Venus: Earth's Treacherous Twin

ASTRON/EPS C162 - Mariam Helal - May 15, 2025

Introduction:

Venus appears to life on Earth as the brightest object in the sky after the Moon and Sun, with a namesake of the Roman goddess of love. Venus was historically thought to be similar to Earth, with romantic ideas of a surface covered in thick jungles being conjured due to the planet's thick visible clouds [1]. In truth, Venus and Earth are similar in some ways. They lie at comparable distances to the Sun, with the Earth being 1 AU away and Venus being 0.7 AU away. They also resemble each other in terms of size and bulk composition [1], and have an overall similar initial accretionary and initial geological history [2]. However, later study of Venus revealed that the similarities end there. Venus, in reality, is not a lush flora-filled heaven. Rather, Venus is the hottest of all planets in the Solar System [1], shrouded with thick sulfuric acid (H_2SO_4) clouds and an atmosphere composed almost entirely of carbon dioxide (CO_2). Specifically, initial spectral data and later *in situ* measurements by Venera 4, a 1967 Soviet probe that entered the Venusian atmosphere [3], placed the CO_2 content to be over 80%, with more recent research placing estimates $\sim$96.5% CO_2 [2]. Additionally, Venera 7, a 1972 Soviet probe that was the first to reach the Venusian surface [4] [1], revealed surface temperatures to be $\sim$739 K [1].

Interestingly, this temperature is not what would be expected through calculations equating the energy received by Venus from the Sun and the energy Venus would radiate as a blackbody. Doing such a calculation would yield the following formula for the surface temperature of the planet, known as T_{eff}:

$$T_{\text{eff}} = \left[\frac{L_\odot}{4\pi a^2 \sigma_{SB}} (1 - A) \right]^{\frac{1}{4}} \tag{1}$$

where a is the distance from Venus to the Sun, $L_\odot$ is the luminosity of the Sun, σ_{SB} is the Stefan–Boltzmann constant, and A is the Bond albedo of Venus (Bond albedo is a measure of the fraction of light a body reflects, and is quite high on Venus due to its thick cloud cover [5]). The temperature of Venus near its cloud tops is well-represented by this calculation [1], which outputs $T_{\text{eff}} = 223$ K. However, as discussed above, this temperature is not accurate to the true atmospheric profile of Venus. This is known through data from the NASA Pioneer Venus probe, which descended through the Venusian atmosphere in 1978, collecting temperature measurements that can be seen in Figure 1 below [6]:

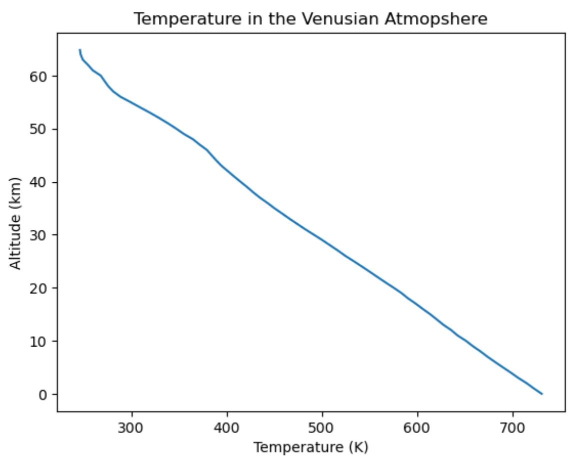

Figure 1: A plot of the Venusian atmospheric temperature profile, as recorded by Pioneer Venus [7].

A Runaway Greenhouse:

The question therefore arises: What is causing the discrepancy between the expected and actual temperature of Venus? The answer lies in the thick CO_2 atmosphere of the planet. CO_2 is a greenhouse gas, essentially acting as a blanket around Venus and trapping infrared heat. Specifically, infrared radiation is emitted from the surface of the planet and as it travels out to leave, it hits a CO_2 molecule and begins a random walk process, bouncing around between CO_2 molecules and increasing the surrounding temperature. This is why the temperature profile shown above increases closer to the surface of Venus: there is more CO_2 concentrated at lower depths, which makes it harder for the infrared photons to escape. With this new physics in mind, a new equation for Venus' atmospheric temperature profile can be formulated:

$$T(\tau) = \left[\frac{T_{\text{eff}}^4}{4}(3\tau + 1)\right]^{\frac{1}{4}} \tag{2}$$

where τ is the optical depth. The optical depth of an atmosphere represents how "thick" it is to photons of a certain wavelength, and can be calculated by the following equation:

$$\tau(z) = -\int_{\infty}^{z} n(z)\sigma(z)dz \tag{3}$$

where n is the number density of CO_2 molecules, σ is the collision cross-section of CO_2 molecules, and z is altitude which the optical depth is being evaluated. Unfortunately, the collision cross-section σ is a difficult variable to constrain, as it depends on the cross-sectional area of CO_2 that can absorb a photon. This absorption can occur at different infrared wavelengths which all have different absorption cross-sections associated with them. This means that CO_2 has several different σ values at a given altitude that must be considered to get a full picture of optical depth in the Venusian atmosphere. To get this full picture, the Rosseland mean optical depth can be calculated, which takes into account these changes in cross-section by integrating over different wavelengths. Solving for the Rosseland mean optical depth at different altitudes and plugging into Equation 2 yields the following plot:

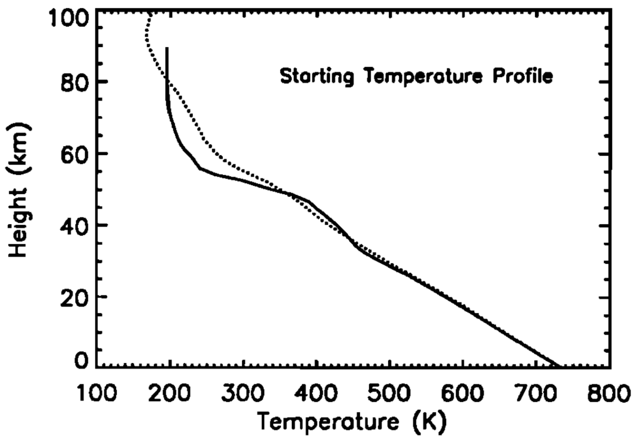

Figure 2: A plot of temperature profile in the Venusian atmosphere, where the solid line shows the temperature calculated using Equation 2 and the dotted line shows the actual temperature profile measured by Pioneer Venus, as also shown in Figure 1 [8].

Figure 2 shows how the actual temperature profile of Venus and the one calculated using Equation 2 are very similar, validating that Equation 2 accurately models the temperature profile of the Venusian atmosphere!

A Diverging Path:

With the question of temperature discrepancy answered and a proper temperature profile equation provided, another question remains looming: why is Venus so much hotter than Earth if they had such similar early histories? The reality is, the same greenhouse effect that caused the inhospitable temperatures on Venus also occurs here on Earth, and is actually the reason why life can exist: Earth would be too cold otherwise! The key difference is in the fact that Venus is a "runaway greenhouse." The remainder of this article will be dedicated to exploring what this means and how exactly Venus became one.

To understand these topics, the early history of Venus must be first understood. Venus and Earth were likely initially covered in magma due to the energy from the heat of formation of the planets allowing temperatures to exceed the melting temperatures of rocks [2]. Within the magma, certain elements are known as *incompatible*. This means that their size or charge makes them unable to replace the major element of a given compound. Therefore, as the magma cools, incompatible elements are the last to crystallize (because it is most "difficult" for them to solidify within mineral compounds), and are therefore found more abundant in liquid form. Within this liquid, each compound has a specific equilibrium solubility, and if the compound exists at a higher concentration than the equilibrium solubility dictates, it will be out-gassed. One such compound, formed out of the incompatible elements carbon and oxygen, is CO_2 [2]. CO_2 has a very low solubility and was therefore out-gassed out of the magma oceans of Venus and Earth fairly quickly [2]. Since CO_2 is a greenhouse gas, it then warms the atmospheres of these planets, which keeps the magma oceans liquid for a longer period of time. This allows for further out-gassing of CO_2. Although this process occurred for both Venus and Earth, Venus is $\sim$28% closer to the Sun than Earth is, meaning it receives more solar flux and therefore had higher initial temperatures. It is thought that is what prevented Venus from stabilizing this cycle and left it a runaway greenhouse, as opposed to Earth [2].

Specifically, there are two effects of this higher initial temperature that caused Venus to be unable to regulate its temperature. The first is that it caused it to take longer for Venus' magma ocean to solidify, which left even more time for CO_2 to be out-gassed into the Venusian atmosphere. The second is that higher temperatures caused water to disassociate via a reaction with surface rocks, leaving the oxygen in the water to be absorbed by the rocks and the hydrogen to escape the atmosphere into space [9]. This escape occurred due to both solar radiation and solar wind. Solar radiation, specifically UV and X-ray radiation, carries energy. When the photons hit molecules in the atmosphere, their temperatures and therefore velocities increase, allowing them to escape the planet's sphere of influence [10] [11]. This phenomenon affects planets close to the Sun the most, as they receive the highest levels of solar flux [12]. Solar wind, on the other hand, contains protons which can exchange charge with atmospheric hydrogen atoms, causing the hydrogen atom to become a proton and the solar wind proton to become a hydrogen atom [12]. The new hydrogen atom still has the high energy of the solar wind proton it was produced from, causing the energy of hydrogen atoms in the atmosphere to increase and allowing for escape. Solar wind is more effective at removing hydrogen atoms from an atmosphere, accounting for $\sim 2/3$ of the energy used for hydrogen to escape [13] [12]. A magnetic field can actually protect against this solar wind, as it can interact with the charged particles contained in the solar wind and deflect them [12]. However, Venus lacks a strong magnetic field, and therefore does not receive this protection, whereas Earth does [10].

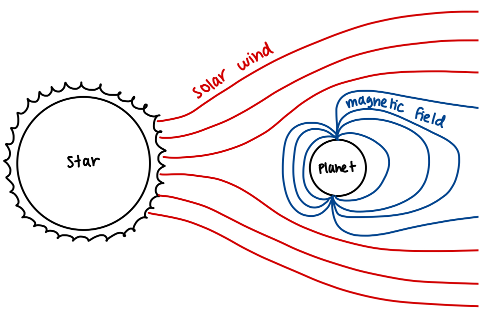

Figure 3: Illustration of a planet with a magnetic field deflecting a star's solar wind [12].

Furthermore, the fact that water existed on Venus before somehow escaping is not just theorized, but known through measurements of D/H in Venus' atmosphere [2]. This is the ratio of deuterium to hydrogen, which was recorded by Pioneer Venus [14]. The D/H ratio measured in Venus is higher than Earth's, which indicates that hydrogen must have escaped the Venusian atmosphere since Earth and Venus had similar early bulk compositions and therefore D/H ratios [14]. Specifically, Venus is thought to have at one point had at least $4.2 \cdot 10^{21}$ g of water, corresponding to 0.3% of the Earth's ocean [14].

Water vapor is actually a greenhouse gas as well, one even more potent than CO_2. This is due to its bent molecular structure, as opposed to the linear structure of CO_2, causing it to have more degrees of freedom and therefore the ability to absorb and re-emit higher energy photons. It is therefore logical to think that the escape of water from the Venusian surface would slow its warming. However, though water vapor did contribute to the warming of early Venus, the loss of water ironically had a accelerated the warming of the planet and led CO_2 to be the dominant greenhouse gas. This is because water and CO_2 are both a part of a cycle known as the **carbon-silicate cycle**, outlined below.

The Carbon-Silicate Cycle:

Step 1:
Increase of CO_2 in atmosphere.
↓
Step 2:
The CO_2 causes the greenhouse effect, making the atmosphere warmer. This leads water (H_2O) to evaporate, causing an increase of water in the atmosphere.
↓
Step 3:
The increased water in the atmosphere reacts with the CO_2 to form carbonic acid (H_2CO_3). This acid is then rained down on silicate rocks, a type of rock that contains silicon tetrahedrons (SiO_4). The carbonic acid then reacts with the silicate rock to producing a different type of rock, calcium carbonate ($CaCO_3$). Through these process, water facilitates the sequestration of CO_2 into rock [15].
↓
Step 4:
With this decrease in CO_2 due to it being sequestered, the greenhouse gas effect is less severe, causing atmospheric temperatures to decreases. This leads to less water in the atmosphere.
↓
Step 5:
Lower temperatures and atmospheric water levels reduce weathering rates of silicate rocks.
↓
Step 6:
This reduces the rate of CO_2 sequestration, leading to an increase in atmospheric CO_2.

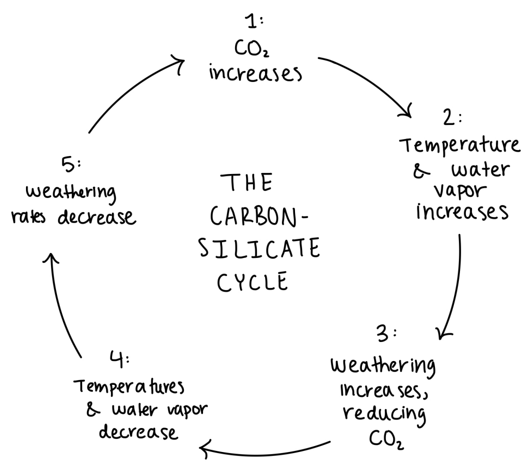

Figure 4: A summary of the carbon-silicate cycle.

The above cycle is a negative feedback loop, meaning it stabilizes itself. However, as mentioned previously, water is necessary for the continuation of this cycle. The fact that Venus' water escaped meant that the carbon-silicate cycle did not occur, preventing CO_2 from being sequestered in rocks and leading to an increase in atmospheric CO_2 [16]. Despite the fact that it is known that water existed on Venus at some point, though, the exact timeline of water's existence on Venus is not well-constrained [14]. There are two main possibilities for the specific process by which Venus became a runaway greenhouse, outlined below.

The Path to a Runaway:

One possibility for how Venus became a runaway greenhouse is that water never condensed in Venus' atmosphere. Specifically, Venus' close proximity to the Sun, and therefore increased temperatures, led water to never condense in Venus' atmosphere, with the hydrogen escaping the planet early in its history [2]. This led CO_2 to be out-gassed uncontrollably, which in turn led to rapid increases in temperature and solidified Venus' status as a runaway greenhouse. Alternatively, another possibility is that water did condense on Venus at some point after its magma oceans cooled, but as solar flux increased with time, it eventually reached a point that all water evaporated and hydrogen escaped [2]. This lack of water then halted the carbon-silicate cycle and led atmospheric CO_2 levels to wildly increase, and subsequently the temperature as well. Although the exact steps by which Venus became a runaway are not certain, it is thought that water escaped Venus sometime before the Solar System was 100 Myr old [2]. This leads the first possibility to be more plausible, as the condensation of water on Venus and subsequent escape would have happened on much longer timescales of 0.7 - 3 Gyr [2].

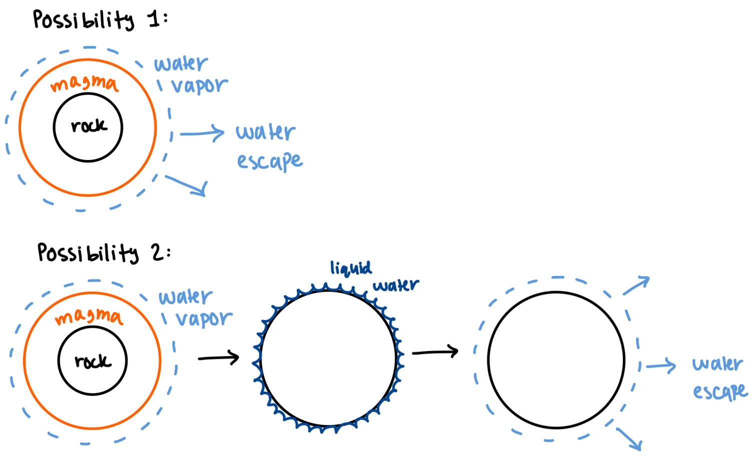

Figure 5: 2 possibilities for the evolution of Venus losing its water.

Conclusion:

Ultimately, the details of Venus' climatic and geological history is a complicated one, with efforts to better understand the planet still underway. In fact, space agencies such as NASA and the ESA are planning three missions to Venus in the near future: VERITAS, DAVINCI, and EnVision [17]. The VERITAS orbiter will collect images and record the topography of the Venusian surface, allowing for a better understanding of the geology of the planet [17]. The DAVINCI probe will measure atmospheric composition, looking for data such as noble gases and D/H ratios [17]. Lastly, the EnVision orbiter will look for active volcanism with the hope of understanding the geology of the planet as well as how it relates to the atmosphere [17]. Despite current gaps in the picture of Venus, such breakthroughs and innovations in planetary science and solar system exploration have shown that, summarizing the above article, Venus is likely a runaway greenhouse for two main reasons: its proximity to the Sun led it to lose its water early on, leading to an uncontrollable increase in greenhouse gases in its atmosphere [18], and its lack of a magnetic field causing Venus' water to escape and preventing CO_2 from being sequestered. Earth, on the other hand, remained cool enough and had a strong magnetic field that prevented it from losing its water, allowing the carbon-silicate cycle to continue and for Earth's greenhouse gas levels to be regulated to the ideal level for life. Although the 30% difference between Earth and Venus' distance to the Sun seems small, it was enough to secure Venus' fate as an inhospitable landscape while Earth became a haven for life. Poetically, as solar flux increases, it is likely Earth will reach temperatures hot enough to lose its water and become a runaway greenhouse as well [18], once again joining Venus in its fate.

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