Climate Change Science
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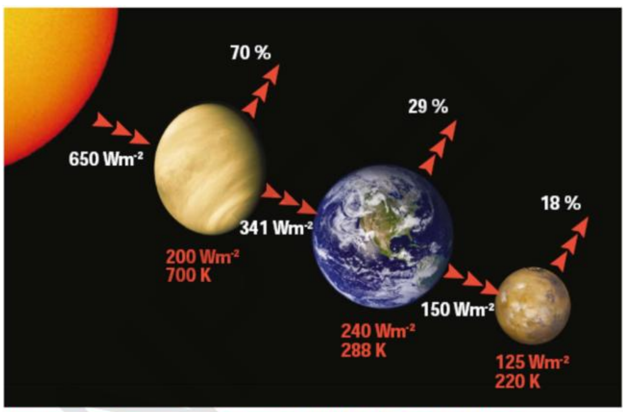
Lecture 57
Why is Venus hot?

In this lecture, we explore the runaway greenhouse effect, using Venus as a case study. Venus and Earth are often considered twin planets due to their similar size and composition, but their climates diverged drastically. While Earth supports life in a relatively stable climate, Venus is extremely hot, and understanding why offers insight into planetary climate limits. The concept gained attention from Dr. James Hansen, who warned that burning all fossil fuel reserves on Earth could potentially trigger such a runaway effect here on Earth, though the likelihood is small, the implications are severe.

A runaway greenhouse effect occurs when greenhouse gases increase with temperature, while solar absorption remains nearly constant, leading to unstoppable temperature rise. As greenhouse gas concentrations increase, outgoing infrared radiation decreases, while the incoming solar radiation remains roughly unchanged. This imbalance drives a continuous rise in planetary temperature, the core mechanism behind a runaway greenhouse state.



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Let's compare the three familiar planets: Venus, Earth, and Mars, focusing on their energy balance and climate. Venus is entirely covered by clouds, giving it a high albedo of 70%, meaning it reflects most of the sunlight it receives. Earth has an albedo of about 29–30%, while Mars, with a very thin atmosphere, reflects the least, with an albedo of 18%.

Despite being closer to the Sun, and thus receiving nearly twice the solar radiation as Earth, Venus absorbs less net radiation, about 200 W/m² compared to Earth's 240 W/m², due to its high reflectivity. This leads to an important question: Why is Venus so much hotter (over 700 K) than Earth (about 288 K), even though it absorbs less net solar energy?

The answer lies not in its proximity to the Sun, but in its thick atmosphere, which traps heat through an extreme greenhouse effect. The high surface temperature of Venus is primarily due to this atmospheric composition, not the amount of solar radiation it receives.

Venus, despite being Earth’s closest planetary twin in terms of size, mass, and general proximity to the Sun, presents a stark contrast in terms of its climate and surface conditions. Though it has been under scientific observation since the early days of the space age in the 1960s, Venus continues to be one of the most mysterious planets. As noted by Crisp et al. (2002), the surface and atmosphere of Venus exhibit some of the most enigmatic features among all planets.

The concept of a runaway greenhouse effect on Venus was first proposed by the renowned astronomer Carl Sagan, who popularized planetary science and gave widely appreciated public lectures about our solar system. For a long time, Venus remained a mystery because it is permanently shrouded in thick clouds, making direct visual observation of the surface impossible. It was only through microwave observations, which can penetrate the cloud layer, that astronomers detected unexpectedly high surface temperatures greater than 700 K. This discovery was initially met with skepticism due to its surprising nature. However, the reality was confirmed when spacecraft sent to Venus actually landed on the surface and recorded these extremely high temperatures, firmly establishing the planet's scorching conditions and supporting the theory of a runaway greenhouse effect.

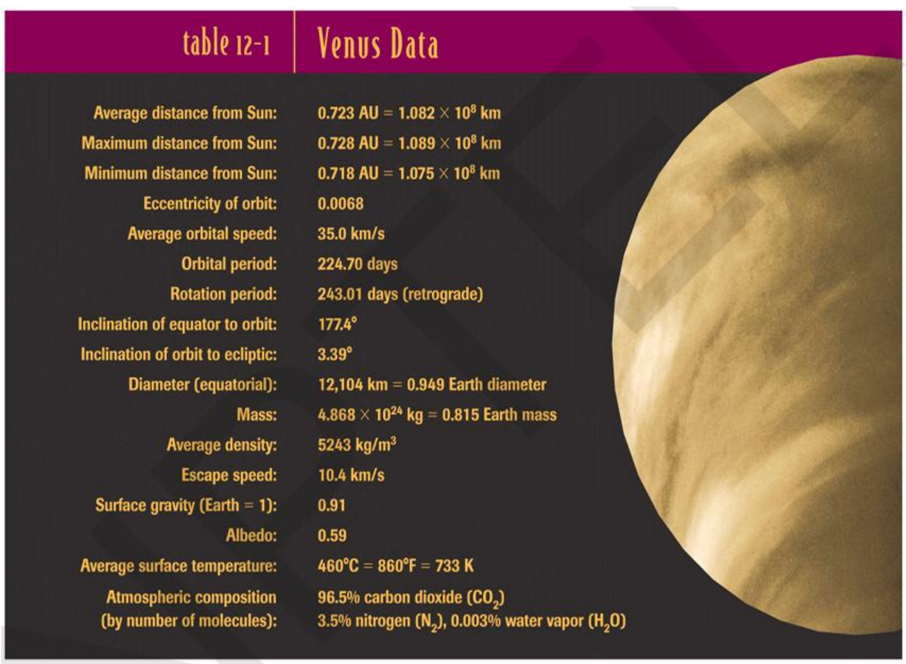


table 12-1	Venus Data
Average distance from Sun:	0.723 AU = 1.082×10^8 km
Maximum distance from Sun:	0.728 AU = 1.089×10^8 km
Minimum distance from Sun:	0.718 AU = 1.075×10^8 km
Eccentricity of orbit:	0.0068
Average orbital speed:	35.0 km/s
Orbital period:	224.70 days
Rotation period:	243.01 days (retrograde)
Inclination of equator to orbit:	177.4°
Inclination of orbit to ecliptic:	3.39°
Diameter (equatorial):	12,104 km = 0.949 Earth diameter
Mass:	4.868×10^{24} kg = 0.815 Earth mass
Average density:	5243 kg/m^3
Escape speed:	10.4 km/s
Surface gravity (Earth = 1):	0.91
Albedo:	0.59
Average surface temperature:	460°C = 860°F = 733 K
Atmospheric composition (by number of molecules):	96.5% carbon dioxide (CO_2) 3.5% nitrogen (N_2), 0.003% water vapor (H_2O)

Venus shares many similar physical characteristics with Earth, making it our most Earth-like planetary neighbour. Its orbit is nearly circular, with a period of 225 Earth days, and it has very low orbital inclination, meaning it moves almost in the same plane as Earth around the Sun. However, one major difference lies in its rotation. Venus rotates very slowly and in the opposite direction to most planets, including Earth. This gives it an extremely long day compared to its year.

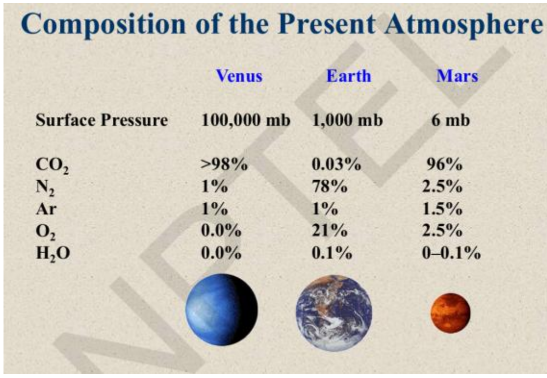
Venus and Earth are very similar…

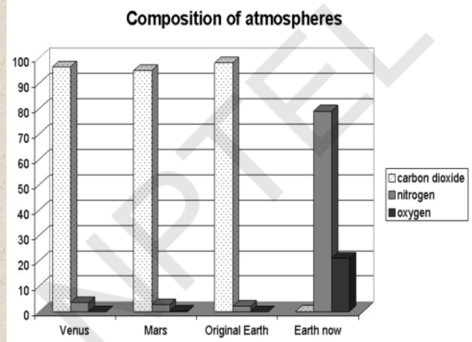
Property	Earth	Venus
Diameter (km)	12,756	12,104
Mass (kg)	$6.0x10^{24}$	$4.9x10^{24}$
Density (g/cm^3)	5.52	5.25

In terms of size and mass, Venus is remarkably similar to Earth. Its diameter and density are close to Earth's, and its surface gravity is about 90% that of Earth, suggesting strong structural similarities. However, the climatic conditions differ drastically. Venus has a much higher albedo than Earth due to its thick cloud cover, yet its surface temperature is around 733 K, significantly hotter than Earth's average of 288 K.

The key difference lies in atmospheric composition. Venus's atmosphere is made up of 96.5% carbon dioxide, whereas Earth's CO_2 concentration is only around 420 parts per million (ppm) today. Interestingly, when both planets formed about 4.5 billion years ago, they likely had similar CO_2-rich atmospheres. Over time, Earth's atmospheric composition changed dramatically due to biological processes, especially the emergence of cyanobacteria, which began producing oxygen and reducing atmospheric CO_2. This shift made Earth habitable, while Venus, lacking such a transformation, remained inhospitable. Despite their physical similarities, Earth and Venus ended up on vastly different climate trajectories.

Venus, Earth, and Mars are three neighbouring planets with very different climates, primarily due to differences in atmospheric composition and surface pressure. One of the most striking contrasts is the surface pressure: Venus has a surface pressure about 100 times greater than Earth's, indicating a very thick and dense atmosphere. In contrast, Mars has an extremely thin atmosphere, resulting in very low surface pressure.





As mentioned earlier, a key factor in climate regulation is the concentration of CO_2. Venus's atmosphere is composed of approximately 97–98% CO_2, which drives an intense greenhouse effect and extremely high surface temperatures. Earth's current atmosphere, on the other hand, contains only about 0.04% CO_2 (around 420 ppm), while Mars, though it has a similar CO_2 percentage to Venus (~96%), has so little total atmospheric mass that it cannot trap much heat.

Other gases also play a role in shaping planetary climates. Nitrogen is the most abundant gas in Earth's atmosphere, making up about 78%, but is present only in small amounts on Venus and Mars. Argon is approximately about 1% on Earth and Mars but is negligible on Venus. Oxygen, which is essential for life as we know it, is abundant on Earth (about 21%) but nearly absent on Venus and very low on Mars. Water vapor, a vital component of Earth's climate system, is also abundant and variable on Earth, while both Venus and Mars have only trace amounts.

Interestingly, when Earth first formed, its atmosphere likely had high levels of CO_2 comparable to Venus. Over time, however, Earth underwent major atmospheric transformations. CO_2 was gradually removed from the atmosphere and stored in rocks and oceans, nitrogen accumulated to become the dominant gas, and oxygen levels rose significantly due to the emergence of life, particularly photosynthetic microorganisms. These changes made Earth habitable, while Venus remained hot and hostile, and Mars cold and barren.

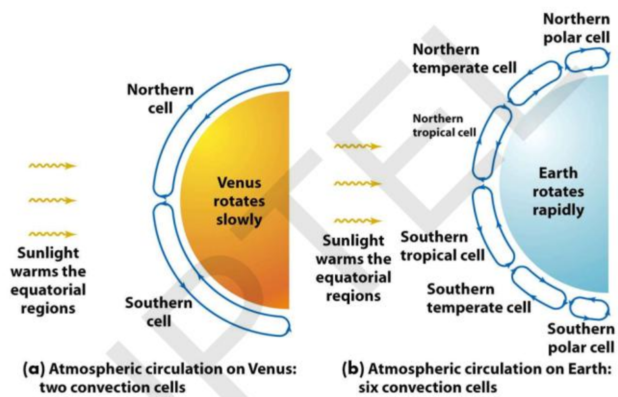
Table 4-3 Carbon, Hydrogen, and Nitrogen Contained In Combined Atmospheres, Hydrosphere, Polar Caps, and Sediments of Planets

Planet	CARBON (kg/cm²)	HYDROGEN (kg/cm²)	NITROGEN (kg/cm²)
VENUS	30	<0.06	<1.5
EARTH	20.4	50	0.8
MARS	~0.004	~0.06	~4 × 10^{-4}

The total amount of carbon present on both Venus and Earth is quite comparable. On Earth, the combined carbon stored in the atmosphere, oceans, and solid Earth is about 20.4 kg/cm^2, while on Venus it is slightly higher, around 30 kg/cm^2. This indicates that both planets possess plenty of carbon.

However, the key difference lies in the form and location of this carbon. On Venus, most of the carbon exists in the atmosphere in the form of carbon dioxide, contributing to its extremely strong greenhouse effect and very high surface temperatures. In contrast, on Earth, the majority of carbon is not in the atmosphere but stored in the oceans and locked up in solid rocks as carbonates. This sequestration of carbon helps regulate Earth's climate and keeps the atmospheric CO_2 levels much lower than those of Venus.

Additionally, Earth has a large amount of water, and therefore hydrogen, while Venus has lost most of its hydrogen. This further influences the chemical processes and the ability to form and store compounds like water and carbonates. Thus, while both planets began with similar carbon inventories, the way this carbon is distributed and stored makes a major difference in their present-day climates.



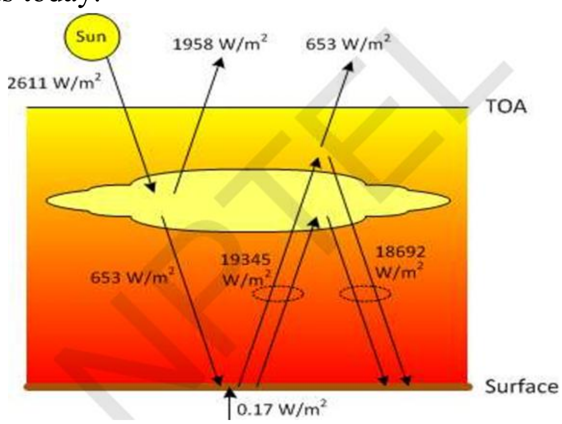
The circulation of the Venusian atmosphere is dominated by two huge convection currents in the cloud layers, one in the northern hemisphere and one in the southern hemisphere

Due to Venus's slow rotation rate, its atmospheric circulation is simpler compared to Earth's. Venus has two large circulation cells—one in the northern hemisphere and one in the southern—while Earth, which rotates more rapidly, has a more complex system. On Earth, the rotation leads to the formation of multiple circulation cells: the Hadley cell in the tropics, the mid-latitude Ferrel cell, and the polar cell, creating a more dynamic and varied climate system.

Another major difference between the two planets is the absence of oceans on Venus. Without water, there is no weathering process, which on Earth plays a crucial role in removing carbon dioxide from the atmosphere and storing it in the form of carbonates in rocks. Additionally, there is no evidence of plate tectonics on Venus. On Earth, plate tectonics allows carbon stored in rocks to be subducted into the mantle, thus regulating atmospheric CO_2 over geological time. In contrast, since Venus lacks both weathering and tectonic recycling, almost all of its carbon dioxide remains in the atmosphere, contributing to its extreme greenhouse conditions.

The earliest direct knowledge about the atmosphere of Venus came from the Soviet mission Venera 7, which successfully landed on the planet on 15 December 1970. This marked the first soft landing on Venus and provided the first in situ measurements from its surface. The data confirmed that Venus has an extremely harsh environment, with surface pressure approximately 100 times that of Earth, comparable to the pressure found 1 km underwater on Earth. The surface temperature was found to be exceedingly high, consistent with previous remote sensing estimates.

However, due to the extreme heat and pressure, the lander's instruments could function only briefly. The Venera 7 probe transmitted data for just 23 minutes before succumbing to the planet's hostile conditions. Despite the short transmission time, these 23 minutes of data provided critical insights into the atmospheric structure and surface conditions of Venus, laying the groundwork for future planetary exploration. Remarkably, these measurements were taken over five decades ago, yet they continue to influence our understanding of Venus today.

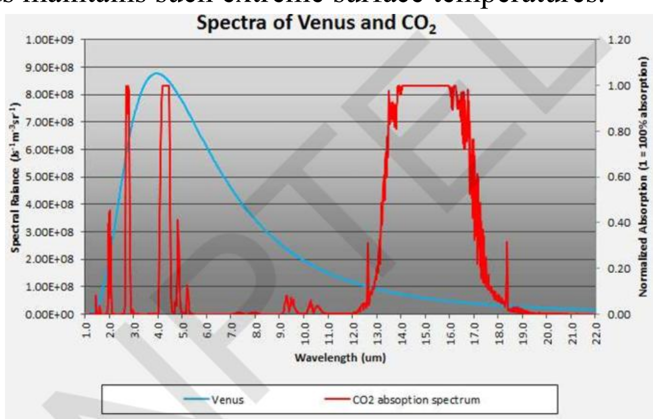


Today, our understanding of Venus has advanced significantly, thanks to the extensive data collected by various satellites orbiting the planet. These missions have provided detailed insights into Venus' radiation budget, a key aspect in understanding its extreme climate.

Venus receives a much higher amount of solar radiation than Earth due to its proximity to the Sun. The incoming solar radiation at the top of Venus' atmosphere is around 2611 W/m², compared to Earth's 1360 W/m². However, Venus' thick cloud cover, which reflects about 75% of the incoming sunlight, causes a large portion, approximately 1958 W/m², to be reflected back into space. This results in only a fraction of the solar energy being absorbed.

The outgoing thermal emission from Venus is around 653 W/m², which matches the energy received at the surface after accounting for reflection and atmospheric absorption. However, the most striking observation comes from the near-surface thermal emission, which is approximately 19,345 W/m², an enormous value driven by the extremely high surface temperature of Venus (over 700 K). In comparison, Earth's surface emits only about 390 W/m².

This immense surface radiation on Venus is largely absorbed and re-radiated back by its dense carbon dioxide-rich atmosphere. The high concentration of greenhouse gases traps the heat, leading to a strong greenhouse effect. Despite the high surface emissions, the actual net heating at the surface is very small due to a close balance between the energy absorbed, emitted, and returned by the atmosphere. This tightly coupled radiation balance explains why Venus maintains such extreme surface temperatures.



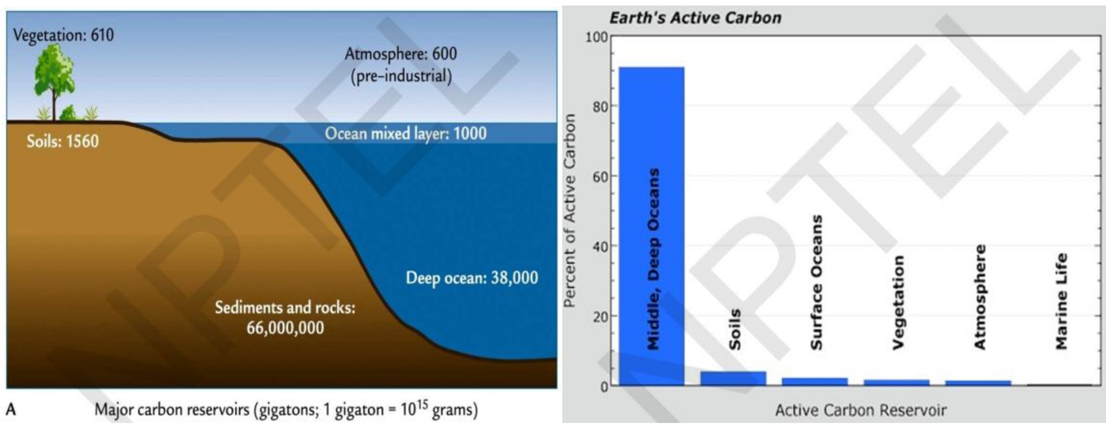
Let us now examine the spectrum of radiation emitted by the surface of Venus. Due to its high surface temperature of over 700 K, the peak of Venus' thermal emission lies between 4 to 5 microns in wavelength. In contrast, Earth, with an average surface temperature of about 288 K, emits radiation that peaks around 10 microns. This difference is explained by Wien's displacement law, which states that the product of the peak wavelength of emission and the surface temperature is approximately 2898 μmK.

Applying this to Venus, we get:

$$\lambda_{max} = \frac{2898}{700} \approx 4.14\ \mu m$$

This confirms that Venus emits most of its radiation around 4 μm. Now, when we compare this with the absorption characteristics of carbon dioxide, we find that the wellknown CO_2 absorption band at 15 µm is not very effective on Venus, because the planet emits relatively little radiation at that wavelength.

Instead, Venus emits strongly in regions where carbon dioxide has other absorption bands, notably around 4.3 µm, 2.7 µm, and 2 µm. These bands are more relevant for the greenhouse effect on Venus, as they correspond to the wavelengths where most of the surface radiation is emitted and absorbed. Therefore, the strong greenhouse warming on Venus is largely due to CO_2 absorption in these shorter wavelength bands, rather than the familiar 15 µm band dominant in Earth's atmosphere.

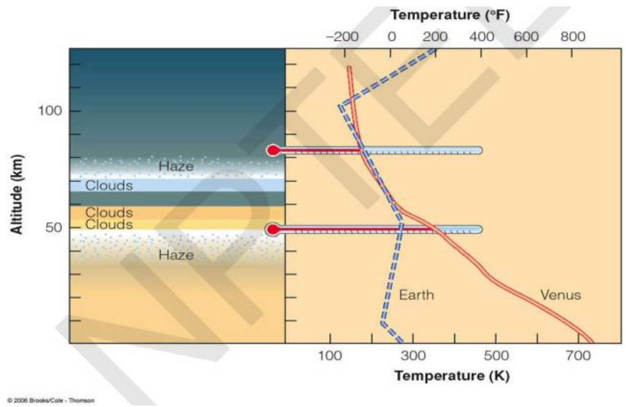


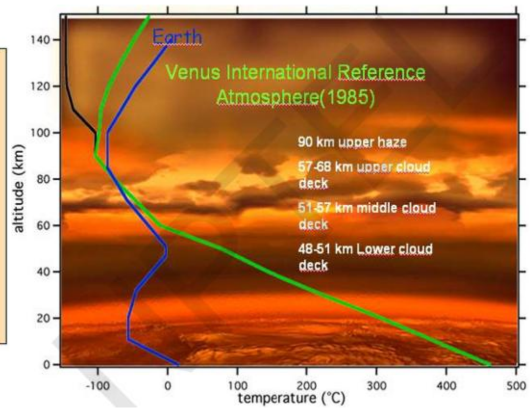
On Earth, the vast majority of carbon of about 66 million gigatons is stored securely in rocks and sediments, forming a long-term reservoir that plays a critical role in regulating the planet's climate. A significant portion is also dissolved in the deep ocean, with smaller amounts distributed in the mixed layer of the ocean, atmosphere, and terrestrial vegetation. This distribution ensures that only a relatively small fraction of Earth's total carbon is actively participating in the climate system at any given time.

In contrast, on Venus, much of this stored carbon, particularly in the form of carbon dioxide, has been released into the atmosphere. As surface temperatures on Venus rose, likely through a runaway greenhouse effect, carbon that might have otherwise remained trapped in rocks was liberated, contributing to the thick, CO_2 rich atmosphere we observe today. This release further intensified the greenhouse effect, leading to even higher temperatures, creating a positive feedback loop.

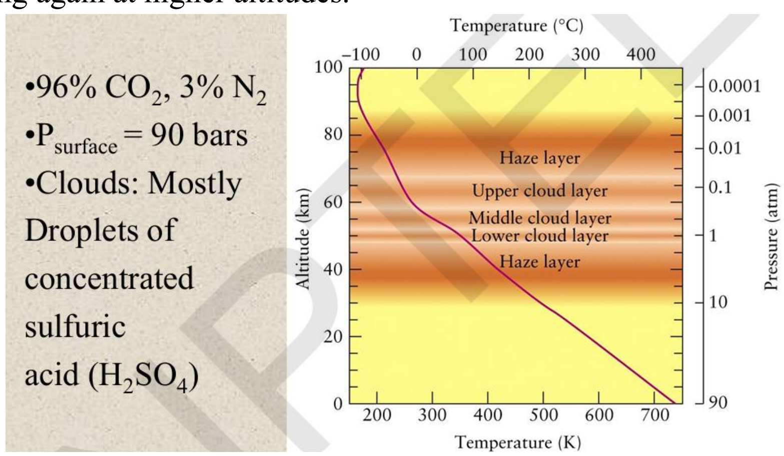
Thus, the key distinction is not the total amount of carbon, which is somewhat comparable between Earth and Venus, but rather its location: Earth's carbon is mostly sequestered, while Venus' is largely atmospheric, directly driving its extreme surface temperatures.

The temperature profile of Venus, when compared to that of Earth, reveals a striking divergence in the lower atmosphere, while showing surprising similarity at higher altitudes. At the surface, Venus exhibits extreme temperatures around 720 K (447°C) due to its dense CO_2-rich atmosphere and a strong greenhouse effect. However, this temperature drops rapidly with altitude. By the time we reach about 50 kilometres above the surface, the temperature on Venus falls to around 200–240 K, which is comparable to temperatures found in Earth's upper troposphere or lower stratosphere.



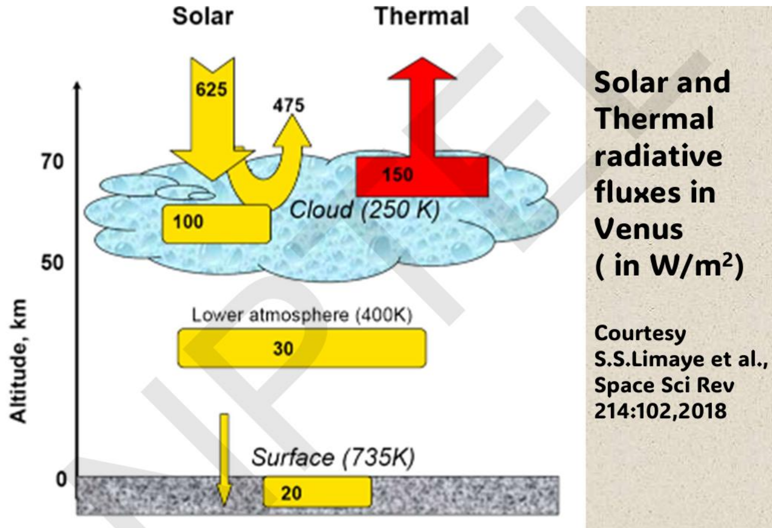


A graphical comparison illustrates this well: the green curve representing Venus shows a steep decline from surface to about 50 km, while the blue curve for Earth begins at approximately 15°C (288 K) at the surface, decreases to the tropopause (about 200 K), and then increases in the stratosphere due to ozone absorption of ultraviolet radiation, before declining again at higher altitudes.



Another key difference between the two planets is the absence of a stratosphere on Venus. This is because Venus lacks ozone, which on Earth plays a central role in warming the stratosphere. Instead, Venus' upper atmosphere contains multiple layers of sulphuric acid clouds and aerosols. These include a dense cloud deck, aerosol haze layers, and scattering layers above the troposphere. These sulphuric acid clouds are not only crucial for Venus' high albedo (reflectivity), but they also modulate the vertical temperature structure and radiative balance of the planet.

The above figure depicts this structure in more detail, showing the multi-layered nature of Venus' atmosphere, with sulphuric acid droplets dominating the cloud regions and aerosol haze extending well above the clouds. Despite the high surface temperatures, at higher altitudes Venus experiences a much cooler, more Earth-like environment, sparking scientific interest in these regions as potential locations for future atmospheric research or even high-altitude exploration.



The energy budget of Venus presents a striking contrast to that of Earth and helps explain the planet's extremely high surface temperatures, despite receiving only modest net solar energy. According to data from Limaye et al. (2018, *Space Science Reviews*), when calculated per unit surface area of Earth, Venus receives about 625 W/m² of solar radiation, compared to Earth's average of 340 W/m². However, due to Venus' high albedo (~70%), a substantial 475 W/m² is reflected back to space. An additional 100 W/m² is absorbed by the thick cloud layer, and about 30 W/m² is absorbed in the troposphere, leaving only 20 W/m² that actually reaches the planet's surface.

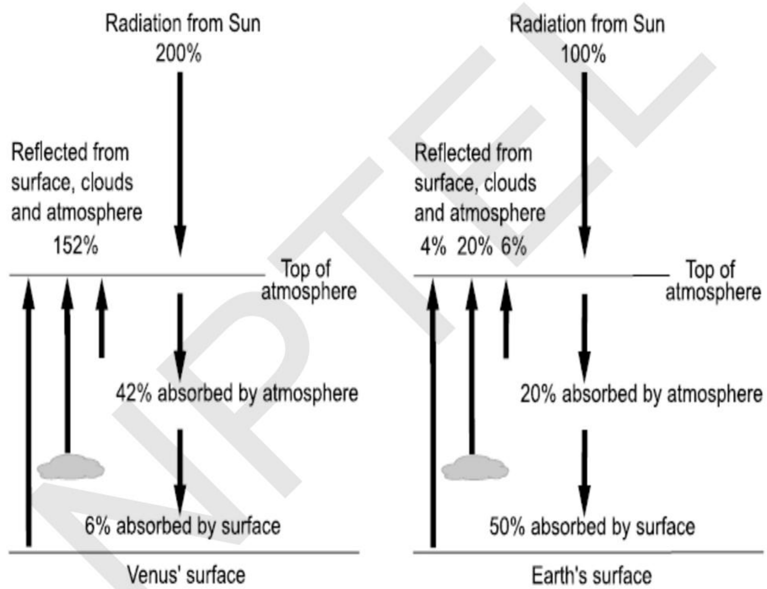
Despite such a small fraction of solar radiation reaching the ground, Venus maintains surface temperatures exceeding 700 K. This is a direct consequence of its intense greenhouse effect, driven by the planet's dense carbon dioxide-rich atmosphere and extreme surface pressure about 100 times that of Earth. The greenhouse gases trap thermal infrared radiation emitted from the surface, preventing it from escaping to space.

The outgoing longwave radiation (OLR) on Venus is around 150 W/m², much less than Earth's OLR of approximately 240 W/m². However, the surface of Venus emits around 16,100 W/m², due to the planet's extreme surface temperature. But most of this radiation is trapped and reabsorbed by the thick CO_2 atmosphere, with only 150 W/m² escaping to space.

To quantify the greenhouse effect, we subtract the radiation escaping to space from the total emitted by the surface:

- For Earth, the surface emits ~390 W/m² and 240 W/m² escapes to space → greenhouse effect = 150 W/m²
- For Venus, the surface emits ~16,100 W/m² and only 150 W/m² escapes → greenhouse effect = 15,950 W/m²

This means the greenhouse trapping on Venus is nearly 100 times that of Earth. Such an immense greenhouse effect makes Venus the hottest planet in the solar system, even hotter than Mercury which is closer to the Sun but lacks a substantial atmosphere. The case of Venus underscores the critical role of atmospheric composition and pressure in governing planetary surface temperatures, far beyond just the amount of incoming solar radiation.



Let us revisit the energy budget of Venus by expressing it in relative terms compared to Earth. Venus receives approximately twice the solar radiation that Earth does, about 200% of Earth's value. However, due to its highly reflective cloud cover and atmospheric composition, about 152% of this incoming solar radiation is reflected back to space, compared to 30% on Earth. This means that Venus absorbs only a small fraction of roughly 6% of the incident solar radiation at the surface, while Earth's surface absorbs nearly 50%. Additionally, about 42% of Venus' solar energy is absorbed within its thick atmosphere, compared to only about 20% in Earth's atmosphere.

These substantial differences in solar (shortwave) radiation absorption have implications for the planets' surface energy balance. However, the most dramatic contrast lies in the longwave (thermal infrared) side of the energy budget. As discussed earlier, Venus exhibits an extreme greenhouse effect, where most of the radiation emitted by its hot surface is trapped by the atmosphere and re-radiated back downward, with only 150 W/m² escaping to space. This is the defining factor that makes Venus drastically hotter than Earth.

To underscore the role of carbon dioxide in this process, theoretical estimates show that if all CO_2 were removed from Venus' atmosphere, its surface temperature would drop by around 420 K. This emphasizes the dominant role of CO_2 in sustaining Venus's extreme temperatures. In addition to carbon dioxide, clouds primarily composed of sulfuric acid also contribute to the greenhouse effect, and their removal would result in a cooling equivalent to about 140 W/m^2. Although water vapor is present only in trace amounts, its contribution is non-negligible. Its removal would cause an estimated 70 K cooling. There are also other minor gases, but their cumulative effect is small compared to CO_2, clouds, and water vapor.

In summary, the extremely high surface temperature of Venus is primarily maintained by the greenhouse effects of CO_2, clouds, and water vapor, with carbon dioxide being by far the most significant contributor. The lecture will continue in the next session with further exploration of Venusian climate and atmospheric processes.