO₂ in Venus atmosphere by as much as a factor of 90, they already indicated much higher temperatures which were incompatible with liquid water being able to exist on the surface of Venus (O'Rourke et al., 2023). This paradigm shift with respect to our understanding of Venus was further compounded by measurements of radio emission from Venus in the latter half of the 1950s as well as the early 1960s (Mayer et al. 1958, Kislyakov et al. 1962, Kuz'min and Salomonovich 1960). These measurements already indicated that high temperatures up to $620\text{ K} \pm 110\text{ K}$ (Mayer et al., 1958) were present on Venus, although it was then still unclear where on Venus this radiation originated as these measurements were compatible with either a hot surface or hot upper atmosphere and a temperate surface. As such a wide range of models for conditions on Venus were competing with each other up to the advent of space age in the early 1960s. It was then that findings from the Mariner 2 space probe and later by the soviet Venera landers put the final nail in the coffin of the theory of a clement and humid Venus by measuring its atmospheric composition as well as surface temperature and pressure to be close to the inhospitable conditions we know of today (O'Rourke et al., 2023).

In the last three and a half decades Venus began to take a back seat in the exploration of the solar system and especially the search for extraterrestrial life. This shift was likely caused by a combination of two factors. One of these was the aforementioned discovery that Venus' surface conditions do not allow for life as we know it. The other

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major factor was the dissolution of the Soviet Union in 1991, which was responsible for the vast majority of space craft launch attempts (29 out of a total of 35) directed at Venus until then (Siddiqi, 2018). Since 1991 only four space missions (excluding gravity assists) were directed at Earth’s sister planet, with just two of them carrying out observations of Venus (Siddiqi, 2018). In recent years, however, this has begun to change as researchers increasingly started to look to the skies in their search for potential habitats on Venus (Seager et al. 2021, Kotsyurbenko et al. 2021, Jordan et al. 2022, Bains et al. 2024). Especially the purported discovery of phosphine in Venus’ atmosphere by Greaves et al. 2021, although it is very much disputed, nonetheless proves that the possibility of life in the Venusian clouds is being seriously considered within the scientific community.

Ranging from 48 km to 70 km in altitude (O’Rourke et al. 2023, Cockell 1999) the clouds of Venus exhibit temperatures between ~ 360 K at the lower boundary and ~ 230 K at the upper boundary with corresponding pressures of around 135 kPa and just over 3 kPa respectively (Seiff et al. 1985, Limaye et al. 2017). These pressures and temperatures lie well within the boundaries of life on Earth (e.g. Cockell 2020, Schulze-Makuch and Irwin 2018, Merino et al. 2019) and thus do not rule out the habitability of Venus’ cloud layers. These two factors alone, however, are not sufficient to determine whether life could exist there and many other aspects and open questions remain. These include salinity, pH-value, nutrient availability, ultraviolet (UV) radiation and the question of where this life might have arisen and how it got into the clouds in the first place.

It is the aim of this thesis to further constrain the potential for habitability of the Venusian clouds today and in the past by investigating one of these aspects: namely the amount of UV radiation reaching the top of the cloud layer at different points in time starting from current conditions and extending up to 3.2 Gyr into the past. This is an important piece of the habitability-puzzle since UV radiation (especially at higher frequencies - i.e. in the UV-B and -C bands) can very efficiently destroy DNA while at the same time serving as an important source of energy for pre-biotic chemistry (and possibly early life) on Earth (Toupance et al. 1977, Buccino et al. 2006). To calculate the evolution of the solar UV-flux reaching the top of Venus’ clouds, the Kompot code developed by Johnstone et al. 2018 is used. This is a one dimensional hydrodynamic/-static model which calculates the thermal and chemical structure of a planet’s atmosphere given arbitrary planetary parameters, chemical compositions and stellar input spectra (see 3.1).

2. Fundamentals

This chapter aims to give a general overview of the fundamental physical, chemical as well as biological concepts and processes that need to be considered when discussing potential life on Venus. Firstly by examining Earth's inner neighbor with a focus on its atmosphere and clouds, since the cloud layer is the region on Venus most likely to be habitable (Bains et al. 2024, Kotsyurbenko et al. 2021, Cockell 1999). Following this life, its limits and the role of ultraviolet (UV) radiation therein is explored.

2.1. Venus

2.1.1. Overview and Evolution

Venus has often been called Earth's sister planet (e.g. O'Rourke et al. 2023). The surface conditions of the two planets, however, have only very little in common. The semi-major axis of Venus' orbit around the Sun is 0.723 AU. This places the planet close to the inner edge of the solar system's habitable zone (HZ), with various estimates putting it either just inside (Dole 1964, Yang et al. 2014) or just outside (Kasting et al. 1993, Abe et al. 2011, Vladilo et al. 2013) the HZ. But whether or not Venus lies within the habitable zone - traditionally defined as the area around a star within which liquid water is stable on the surface of a planetary body (Cockell, 2020) - around the Sun is a moot point when considering Venus' present day habitability. With a temperature of 737 K at the mean planetary radius of 6051.5 km (Seiff et al. 1985, O'Rourke et al. 2023) there can be no stable bodies of liquid water on Venus' surface today. Nonetheless these considerations are important to figuring out the past evolution of Venus, about which we currently only know very little (Gillmann et al. 2022, Rolf et al. 2022). The past evolution of Venus, in turn, is crucial for our understanding of and search for potential current life in the Venusian clouds since, to the best of our knowledge, life needs some kind of solvent (generally assumed to be liquid water) in which prebiotic chemistry can efficiently happen and produce the necessary building blocks for the eventual emergence of living organisms (Cockell 2020, Schulze-Makuch and Irwin 2018). It is, however, not guaranteed that Venus ever possessed stable bodies of liquid water at any point in its history. Gillmann et al. (2022) propose three contrasting scenarios that could have ultimately given rise to Venus' current state under the assumption that Venus started out with similar initial ingredients to Earth's:

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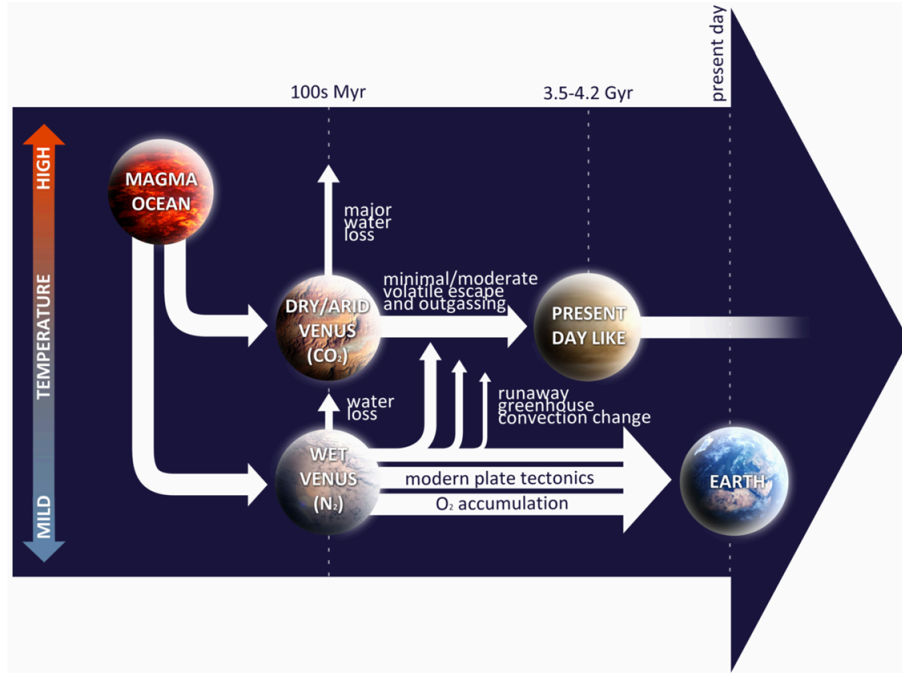


Figure 2.1.: The speculative evolutionary scenarios that could have led to the present-day state of Venus' surface conditions from Gillmann et al. 2022. In the top path Venus transitioned directly into a dry/arid world with a CO₂-dominated atmosphere from its initial magma ocean state after losing its surface water content early on as opposed to the bottom path, where Venus would have initially evolved more similarly to Earth, managing to hold on to a larger part of its water inventory and developing an atmosphere dominated by N₂ until its climate eventually became unstable and ultimately caused the planet to transition to its present-day state. This graphic represents only general evolutionary trends and includes Earth-related processes (O₂ accumulation and modern plate tectonics) only as a contrast to the proposed mechanisms shaping the shown evolutionary scenarios of Venus.

1. Dry Venus

The first scenario is sketched out in the top path of figure 2.1. In this framework, which is described in detail in Salvador et al. (2023), Venus experienced an extended magma ocean phase, as its closer proximity to the Sun would result in slower solidification - possibly taking up to 100 Myr. If this hypothesis holds, Venus is an example of a Type-II planet¹ according to the Hamano et al. (2013) classification scheme, as opposed to Type-I planets² like Earth, whose magma ocean lasted only for around 1 Myr. During this long-lasting magma ocean phase Venus would have

¹Characterized by slow magma ocean solidification

²Typified by significantly more short-lived magma oceans

slowly lost large fractions of its initial water inventory via hydrodynamic escape of hydrogen from its accompanying steam atmosphere, while the left-over oxygen would be subsumed into the magma ocean via oxidation (Hamano et al. 2013, Gillmann et al. 2009). The resulting desiccation of Venus would consequently render water condensation into large, stable bodies of liquid water onto the planet’s surface (such as happened on Earth) impossible. Consequently Venus could have relatively quickly (on the order of 100 Myr) evolved to closely resemble its present-day state. It would already possess an atmosphere predominantly made up of CO_2 and N_2 which would, in time, accumulate more mass via outgassing until the atmosphere eventually ends up at its present-day level. The likelihood of this hypothesis could be tested by investigating the redox-state of Venus’ basalts and upper mantle rocks.

2. Temperate Venus

In this possible evolutionary pathway (corresponding to the bottom path of figure 2.1) Venus initially evolved more similarly to Earth. Because Venus’ orbit is close to the critical distance from the Sun, which separates Type-II and Type-I planets, the planet could also have followed a Type-I evolution. This would mean that the Venusian magma ocean could have cooled and solidified much faster, allowing Venus to initially retain its atmospheric water and subsequently have it condense onto the surface. There the water could have formed oceans and Venus would have had a temperate, Earth-like climate for unknown amount of time. One indicator supporting this hypothesis is the comparatively large ratio of deuterium to hydrogen (D/H, see sec. 2.1.2) on Venus, which could imply that Venus possibly had at least a shallow ocean for an extended period of time in its history (Way and Del Genio, 2020). This option is, however, only plausible if efficient cooling mechanisms were present on early Venus. These cooling mechanisms are needed to offset the high flux of incoming solar radiation and thus enable the magma ocean to cool significantly faster. One example for such a mechanism could be the formation of highly reflective clouds during the magma ocean phase, although it is currently not possible to definitively assert details about the formation and exact effects of such clouds due to a lack of the kind of model required to simulate realistic clouds within a magma ocean atmosphere (Way and Del Genio 2020, Salvador et al. 2017, Gillmann et al. 2022). Assuming that a cooling mechanism was indeed present on early Venus to allow for rapid magma ocean solidification, the planet may have initially harbored temperate conditions, similar to Earth. These conditions could then favour the formation of carbonates or even the advent of a limited carbon cycle, which would pull CO_2 out of the atmosphere and allow for lower CO_2 partial pressures and thus an atmosphere dominated by N_2 to hold sway for an extended period of time (Gillmann et al., 2022). Eventually, however, Venus underwent a runaway greenhouse effect, possibly triggered by geological upheaval (Way and Del Genio, 2020), a collision with a large impactor, the increase in solar luminosity over time or a combination of these factors. These factors could have led to the release of magmatic CO_2 into the atmosphere, leading to ever-increasing temperatures and eventually the dissolution of carbonates previously bound within Venus’ crust as

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well as the loss of Venus' water (Gillmann et al., 2022). This process is shown in figure 2.2 and would in time result in the hot and desiccated Venus we observe today.

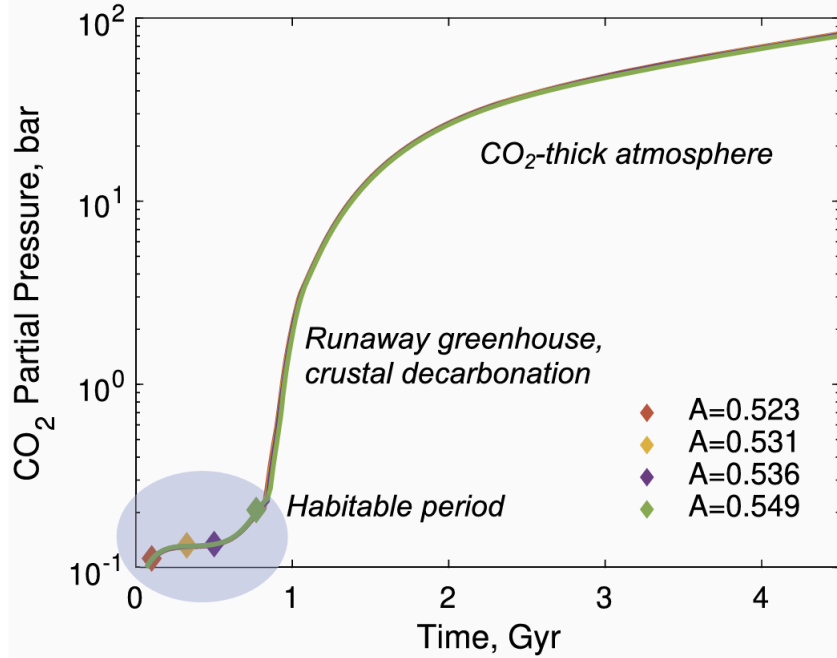


Figure 2.2.: CO_2 partial pressure versus time in Venus atmosphere. This plot by Gillmann et al. (2022) shows results from a coupled interior-atmosphere model under the assumption of a stagnant lid Venus and accounting for different planetary albedos (Höning et al., 2021). The model starts after the solidification of Venus' magma ocean and assumes an initial atmosphere made up solely of the current N_2 inventory. The different albedos (denoted by the diamond-shapes in the plot) were obtained by conducting validation runs in a 3D general circulation model (Way et al. 2016, Way and Del Genio 2020) with the corresponding time and CO_2 partial pressures as inputs.

3. Stifled Outgassing

Lastly Venus initial water content could have been retained by its interior as a result of inefficient outgassing from (Ikoma et al. 2018, Solomatova and Caracas 2021) as well as oxidisation of (Gaillard et al., 2022) its primordial magma ocean. At later times this status quo could have been maintained via the prevention of efficient H_2O outgassing due to Venus' high surface pressure (Gaillard and Scaillet, 2014). The suffused water could then have been partitioned with large amounts of hydrogen being sequestered into the core while the left-over oxygen would go on to form FeO and thus oxidize the mantle (Ringwood and Anderson 1977, Okuchi 1997). If this hypothesis holds, Venus would still end up in its current, desiccated

state but the planet’s water inventory would end up bound inside the mantle/core instead of being lost to space as was the case in the two prior scanrios.

As we currently do not have a concrete understanding of the evolutionary pathway that Venus took to arrive at its current state, only the present-day conditions are taken into account for the remainder of this thesis.

2.1.2. Atmosphere

Despite having only about 81.5% of Earth’s mass (Konopliv et al., 1999), Venus possesses the most massive atmosphere of all rocky bodies in the solar system. With a mass of $4.8 \cdot 10^{20}$ kg making up almost 0.01% of Venus’ total mass the Venusian atmosphere dwarfs its Earthly counterpart with only $0.051 \cdot 10^{20}$ kg and $8.54 \cdot 10^{-5}\%$ respectively (O’Rourke et al., 2023). This, in turn, also leads to a much higher surface pressure of 9.2 MPa (Seiff et al., 1985) on Venus compared to Earth’s 0.1014 MPa. Furthermore the atmospheres of Venus and Earth have very different chemical compositions, with Venus’ atmosphere consisting mostly of CO₂, while the main constituent of Earth’s atmosphere is N₂. The five most abundant constituents (by volume) of both atmospheres are shown in table 2.1.

Table 2.1.: The five most abundant atmospheric constituents of Venus and Earth by volume (von Zahn et al., 1983).

Venus	Earth
96.5% CO ₂	78.1% N ₂
3.5% N ₂	21.0% O ₂
20 ppm H ₂ O	~ 1% H ₂ O
70 ppm Ar	9340 ppm Ar
150 ppm SO ₂	412 ppm CO ₂ and rising

One important thing to note here in regards to the water contents of the Venusian and terrestrial atmospheres is that both atmospheres contain about the same total amount of water vapour, even though H₂O makes up a much smaller share of Venus’ atmosphere (as seen in table 2.1) due to its much higher total mass (O’Rourke et al., 2023). Additionally the ratio of Deuterium to hydrogen (D/H) in Venus’ water vapour is larger by a factor of 157 than it is on Earth. This may indicate that Venus has lost large quantities of water vapour (or at least hydrogen) in the past as the lighter hydrogen atoms are more easily lost to space when compared to heavier Deuterium atoms (Donahue et al., 1982). The second most abundant chemical species in Earth’s atmosphere is molecular oxygen (O₂), which accounts for 21% of its total volume. In contrast O₂ constitutes only about 50 ppm or less of the Venusian’ atmosphere, placing its absolute mass at least two orders of magnitude below that of Earth’s O₂ content (von Zahn et al., 1983). The large amount of molecular oxygen in Earth’s atmosphere is a result of the dense biosphere on our planet and highlights the importance of the co-evolution of our planet

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with the organisms inhabiting it. Molecular oxygen is a byproduct of the metabolisms of many photoautotrophic organisms, such as cyanobacteria, algae and plants. These organisms convert CO_2 , H_2O and energy from photons into glucose ($\text{C}_6\text{H}_{12}\text{O}_6$), H_2O and molecular oxygen (O_2) in a process known as *oxygenic photosynthesis* as shown in equation 2.1 (Cockell, 2020). Before these organisms started producing oxygen on early Earth, atmospheric O_2 levels were six orders of magnitude lower than they are currently (Chen et al., 2022). As Venus lacks a dense biosphere it also lacks molecular oxygen in its atmosphere. Accordingly Venus' atmosphere has been unable to accumulate and maintain an ozone (O_3) layer, the significance of which will be explained in section 2.2.3.

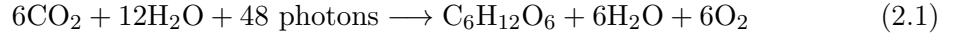


Figure 2.3 shows the vertical structure of Venus' atmosphere. As can be seen there are multiple haze layers: one at the surface and one each below and above the clouds, which extend in three separate layers from 47.5 km up to 70 km in height (Titov et al., 2018). The solid black line in figure 2.3 represents a temperature profile from the Venus International Reference Atmosphere (VIRA), which shows the temperature steadily decreasing from 737 K at the surface (Seiff et al. 1985, O'Rourke et al. 2023) until a height of 95 km, whereupon the temperature reaches a minimum of ~ 170 K (Seiff et al. 1985, O'Rourke et al. 2023, Titov et al. 2018) before rising again and thus forming an inversion layer above the upper haze layer.

2.1.3. Clouds

As previously mentioned Venus possesses multiple kinds of aerosols in its atmosphere. These are categorized as belonging to one of two groups:

- **Clouds**

Clouds are a type of aerosol made up of liquid droplets. On Earth clouds consist most commonly of liquid water (H_2O) and are formed when the air is saturated with water and reaches its dew point, which causes the water to condense onto cloud condensation nuclei (tiny particles which provide the water with a solid surface to condense onto). The clouds of Venus on the other hand mainly consist of sulphuric acid (H_2SO_4) (Titov et al. 2018, O'Rourke et al. 2023). H_2O has long been estimated to only be a minor component of Venus' clouds, making up less than 25% of the Venusian clouds by weight (O'Rourke et al., 2023). Recently, however, the re-evaluation of measurements from the Pioneer Venus Large Probe by Mogul et al. (2025) has called this into question, suggesting instead that H_2O may be much more abundant than previously thought. Mogul et al. (2025) present a bulk aerosol composition consisting of $62 \pm 8\%$ H_2O , $22 \pm 4\%$ H_2SO_4 and $16 \pm 3\%$ $\text{Fe}_2(\text{SO}_4)_3$.

- **Hazes**

Contrary to clouds, hazes do not consist of liquid droplets. Rather they are made up of tiny, solid particles such as dust or smoke. These particles can serve as cloud

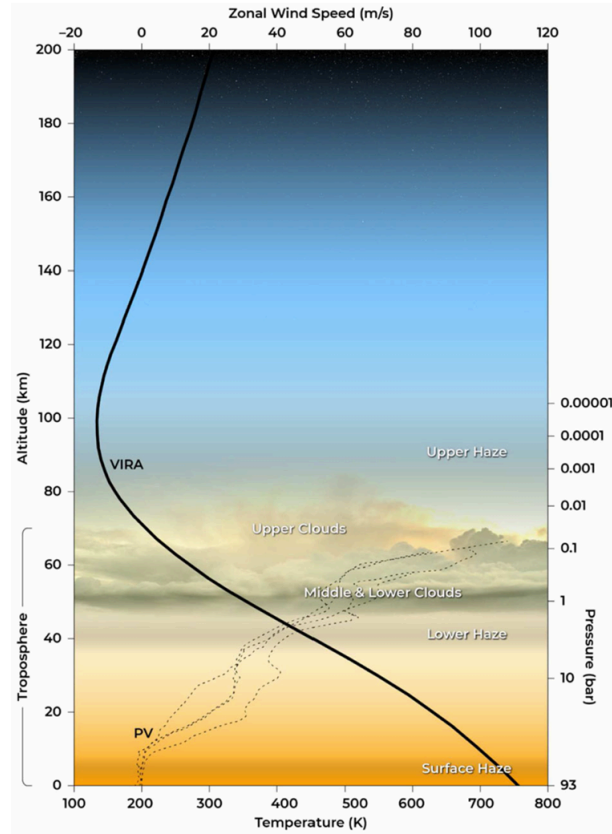


Figure 2.3.: The structure of Venus' present-day atmosphere. The artistic rendition in the background illustrates the location of the Venusian cloud- as well as various haze layers with respect to their altitude and corresponding atmospheric pressure. The solid black line (corresponding to the lower horizontal axis) shows an equatorial temperature profile taken from the Venus International Reference Atmosphere (VIRA), while the dashed lines (relating to the upper horizontal axis) denote zonal wind speed measurements gathered by the Pioneer Venus entry probes. Figure by O'Rourke et al. 2023.

condensation nuclei and subsequently allow clouds to form. On Earth these haze-particles can stem both from natural sources such as wildfires or volcanic activity or they can be caused by human activity such as industry or traffic. The Venusian haze layers are presumed to consist predominantly of sulphuric acid particles (Titov et al., 2018).

The clouds and hazes are then further subdivided into different layers as seen in figure 2.4. There is an upper haze layer extending from the cloud top at ~ 70 km up to a height of ~ 90 km (possibly even stretching as high as ~ 110 km), a lower haze layer stretching from the bottom of the clouds at 47.5 km down to ~ 33 km and possibly a surface layer

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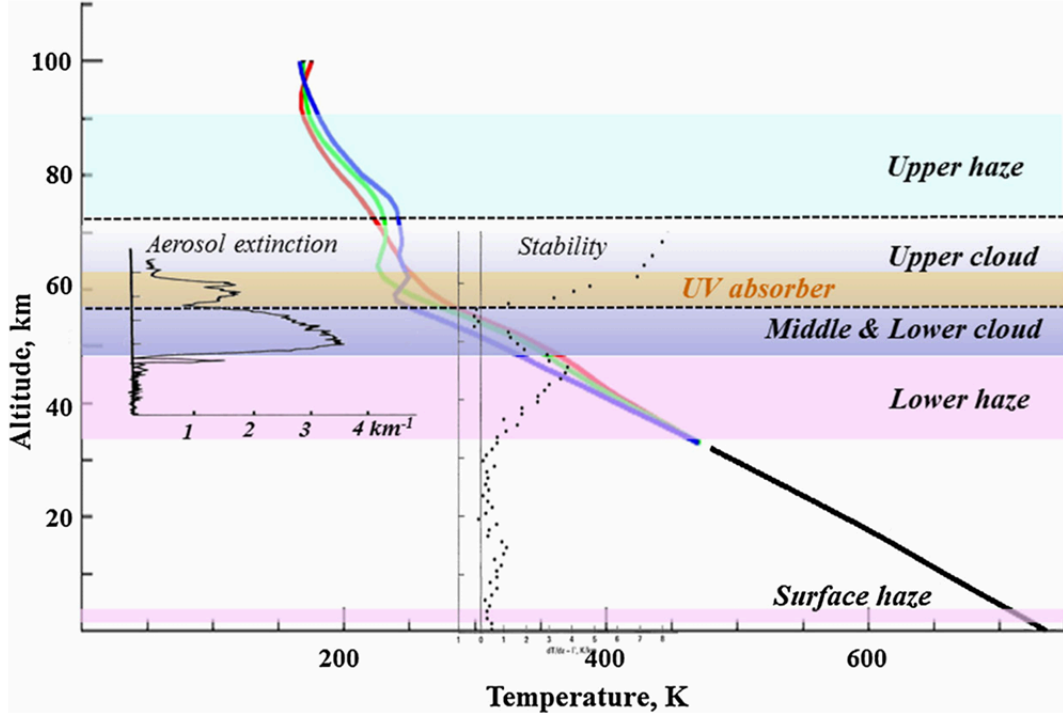


Figure 2.4.: This diagram from Titov et al. (2018) reveals a more detailed look at the vertical structure of Venus' various layers of clouds and hazes according to data from the Venera and Pioneer descent probes. The colored lines show mean temperature profiles, where black represents the temperature structure below 30 km while for higher altitudes the red, blue and green lines represent low, middle and high latitudes respectively. Additionally two smaller plots are overlaid. The one on the left shows the typical vertical profile of aerosol extinction obtained by Ragent et al. (1985). Lastly the one in the middle shows a static stability profile from the Venus International Reference Atmosphere by Seiff et al. (1985).

located between 1 km and 2 km above ground with an extinction of around 1.5 km^{-1} (Titov et al., 2018). The clouds are similarly grouped into three different layers:

Upper Cloud Layer (56.5km - 70km)

The top of the clouds is defined as the altitude at which the optical depth τ is equal to one and as such is highly wavelength-dependent. Furthermore the cloud top altitude shows considerable variation with respect to latitude. As seen in figure 2.5 each of these factors can influence the height of the cloud tops by a margin of 5 km – 10 km. As such it is difficult to define a single universal cloud top altitude but generally the upper boundary of Venus' clouds is taken to be located between 65 km and 70 km of height in the literature (Titov et al. 2018, Ignatiev et al. 2009, O'Rourke et al. 2023). The upper

clouds are also the region where water and sulfur oxides are driven by photochemistry to form sulfuric acid, which then condenses together with water vapor and forms the droplets the clouds themselves are made up of (O'Rourke et al., 2023). Another interesting characteristic of the upper cloud layer is a so-called "*mysterious UV(-blue) absorber*" (MUBA). This feature is characterized by a strong absorption in the wavelength span between $0.3 \mu\text{m}$ and $0.5 \mu\text{m}$ (i.e. the UV-A band as well as the blue part of the visible light spectrum) and absorbs about 50% of the solar energy received by Venus (Titov et al. 2018, O'Rourke et al. 2023). As of yet there is no clear consensus of what exactly this mysterious absorber is. A recent study by Jiang et al. (2024), however, suggests that a combination of rhomboclase $(\text{H}_5\text{O}_2)\text{Fe}(\text{SO}_4)_2 \cdot 3\text{H}_2\text{O}$, acid ferric sulfate $(\text{H}_3\text{O})\text{Fe}(\text{SO}_4)_2$ and dissolved ferric iron Fe^{3+} could explain the observed absorption in the previously mentioned wavelength range, hinting at the possibility of a rich and so far for the most part unexplored diverse chemistry in the clouds of Venus.

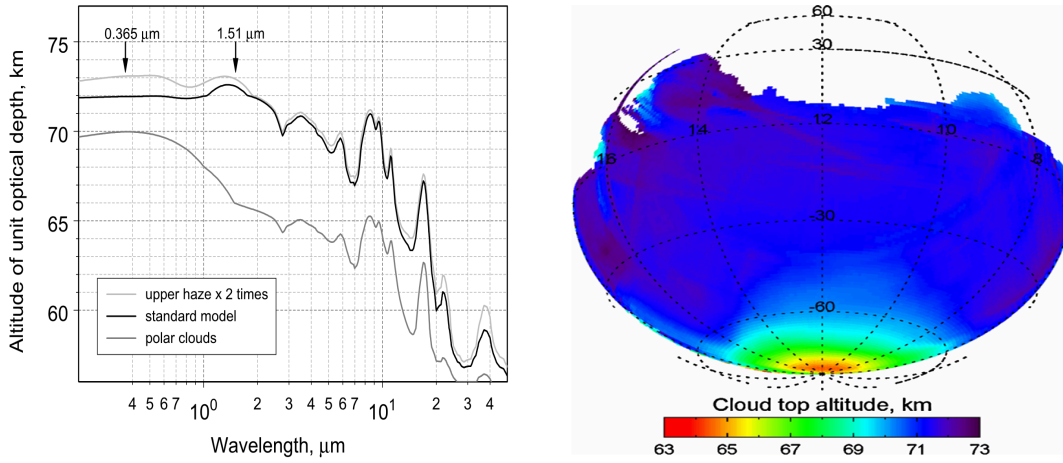


Figure 2.5.: The altitude of the cloud tops on Venus varies strongly with wavelength and location (i.e. latitude). The plot on the **left** shows the cloud top altitude as a function of wavelength at low latitudes (standard model) as well as for the polar clouds and for a variation of the standard model with the upper haze enhanced by a factor of 2 from Ignatiev et al. (2009). The plot on the **right** on the other hand shows the mean cloud top altitude at $1.51 \mu\text{m}$ with respect to altitude and local time from Ignatiev et al. (2009) including systematic error correction by Titov et al. (2018).

Middle (50.5km - 56.5km) and Lower (47.5km - 50.5km) Cloud Layers

Around a height of $\sim 56 \text{ km}$ a gap with a diameter of about 1 km to 2 km, characterized by reduced extinction, separates the upper and middle cloud layers. Below this gap the cloud density gradually increases again until it reaches its maximum at $\sim 50 \text{ km}$ of height, which is also where the boundary between the lower and middle cloud layers is generally

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placed although this threshold is not particularly well defined as both layers are rather similar (Titov et al. 2018, O’Rourke et al. 2023). The middle and lower clouds also play an important role in the chemical cycles of Venus atmosphere. It is at the lower boundary of the clouds that the sulfuric acid, which was formed in the upper clouds, begins to evaporate and eventually decomposes into water and sulfur trioxide (SO_3). This SO_3 can, in turn, be an important driver for other chemical reactions as it is highly reactive while going on to form SO_2 (O’Rourke et al., 2023). Furthermore the middle and lower clouds have been found to contain major reservoirs of chlorine and phosphorus (Andreichikov, 1987), which further highlights the potential for complex heterogeneous chemistry taking places in and around Venus’ clouds.

2.2. Life on Venus

Even after the truth about the hellish climate conditions prevailing on Venus’ surface became apparent during the latter third of the previous century, researchers have continued to debate the possibility of life persevering on Venus against the odds (Morowitz and Sagan 1967, Sagan 1967, Seckbach and Libby 1970, Ichinose and Folsome 1973, Cockell 1999). Neither has the interest in potential Venusian life dimmed in recent years, especially in the wake of the purported discovery of phosphine on Venus by Greaves et al. (2021)(Seager et al. 2021, Mogul et al. 2021, Kotsyurbenko et al. 2021, Jordan et al. 2022, Seager et al. 2021, Bains et al. 2021, Bains et al. 2024). Nowadays, however, such life is no longer searched for on Venus’ surface, as earlier authors suggested (Arrhenius 1918, Sagan 1967), but rather in the planet’s cloud layers, where pressures and temperatures are more conducive to life as we know it (see section 2.1.2). The following sections will examine the possibility as well as the limitations (especially with respect to ultraviolet radiation) of potential Venusian cloud-based life.

2.2.1. Clouds as a Potential Habitat

The idea that life could persist in the clouds of Venus is not a new one. Morowitz and Sagan (1967) already suggested that the presence of H_2O , CO_2 and sunlight combined with clement temperatures and pressures around 1 bar would make the existence of simple, photoautotrophic organisms possible. These organisms were envisaged by the authors to essentially be isopycnic³ float bladders filled with molecular hydrogen, functioning in principle similar to fishes’ swim bladders. The necessary hydrogen was to be sourced as a byproduct of anoxygenic photosynthesis, such as practiced by e.g. purple bacteria (Tichi and Tabita, 2001).

More recently Seager et al. (2021) offered a more detailed exploration of what the life cycle of a possible biosphere in the clouds of Venus might look like.

³in a state of equal density with their surroundings

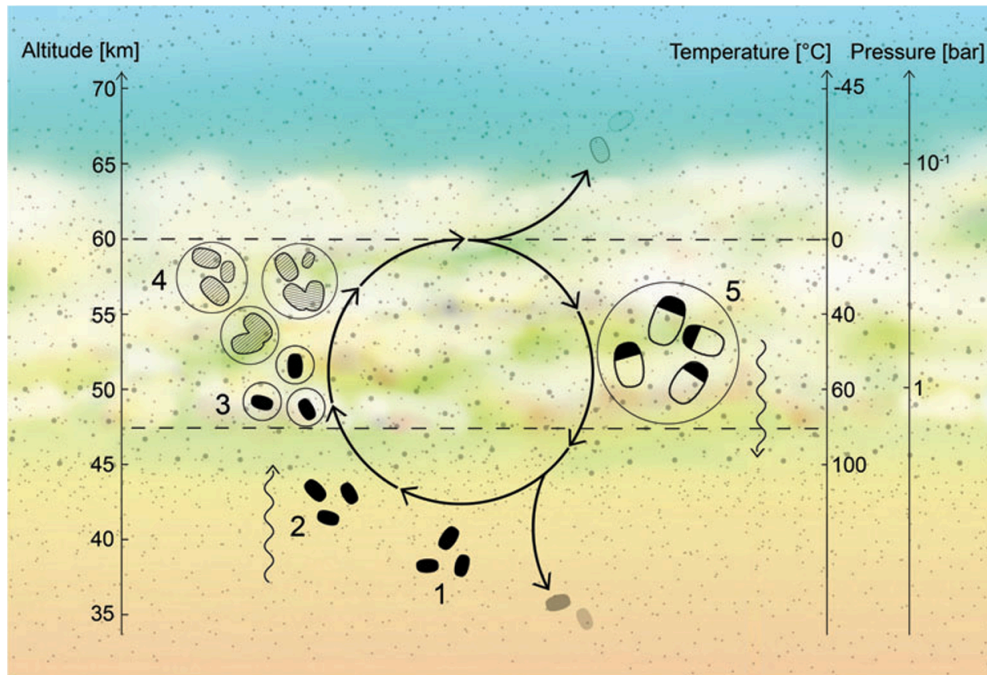


Figure 2.6.: The life cycle of a potential cloud-borne microbial biosphere on Venus as proposed by Seager et al. (2021). (1) Dormant, desiccated spores (depicted as black blobs) floating within the lower haze. (2) Spores are transported into the habitable lower and middle cloud layers via updraft. (3) Spores serve as cloud condensation nuclei (CCN), causing liquid droplets (shown as solid circles) made up of H_2SO_4 and H_2O to form around them. The spores then germinate and start metabolic activity. (4) The metabolically active spores (denoted by dashed blobs) grow and multiply within their droplets, while the liquid droplets themselves experience growth by coagulation. (5) Eventually the droplets become large enough that they are forced downwards by gravitational settling. As temperatures rise with decreasing altitudes and their host-droplets begin evaporating, microbes start to sporulate. The resulting spores are once again small enough to resist further gravitational settling and "hibernate" within the lower haze until the cycle begins anew.

As seen in figure 2.6, the cycle begins just below the clouds in the lower haze layer. The lower haze acts as a sort of depot for dormant, desiccated spores of microorganisms. These spores are eventually transported higher up by way of vertical mixing due to gravity waves until they reach the lower/middle cloud layers. In these regions the spores serve as cloud condensation nuclei (CCN), providing a surface for liquid droplets made up of H_2SO_4 and H_2O to condense onto. Inside of these newly formed droplets the spores subsequently germinate and start metabolic activity. The metabolically active spores then grow and multiply within their droplets, while the liquid droplets themselves grow via coagulation on timescales of days to months. These growing droplets remain in the habitable cloud

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layer for varying amounts of time, ranging from hours to months or even years depending on altitude and particle size. Eventually the droplets become large enough that they are forced downwards by gravitational settling because the sedimentation timescale becomes shorter than the coagulation timescale. Two important questions at this point are whether microbes have enough time as well as space inside the droplets to grow and divide. Seager et al. (2021) suggest that the answer in both cases is yes. They argue that a particle with a radius of $3\text{ }\mu\text{m}$ remains in the lower cloud layer for close to 6 months and that this leaves comfortably enough time for a spore to germinate, initiate its metabolism and growth as well as divide all within the same droplet. Similarly the authors assert that the cloud droplets with a mode diameter of $2\text{ }\mu\text{m}$ offer enough space for monocellular organisms to grow and divide, as exemplified by the fact that free-living soil bacteria and archaea commonly measure less than $0.5\text{ }\mu\text{m}$ in diameter (Portillo et al. 2013, Hahn 2004) with the smallest free-living cells on Earth having a diameter of only about $0.2\text{ }\mu\text{m}$ (Luef et al., 2015). These sizes allow for multiple cells to inhabit the most commonly found $2\text{ }\mu\text{m}$ -diameter droplets, while larger droplets ($\sim 10\text{ }\mu\text{m}$ or more) could even be inhabited by dozens of cells.

Once the droplets reach a certain size they are unable to maintain their altitude within the lower and middle clouds and start getting forced downwards by gravity. As temperatures rise with decreasing altitude the droplets slowly start evaporating. As a reaction to these increasingly adverse conditions, the cells within the droplets begin to sporulate. This is a process known to occur among many different species of microorganisms on Earth, wherein they dry up, shrink and become metabolically inactive to preserve their genetic material and it is usually triggered by unfavourable environmental conditions (Setlow, 2006). In this state the resulting spores are highly resistant against numerous environmental stress-factors, such as extreme temperatures or pressures (both high and low), toxic chemicals, radiation and desiccation (Nicholson et al., 2000). This allows the microorganisms to remain dormant and endure in hostile environments until conditions improve, whereupon the cells become active once again and restart metabolic activity. Within their spore-state the cells survive the evaporation of their host-droplet and are small enough to resist further gravitational settling, instead remaining suspended in the lower haze layer until the cycle begins anew (although some spores are inevitably also pushed downwards by gravity waves into hotter atmospheric layers and thus likely become lost from the cycle).

This life cycle is entirely possible within the framework of life on Earth. On our own planet there already is an aerial biosphere inhabiting the clouds. It consists of various kinds of microbes, encompassing different species of archaea, bacteria, eukaryotes as well as viruses (Amato et al. 2019, Amato et al. 2017). While some of these organisms live free-floating in the atmosphere, most use liquid droplets within clouds as a habitat. Due to the fragmented and rather short-lived nature of Earth's clouds there are as of yet no microorganisms that have been observed to permanently inhabit them. Instead bacterial aerosols spend only a few days to weeks in the atmosphere on average (Burrows et al., 2009) before being delivered back onto the surface via precipitation (Vähtilä et al., 2012). Thus Earth's clouds only serve as a transient biotope, in which microbes

temporarily reside before coming back to the surface where the majority of their life cycle takes place. On Venus this would have to be different. Due to the inhospitable surface conditions, hypothetical Venusian life would have to permanently inhabit the clouds. This assumption is the foundation of the hypothetical life cycle proposed by Seager et al. (2021). It is supported by the much more constant nature of Venus' clouds, compared to those on Earth, as well as the fact that natural selection would have pushed life towards developing mechanisms allowing it to permanently inhabit the temperate clouds as surface conditions worsened due to Venus' runaway greenhouse effect (if indeed the surface ever was habitable). Even if life on Venus could have adapted to permanently colonize the planet's clouds, however, many other problems still remain.

2.2.2. The Limits of Life

Life, no matter where it might have developed, is faced by a variety of environmental factors that may limit its survival. Even though life is highly adept at adapting to its environment, there are fundamental, universal principles provided by the laws of physics and chemistry that life has to follow. In their most general form, these principles tell us that the following criteria need to be met for the emergence of life to be possible (Cockell 2020, Schwieterman et al. 2018, Schulze-Makuch and Irwin 2018):

- **Elementals Requirements**

The fundamental building blocks of life (the CHNOPS⁴-Elements) need to be present in sufficient quantities.

- **A Solvent**

A solvent (generally assumed to be liquid water, as is the case for life on Earth) is needed for life to emerge.

- **Energy**

Some form of energy to sustain the metabolism of living organisms needs to be available.

- **Appropriate Physicochemical Conditions**

Certain physical and chemical factors (i.e. temperature, pressure, salinity, acidity, radiation dosage, etc.) need to be within tolerable limits for life to survive, grow and procreate.

⁴Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus and Sulphur

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In the following it will be assumed that Venusian life has originated on the planet's surface at some point in the past, before the runaway greenhouse rendered it uninhabitable, and subsequently migrated into the temperate clouds as they are the only potentially habitable environment left on Venus. This is, of course, in no way assured but solves the problem of the emergence of life on Venus. Even glossing over this non-trivial problem, a potential biosphere in the clouds of Venus has to contend with many other obstacles. These mainly consist of the availability of energy as well as various environmental conditions and will be examined closer in the following.

Pressure

While pressure extremes cause significant problems for us humans, microbial (and even some more complex, multicellular organisms) can easily adapt to these conditions. The archaea *Thermococcus piezophilus*, for example, lives near deep sea hydrothermal vents and can grow at pressures up to 125 MPa, although optimal growth occurs at "only" 50 MPa (Dalmasso et al., 2016). Similarly it has been shown that various microorganisms, including prokaryotes, fungi and lichen, can survive under space conditions (10^{-13} MPa - 10^{-11} MPa at low Earth orbit, Horneck et al. 2010) for several months or even years (de Vera et al. 2012, Horneck et al. 2010, Onofri et al. 2018). This means that even the comparatively high surface pressure of Venus at 9.2 MPa (Seiff et al., 1985) lies well within the pressure-limits of life as we know it.

Temperature

Another important environmental factor is temperature. This is due to multiple reasons. Firstly life as we know it needs liquid water as a solvent, meaning that temperatures have to stay below the boiling point of water (though this can be offset by higher pressures, e.g. at deep sea hydrothermal vents) to be conducive to life. Secondly temperature influences the speed at which chemical reactions can occur in a given medium. If the temperature is too low, reactions occur very slowly if at all. If the temperature is too high, on the other hand, more complex molecules (such as nucleic acids) become unstable (Merino et al. 2019, Cockell 1999). For these reasons to the best of our current knowledge life is only possible between -40 °C (Price and Sowers, 2004) and 150 °C (Merino et al., 2019). The boundaries within which microorganisms have been found to be metabolically active, meanwhile, lie between -20 °C (Rivkina et al., 2000) and 122 °C (Takai et al., 2008). Temperatures in the clouds of Venus have been found to lie between ~ 80 °C at the lower boundary (48 km) and about -45 °C (though exact values depend on latitude) at the upper boundary (70 km) (Seiff et al., 1985). Temperatures within the lower and middle cloud layers are thus consistent with the boundaries of life observed on Earth, while the upper clouds are likely too cold (although it has to be noted that even in the upper clouds temperatures are mostly within the theoretical boundaries of life).

Acidity and Alkalinity

Acidity and alkalinity are measured on the pH-scale. This scale is given by the negative logarithm of the activity of the hydronium ion (H_3O^+). As hydronium is protonated

water, the pH-scale can be thought of in more simple terms as measuring the concentration of protons in water. A pH-value of 7 at room temperature denotes a neutral solution. Values lower than 7 indicate higher proton concentrations and thus acidic solutions, while solutions with pH-values higher than 7 denote lower proton concentrations and are called alkaline or basic. As in the case of temperature, life is confined to a "goldilocks zone" between the extremes of the pH-scale. If the pH within a cell's cytoplasm is too low protein denaturation can occur, while a high pH outside the cell makes it harder to maintain the proton gradient across the cell membrane needed to obtain energy via electron transport (Cockell, 2020). The most extreme pH-conditions within which microbes have been observed to survive thus far are acids with a pH of 0 and bases with a pH of 12.5 (Merino et al., 2019). Measuring the pH of the Venusian clouds is challenging as the pH-scale is meant to represent solutions made up mainly of water. This is however not the case for the clouds of Venus, as these are predominantly made up of sulfuric acid. In the Hammett scale, which continues the pH-scale to account for highly concentrated acids (e.g. sulfuric acid) (Liler, 1971), a solution of 85% H_2SO_4 (as might be representative of the Venusian clouds⁵) corresponds to an acidity of -11.5 (Yates et al., 1964). The clouds of Venus thus represent an environment without any naturally occurring analogues on Earth with an acidity more than 10^{11} times that of the most acidic environment at which microbes have been found to survive on Earth. This does not bode well for the habitability of Venus' clouds, although there are some proposed mechanisms that could shield potential cloud-borne microbes from these harsh conditions. One such mechanism could be the development of elemental sulfur shells (Schulze-Makuch et al., 2004) to insulate cells from their hyper-acidic surroundings as elemental sulfur has been found within the clouds of Venus (Taylor et al., 2018).

Salinity

High salinity can become problematic for living organisms as water tends to flow from areas with a low concentration of dissolved salts to those with a higher salt concentration, which causes osmotic stress. Cells can mitigate this by either maintaining high salt concentrations within them or by actively pumping out the accumulating salts (called the "Salt-In" and "Salt-Out" strategies respectively) (Cockell, 2020). The highest salt concentration currently known to be survivable for microorganisms on Earth lies at 35%, which has been achieved by *Halarsenatibacter silbermanii* (Blum et al., 2009). The salinity of Venus' clouds is currently not known (Merino et al., 2019) and thus cannot be compared to the salinity tolerance of life on Earth.

Available Energy

All life needs some form of energy to grow and reproduce. This energy can either be obtained either from abiotic or organic sources. Organisms belonging to the former group are called autotrophs, while those belonging to the latter group are called heterotrophs. Heterotrophs cannot use energy from inorganic sources and thus cannot exist without

⁵As previously stated this percentage might actually be lower according to a recent study by Mogul et al. (2025).

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autotrophs being present, as these represent the basis of the food chain. For this reason the following will focus solely on autotrophs. Autotrophs can obtain energy from two main sources: light and inorganic chemical compounds. They are thus subdivided into photoautotrophs (using energy from light) and chemoautotrophs (obtaining energy from chemical compounds). The clouds of Venus are rather poor with respect to their chemical energy potential and the surface is beyond the reach of cloud-borne lifeforms due to the high temperatures reigning there (Seager et al., 2021). This means that the primary producers of a potential aerial biosphere on Venus will likely be photoautotrophic in nature rather than chemoautotrophic. Different studies have argued that Venus' cloud layers receive sufficient energy from solar radiation to make the existence of photosynthetic lifeforms there possible (Morowitz and Sagan 1967, Cockell 1999, Mogul et al. 2021, Limaye et al. 2018, Kotsyurbenko et al. 2021). It has even been proposed that the MUBA, which is responsible for absorbing around 50% of the incident UV-radiation on Venus, could be the result of a photosynthetic aerial biosphere (Limaye et al., 2018). It has to be noted, however, that the low temperatures in the upper clouds (where the UV-absorber is located) mean that the potential for life in this region is limited as discussed above.

Radiation

While radiation serves as the primary energy source for photoautotrophs, the presence of highly energetic ionizing radiation can also have highly detrimental effects on life. The effects of radiation (especially ultraviolet radiation between 100 nm and 400 nm) will be discussed in detail in the following section as this environmental factor is the main focus of this thesis.

2.2.3. Ultraviolet Radiation

Ultraviolet (UV) radiation consists of light within the wavelength range of 100 nm to 400 nm and is further subdivided into three separate categories:

- **UV-A** (400 nm - 315 nm)
- **UV-B** (315 nm - 280 nm)
- **UV-C** (280 nm - 100 nm)

As stated in the previous section, UV (along with other kinds of ionizing radiation like X-rays and gamma rays) can cause significant harm to living organisms. These kinds of radiation (especially UV-C and gamma rays) can damage cells both directly and indirectly. Direct damage occurs for example when energetic photons interact with DNA. This can cause significant damage to the nucleobases (or dissociate DNA entirely, Buccino et al. (2006)) that encode the genetic information contained within the DNA and thus cause mutations (Cockell 2020, Merino et al. 2019). Indirect damage occurs only as a secondary effect of the photon interaction. For example by the creation of free oxygen radicals via the radiolysis (dissociation) of water within a cell. These oxygen radicals can then go on

to damage DNA, RNA, proteins as well as lipids within the cell (Cockell 2020, Merino et al. 2019) or initiate Fenton-type reactions via the release of Fe^{2+} , which produce highly reactive hydroxyl radicals ($\cdot\text{OH}$) that further damage the cell (Webb and DiRuggiero, 2013). The susceptibility of DNA to be damaged by radiation as a function of wavelength is indicated by the dashed black line in figure 2.7.

There are many different ways for life to mitigate the damage caused by ionizing radiation. As listed by e.g. Cockell (2020) and Merino et al. (2019) these include:

- Possessing multiple copies of the genome. This creates redundancy because different copies of the genome act as failsafes against undesired mutation in case one copy is damaged (Anitori, 2012).
- Efficient DNA repair mechanisms, which keep mutations and deterioration of the genome in check by constantly repairing damaged sections (Byrne et al., 2014).
- Having a condensed nucleoid (Anitori, 2012) or smaller amino acids (Sghaier et al., 2013).
- Production of pigments such as carotenoids (Mojib et al., 2013) or the accumulation of high concentrations of manganese (Mn(II)) within the cell (Daly et al., 2004). Both of these measures protect the cell from the indirect effects of ionizing radiation by quenching free oxygen radicals which would otherwise go on to damage the cell due to their highly reactive nature.

A number of microbes have been found to possess extraordinary radiation resistance. One of the first to be isolated and therefore also one of the most well studied of these is the bacterium *Deinococcus Radiodurans*. This remarkable organism can withstand radiation doses of 10 kGy (Cockell 2020, Bauermeister et al. 2011), while other species, like the thermophile *Thermococcus Gammatolerans*, have been shown to withstand even higher doses (30 kGy in the case of *T. gammatolerans*, Krisko and Radman 2013). To put this into perspective: To kill a human, a dose of merely 5 Gy of equivalent ionizing radiation is sufficient (Cockell, 2020). This is usually not a problem for humans since high doses of radiation are exceedingly rare in natural environments, which does, however, raise the question of why organisms like *D. radiodurans* evolved such a high degree of radiation resistance.

One hypothesis states that the high radiation tolerance of some microorganisms could be a remnant of past evolutionary pressure on early Earth (Merino et al., 2019). Currently most of the incident UV-radiation (especially UV-C) on Earth is absorbed in the ozone (O_3) layer of Earth’s atmosphere (Ranjan and Sassellov 2017, Buccino et al. 2006, Patel et al. 2022, Nakagawara et al. 2007). Before the Great Oxidation Event (the large-scale release of oxygen by photosynthetic microorganisms on archaean Earth) there was, however, no ozone layer yet, with possibly only temporary photochemically produced hazes at various intervals providing at least some measure of protection from UV (Arney et al.,

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2016). As such the Archean Earth's surface likely received orders of magnitude higher levels of UV-radiation than is currently the case (Cnossen et al. 2007, Cockell and Raven 2007), which could have forced early life to adapt and develop mechanisms to deal with the harmful effects of this high-radiation environment. Figure 2.7 illustrates this by showing the difference between the transmission spectra of early and present-day Earth as well as the biological sensitivity to the different parts of the UV-spectrum.

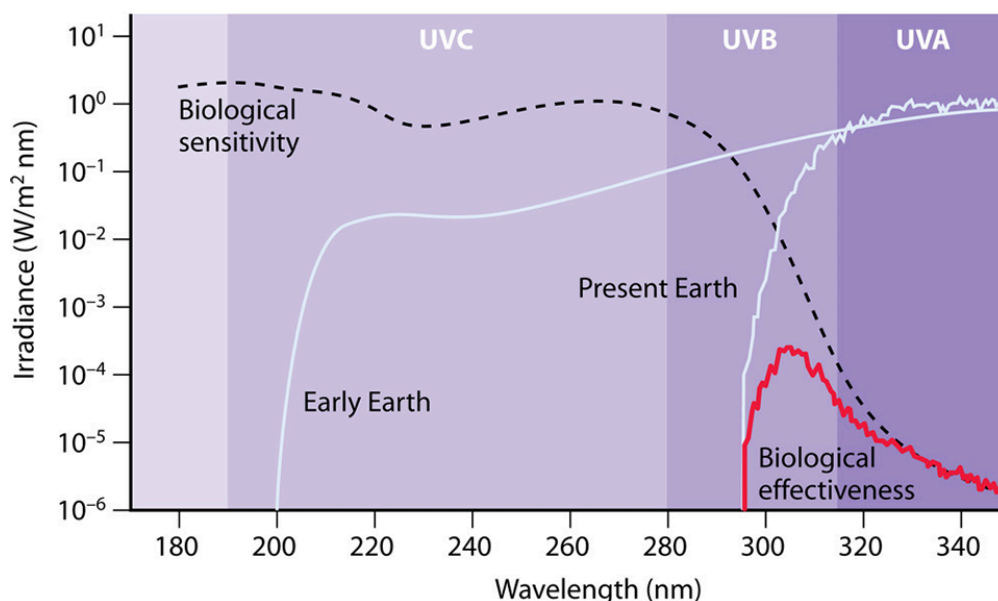


Figure 2.7.: This plot by Horneck et al. (2010) shows the biological effectiveness spectrum (red line) of UV radiation on Earth. This results from a combination of the biological sensitivity spectrum (dashed black line, shows the susceptibility of DNA to be damaged by radiation of a given wavelength) and the transmission spectrum on present day Earth's surface (light blue line labelled "Present Earth"). The transmission spectrum of the Early Earth (light blue line labelled "Early Earth") is included for comparison to pre-ozone conditions.

Another hypothesis is that the radiation resistance observed in Microbes like *D. radiodurans* or *T. gammatolerans* is not (or at least not primarily) an adaptation against high doses of radiation at all, but rather a useful side-effect of other adaptations (Cockell 2020, Merino et al. 2019). These organisms are often polyextremophiles. This means that they are adapted to different kinds of extreme environmental conditions, like high pressure and high temperatures in the case of *T. gammatolerans*, whose natural habitat are deep-sea hydrothermal vents (Jolivet et al., 2003). Since not just radiation but also these other environmental factors (e.g. desiccation or high temperatures Cockell 2020) can damage DNA or other cell components, the organisms living in these environments face natural selection pressure to adapt by developing efficient methods to repair this damage. To

them it ultimately doesn't matter whether the damage is caused by extreme heat, high doses of ionizing radiation or other factors as long as they can repair it efficiently enough.

2.3. Solar Flux Evolution

Another important factor to consider with respect to the long-term survival of possible Venusian life is the evolution of the incident solar radiation over the planet's history. Solar radiation impacts planetary atmospheres in a variety of ways, such as governing the vertical temperature profile (Fleming et al., 1995), driving molecular reaction rates (Ribas et al., 2010) or inducing atmospheric escape (Odert et al., 2010). A hypothetical aerial biosphere on Venus would on the one hand be influenced indirectly by all of these factors due to their effect on the lifeforms' habitat: the clouds. On the other hand, for the reasons discussed in the previous section, the change in solar flux (especially at lower wavelength regimes like the UV, x-ray or gamma ray ranges) also affects life directly. It is thus imperative to understand the past evolution of the solar flux in order to adequately model the viability of Venus' clouds as a potential habitat for life.

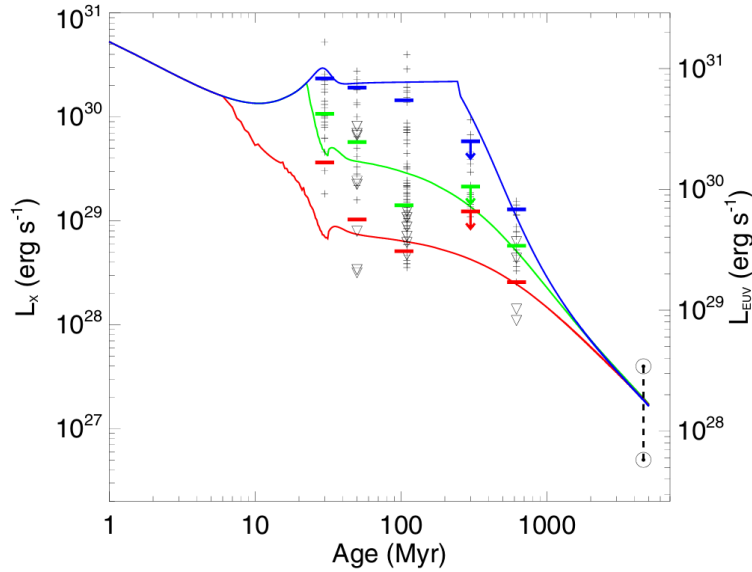


Figure 2.8.: This plot by Tu et al. (2015) shows possible evolutionary pathways of the solar X-ray (left vertical axis) and extreme ultraviolet (EUV, right vertical axis) luminosity for the Sun as a fast (blue), intermediate (green) or slow (red) rotator. The solar symbols with the dashed black line between them at 4.5 Gyr indicate the variations of L_x and L_{EUV} over the course of the 11 year solar cycle.

The Sun's X-ray and ultraviolet (XUV) luminosity is strongly linked to its rotation

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period, which drives the solar dynamo and thus influences the solar magnetic field (Tu et al. 2015, Claire et al. 2012). This behaviour is also known as the "age-activity-rotation" effect. As the Sun's rotation rate has decreased with time (also called spin-down), so too did its XUV luminosity (see figure 2.8). It is, however, difficult to estimate exact levels of XUV luminosity in the past as we do not know whether the Sun started out as a fast rotator (blue line in figure 2.8), a slow rotator (red line in figure 2.8) or anything in between, leaving an uncertainty of up to two orders of magnitude. As seen in figure 2.8 the difference between the different initial rotation cases is most apparent at a solar age of around 100 Myr and becomes gradually more negligible after about 600 Myr (Claire et al., 2012). The earliest point in time considered for this thesis lies 3.2 Gyr in the past and is thus luckily not subject to the uncertainty induced by our current ignorance of the Sun's initial rotation rate.

While the solar XUV flux was higher in the past, this was not the case for other wavelength-ranges. As seen in figure 2.9 (a) the solar flux in the visible spectrum has actually increased in time (and will likely continue to do so). And even within the XUV-range higher flux values in the past are not ubiquitous. This is illustrated in figure 2.9 (b), which shows fluxes at wavelengths below approximately 210 nm generally decrease with solar age, while fluxes at wavelengths higher than this threshold are increasing with solar age. These models by Claire et al. (2012) show that the generally higher solar XUV-flux in the past is mostly driven by short wavelengths (i.e. gamma rays, x-rays, extreme UV and parts of the UV-C range), while most of the conventional UV-range (UV-A and UV-B in their entirety as well as UV-C above the 210 nm threshold) is merely "dragged along" when being grouped together under the XUV-umbrella.

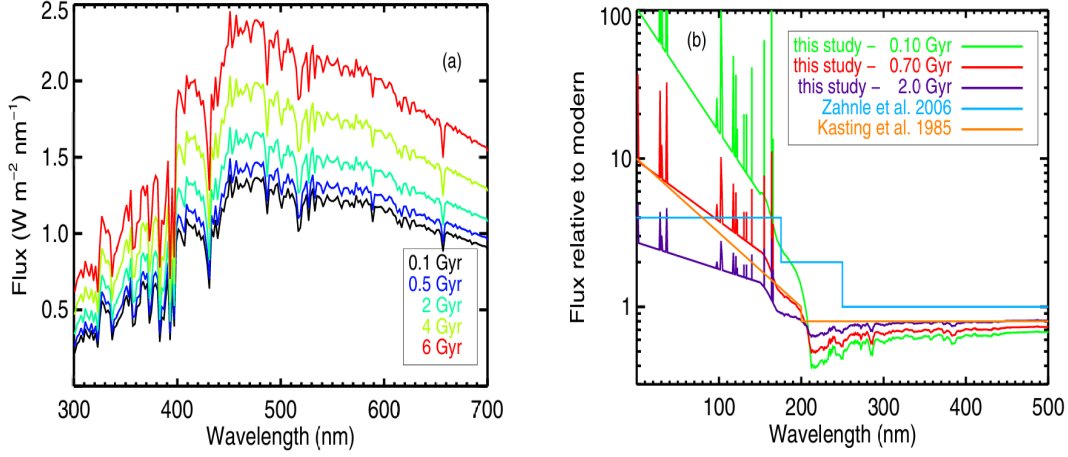


Figure 2.9.: The evolution of the solar flux modelled by Claire et al. (2012). **(a)** shows the solar flux between 300 nm and 700 nm (i.e. roughly the visible spectrum) at various points in time between a solar age of 0.1 Gyr and 6 Gyr. **(b)** depicts the solar flux ratio with respect to current levels at solar ages of 0.10 Gyr (green), 0.70 Gyr (red) and 2.0 Gyr (purple) for the entire wavelength-range below 500 nm with earlier models by Zahnle et al. (2006) (blue) and Kasting (1985) (orange) included for comparison.

The different evolutionary trends of the different parts of the solar spectrum are a result of their respective heating mechanisms. Figure 2.10 shows the origins of the different parts of the solar spectrum. As can be seen there, the solar spectrum at shorter wavelengths (below ~ 200 nm) is dominated by emissions originating from the chromosphere and the corona, the heating of which is caused by the Sun’s magnetic field (Johnstone, 2017). As the solar magnetic field is in turn induced by the solar dynamo, these wavelength ranges (i.e. far and extreme UV as well as X-rays) have experience a decrease in flux with time as the Sun is spinning down. The photosphere, where most of the infrared, visible and ultraviolet radiation originates, on the other hand is heated mainly via convective energy transport from deeper within the Sun (Gray, 1976) and is thus not affected by solar spin-down.

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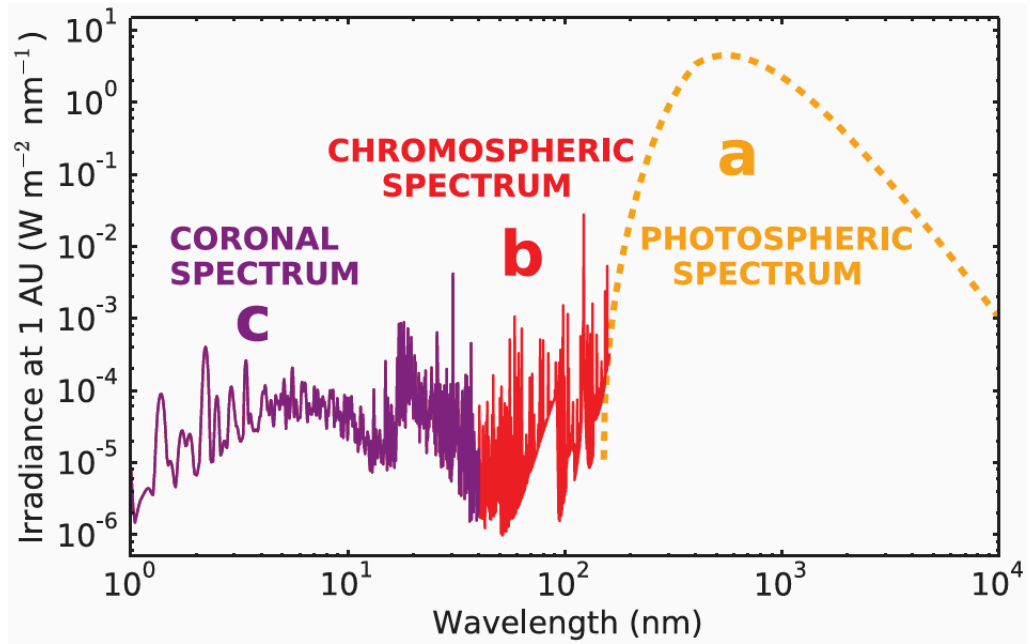


Figure 2.10.: This plot by Johnstone (2017) shows the solar spectrum between 1 nm and 10^4 nm. The spectrum is divided into three parts, each corresponding to the region of the Sun where the majority its radiation originates. At longer wavelengths (above ~ 200 nm) the spectrum is dominated by photospheric emission (a). The photospheric spectrum is then followed by the chromospheric spectrum (b), which dominates the wavelength range between roughly 40 nm and 200 nm. Lastly at short wavelengths (below ~ 40 nm) the solar spectrum is dominated by emission originating in the corona (c). Chromospheric and coronal spectra calculated by Fontenla et al. (2011).

3. Methods

3.1. The Kompot Code

The Kompot code was developed by Johnstone et al. (2018). It is a first principles one dimensional model of the thermal, chemical as well as hydrodynamic structures of planetary upper atmospheres given arbitrary planetary, atmospheric and stellar input parameters. As such the code is applicable to a wide and diverse range of planetary conditions. Kompot's simulation domain extends radially outward starting from an arbitrary point in the planet's atmosphere and extending up to the exobase at an arbitrary zenith angle. An illustration of the code's geometry can be seen in figure 3.1. The authors have made three basic assumptions about the state of the simulated atmospheres:

1. The gas has one bulk advection speed which is shared by the entire gas. Individual diffusion speeds are, however, taken into account for different chemical species.
2. The gas is made up of three components: Neutrals, Ions and Electrons. Each of these have their own individual temperatures, which evolve separately from each other.
3. Quasineutrality holds within the entire gas, meaning that the electron density must be equal to the total ion density everywhere.

In addition to the three gas components described above, the gas is also broken down into different chemical species (e.g. N_2 , O_2 , CO_2 , etc.). With regards to the stellar input, the model takes into account two crucial wavelength ranges:

- the X-ray and ultraviolet (XUV) field in the range of $10\text{\AA}$ and $4000\text{\AA}$ and
- the infrared (IR) field between $1\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$.

These wavelength ranges are vital for accurately modelling a planet's atmosphere because XUV is very efficiently absorbed by atmospheric gases high up in the atmosphere. There it can significantly influence gas temperatures because of the low gas density at these altitudes, which makes it possible for comparatively low amounts of input energy change the gas temperature by large margins. XUV further serves as a vital driver of photochemistry in the upper atmospheres of planets and therefore needs to be taken into account to accurately model the atmosphere's chemical structure. Additionally IR wavelengths are strongly absorbed by CO_2 , which makes modelling this wavelength range's effects particularly important for simulations of planets with CO_2 -dominated atmospheres, such as Venus.

3. Methods

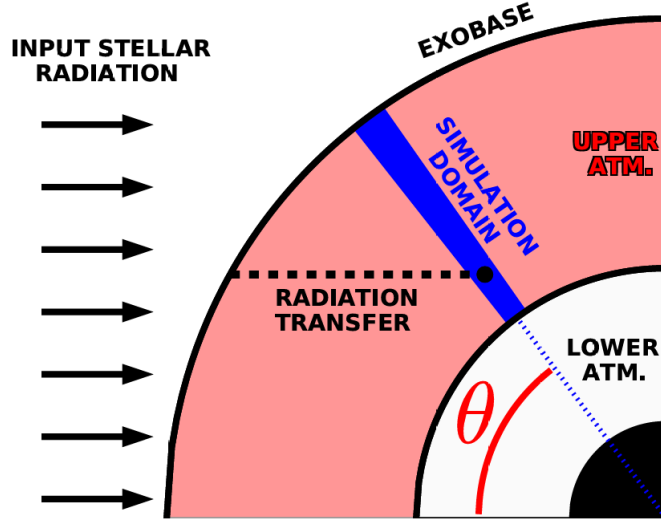


Figure 3.1.: A schematic illustration of the Kompot code’s geometry from Johnstone et al. (2018). The bottom right symbolizes the planet’s center, radially outward from it extends first the planet up to the surface (black), then the lower atmosphere (white) until an arbitrary point chosen by the user which denotes the boundary to the upper atmosphere (red). Kompot’s simulation domain (blue) is a one dimensional slice of the upper atmosphere that points radially outward from the planet’s center and extends from said arbitrary point all the way up to the exobase. The simulation domain is located at an arbitrary angle (θ) relative to the incoming stellar radiation (i.e. the zenith angle), which propagates from left to right and is represented by the black arrows on the left part of the figure.

The most important physical processes taken into account by Kompot as listed by Johnstone et al. (2018) are:

- atmospheric expansion/contraction in response to changes in the gas temperature and composition;
- the transfer of X-ray, ultraviolet, and infrared radiation through the atmosphere, including the production of non-thermal electrons by photoionization reactions;
- atmospheric chemistry, including photochemistry and reactions driven by impacts with non-thermal electrons,
- molecular and eddy diffusion;
- neutral heating by stellar XUV and IR radiation;
- electron heating by impacts with non-thermal electrons;
- infrared cooling, particularly by CO_2 molecules;

- heat conduction for each gas component;
- and energy exchange between the components.

In the code these processes are modelled via the following equations (eqs. 3.1 - 3.5):

$$\frac{\partial n_j}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} [r^2(n_j v + \Phi_{d,j})] = S_j, \quad (3.1)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} [r^2(\rho v^2 + p)] = -\rho g + \frac{2p}{r}, \quad (3.2)$$

$$\begin{aligned} \frac{\partial e_n}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} [r^2 v(e_n + p_n)] &= -\rho_n v g + (Q_{h,n} - Q_{c,n} - Q_{in} - Q_{en}) \\ &+ \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \kappa_{\text{mol}} \frac{\partial T_n}{\partial r} \right] \\ &+ r^2 \kappa_{\text{eddy}} \left(\frac{\partial T_n}{\partial r} + \frac{g}{c_P} \right), \end{aligned} \quad (3.3)$$

$$\begin{aligned} \frac{\partial e_i}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} [r^2 v(e_i + p_i)] &= -\rho_i v g + (Q_{h,i} - Q_{c,i} - Q_{ei} + Q_{in}) \\ &+ \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \kappa_i \frac{\partial T_i}{\partial r} \right], \end{aligned} \quad (3.4)$$

$$\begin{aligned} \frac{\partial e_e}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} [r^2 v(e_e + p_e)] &= -\rho_e v g + (Q_{h,e} - Q_{c,e} + Q_{ei} + Q_{en}) \\ &+ \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \kappa_e \frac{\partial T_e}{\partial r} \right], \end{aligned} \quad (3.5)$$

where r denotes radius, n_j is the number density of the j th species, ρ represents the total mass density and v is the bulk advection velocity. The quantity ρv corresponds to the momentum density, while ρ_k , e_k , p_k , and T_k denote the mass density, energy density, thermal pressure, and temperature of the k th gas component, respectively. The terms $\Phi_{d,j}$ and S_j represent the diffusive particle flux as well as the chemical source term for the j th species, while g represents the gravitational acceleration. Furthermore, $Q_{h,k}$ and $Q_{c,k}$ describe the heating and cooling functions for the k th component (i.e. neutrals, ions or electrons), whereas Q_{ei} , Q_{in} , and Q_{en} correspond to electron-ion, ion-neutral, and electron-neutral heat exchange functions. The coefficients κ_{mol} , κ_{eddy} , κ_i and κ_e denote the molecular, eddy, ion and electron thermal conductivities respectively. Finally, c_P is the specific heat at constant pressure. Equation 3.1 corresponds to the mass continuity equation, as diffusion processes and chemical reactions do not alter the total mass density of the entire gas (Johnstone et al., 2018), equation 3.2 is the momentum equation and equations 3.3 - 3.5 are energy equations and describe the evolution of the thermal energy of neutral particles (eq. 3.3), ions (eq. 3.4) and electrons (eq. 3.5).

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3.2. Fitting the Eddy Diffusion Parameters

One large hurdle encountered during my work on this thesis was fitting the correct eddy diffusion parameters for Venus' atmosphere within the Kompot code. This problem came up initially when my supervisor, Dr. Kislyakova, and her research group noticed that the mixing ratios of the chemical species at Venus' exobase in my preliminary simulations did not match observations. As shown in the left plot of figure 3.3, the code initially predicted CO₂ molecules to make up the majority (> 60%) of the particles at the exobase, followed by N₂, CO and O with just over 10% each and N with almost 0.2%. In reality, however, this should not be the case as CO₂ would get broken up via photodissociation at these heights (Gérard et al. 2009, Keating et al. 1980). Eventually the cause of this inaccuracy was traced back to eddy diffusion, as the initially assumed values for the eddy diffusion parameters did not accurately reproduce the observed Venusian atmosphere. This resulted in the simulated atmosphere experiencing stronger mixing than it should have, which caused large quantities of CO₂ from lower atmospheric layers to be transported higher upwards than is realistically the case. This is illustrated in figure 3.2. Here the top panels show that before the correction of the eddy diffusion parameters the same three chemical species remain dominant across all altitudes, meaning that these are efficiently replenished via mixing at higher altitudes, where their abundances would otherwise decrease due to photodissociation. The middle panels, on the other hand, offer a much more diverse picture with none of the five most abundant species at the simulation's base remaining in the same order of abundance at the exobase. The most extreme case is depicted in the lower panels, which correspond to Venus 3.2 Gyr ago. At this time the Sun's higher XUV-flux in the past leads to a more extended atmosphere, a much stronger reduction of CO₂ due to photodissociation and an enhanced ionisation of the atmosphere, as evidenced by three of the five most abundant species at the exobase at this time consisting of ions and electrons.

Eddy diffusion describes the mixing of fluids via turbulent motion. It occurs for example when a fluid flows past an obstacle in its way and is characterised by parcels of fluid moving in swirling motions (called "eddies", hence the name "eddy diffusion") of various sizes, continuing downwards in scale until the regime where molecular diffusion takes over (Kalinske and Pien, 1944). In the context of this thesis eddy diffusion is a vital contributor to the propagation of heat and chemical species within the atmosphere of Venus. In the Kompot code diffusion is modelled by solving equation 3.6, where $\Phi_{d,j}$ is the diffusive flux, n_j is the particle number density and $v_{d,j}$ is the diffusion speed for the j th chemical species respectively. This equation takes into account both molecular as well as eddy diffusion via $v_{d,j}$.

$$\Phi_{d,j} = n_j v_{d,j}. \quad (3.6)$$

3.2. Fitting the Eddy Diffusion Parameters

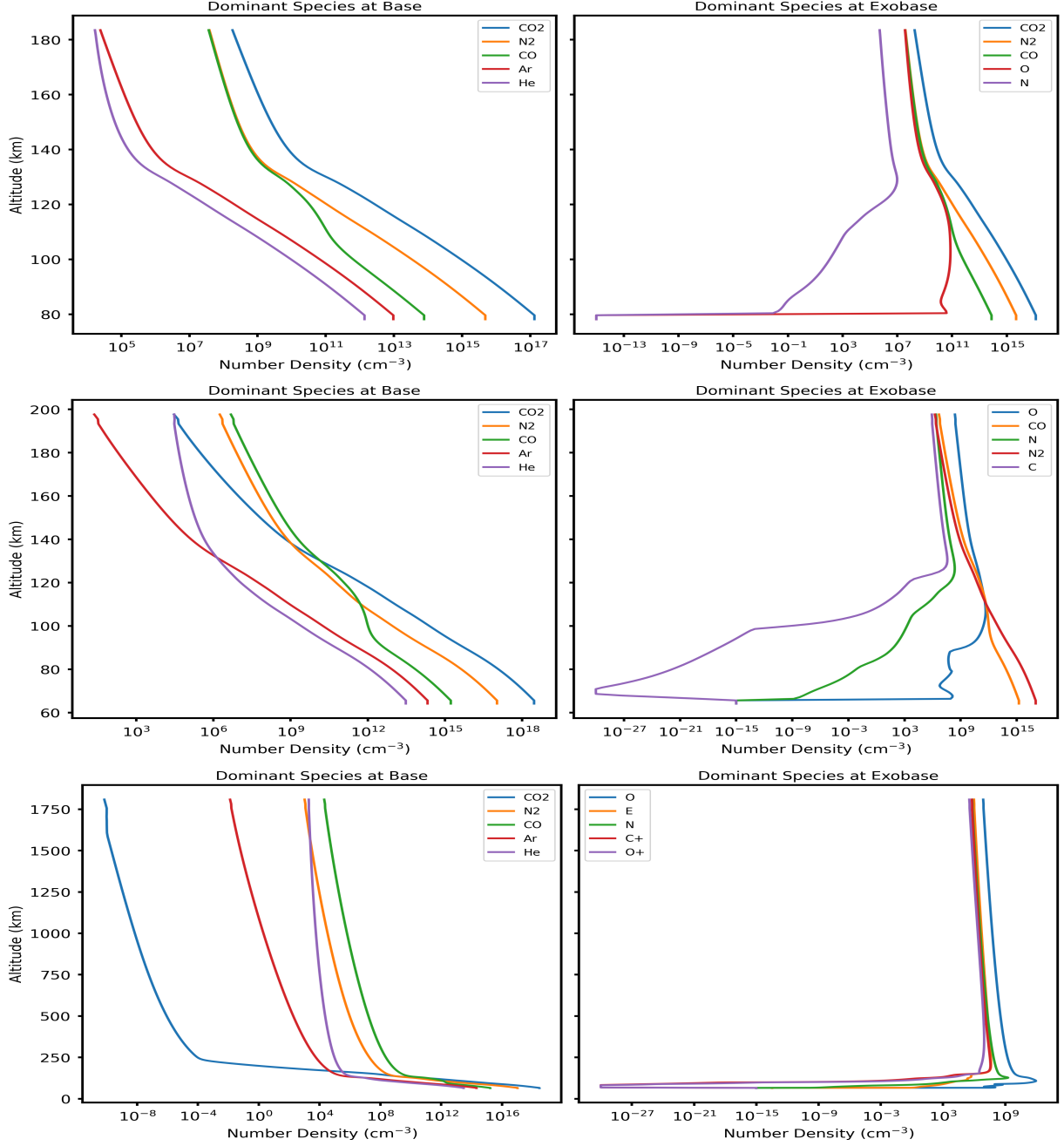


Figure 3.2.: The vertical profiles of the five most abundant chemical species at the base of the simulation (left panels) and at the exobase (right panels) before the correction of the eddy diffusion parameters (top panels) and after the correction (middle panels) for current Venus as well as for Venus 3.2 Gyr ago (bottom panels).

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The diffusion speed, $v_{d,j}$, is in turn given by equation 3.7. Here D_j and K_E denote the molecular and eddy diffusion coefficients respectively, N is the particle number density of the entire gas, m_j and $\bar{m}$ are the molecular masses of the j th species and the gas as a whole, p and T are the thermal pressure and temperature of the entire gas and $\alpha_{T,j}$ is the thermal diffusion factor.

$$v_{d,j} = -D_j \left[\frac{1}{n_j} \frac{dn_j}{dr} - \frac{1}{N} \frac{dN}{dr} + \left(1 - \frac{m_j}{\bar{m}} \right) \frac{1}{p} \frac{dp}{dr} + \frac{\alpha_{T,j}}{T} \frac{dT}{dr} \right] - K_E \left[\frac{1}{n_j} \frac{dn_j}{dr} - \frac{1}{N} \frac{dN}{dr} \right]. \quad (3.7)$$

Lastly the eddy diffusion coefficient K_E (with dimensions of cm^2s^{-1}) is given by equation 3.8, where A and B are free parameters and dimensionless and N is the particle number density of the entire gas.

$$K_E = AN^B. \quad (3.8)$$

Thus there are a total of three free parameters that influence eddy diffusion in the Kompot code: A , B and $K_{\text{eddy, max}}$ (the upper limit of K_E). Initially these parameters were assumed to be: $A = 2 \cdot 10^{13}$, $B = -0.5$ and $K_{\text{eddy, max}} = 2 \cdot 10^8 \text{ cm}^2\text{s}^{-1}$ (Johnstone et al., 2018) based on earlier studies by Fox (2015) and von Zahn et al. (1980). In order to test which values for these parameters provided the best fit for Venus' atmosphere, I adopted three possible values for each of the three parameters (see table 3.1) and conducted a simulation for every possible combination of these. This resulted in a total of 27¹ simulations.

Table 3.1.: The different values for the three eddy diffusion parameters A , B and $K_{\text{eddy, max}}$ used to test which combination of these yielded the best results for Venus' atmosphere.

A	B	$K_{\text{eddy, max}} (\text{cm}^2\text{s}^{-1})$
1.0×10^7	-0.01	6.0×10^7
1.0×10^8	-0.1	6.0×10^8
1.0×10^9	-0.5	6.0×10^9

In the end the following combination of numerical values were adopted for the eddy diffusion parameters:

- $A = 1.0 \times 10^7$
- $B = -0.1$
- $K_{\text{eddy, max}} = 6.0 \times 10^9 \text{ cm}^2\text{s}^{-1}$

¹In actuality only 21, as the simulations with $B = -0.5$ proved rather unstable and in most cases either terminated before reaching a steady state or did not run at all.

3.2. Fitting the Eddy Diffusion Parameters

As seen in the right plot of figure 3.3, adopting these new values for the eddy diffusion parameters has led to the model now correctly predicting atomic oxygen to be the main component of the atmosphere at higher altitudes, particularly at the exobase (Hedin et al. 1983, Gérard et al. 2009, Keating et al. 1980). Table 3.2 further compares the mixing ratios of O, CO, N and N₂ as obtained by Kompot (at the exobase, calculated at ~ 198 km) after the eddy diffusion correction to the previous model of Hedin et al. (1983) (at an altitude of 200km) as well as the number densities of O, CO, N and CO₂ (at 100 km) with a previous model by Krasnopolsky (2012). These seem to be in good general agreement, although there are still some noticeable differences. The mixing ratio of atomic oxygen, for example, is about 10 percentage points lower in the Hedin et al. (1983) model than predicted by Kompot, while all of the other species have correspondingly higher mixing ratios (except for C, which is not part of the dataset by Hedin et al. 1983). This is especially true for CO, which is higher by a factor of 4.5. Furthermore the Hedin-model predicts He to be a major component at the considered altitude, which Kompot does not reproduce. A reason for these discrepancies could be the different locations of evaluation between the two models. The Kompot data corresponds to a latitude of 66°, while the Hedin-model evaluated conditions at 0° (i.e. at the equator). The number densities obtained via Kompot meanwhile are also reasonably close to those predicted by the model of Krasnopolsky (2012). The number densities of O and CO from Kompot are each higher than those by Krasnopolsky (2012) by a factor of approximately 4, while that of CO₂ is correspondingly lower by a factor of ~ 3 , suggesting that Kompot exhibits an enhanced dissociation of CO₂ at this altitude when compared to the Krasnopolsky (2012) model. A notable exception, however, is N, which is 4 orders of magnitude more abundant in the model of Krasnopolsky (2012) than in Kompot. This could be a result of the fact that the Krasnopolsky (2012) model does not include N₂, which is a major atmospheric component at 100 km. As such a rather small change in the number density of N₂ can significantly influence the abundance of N.

Table 3.2.: Comparison between the mixing ratios and number densities of the five most abundant chemical species at Venus’ exobase as well as CO₂ obtained in this work via the Kompot code with the corresponding values from Hedin et al. (1983) (mixing ratios at 200 km) and Krasnopolsky (2012) (number densities at 100 km). Values from Hedin et al. (1983) were modelled for the equator at noon. Kompot calculations were obtained for a latitude of 66°.

Source	Height (km)	O	CO	N	N ₂	C	CO ₂
This work	198	96.03%	1.89%	0.89%	0.70%	0.33%	0.01%
Hedin et al. (1983)	200	85.98%	8.53%	1.56%	1.92%	N/A	N/A
This work	100	$2.72 \cdot 10^{11}$	$1.01 \cdot 10^{12}$	$1.88 \cdot 10^3$	$8.81 \cdot 10^{12}$	$1.17 \cdot 10^{-9}$	$2.38 \cdot 10^{14}$
Krasnopolsky (2012)	100	$6.38 \cdot 10^{10}$	$2.33 \cdot 10^{11}$	$2.67 \cdot 10^7$	N/A	N/A	$7.99 \cdot 10^{14}$

For further validation, vertical CO₂-, CO-, H₂O- and temperature-profiles obtained via Kompot have been compared to data obtained by Mahieux et al. (2023) and Fedorova et al. (2008) from the SOIR-instrument aboard ESA’s Venus Express spacecraft. This comparison can be seen in figure 3.4. The top left plot shows that the vertical CO₂ number

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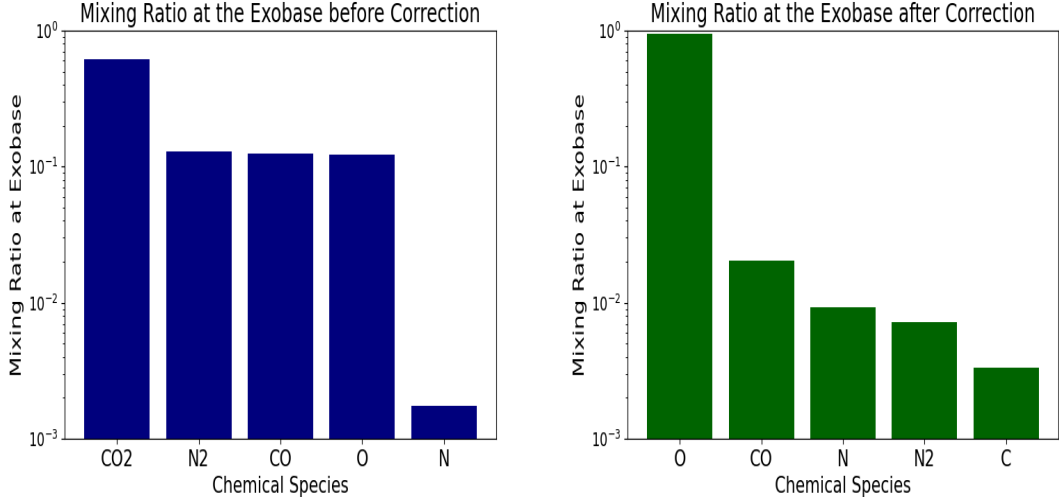


Figure 3.3.: Comparison of the five most abundant chemical species at the exobase before (left) and after (right) adopting the new values for the eddy diffusion coefficients.

densities of Kompot and SOIR align rather well. For CO (top right) the general shape of both profiles similarly fit reasonably well, although there is a systematic shift in altitude. This could be a result of the way the altitude is inferred via the pressure-temperature profile, which can exhibit large variations (Mahieux et al., 2023). An additional factor could be that the SOIR data by Mahieux et al. (2023) was plotted against pressure while the Kompot data is calculated directly from altitude. As such the SOIR data had to be converted from pressure to altitude for comparison. This was done via the linear *interp1d*-function of the Scipy Python package as this interpolation method produced the smallest relative error of the tested interpolation functions (see figure A.5). In the case of H₂O (bottom left) the VMR (volume mixing ratio) calculated by Kompot differs both in shape and magnitude from the data of Mahieux et al. (2023), while measurements by Fedorova et al. (2008) occupy a sort of "middle ground" between the previous two profiles. This is, however, not overly surprising as the H₂O mixing ratio in the Venusian atmosphere has been shown by e.g. Fedorova et al. (2008) to vary both with time and latitude, as can be seen in figure 3.5. Lastly Kompot's vertical temperature profile aligns well with the SOIR measurements of Mahieux et al. (2023) above an altitude of roughly 110 km (albeit with a similar vertical shift to the one discussed previously in the case of CO) but does not reproduce the temperature peak at just above 100 km and diverges below ~ 80 km. It has to be noted, however, that this peak is not present in the temperature profile of Fedorova et al. (2008) or the VIRA profile (Seiff et al., 1985), both of which also generally agree with the higher temperatures below 80 km predicted by Kompot.

3.2. Fitting the Eddy Diffusion Parameters

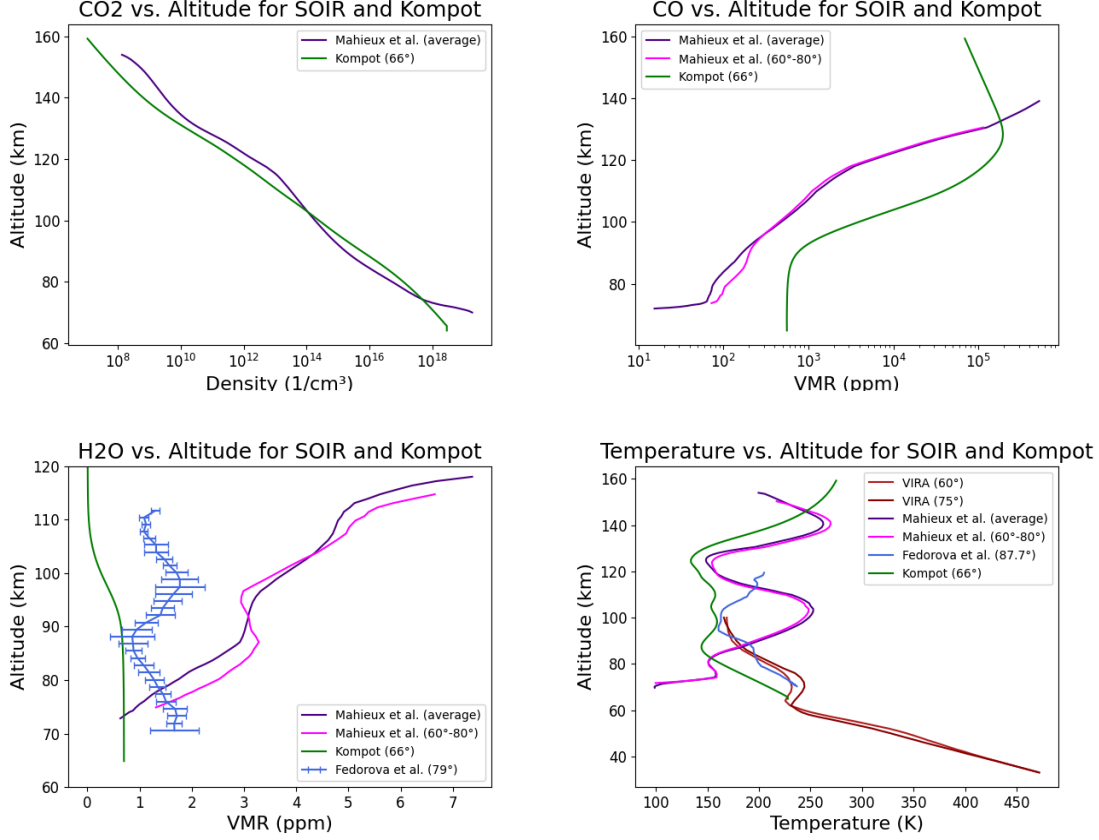


Figure 3.4.: Comparison of CO₂ (top left), CO (top right), H₂O (bottom left) and temperature (bottom right) profiles between Kompot and SOIR-data from Mahieux et al. (2023). H₂O has additionally been compared to H₂O measurements from Fedorova et al. (2008), while Kompot's temperature profile has been compared to the Venus International Reference atmosphere (VIRA) (Seiff et al., 1985) as well as the model used by Fedorova et al. (2008). CO₂ and temperature data is given in number density (cm⁻³) and Kelvin respectively, while for CO and H₂O the data is presented in VMR (volume mixing ratio) in parts per million (ppm). For the original SOIR-profiles from Mahieux et al. (2023) and their associated uncertainties see figures A.1, A.2, A.3 and A.4 in appendix A.

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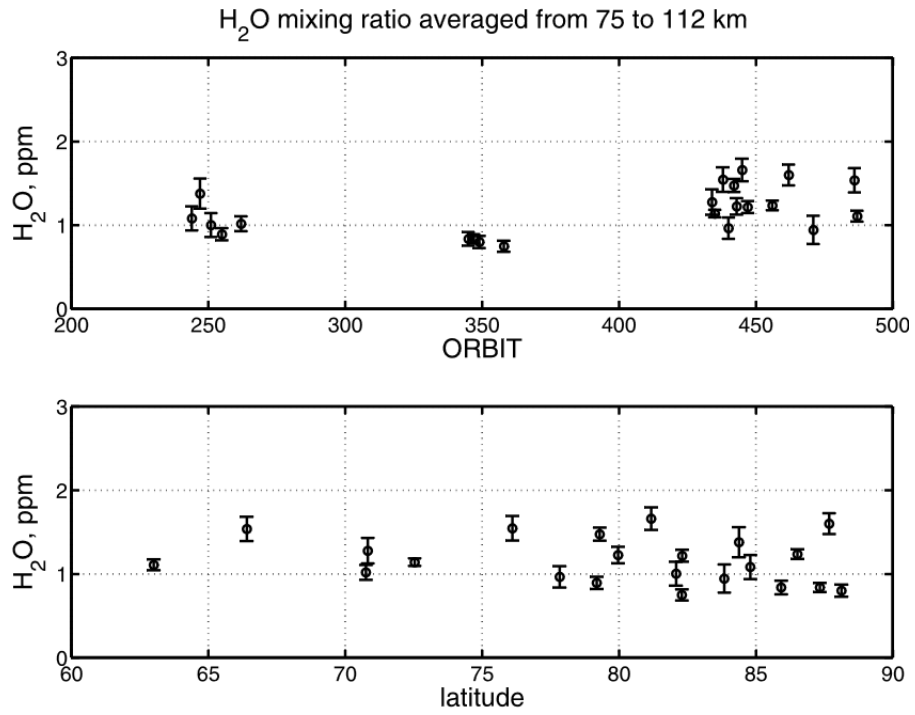


Figure 3.5.: This plot by Fedorova et al. (2008) shows the variability of the H₂O mixing ratio between altitudes of 75 km and 112 km measured by Venus Express' SOIR instrument with respect to time (top) as well as latitude (bottom). In the top plot one orbit corresponds to one day.

4. Results

The first quantity investigated over the course of this thesis was the height of Venus' exobase and how it has evolved in the past. This can be seen in figure 4.1, where the vertical axis shows the exobase altitude in kilometers, while the horizontal axis displays time in gigayears from 3.2 Gyr in the past to now (0.0 Gyr). The height of the Venusian exobase shows a continual decrease from ~ 1800 km 3.2 Gyr ago to ~ 200 km for today's Venus, which corresponds to a contraction by a factor of 9.

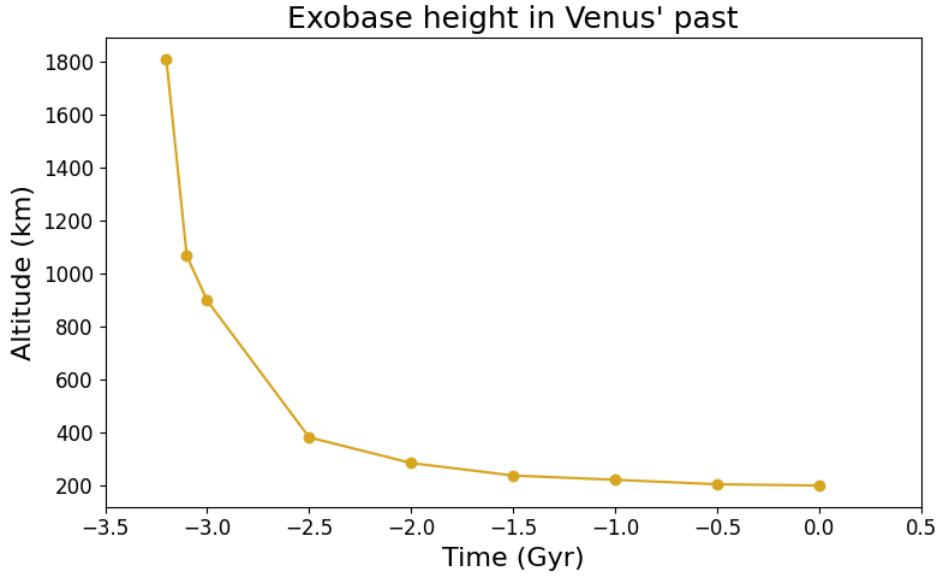


Figure 4.1.: The temporal evolution of the altitude of Venus' exobase (in km) from now to 3.2 Gyr in the past.

In a further step the temporal evolution of solar ultraviolet radiation on Venus was investigated. Figure 4.2 shows the flux (in erg/s/cm^2) of UV-A (400 nm - 315 nm), UV-B (315 nm - 280 nm) and UV-C (280 nm - 100 nm) radiation with respect to time from 3.2 Gyr in the past to current conditions (0.0 Gyr) for both the incident flux at the top of the atmosphere (labelled TOA, green shades) as well as the remaining flux that reaches the top of the cloud layer at 65 km (purple shades). Figures 4.3, 4.4 and 4.5 provide a more detailed look at the individual data for UV-A, UV-B and UV-C respectively. Each of the three investigated wavelength ranges shows a steady increase from their lowest levels 3.2 Gyr ago to those corresponding to the present day. The increases amount to 36.70% for UV-A, 40.83% for UV-B and 48.14% for UV-C. The difference between

4. Results

the flux at the top of the atmosphere and the flux reaching the top of the cloud layers, meanwhile, is negligible for both UV-A and UV-B and amounts to $\sim 10\%$ for UV-C without a significant dependence on time.

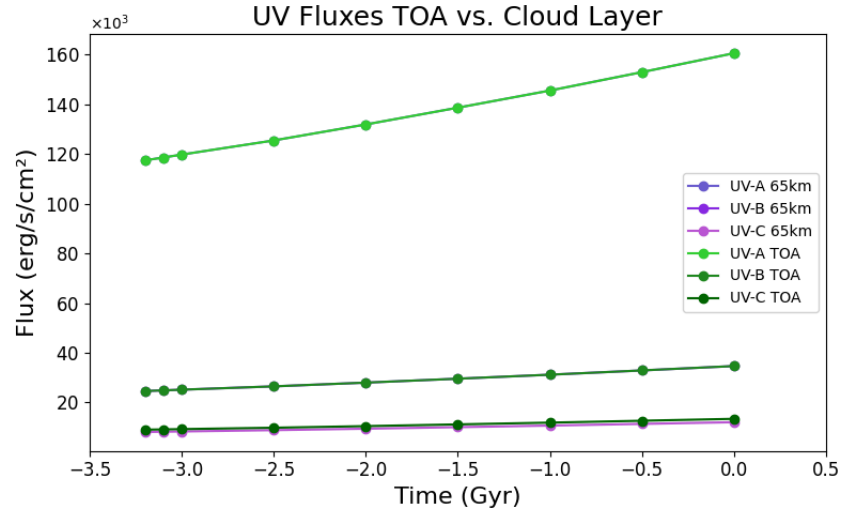


Figure 4.2.: The change of the UV-A, -B and -C flux striking the top of the Venusian atmosphere (green shades) and reaching the cloud layer at 65 km (purple shades) with respect to time. For UV-A and -B the TOA and 65 km lines overlap as there is only a negligible difference between them. Flux values in erg/s/cm^2 , time in gigayears from now to 3.2 Gyr in the past.

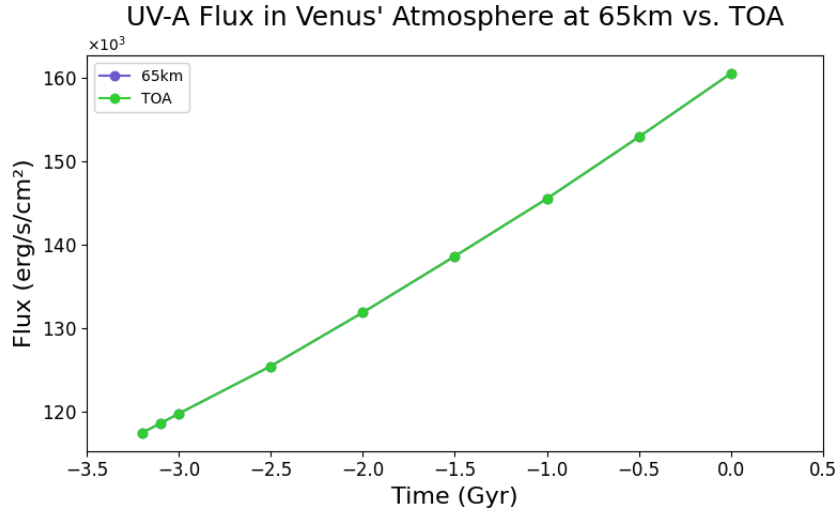


Figure 4.3.: The change of the UV-A flux striking the top of the Venusian atmosphere (green) and reaching the cloud layer at 65 km (purple) with respect to time. TOA and 65 km lines overlap as there is only a negligible difference between them. Flux values in erg/s/cm^2 , time in gigayears from now to 3.2 Gyr in the past.

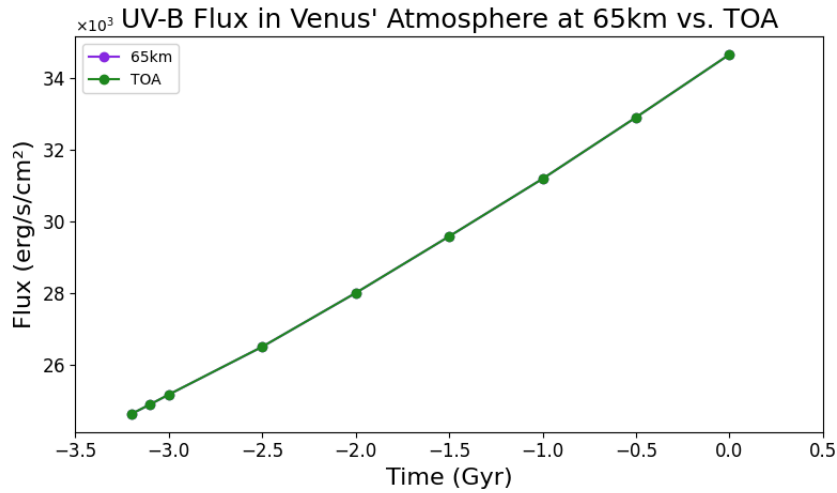


Figure 4.4.: The change of the UV-B flux striking the top of the Venusian atmosphere (green) and reaching the cloud layer at 65 km (purple) with respect to time. TOA and 65 km lines overlap as there is only a negligible difference between them. Flux values in erg/s/cm^2 , time in gigayears from now to 3.2 Gyr in the past.

4. Results

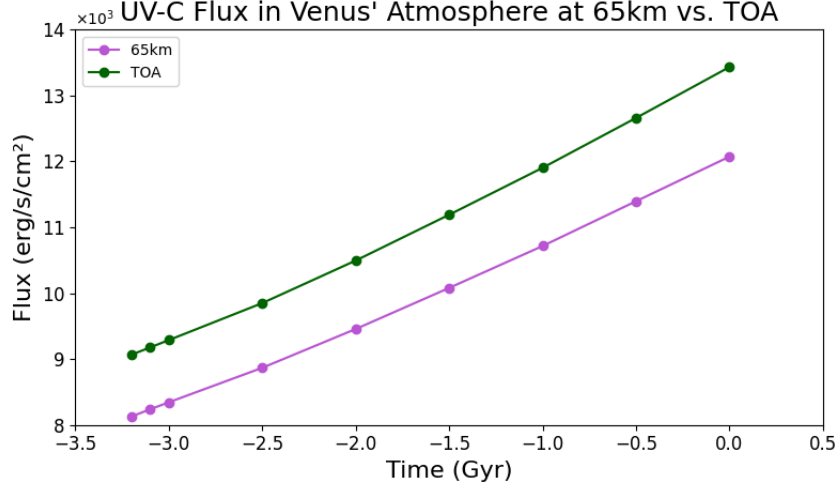


Figure 4.5.: The change of the UV-C flux striking the top of the Venusian atmosphere (green) and reaching the cloud layer at 65 km (purple) with respect to time. Flux values in erg/s/cm^2 , time in gigayears from now to 3.2 Gyr in the past.

Finally the UV-C fluxes at 65 km were compared to the radiation dosage necessary to achieve a 2 log (99%) reduction in microbial populations of bacterial species. The survival times of the ten most resilient bacteria of this thesis' dataset are shown in figure 4.6 for the limiting cases of the current UV flux (dark green) as well as the flux 3.2 Gyr ago (light green). A complete list of the entire dataset can be found in table A.1 in appendix A. The dosages in the table correspond to a 90% (1 log) reduction in microbial population. These were multiplied by a factor of 2 to obtain the required dosage for 2 log (99%) reduction. The time until this dosage was reached was then calculated by solving equation 4.1

$$D_{99} = E \times t_{99} \quad (4.1)$$

for the exposure time needed for 99% reduction, t_{99} , (in seconds), with D_{99} being the UV dosage (in J/m^2) required for 99% reduction and E being the UV irradiance (in W/m^2). The organism with the longest survival time under current conditions on Venus in figure 4.6 is *Deinococcus radiodurans*, with 227 seconds (just shy of 4 minutes) until 99% reduction. Together with the spores of *Bacillus anthracis* it was the only species exhibiting a t_{99} of over 100 seconds. The average t_{99} of the 70 bacteria that were researched in this thesis amounts to just over 15 seconds (or 10.5 seconds if *D. radiodurans* and *B. anthracis* spores are excluded).

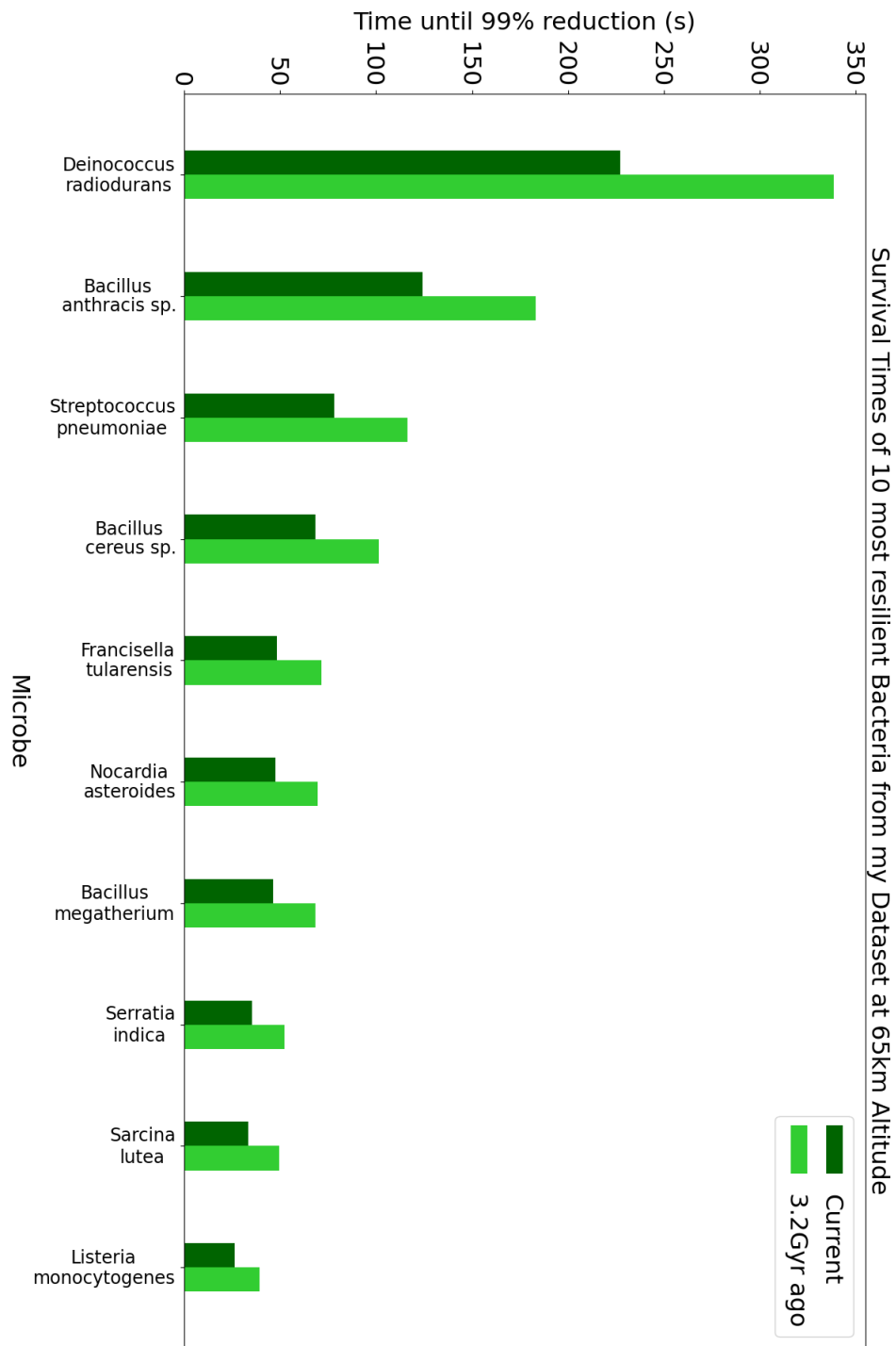


Figure 4.6.: Time (in seconds) until 99% reduction in microbial population for the 10 most resilient bacterial species analysed in this thesis under both current conditions (dark green) as well as conditions 3.2 Gyr in the past (light green). For a complete list of all bacteria, their associated radiation tolerances, resulting survival times and sources of these data see table A.1 in appendix A.

5. Discussion and Conclusions

As is evident in figure 4.1, the altitude of Venus’ exobase increases substantially when going back in time. This result is not surprising as the sun’s X-ray and ultraviolet (XUV) luminosity used to be significantly higher in the past (see section 2.3). XUV radiation is absorbed in the upper regions of planetary atmospheres and thus deposits heat there, which causes the gas to expand and leads to a more extended atmosphere (Johnstone et al. 2021, Lammer et al. 2006, Kulikov et al. 2007, Tian et al. 2008). The resulting atmospheric expansion is further exacerbated by the fact that XUV radiation leads to dissociation of CO_2 (Johnstone et al. 2021, Tian 2009), which would otherwise cool the upper atmosphere via emission of infrared radiation (Roble 1995, Kulikov et al. 2007). A more extended atmosphere in turn means that its upper regions experience a weaker gravitational pull, while higher temperatures result in a larger number of particles being sufficiently accelerated to achieve escape velocity. Both of these effects taken together lead to higher atmospheric loss by increasing Jeans escape rates or in more extreme cases inducing the bulk outflow of atmospheric gas via hydrodynamic escape (Gronoff et al. 2020, Gross 1972). Thus understanding atmospheric expansion is vital for accurately modelling the evolution of planetary atmospheres.

Figures 4.2, 4.3, 4.4 and 4.5 show that the incident fluxes of UV-A, -B and -C on Venus were generally lower in the planet’s past. 3.2 Gyr ago the flux at the top of the atmosphere (TOA) made up only 73.15%, 71.01% and 67.51% of the current levels for UV-A, -B and -C respectively. As mentioned above and discussed in more detail in section 2.3 this is a result of the evolution of the solar flux. While the XUV field as a whole used to have a higher flux in the past, the fluxes for most of the UV-range were actually lower than current values and instead increased with time (Claire et al., 2012), as is shown in figure 2.9. This is due to the different origins of these wavelength ranges. The majority of the solar UV radiation originates in the photosphere and is thus not affected by solar spin-down. Lower wavelengths, originating from the chromosphere and the corona, on the other hand are tightly linked with the evolution of the solar dynamo and thus affected more strongly by the solar spin-down. More interesting, perhaps, than the change in flux with respect to time is the change with respect to altitude. For UV-A and UV-B there is almost no difference between the TOA flux and the flux at 65 km, meaning that there is practically no mitigation of the radiation at these wavelengths. Even for UV-C this mitigation is rather minuscule, as the flux only drops by just over 10% between the top of the atmosphere and the upper boundary of the cloud layer at 65 km. This result shows that the Venusian atmosphere above the cloud layer lacks an efficient UV-absorber like ozone and is consistent with the results of previous studies (e.g. Patel et al. 2022).

5. Discussion and Conclusions

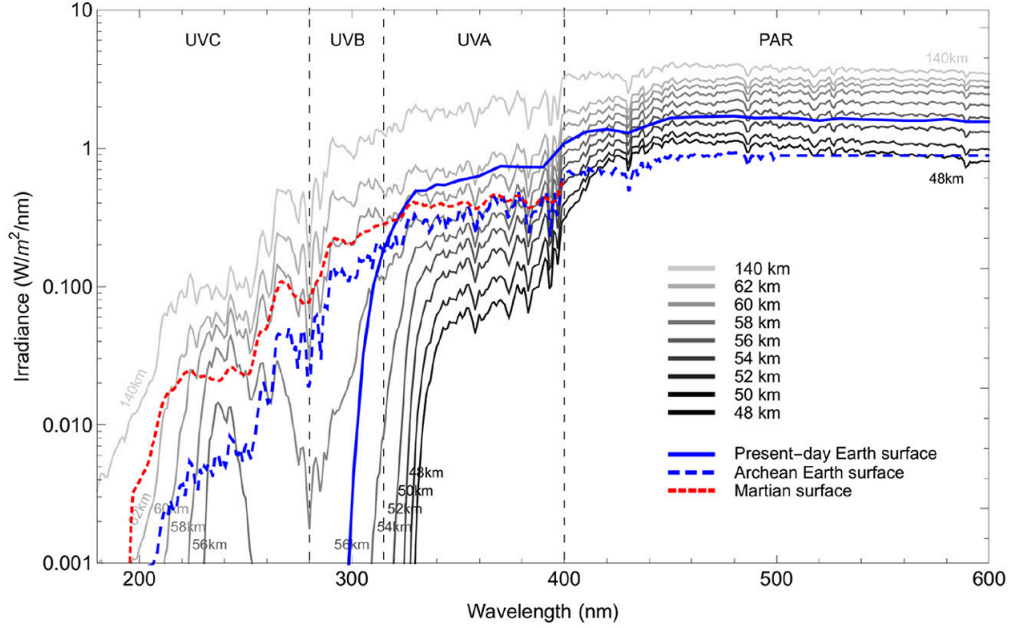


Figure 5.1.: This plot by Patel et al. (2022) shows the change in irradiance between 180 nm and 600 nm for different altitudes on Venus. Spectra for present day Earth (continuous blue line) and Archean Earth (dashed blue line) by Ranjan and Sasselov (2017) as well as present day Mars (dashed red line) by Patel et al. (2004).

Figure 5.1 shows the irradiance spectrum between 180 nm and 600 nm at various altitudes in the Venusian atmosphere compared to the surfaces of present day Earth and Mars as well as that of the Archean Earth. Here too the UV spectra show only little decrease between the highest modelled altitude (140 km) and the next increment (62 km), with that decrease mostly being caused by the clouds (see figure 5.2). The two Earth-spectra illustrate the importance of ozone as a UV-absorber. On present day Earth almost no radiation at wavelengths lower than 300 nm (i.e. most of the UV-B range and all of UV-C) reaches the surface, while the Archean Earth, before the great oxidation event enriched Earth's atmosphere with oxygen and thus allowed for the formation of the ozone layer (Chen et al. 2022, Ranjan and Sasselov 2017), was exposed to radiation at wavelengths as low as ~ 200 nm (see also figure 2.7). Furthermore the differences of the UV fluxes at the top of Venus' atmosphere and at 65 km from figures 4.2, 4.3, 4.4 and 4.5 exhibit no dependence on time, indicating that Venus did not have significant amounts of ozone in its upper atmosphere at any point during the last 3.2 Gyr. It does, however, have to be noted that this thesis assumed the basic composition of Venus' atmosphere to remain constant at all times and thus did not take major changes to atmospheric makeup (e.g. via outgassing) into account, as we currently lack a clear picture of the past evolution of Venus (see section 2.1.1).

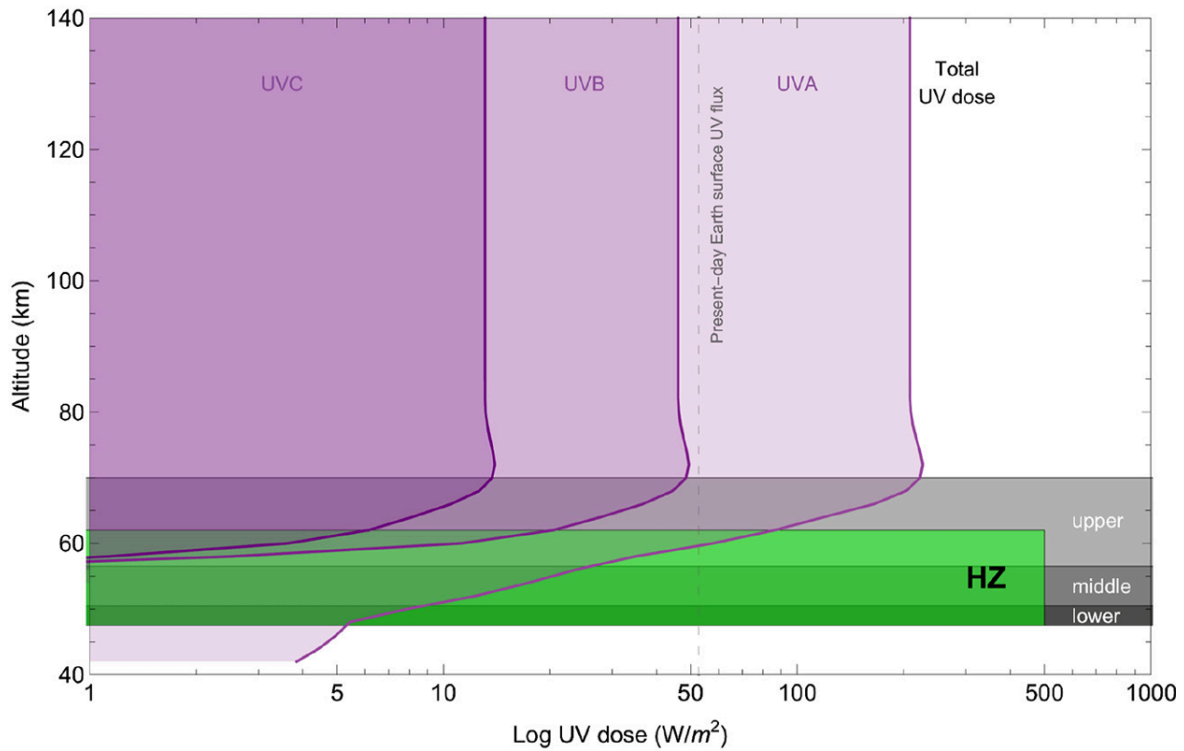


Figure 5.2.: This plot by Patel et al. (2022) shows the change in integrated UV irradiance between 200 nm and 400 nm for UV-A, -B and -C as a function of altitude in the Venusian atmosphere. The positions of the cloud layers are included in shades of grey. Lastly the likely habitable zone within the clouds, which was defined by Patel et al. 2022 as extending from the lower cloud boundary up to the altitude where temperatures drop to -20°C (62 km), is marked by the green area.

The survival timescales in figure 4.6 paint a stark picture for the possibility of Venusian life. For *Deinococcus radiodurans* (the most resilient bacterium of this thesis' dataset) 99% reduction in microbial population occurs after only 227 seconds of exposure to current Venusian levels of UV-C radiation. Even at the lower radiation levels experienced by Venus 3.2 Gyr ago *D. radiodurans* would only survive somewhat longer (338 seconds until 99% reduction instead of 227 seconds for present-day Venus), but not long enough to significantly change this picture. There are, however, some caveats to this that apply and need to be considered:

5. Discussion and Conclusions

The Wavelength used for Calculation

The D_{90} -values displayed in table A.1 were obtained in the lab by exposing the tested microbes to UV-C radiation at a wavelength of 254 nm. This is generally done because it is easier to manufacture lamps that emit at certain specific wavelengths than ones that cover wider wavelength ranges, even though the latter would more accurately simulate the conditions in real environments. The fluxes used for the calculation of the time until 99% reduction, meanwhile, consist of the entire UV-C range (i.e. 100 nm to 280 nm) and thus do not translate one to one to laboratory measurements. This discrepancy is, however, unlikely to significantly impact the results of this thesis as the biological sensitivity to UV-C radiation remains relatively constant across most of the UV-C range (see figure 2.7). As such the effects of a given dose of radiation originating from a narrow 254 nm emission lamp and those of a more realistic emission spectrum consisting of the complete UV-C range should be very similar and are not expected to lead to vastly different results.

Enhanced Radiation Resistance

While *D. radiodurans* possesses a significant resistance to radiation it is by no means the most radiation-resistant lifeform that is currently known. Experiments within ESA's BIOPAN-5 facility aboard the Russian satellite FOTON-M2 have for example shown that certain species of lichen (symbiotic colonies of algae/cyanobacteria and fungi) can survive full exposure to space for extended periods of time. The two tested lichen species, *Rhizocarpon geographicum* and *Xanthoria elegans* were fully exposed to space for 16 days during the experiment and showed almost no adverse effects. They managed to restore their metabolic activity in full from the extreme dehydration induced by the vacuum of space within 24 hours and exhibited nearly the same level of photosynthetic activity before and after the experiment (Sancho et al., 2007). This proves that there are indeed lifeforms on Earth that would likely be able to withstand the extreme UV-C radiation on Venus, although it has to be noted that these lichens only survived and did not grow under exposure to the full space conditions. Additionally there is no environment on Earth that experiences similar levels of UV radiation to those arriving at the Venusian cloud tops. As such it is not hard to imagine that potential life on Venus would likely have experienced significantly higher natural selection pressure to develop countermeasures to high doses of radiation. This adaption could even have developed gradually during the course of Venus' runaway greenhouse effect to counter the DNA damage caused by increasing temperatures and aridity. It does have to be noted, however, that this last point is pure conjecture, as no Venusian life has been found so far and there have, to the best of my knowledge, not been any experiments studying the long term adaption of microbes to Venus-like environments.

Clouds

The simulations conducted in this thesis deal solely with atmospheric gases and thus do not take into account aerosols, such as clouds or hazes. For this reason the lower boundary of the simulations was chosen at 65 km (i.e. the upper boundary of the cloud layers). The main absorption of UV-radiation in Venus' atmosphere, however, has been found to take place in the upper clouds, where the "mysterious UV-blue absorber" (MUBA) is located (Titov et al. 2018, Jiang et al. 2024, Patel et al. 2022) (see figure 5.2) instead of higher up in the atmosphere, as is the case on Earth due to its ozone layer. This means that the most important mechanism mitigating the influx of ultraviolet radiation on Venus is not taken into account in this thesis. Furthermore the region in the Venusian cloud system that is generally assumed to be most conducive to life lies within the middle and lower clouds (e.g. Seager et al. 2021, Patel et al. 2022, Limaye et al. 2018, Kotsyurbenko et al. 2021) rather than the upper clouds and thus below the MUBA (see the HZ in figure 5.2). As such this region is significantly more insulated from the incoming UV-radiation than the upper boundary of the clouds, meaning that while my findings likely rule out the possibility of life as we know it existing near the upper boundary of the cloud layers due to the intense UV-radiation in this region, they are not conclusive enough to indicate that UV-radiation is a limiting factor to a potential cloud-borne biosphere in the middle and lower clouds of Venus.

6. Summary

Ever since the discovery of the hellish conditions on its surface, Venus has taken a back seat in our search for potential habitats of life outside of Earth. Life may, however, not be confined to Venus' surface. The middle and lower cloud layers of Venus are home to pressures and temperatures in ranges where life has been observed to survive and even thrive on Earth. It is thus entirely possible that life could have arisen on Venus before the onset of its runaway greenhouse effect and over time slowly migrated upwards into the planet's clement cloud layers driven by evolutionary pressure as conditions on the surface gradually deteriorated. Pressure and temperature, however, are not the only environmental factors a potential Venusian biosphere has to contend with. Another important piece of the puzzle whether life as we know it could persist in the clouds of Venus is exposure to short wavelength ultraviolet (UV) radiation. UV (especially UV-C) can very efficiently damage DNA and thus could render the clouds of Venus uninhabitable without some form of shielding mechanism akin to Earth's ozone layer. For this reason it was the aim of this thesis to investigate whether the Venusian atmosphere currently possesses or has in the past possessed such a mechanism capable of mitigating the influx of UV radiation. This was achieved via simulations using the Kompot code. Kompot is a state of the art model that calculates the chemical and thermal structure of a planet's upper atmosphere within a one dimensional simulation domain for arbitrary planetary parameters and stellar input spectra. In my case the chosen planetary parameters were those of Venus, while the stellar input spectra consisted of different solar spectra corresponding to various epochs of the sun's evolution to allow for the evaluation of the Venusian atmosphere at different points in time.

Before being able to run my suite of simulations I first had to find the best fitting values for the three free eddy diffusion parameters ($K_{\text{eddy,max}}$, A and B) for the Venusian atmosphere, as the initial values led to unrealistic results. This was done by running simulations with all possible combinations of three values for each of the three parameters. After evaluating the results of these and comparing them to measurements from Venus Express' SOIR instrument $K_{\text{eddy,max}} = 6.0 \times 10^9 \text{ cm}^2\text{s}^{-1}$, $A = 1.0 \times 10^7$ and $B = -0.1$ were chosen as the final values for the eddy diffusion parameters. Following the eddy diffusion correction I was able to conduct a set of simulations of the Venusian atmosphere beginning at present-day conditions and spanning back 3.2 Gyr into the past.

6. Summary

The results of these simulations have shown that the altitude of Venus' exobase increased the further back in time the simulations went. This increase especially accelerated for times prior to 2.5 Gyr in the past and is in all likelihood a result of the higher solar XUV flux at these times. In a further step the UV-A, -B and -C fluxes in the Venusian atmosphere were analysed. This analysis has shown that all three spectral ranges exhibited a similar temporal evolution, where their respective fluxes were lowest 3.2 Gyr ago and steadily increased to their highest values at the present day. As for their spatial evolution within Venus' atmosphere there was no significant difference between the incident fluxes of UV-A and UV-B at the top of the atmosphere and those striking the top of the cloud layer at 65 km. Only the UV-C flux exhibited a noticeable difference between the top of the atmosphere and 65 km, decreasing by about 10% without any significant temporal variations. This means that Venus does not possess and likely has never possessed an ozone layer that could mitigate the influx of UV radiation. The UV fluxes at 65 km were then used to calculate the time until 99% reduction in microbial population (t_{99}) for a variety of bacteria. The most resilient of these was *Deinococcus radiodurans* with a t_{99} of 227 seconds under present-day conditions or 338 seconds at the radiation levels 3.2 Gyr ago. These findings indicate that the cloud layers of Venus are likely not habitable due to the intense UV radiation at these heights. A major caveat to this result, however, is the fact that the main absorber of UV radiation in the Venusian atmosphere (the "mysterious UV-blue absorber" or MUBA) is located within the upper cloud layer and thus not accounted for in my simulations. As such the middle and lower clouds of Venus experience significantly lower levels of UV radiation than the simulated fluxes at 65 km. Thus my findings are not conclusive enough to preclude the possibility of life persisting against the odds on Earth's sister-planet and more research into Venus' clouds and the MUBA is needed to definitively answer this question.

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A. Appendix

Table A.1.: Dataset of bacterial species investigated in this thesis. The table shows the name of the bacteria, its type (i.e. if it is in the vegetative or spore form), the dosage of ultraviolet light at 254 nm required for a 1 log (90%) reduction in population (D_{90}), the time (in seconds) until 99% (2 log) reduction in population under current conditions on Venus, the medium and lastly the source of the data. The table (except for *D. radiodurans*) was adapted from UV Light Technology (2020) with some minor corrections as well as the addition of t_{99} , which was calculated in this thesis.

Microbe	Type	D_{90} (J/m^2)	t_{99} (s)	Medium	Source
<i>Acinetobacter baumannii</i>	Veg	18	3	Surface	Rastogi et al. (2007)
<i>B. atrophaeus</i> (<i>B. globigii</i>)	Sp	144	24	Air	EPA (2006)
<i>Bacillus anthracis</i> spores	Sp	743	124	Surface	Knudson (1986)
<i>Bacillus cereus</i> spores	Sp	408	68	Surface	Benoit et al. (1990)
<i>Bacillus megatherium</i>	Sp	273	46	Surface	Hercik (1937)
<i>Bacillus subtilis</i>	Veg	14	3	Air	Nakamura (1987)
<i>Bacillus subtilis</i> spores	Sp	149	25	Air	Ke et al. (2009)
<i>Burkholderia cepacia</i>	Veg	22	4	Air	Fletcher (2004)
<i>Corynebacterium diphtheriae</i>	Veg	33	6	Surface	Sharp (1939)
<i>Escherichia coli</i>	Veg	55	10	Surface	Hollaender (1955)
<i>Escherichia coli</i>	Veg	11	2	Air	Koller (1939)
<i>Francisella tularensis</i>	Veg	288	48	Air	Beebe (1959)
<i>Haemophilus influenzae</i>	Veg	38	7	Surface	Mongold (1992)
<i>Halobacterium</i> sp. NRC-1	Veg	25	5	Surface	Crowley et al. (2006)
<i>Legionella dumoffi</i>	Veg	24	4	Surface	Knudson (1985)
<i>Legionella bozemanii</i>	Veg	15	3	Surface	Knudson (1985)
<i>Legionella gormanii</i>	Veg	26	5	Surface	Knudson (1985)
<i>Legionella jordanii</i>	Veg	11	2	Surface	Knudson (1985)
<i>Legionella longbeach</i>	Veg	11	2	Surface	Knudson (1985)
<i>Legionella micdadei</i>	Veg	15	3	Surface	Knudson (1985)
<i>Legionella oakridgensis</i>	Veg	22	4	Surface	Knudson (1985)
<i>Legionella pneumophila</i>	Veg	5	1	Surface	Knudson (1985)
<i>Legionella wadsworthii</i>	Veg	4	1	Surface	Knudson (1985)
<i>Listeria monocytogenes</i>	Veg	156	26	Surface	Kim et al. (2002)
<i>Micrococcus candidus</i>	Veg	61	11	Surface	Hollaender (1955)
<i>Micrococcus piltonesis</i>	Veg	81	14	Surface	Rentschler et al. (1941)
<i>Micrococcus sphaeroides</i>	Veg	100	17	Surface	Rentschler et al. (1941)
<i>Mycobacterium bovis</i> BCG	Veg	22	4	Surface	Collins (1971)
<i>Mycobacterium bovis</i> BCG	Veg	33	6	Air	Ko et al. (2000)
<i>Mycobacterium parafortuitum</i>	Veg	46	8	Air	Peccia and Hernandez (2001)
<i>Mycobacterium phlei</i>	Veg	63	11	Air	Riley et al. (1976)
<i>Mycobacterium smegmatis</i>	Veg	12	2	Air	Gillis (1974)
<i>Mycobacterium tuberculosis</i>	Veg	11	2	Surface	Collins (1971)
<i>Mycobacterium tuberculosis</i>	Veg	5	1	Air	Riley et al. (1976)
<i>Mycoplasma arthritidis</i>	Veg	7	2	Surface	Furness (1969)

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Bibliography

Microbe	Type	D_{90} (J/m^2)	t_{99} (s)	Medium	Source
Mycoplasma fermentans	Veg	9	2	Surface	Furness (1969)
Mycoplasma hominis	Veg	7	2	Surface	Furness (1969)
Mycoplasma Orale type 1	Veg	11	2	Surface	Furness (1969)
Mycoplasma Orale type 2	Veg	6	1	Surface	Furness (1969)
Mycoplasma pneumoniae	Veg	8	2	Surface	Furness (1969)
Mycoplasma salivarium	Veg	11	2	Surface	Furness (1969)
Neisseria catarrhalis	Veg	44	8	Surface	Rentschler et al. (1941)
Nocardia asteroides	Veg	280	47	Surface	Chick et al. (1963)
Phytomonas tumefaciens	Veg	44	8	Surface	Rentschler et al. (1941)
Proteus vulgaris	Veg	30	5	Surface	Rentschler et al. (1941)
Pseudomonas aeruginosa	Veg	55	10	Surface	Hollaender (1955)
Pseudomonas aeruginosa	Veg	4	1	Air	Sharp (1940)
Pseudomonas fluorescens	Veg	35	6	Surface	Rentschler et al. (1941)
Pseudomonas fluorescens	Veg	3	1	Air	Van Osdell and Foarde (2002)
Salmonella enteritidis	Veg	10	2	Surface	Collins (1971)
Salmonella typhi	Veg	21	4	Surface	Sharp (1939)
Sarcina lutea	Veg	197	33	Surface	Rentschler et al. (1941)
Serratia indica	Veg	209	35	Air	Harstad et al. (1954)
Serratia marcescens	Veg	22	4	Surface	Sharp (1939)
Serratia marcescens	Veg	115	20	Air	Ko et al. (2000)
Shigella paradysenteriae	Veg	17	3	Surface	Sharp (1939)
Spirillum rubrum	Veg	44	8	Surface	Rentschler et al. (1941)
Staphylococcus albus	Veg	33	6	Surface	Rentschler et al. (1941)
Staphylococcus albus (1)	Veg	23	4	Air	Rentschler and Nagy (1942)
Staphylococcus albus (2)	Veg	52	9	Air	Rentschler and Nagy (1942)
Staphylococcus aureus	Veg	66	11	Surface	Gates (1930)
Staphylococcus aureus	Veg	20	4	Air	Nakamura (1987)
Staphylococcus epidermis	Veg	29	5	Air	Van Osdell and Foarde (2002)
Streptococcus agalactiae	Veg	5	1	Air	Luckiesh et al. (1949)
Streptococcus haemolyticus	Veg	22	4	Surface	Sharp (1939)
Streptococcus pneumoniae	Veg	468	78	Surface	Gritz et al. (1990)
Streptococcus pyogenes	Veg	4	1	Surface	Lidwell and Lowbury (1950)
Streptococcus pyogenes	Veg	1	1	Air	Luckiesh et al. (1949)
Streptococcus viridans	Veg	20	4	Surface	Sharp (1939)
Deinococcus radiodurans	N/A	1370	227	Air-dried mono-layer	Bauermeister et al. (2011)

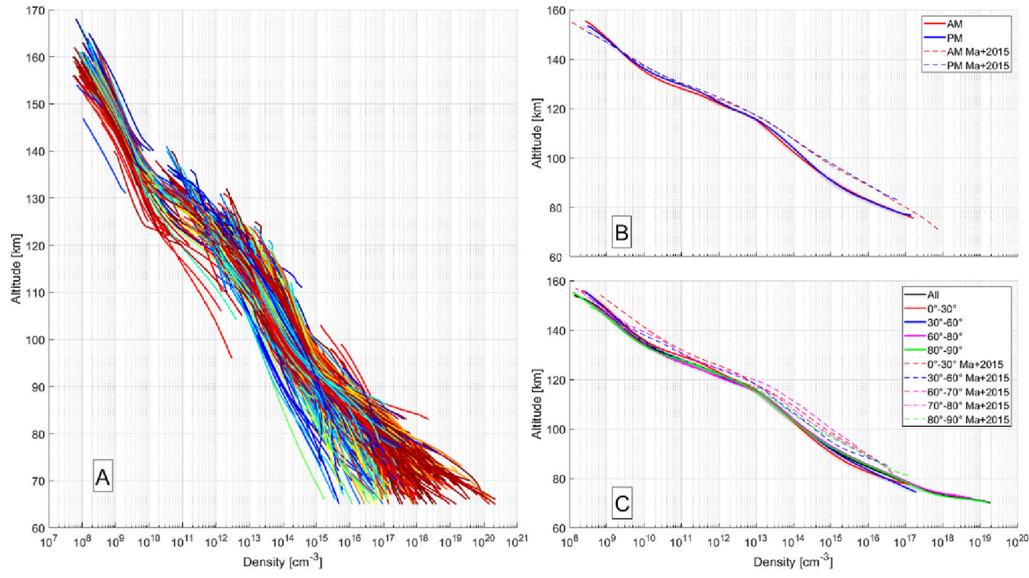


Figure A.1.: Figure 4 from Mahieux et al. (2023). The Mahieux- CO_2 profile from figure 3.4 has been extracted from panel C in this figure. See figures 3.4 and 3.2 for comparison to the corresponding species vertical profiles determined by Kompot.

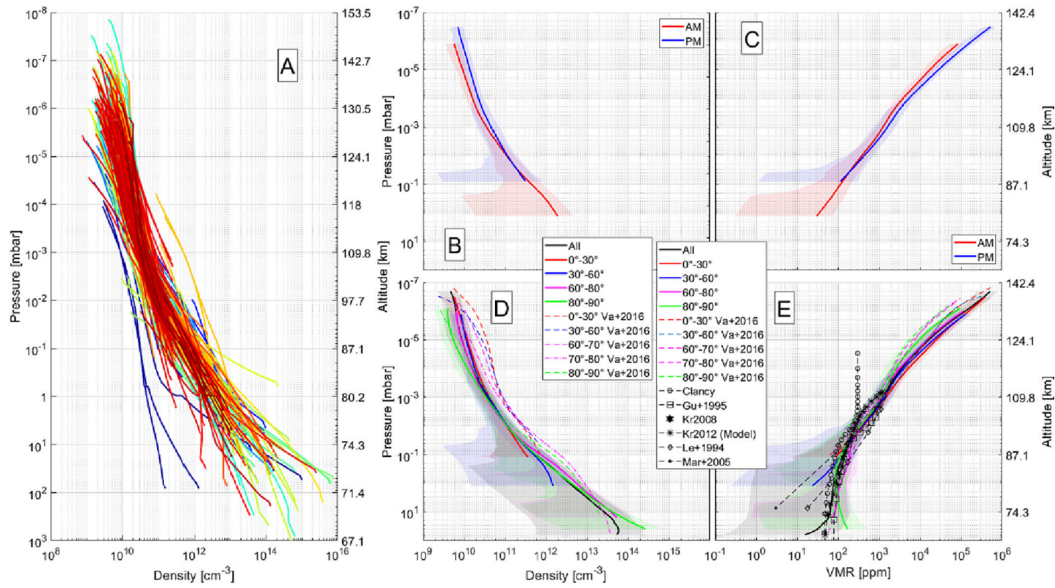


Figure A.2.: Figure 6 from Mahieux et al. (2023). The Mahieux- CO profiles from figure 3.4 have been extracted from panel E in this figure. See figures 3.4 and 3.2 for comparison to the corresponding species vertical profiles determined by Kompot.

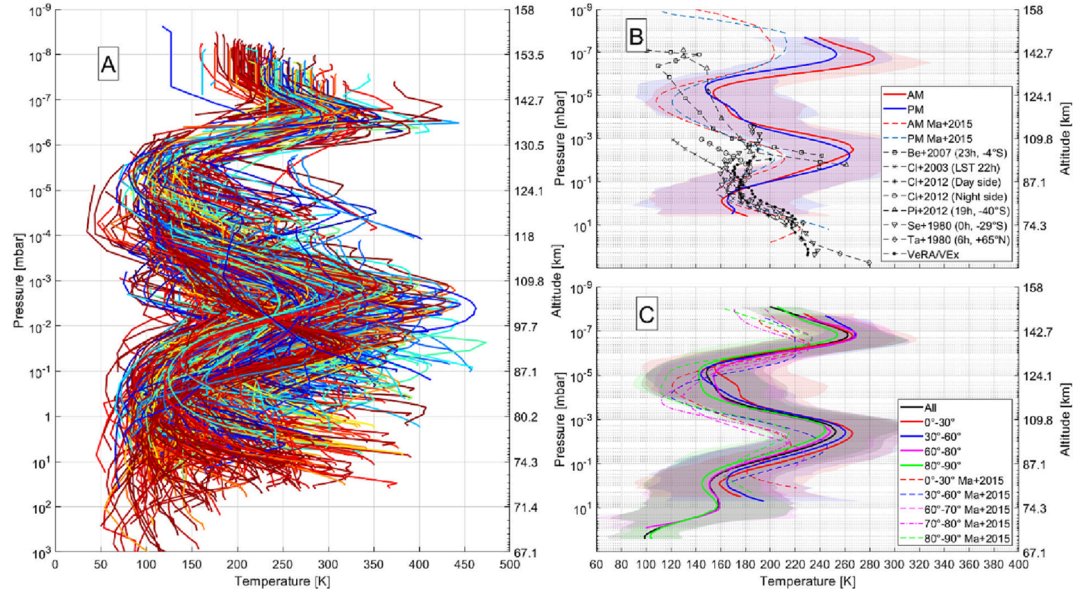


Figure A.3.: Figure 5 from Mahieux et al. (2023). The Mahieux-temperature profiles from figure 3.4 have been extracted from panel C in this figure.

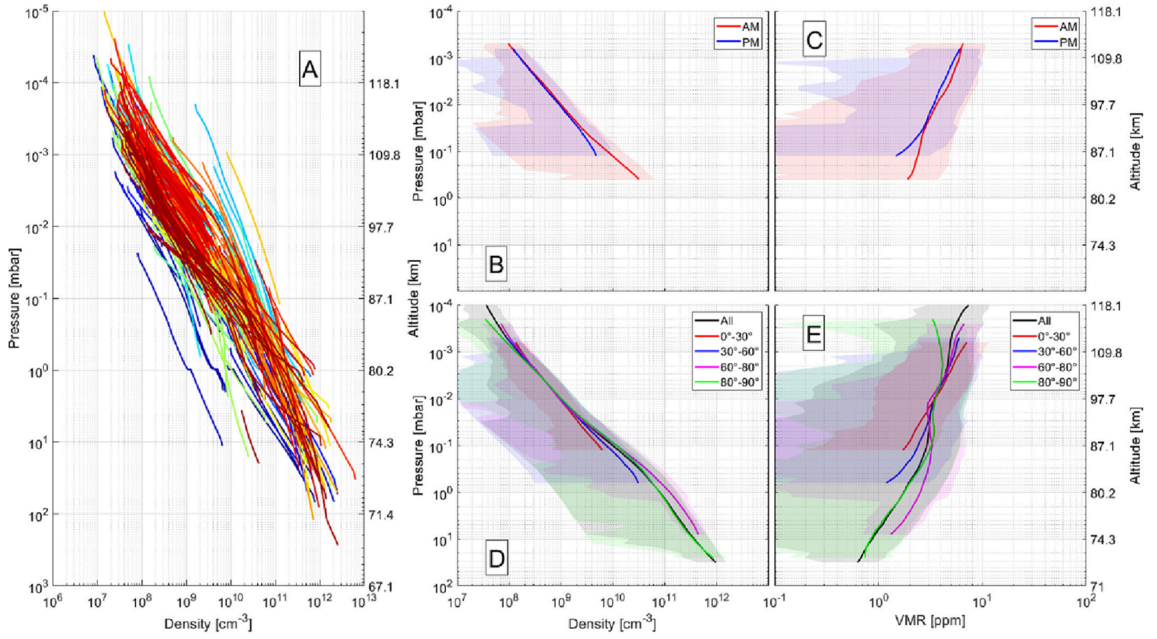


Figure A.4.: Figure 7 from Mahieux et al. (2023). The Mahieux- H_2O profiles from figure 3.4 have been extracted from panel E in this figure. See figures 3.4 and 3.2 for comparison to the corresponding species vertical profiles determined by Kompot.

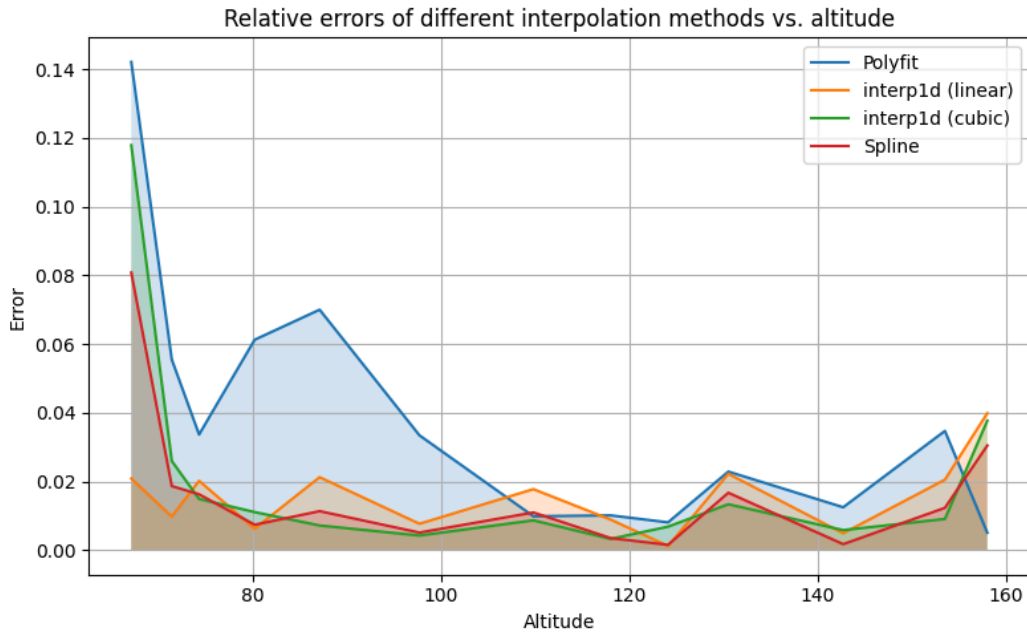


Figure A.5.: Relative interpolation errors for the conversion of pressure to altitude for the SOIR data by Mahieux et al. (2023) with different interpolation methods. The tested functions consisted of Scipy's `interp1d`, both the linear (orange) as well as the cubic version (green), Numpy's `polyfit` function (blue) and Scipy's `PchipInterpolator` (red), which uses a monotonic cubic spline for interpolation.