Venus, the Planet: Introduction to the Evolution of Earth's Sister Planet

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Abstract:

Venus is the planet in the Solar System most similar to Earth in terms of size and (probably) bulk composition. Until the mid-20th century, scientists thought that Venus was a verdant world—inspiring science-fictional stories of heroes battling megafauna in sprawling jungles. At the start of the Space Age, people learned that Venus actually has a hellish surface, baked by the greenhouse effect under a thick, CO_2-rich atmosphere. In popular culture, Venus was demoted from a jungly playground to (at best) a metaphor for the redemptive potential of extreme adversity. However, whether Venus was much different in the past than it is today remains unknown. In this review, we show how now-popular models for the evolution of Venus mirror how the scientific understanding of modern Venus has changed over time. Billions of years ago, Venus could have had a clement surface with water oceans. Venus perhaps then underwent at least one dramatic transition in atmospheric, surface, and interior conditions before present day. This review kicks off a topical collection about all aspects of Venus's evolution and how understanding Venus can teach us about other planets, including exoplanets. Here we provide the general background and motivation required to delve into the other manuscripts in this collection. Finally, we discuss how our ignorance about the evolution of Venus motivated the prioritization of new spacecraft missions that will essentially rediscover Earth's nearest planetary neighbor—beginning a new age of Venus exploration.

Keywords:

Venus | Planetary probes | Planetary climates | Planetary structure | Planetary dynamics | Planetary system formation

1. Introduction

Venus is so hot right now. Literally, its massive, CO_2-rich atmosphere creates a greenhouse effect that makes its surface the hottest in the Solar System on average. Figuratively, Venus is heating up in popularity following recent announcements that NASA and the European Space Agency (ESA) will send three new missions to Earth's sister planet. These capable missions—VERITAS, DAVINCI, and EnVision—will help end a thirty-year drought when visits to Venus were rare—a historical anomaly. Overall, more than forty missions have been launched with Venus on their itinerary (e.g., Taylor et al. 2018)—virtually the same total number that have been sent towards Mars. However, the last NASA-led mission to Venus (Magellan) death-spiraled into the atmosphere in 1994 after finishing its successful radar mapping campaign. Since then, Venus has been relatively lonely, hosting only three flybys (MESSENGER, Galileo, and Cassini) and two orbiters (Venus Express and Akatsuki, which is still operating as of 2022). In the last three decades, spacecraft data from Venus helped illuminate the workings of its modern atmosphere and hinted at its past. New missions will let us better address the profound question: How has Venus evolved over time?

Scientists can tell an alluring story about the evolution of Venus that is impossible to prove or disprove using available data (Figure 1). According to this "habitable hypothesis," a time traveler could visit two clement worlds with oceans early in the Solar System's history. Venus and Earth likely accreted with similar bulk inventories of volatiles (e.g., Chambers 2001; Rubie et al. 2015). Both planets were probably born hot with a steam atmosphere above a magma ocean (e.g., Matsui & Abe 1986; Zahnle et al. 1988; Elkins-Tanton 2008). If Venus shed more heat to space than it absorbed from the Sun, then its magma ocean could solidify within ~10 Myr while its atmosphere cooled enough for the remaining steam to condense onto the surface (e.g., Hamano et al. 2013). Clouds on the dayside of Venus may have kept surface temperatures Earth-like even as the Sun brightened over time (e.g., Yang et al. 2014; Way et al. 2016; Way et al. 2020). Eventually, perhaps as recently as half a billion years ago, increasing solar input and huge amounts of volcanism caused a climatic catastrophe that led to the current, caustic conditions (e.g., Strom et al. 1994; Weller & Kiefer 2020; Krissansen-Totton et al. 2021; Way et al. 2022). This transition may have been rapid in geological terms but slow relative to biological generations. Life might have migrated from the increasingly inhospitable surface to the possibly last habitable niche in the clouds (e.g., Limaye et al. 2018, 2021; Seager et al.

2021). New missions can search for atmospheric signatures of a clement past, geological traces of ancient oceans, and evidence of active biology.

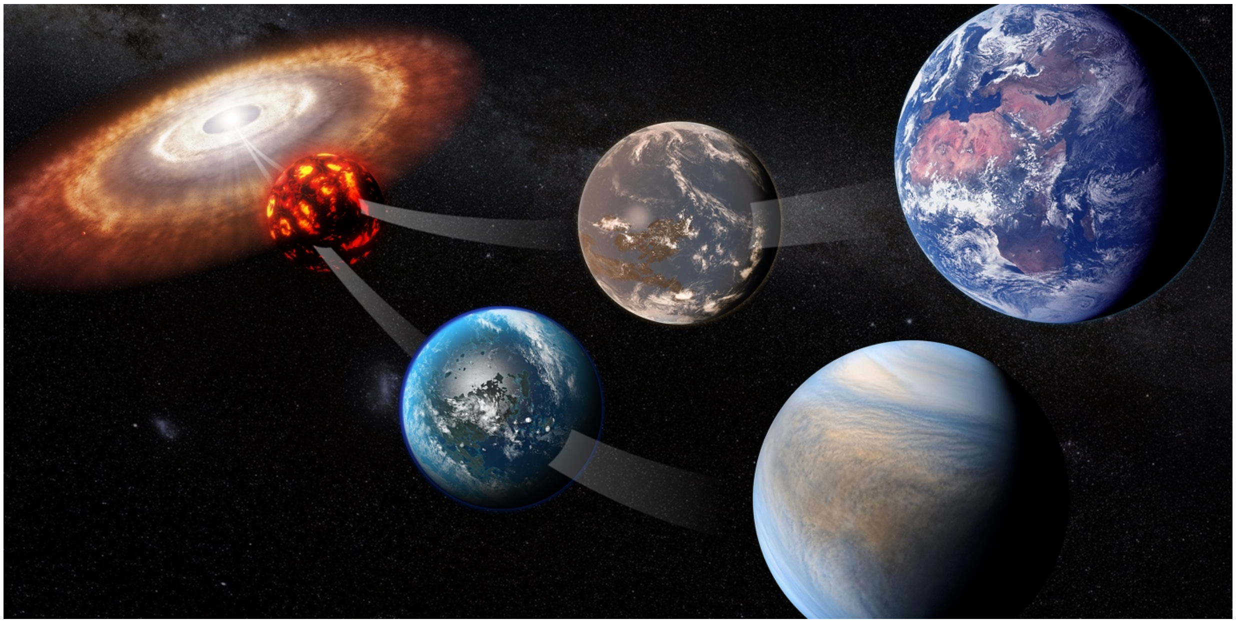

Figure 1. Venus and Earth perhaps resembled each other after their accretion but set off on divergent evolutionary paths after a few billion years. Broadly speaking, the goal of the three newly selected missions to Venus—ESA's EnVision and NASA's VERITAS and DAVINCI—is to determine if this "habitable hypothesis" for the evolution of Venus is correct.

On the flip side, surface conditions may have been hellish since Venus accreted. If the early atmosphere could not radiate away all its absorbed solar radiation, then only the escape of water to space could cause cooling. This process would delay the solidification of the surficial magma ocean to ~100 Myr and could desiccate the interior and surface (e.g., Hamano et al. 2013; Lebrun et al. 2013). Frustratingly, the orbital distance of Venus is so close to the critical value(s) in models that conclusions about its early state are sensitive to assumptions about poorly understood processes. For example, clouds may preferentially exist on the nightside of Venus during the magma ocean phase (Turbet et al. 2021) instead of on the dayside (Way et al. 2020)—in which case they would trap heat in the atmosphere rather than reflect it away. Venus's thick atmosphere could have degassed at early times from the primordial magma ocean, meaning that the total atmospheric mass has not changed much since the period of initial differentiation (e.g., Gillmann et al. 2009, 2020). Yet, at the moment there is little consensus on exactly what sorts of post-accretion atmospheres should be modeled (e.g., Gaillard et al. 2022; Bower et al. 2022; Salvador et al. 2023 this issue). Acidity and low water activity might make the present-day clouds uninhabitable despite their clement temperature and pressure conditions (e.g., Hallsworth et al. 2021). In any case, even if Venus were never habitable, the planetary system—including its atmosphere, crust, mantle, and core—should have evolved over geologic time.

The purpose of this review chapter is to explore big-picture hypotheses for how Venus may have evolved over time and their programmatic implications. We set the stage for the rest of this topical collection—providing the general background needed to delve into detailed models for the evolution of Venus as a planetary system. Section 2 describes the evolution of our understanding of present-day Venus, which was most rapid at the dawn of the Space Age. From the 1950s through the 1970s, more was learned about Venus in three decades than in the prior three centuries since the invention of the telescope. Interestingly, the now-popular story of how Venus evolved over geological time mirrors the changes in our understanding of modern Venus. In the past, we thought Venus was habitable today. Today, we think that Venus was habitable in the past—but is advocacy of this idea only a coping mechanism for the disappointing discoveries of the Space Age? Section 3 presents the fundamental properties of Venus, especially those related to the evolution of its atmosphere, surface, and interior. This section also advertises the chapters in this topical collection that are most relevant to each aspect of Venus. Finally, Section 4 shows how the idea that Venus evolved over time motivates strategies for planetary exploration. For example, the new 2023–2032 Planetary Science and Astrobiology Decadal Survey from the National Academies in the United States highlighted the importance of exploring Venus—with and beyond the newly selected missions—to answering priority scientific questions about the origin and evolution of rocky (exo)planets.

2. Our Evolving Understanding of Venus's Modern State

Before scientists could construct informed models about the evolution of Venus, they needed to understand its present-day state. Venus has been an object of human fascination since prehistory (Figure 2). Until recently, speculation about Venus was only anchored to the observation that Venus appears very bright in visible light. Assuming that the bright things in Venus's sky were H_2O-rich clouds, people thought that the surface of Venus was Earth-like, except with steady, planet-wide precipitation (section 2.1). However, two key discoveries at the dawn of the space age—lots of CO_2 in the atmosphere and strong emission at radio wavelengths—challenged this fantasy. Models of Venus's atmosphere were most “up in the air” in the 1950s and early 1960s (section 2.2). In the 1960s and 1970s, views of modern Venus completed a paradigm shift from habitable to hellish. By 1974, scientists had converged on the correct conception of the present-day atmosphere—it is massive and made almost entirely of gaseous CO_2 plus clouds formed from sulfuric acid droplets (section 2.3). Building on the realization that the surface is scorched, the last few decades of spacecraft visits (section 2.4) and advances in our theoretical understanding of rocky planets—including new numerical and laboratory tools with which to study them (section 2.5)—have painted a detailed picture of Venus's modern state.

Figure 2. Glyph related to Venus in a Mayan bas-relief from the museum of Copan, Honduras. Photo by C. Gillmann.

2.1 Pre-1920s Views of Modern Venus

Venus is typically the second-brightest object in the night sky—and surely has been noticed as such by people and non-human animals since time immemorial (Figure 2). The first telescopic observations circa 1610 revealed that Venus always appears as a crescent from Earth, which served as strong evidence in support of the Copernican and Tychonic models of the Solar System. In 1761, a Russian scientist (Lomonosov) observed the refraction of solar rays during the transit of Venus across the Sun—thus discovering the atmosphere of Venus (e.g., Marov 2005). But little else was learned about Venus itself for hundreds of years. In 1891, a then-famous amateur astronomer wrote a guide for fellow enthusiasts titled *Telescopic Work for Starlight Evenings*. He declared Venus “the most attractive planet of our system” because “none of the other planets can compare with her in respect to brilliancy” (Williams 1891). However, he regretfully confessed that “when the telescope is directed to Venus it must be admitted that the result hardly justifies the anticipation” because “the lustre of Venus is so strong at night that her disk is rarely defined with satisfactory clearness” (Williams 1891). Close-up views of other planets at the time revealed fascinating details: craters on the Moon, polar caps on Mars, cloud bands on Jupiter, et cetera. However, Venus appears almost featureless in the visible wavelengths when viewed through small telescopes (Figure 3).

Reflected light from the dayside crescent of Venus swamps optical observations made from Earth. Supposed sightings of a moon (named Neith by Cassini and Lagrange) starting in the late 1600s were discredited by the late 1700s. Attempts to track faint features to determine a rotation rate of the atmosphere were made inaccurately, and not widely accepted—in fact, rotation rate retrievals remained wrong into the 1960s (e.g., Sagan 1960). For example, Cassini and Bianchini proclaimed incorrect rotation periods of ~1 and 24 Earth-days in the 1660s and 1720s, respectively (Williams 1891). Starting in 1643, some observers reported faint emission from the nightside of Venus, called "ashen light." These reports were dismissed as optical illusions (e.g., Sheehan et al. 2014). However, glimpsing some thermal emission from the night side (Sheehan et al. 2014) or O_2 airglow at wavelengths of ~0.45–0.55 µm with the human eye is perhaps possible (Wood et al. 2022). Until the mid-20th century, observations of Venus had not advanced much from prehistory. To the naked eye, Venus seems bright. When magnified in an optical telescope, Venus looks bigger and brighter.

Planetary scientists never surrender to a lack of data. One secure fact about Venus—its brightness—is enough to tell a fantastic tale about its surface conditions. Specifically, we can calculate the temperature required for equilibrium between the thermal radiation from Venus and the incident radiation from the Sun. First, if the planet radiates as a blackbody with a uniform temperature, then the total emitted flux (i.e., in units of Watts) is

$$F_{out} = 4\pi R^2 (\sigma {T_{eq}}^4), \quad (1)$$

where R is the planetary radius, σ is the Stefan-Boltzmann constant, and T_{eq} is the sought-after equilibrium temperature (e.g., Ingersoll 2013). In other words, the total outgoing radiation equals the product of the surface area of Venus and the flux per unit area from the Stefan-Boltzmann law. Second, any planet reflects a portion of the incident sunlight and absorbs the rest:

$$F_{abs} = \pi R^2 (1 - A) \left(\frac{1\ \mathrm{AU}}{D}\right)^2 F_E, \quad (2)$$

where A is the Bond albedo, and D is the Sun-planet distance (in astronomical units, where 1 AU is roughly the Earth-Sun distance), and F_E ~ 1361 W/m^2 is the solar constant (i.e., the flux density of solar radiation) at 1 AU. In other words, the total absorbed radiation is proportional to the cross-sectional area of Venus (not its total surface area). The term (1 AU / D)^2F_E equals the solar radiation at Venus's orbital distance. If Venus were rotating quickly as a whole with respect to its orbital period (false) or has efficient atmospheric circulation (true), then the incoming and outgoing energy can reach an equilibrium. Setting $F_{out} = F_{abs}$ and rearranging the various terms, the equilibrium temperature is

$$T_{eq} = \left[\frac{F_E}{4\sigma}(1-A)\left(\frac{1\ \mathrm{AU}}{D}\right)^2\right]^{\frac{1}{4}}. \qquad (3)$$

Plugging in numerical values (Table 1), T_{eq} ~ 225 K for Venus today, which is almost 30 K colder than the equilibrium temperature of Earth. Venus orbits closer to the Sun and thus faces more incident radiation than Earth—however, most of that radiation is reflected away without being absorbed (i.e., Venus has a Bond albedo of 0.77 compared to only 0.31 for Earth). Many textbooks elaborate on this calculation and its implications in detail (e.g., Ingersoll 2013). The simplest (but incorrect) interpretation of this quick calculation is that Venus and Earth have similar climates.

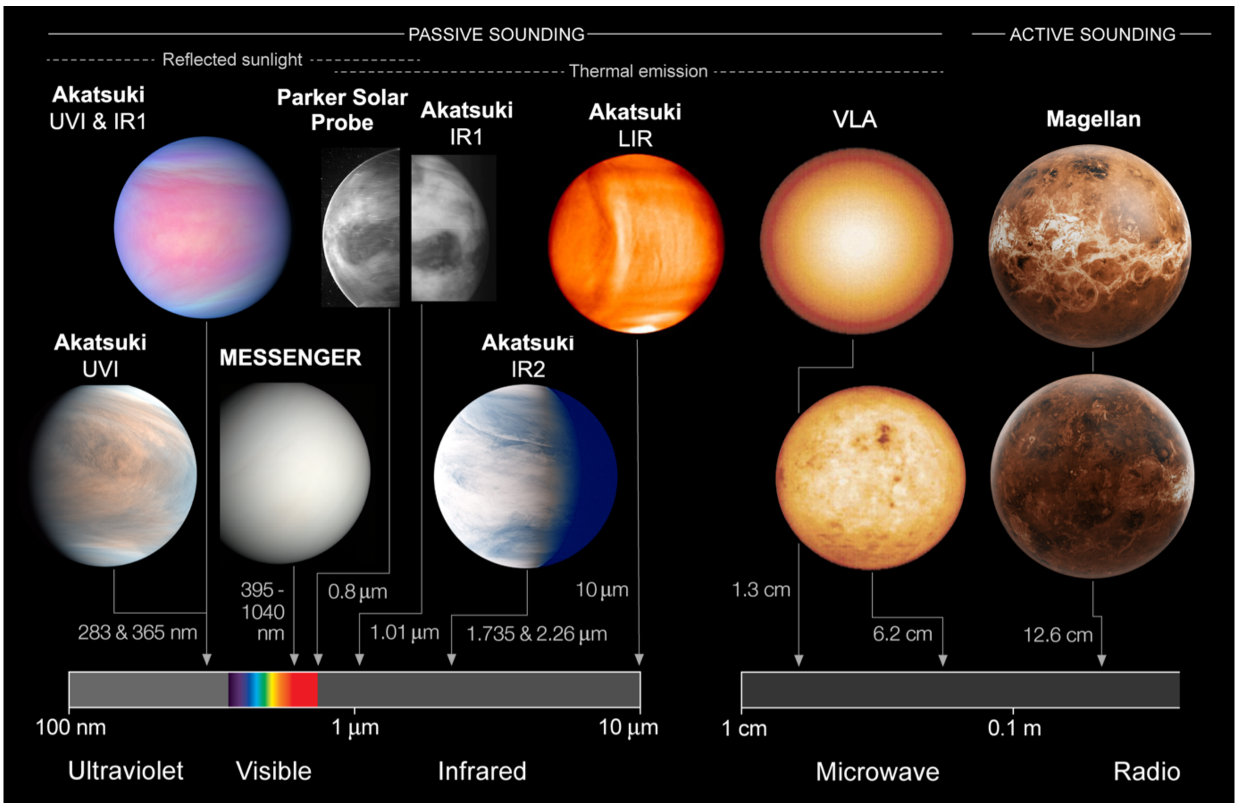

Figure 3. Venus looks bland in nearly all the visible wavelengths—but other wavelengths reveal myriad details. From left to right: dayside false color image from Akatsuki's UVI instrument (PLANET-C Project); dayside false color image from Akatsuki's UVI and IR1 instruments (PLANET-C Project); composite of dayside imagery from MESSENGER that shows natural color (NASA/JHUAPL/CIW/ Gordon Ugarkovic); nightside image from PSP centered on Ovda Regio (Wood et al. 2022); nightside image of the same area from Akatsuki's IR1 instrument, but rotated (PLANET-C Project); nightside synthesized false color image from Akatsuki's IR2 instrument (PLANET-C Project); stack of five pseudo-color infrared images from Akatsuki's LIR

instrument (PLANET-C Project); microwave observations from the Very Large Array (Butler et al. 2001); and a surface 3D model derived from Magellan radar imagery (NASA Visualization Technology Applications and Development). Images at shorter wavelengths are made using sunlight reflected from the dayside of Venus. Longer-wavelength images record thermal emission from the surface and/or atmosphere. Finally, the radar images show the power of active sounding to reveal surface features.

Before the Space Age, scientists surmised correctly that Venus is hotter and cloudier than present-day Earth. However, they erred by hugely underestimating the atmospheric surface pressure on Venus, which underrated the climatic differences between Venus and Earth. They were also incorrect in assuming that the clouds of Venus were made of H_2O (as vapor, droplets, and/or ice), although H_2O clouds can exist on other hot planets in the upper layers of thick, H_2O/CO_2-dominated atmospheres (e.g., Pluriel et al. 2019).. If the Venusian clouds and atmospheric surface pressure were Earth-like, then the climate of modern Venus would resemble that of Earth during, for example, the Carboniferous or Cretaceous Periods. Whereas roughly one third of Earth's skies are clear at any time on average (e.g., King et al. 2013), Venus is always completely shrouded. More clouds were thought to yield more rain, which would lead to a verdant surface. In his 1918 work of popular science, *The Destinies of the Stars*, Nobel laureate Svante Arrhenius declared that "Venus is no doubt covered with swamps" and thus with abundant life "belonging to the vegetable kingdom" (Arrhenius 1918). The uniformity of Venus's visual appearance also led to the idea that the surface climate was spatially consistent—a jungle-analogue from the equator to the poles. This supposition of homogeneity ultimately proved correct, albeit not in the sense that anyone anticipated in the early 20th century.

2.1.1 A Verdant Venus in Popular Culture

Pre-Space Age scientific views of Venus led to a delightful explosion of science fiction. As reviewed in a recent collection of short stories, *Old Venus*, which pays tribute to the classics, Venus was the stage for a subgenre dubbed "Planetary Romance" and/or "Sword and Planet" (Dozois 2016). Heroes tromped around the jungle, battling dinosaur-like beasts and other energetic megafauna. While Mars offered a sort of barren elegance, Venus had perhaps too much life. Exploration of Venus was seen as an optimistic endeavor—a path towards human progress. For example, the Strugatsky Brothers, perhaps the most famous Russian sci-fi authors at the time, published *The Land of Crimson Clouds* in 1959 at the dawn of the Space Age (Figure 4). In this novel, a high casualty rate for the first crew to pierce the eponymous clouds was reckoned a fair trade for an interplanetary future for humanity. A Venus that was far away but maybe not too inhospitable seemed to offer risks and rewards that were relatable to the exploration (and exploitation) of Earth.

Figure 4. Venus has played many roles in popular culture (photos by JGO). For example, *The Land of Crimson Clouds* (top left), published in 1959 by Boris and Arkady Strugatsky, described a trip to Venus in a progressive future when space exploration advanced economic prosperity and social harmony. *Old Venus* (top right) is a collection of short stories published in 2016 that pays homage to the sword and planet sub-genre of pre-1960s science fiction. *The Expanse* (bottom left) reflects the depression that prevailed in the immediate aftermath of Mariner 2—treating Venus as a boring scrap planet. *The House of Styx* (bottom right, published in 2020) is typical of recent fiction set on a Venus where protagonists are reforged in a crucible of pain.

Some fictional works explored the downsides of life on a clement Venus. After all, humans are most comfortable on the planet that they evolved to inhabit—even the planet with the most Earth-like surface, Mars, would be a hard place to live (c.f., Stirone 2021). In the novel *The Space Merchants*, published in 1952 by Frederik Pohl and Cyril M. Kornbluth, an advertising executive lures naive customers to new colonies on Venus. He sells Venus as a land of plenty, waiting to be seized, but economic activity is difficult and dangerous—and, of course, the plot demands dastardly deeds. At an intimate scale, Ray Bradbury portrayed Venus as a wet hell in his short story *The Long Rain*, published in 1950. Four characters compare their surroundings to "an immense cartoon nightmare" and the steady drops of rain to a torture technique. They search in vain for the only bearable habitat—a "Sun Dome… a yellow house, round and bright as the sun" filled with "warmth and quiet and hot food and freedom from rain" (Bradbury 1951). The weather drives the men to hallucination and insanity. They realize (in fleeting moments before the aforementioned insanity) that they cannot survive on Venus without what they left behind on Earth.

2.2 Competing Models to Explain New Observations (1920s to early 1960s)

In the early 20th century, new observations set the stage for a paradigm shift about the evolution of Venus. First, scientists accidentally discovered that carbon dioxide was abundant in the atmosphere. Astronomers had tried but failed to find spectral signatures of oxygen and water vapor at infrared wavelengths from the atmosphere in order to prove that the clouds were Earth-like (e.g., St. John & Nicholson 1922; Adams & Dunham 1932). They instead found unexpected absorption bands that were matched to laboratory measurements of carbon dioxide with an equivalent path length of ~200–400 m at pressure/temperature conditions of 1 atm and 273 K (e.g., Adams & Dunham 1932; Adel 1937). That quantity of CO_2 (~$2–4 \times 10^{17}$ kg) was interpreted as the amount that existed in the atmosphere above the "reflecting layer" where the optical depth was approximately unity. Although roughly the same mass of CO_2 exists in Earth's entire atmosphere, we now know that this lower limit underestimated the true total for Venus by a factor of >90. Still, Wildt (1940) realized that even the claimed amount of CO_2 would cause a greenhouse effect that could raise the surface temperatures to ~366–408 K, which would be incompatible with surface water.

A few decades later, another set of observations further challenged the fantasy of a jungly Venus. Radiometric measurements of Venus at various wavelengths provide "brightness temperatures" if blackbody spectra (Planck's law) are fit to the observed emission. Early studies found brightness temperatures of ~230–250 K in infrared wavelengths, which were near the equilibrium temperature predicted by equation 3 and (correctly) interpreted as the real temperatures at or near the cloud tops (e.g., Pettit & Nicholson 1955; Öpik 1956). Mayer et al. (1958) conducted the first observations of Venus (and any planet) at radio wavelengths, specifically at 3.15 and 9.4 cm. They measured unexpectedly strong emission with brightness temperatures of ~600 K (e.g., Mayer et al. 1958; Barrett 1961). A blackbody with a temperature of only ~260 K would emit less than half the measured radiation at those wavelengths. Subsequent observations at 10-cm wavelength also yielded high brightness temperatures and found little difference (~10s of degrees at most) between the effective temperatures of the dayside and nightsides (Drake 1962). Ultimately, in the early 1960s, the ancient idea that Venus has roughly uniform surface conditions seemed correct—but, if the brightness temperatures from radio observations should indeed be interpreted as surface temperatures, those conditions were perhaps hellish, not humid.

When Mariner 2 was launched towards Venus in 1962, several models of its atmosphere and surface remained in contention (Figure 5). Roughly speaking, in chronological order, they featured 1) the jungly fantasy with H_2O clouds (Arrhenius 1918), 2) a surface entirely covered with a carbonated ocean and H_2O clouds (Menzel & Whipple 1954), 3) a surface covered in hydrocarbons and clouds made of smog (Hoyle 1955), 4) an "aeolosphere" with the top of an unceasing, global dust storm at the clouds (Öpik 1961), and 5) a scorched surface below two cloud decks, the lower made of bright ice crystals and the higher made of an unknown UV absorber (Sagan 1961). Only the last two models correctly predicted that the surface was far too hot for liquid water to survive. As discussed in section 2.3, all these models were ultimately wrong about the composition of the clouds.

Imagine that you were a scientist studying Venus at the dawn of the Space Age. Picking your favorite model was a choose-your-own-adventure process with a few steps. First, you would need to decide if you believed that the "brightness temperature" inferred from radio and microwave observations was the real temperature of the surface (e.g., Mayer et al. 1958; Barrett 1961; Drake 1962). Some scientists argued that the ionosphere of Venus could emit in these wavelengths (e.g., Roberts 1963), meaning that the observed radiation may not be thermal emission from the surface. For example, Jones (1961) proposed that the solar wind could create high brightness temperatures from free-free transitions of electrons in an optically thick ionosphere. If you believed that liquid water could be stable on the surface, then you would next need to decide if you accepted the evidence that CO_2 was abundant in the atmosphere. If so, then you needed to explain why surface rocks had not drawn down that CO_2 gas. However, if you instead agreed that the surface was hellish, then you would next consider if CO_2 alone—or another absorber—provides the opacity that creates a strong greenhouse effect. These branching choices led to the diverse pictures shown in Figure 5.

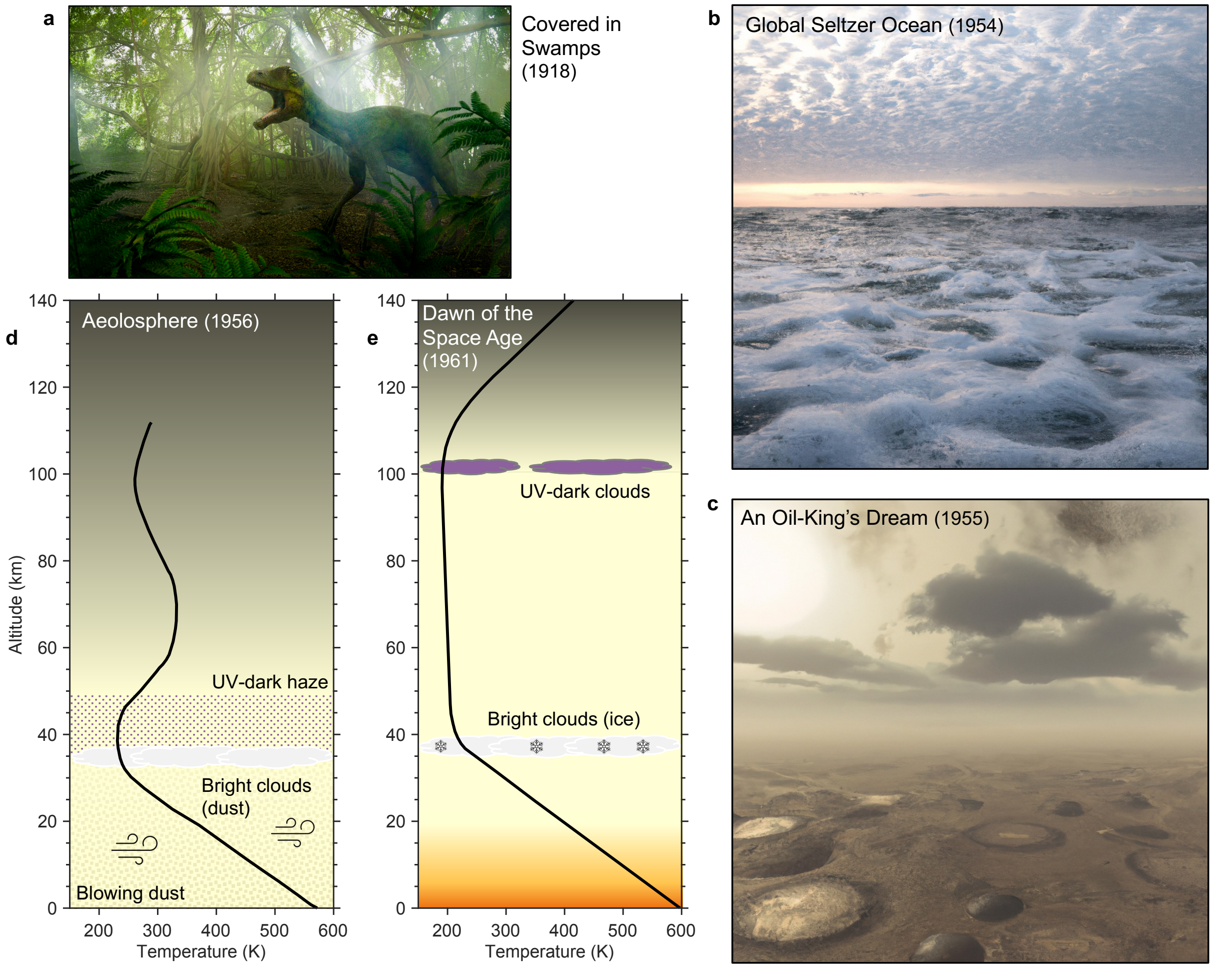

Figure 5. Before the launch of Mariner 2 in 1962, scientific opinion was divided between several different models of the Venusian atmosphere and surface. The ancient notion of a jungly Venus (a) had its proponents but was becoming disfavored because the observed abundance of CO_2 gas was far above the value for Urey equilibrium. Some scientists proposed to avoid Urey equilibrium by drowning the entire surface (b) or coating it in oil (c). Die-hard devotees of these models invoked the ionosphere to explain the strong radio emission detected in the 1950s. Others (correctly) thought that the hot surface produced that radio emission. (d) A global dust storm (e.g., "model I" from Öpik 1961) or (e) an even greater abundance of CO_2 (e.g., Figure 3 in Sagan 1961) were argued to produce bright clouds and the requisite greenhouse heating. Ultimately, all these models were different in key respects from the modern picture shown in Figure 6. We used a stock image from Microsoft for (a) and DALL·E 2 to generate (b) and (c).

Scientists struggled to reconcile models with both abundant CO_2 in the atmosphere and surface temperatures that were compatible with liquid water. Urey (1952) famously proposed that a series of reactions would maintain an equilibrium partial pressure of CO_2 in the atmosphere of a planet with both exposed silicates and liquid water on its surface. For example, enstatite ($Mg_2Si_2O_6$) could react with atmospheric CO_2 to produce magnesite ($MgCO_3$) and quartz (SiO_2). Similarly, wollastonite ($CaSiO_3$) could react with CO_2 to produce calcite ($CaCO_3$) and quartz. However, the inferred atmospheric abundance of CO_2 at Venus was much larger than calculated assuming this Urey equilibrium. Logically, Venus must lack either exposed silicates or liquid water. Menzel & Whipple (1954) proposed that Venus was covered with what Sagan (1961) called a "global Seltzer ocean." Drowning all the rocks could provide ample water vapor for clouds but prevent the Urey reactions. The high partial pressure of CO_2 would lead to carbonation of the ocean—fizzy! Hoyle (1955) argued instead that Venus lacked any surface water. He suggested that Venus accreted with an excess of hydrocarbons relative to water. The oxygen in water oxidized most of the hydrocarbons, producing atmospheric CO_2, while the hydrogen escaped to space. He predicted that the surface was still covered with hydrocarbons ("endowed beyond the dreams of the richest Texas oil-king") and that the clouds contained drops of oil. Petroleum geologists at the time pointed out that Hoyle's belief that hydrocarbons on Earth and Venus were primordial (i.e., delivered by meteorites and comets) conflicted with the oil-kings' notions that oil on Earth was a relatively recent byproduct of fossilized organic material (e.g., Pratt 1956).

Other scientists were quicker to accept that the surface of Venus was hundreds of Kelvins hotter than earlier believed. This paradigm shift eliminated any cognitive barrier to accepting that the atmosphere contained a huge mass of CO_2, which created a planetary greenhouse. However, tension still seemed to exist between the ~600 K brightness temperatures and the ~400 K surface temperatures that earlier greenhouse models predicted (Wildt 1940). Sagan (1961) argued that a CO_2-dominated atmosphere with quadruple the mass of Earth's atmosphere would provide the necessary heating. Based on his calculations of the adiabatic lapse rate, the temperature in the atmosphere would drop rapidly enough with altitude that H_2O could freeze at ~30–40 km to form ice-crystal clouds. Öpik (1961) claimed that CO_2 alone could not provide enough greenhouse heating, even if a minor contribution to the total opacity from water vapor was also considered. He proposed dust as an additional source of greenhouse heating and defined the "aeolosphere" as the region between the solid surface and the clouds. In his models, wind friction provided enough energy to keep the dust lofted. Öpik (1956) had previously argued that the atmosphere rotates at least once every ~10 Earth-days—fast enough to redistribute the required energy around the planet. Sagan (1961) criticized Öpik's aeolosphere models because they predicted a distribution of grain sizes for lofted dust that was inconsistent with the particle sizes derived from observations of their polarization. In contrast, Öpik (1961) argued that Sagan's proposed ice-crystal clouds were unlikely to form because the H_2O content of the atmosphere was below the saturation value. Both categories of cloud-centric criticism from these eminent scientists were soon proved correct. Mariner 2 and subsequent ground- and space-based observations revealed that the atmosphere and surface conditions were different than predicted by any previous study.

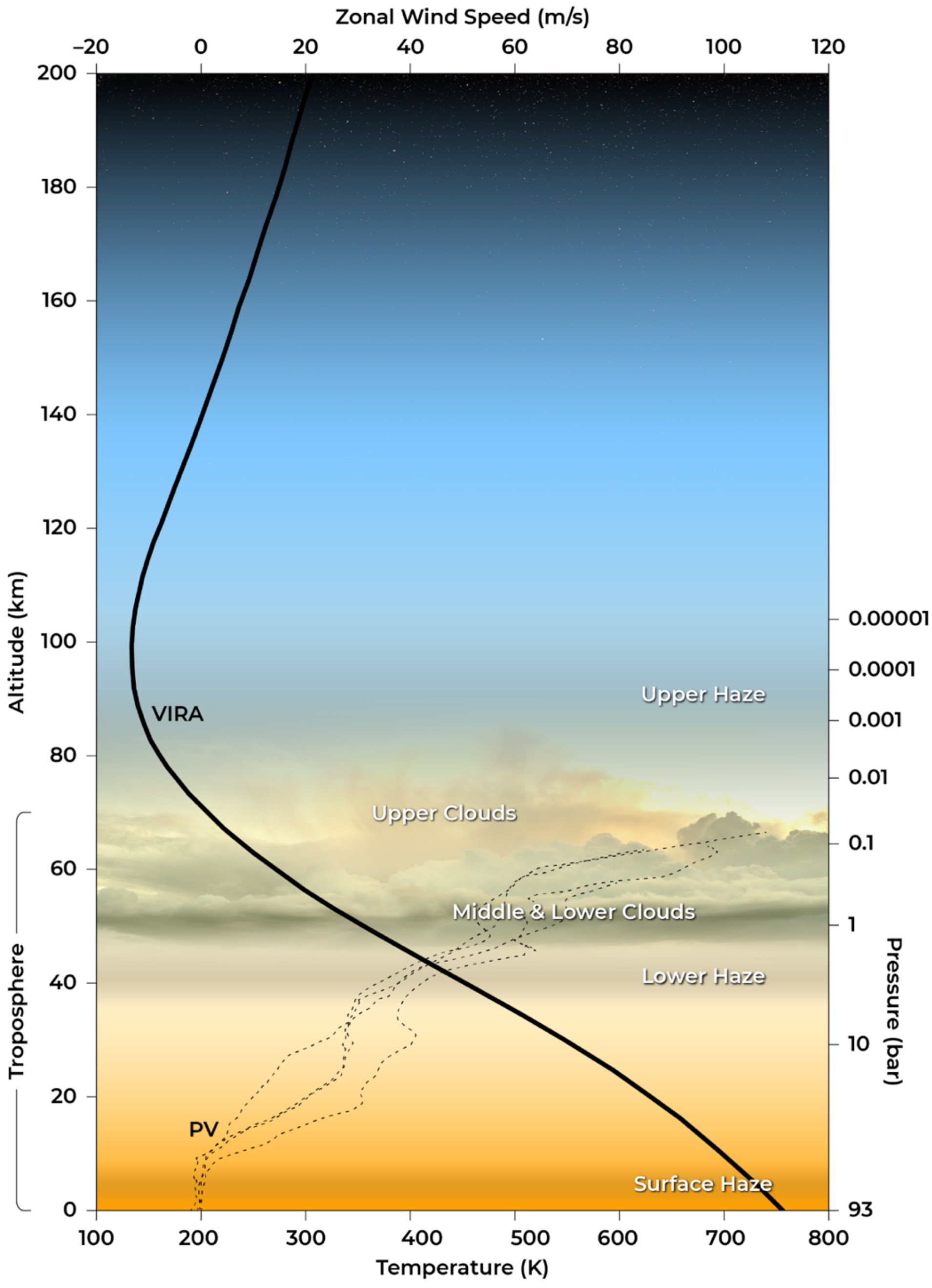

Figure 6. The present-day atmosphere of Venus. Starting in the 1960s, several probes made in situ measurements of temperature and wind speeds in the Venusian atmosphere. Missions also determined the size distribution(s) of aerosol particles in the cloud and haze layers. Black curves show an equatorial temperature profile from the Venus International Reference Atmosphere (solid) and zonal wind speeds from four Pioneer Venus entry probes (dashed).

2.3 Convergence to the Modern Model of Modern Venus (1960s to 1970s)

Mariner 2 encountered Venus in December 1962 at a distance of ~34,000 km at closest approach—and became the last nail in the coffin for the dream of a swampy Venus. As the first successful interplanetary mission, Mariner 2 was designed to accomplish a broad range of scientific investigations, centered on understanding the atmosphere of Venus and the nearby particles and fields environment (e.g., Sonett 1963). One instrument—the microwave radiometer—was designed to test if the brightness temperatures at wavelengths ≥3 cm revealed the actual surface conditions. Arguments that the ionosphere could radiate intensely were the last gasp of the hypothesis that the surface of Venus is habitable today. However, many scientists considered this hypothesis unrealistic because it required huge electron densities (e.g., Roberts 1963). During the Venus flyby (called a "near-collision" by Sonett 1963), the microwave radiometer conducted three scans of the planetary disk at wavelengths of 13.5 and 19 mm to settle this debate (Barath 1964).

Two competing hypotheses for the radio emission observed from Venus at Earth made opposing predictions. If the radio emission were an ionospheric and/or atmospheric phenomenon, then "limb brightening" would be observed with higher brightness temperatures near the edge of the disk, where the atmosphere appeared thickest from the instrument's point of view (e.g., Roberts 1963). If the emission originated from the surface, however, then "limb darkening" would result with the highest brightness temperatures measured at the center of the disk, where the atmospheric path length from the surface to the spacecraft was minimized (e.g., Sagan 1961). Measuring these phase effects from Earth required tracking Venus for its entire orbit and calibrating for the changing Earth-Venus distance, which was difficult. With a single flyby, Mariner 2 found limb darkening and proved that the hypothesis of surface emission was correct. Walker & Sagan (1966) published an "obituary" for the ionospheric hypothesis—and thus for the dream of a clement surface now. More recently, microwave observations of Venus from the Very Large Array (Figure 3) resolved the limb darkening effect across the entire disk (Butler et al. 2001).

A flurry of spacecraft from the USSR provided in situ measurements of the composition and thermal conditions of the atmosphere in the 1960s and 70s. Reaching Venus was the goal of 16 early USSR launches (e.g., Avduevsky et al. 1983). Among these spacecraft, Venera 2 and 3 (1965) missed the planet by so little that the efforts were continued. The first spacecraft to hit Venus and successfully measure the atmospheric parameters during the entry and descent down to 24 km altitude was Venera 4 (1967). The measured temperature was 262 °C at 18 bar pressure. The gas analysis revealed >80% CO_2 atmosphere with <2.5% of nitrogen with an addition of O_2 and traces of H_2O—contrary to the expectation of ≥50% N_2 (e.g., Avduevsky et al. 1983). The common understanding at that time was that the reached physical conditions were representative of the lower atmosphere down to the surface. However, the extrapolation of Venera 4 results already implied the surface temperature and pressure close to their actual values. Still, the next generation Venera 5 and 6 (1969) probes were designed to withstand the pressure of 25 bars only. They operated down to 18 and 22 km altitudes, largely confirming the Venera 4 results (e.g., Avduevsky et al. 1970, 1983). Venera 7 (1970) was the first probe to reach the surface of Venus. It collected a temperature profile from 55 km to the surface, where it measured 457–474 °C. Venera 8 (1972), designed to survive for ~90 minutes at the surface, was the precursor of all subsequent Soviet landers (e.g., Marov et al. 1973). It measured the atmospheric profile at altitudes of 0–100 km, including the first directly measured surface pressure of 93 ± 1.5 bar, detected three levels of clouds (including some that were not visible in IR and UV images), improved the knowledge of the atmospheric composition (97% CO_2, 2% N_2), and provided the first estimates of the surface composition (see section 3.2).

The composition of the clouds remained a mystery even after doubts about the surface temperature dissipated. As reviewed in section 2.2, previous studies suggested water vapor (e.g., Menzel & Whipple 1954), ice crystals (e.g., Sagan 1961), dust (Öpik 1961), oil droplets (e.g., Hoyle 1955), and several other possible candidates (e.g., Hansen & Hovenier 1974 and references therein). The decade after Mariner 2 featured several successful missions to Venus, including the Mariner 5 flyby and the Venera 4–7 atmospheric probes (e.g., Rea 1972; Avduevsky et al. 1970, 1977, 1983; Taylor et al. 2018 and references therein). However, early probes did not provide a convincing answer for the composition of the clouds. Scientists invoked observations of the polarization of reflected light from Venus to argue for and against models of particle size and composition (e.g., Sagan 1961; Rea 1972). Finally, Hansen & Hovenier (1974) developed high-quality models of scattering and matched them to polarization data. They showed that a concentrated solution of sulfuric acid (now estimated at ~80–99 wt% H_2SO_4, depending on altitude) was the best match to the properties of the cloud droplets. Parts of the upper atmosphere of Venus might be cold, but there are no large reservoirs of pure water. A few years later, Venera 9 and 10 provided the first in situ measurements of the clouds (Marov et al. 1984). The Venera missions (9–14) and Pioneer Venus confirmed that the atmosphere was very dry and the clouds were made of sulfuric acid droplets (e.g., Kawabata et al. 1980; Knollenberg & Hunten 1980; Moroz 1983; Esposito et al. 1983; Titov et al. 2018 and references therein).

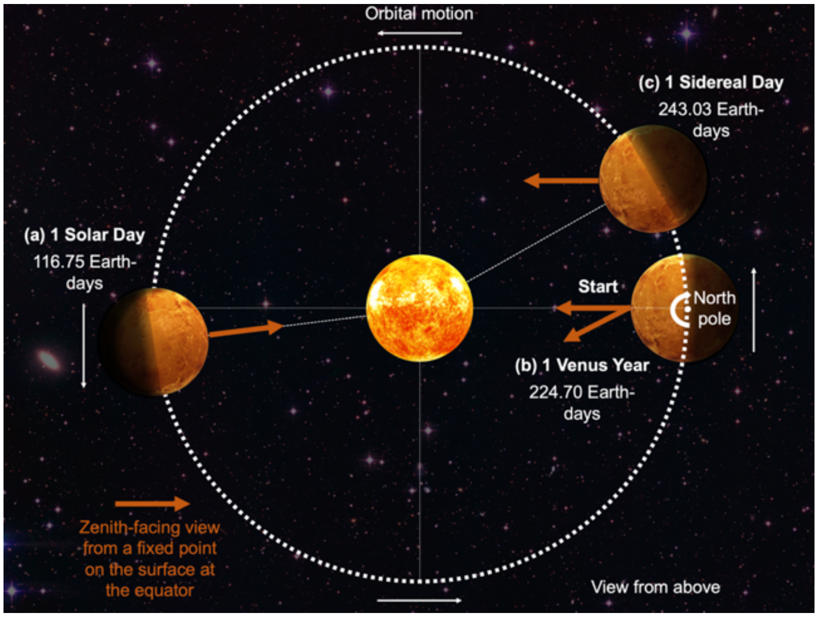

Figure 7. The solid body of Venus rotates more slowly at present day than any terrestrial planet in our Solar System. This cartoon depicts the orbit of Venus around the Sun, viewed from above. The orbital angles are approximately to scale, but the relative sizes of Venus and the Sun are not. After one solar day (a), an observer at a fixed location on the surface of Venus would see the Sun return to its original position in the sky. In one year (b), Venus completes a single orbit around the Sun. In one sidereal day (c), Venus revolves once relative to the celestial sphere (e.g., the background stars). Earth's sidereal day is shorter than its solar day, which is much shorter than our year. In contrast, a Venus-year lasts less than two of its solar days—and one sidereal day on Venus is longer than a Venus-year.

Ground-based measurements also provided surprising information about the rotation of Venus. Scientists tracked surface features visible in radar images from the Arecibo and Goldstone installations. They determined that the solid body rotates very slowly—it takes ~243 Earth-days for the surface of Venus to spin 360° on its rotation axis (e.g., Pettengill et al. 1962; Carpenter 1964; Goldstein 1964; Gold & Soter 1969). Venus also has retrograde rotation and a relatively small obliquity (e.g., Yoder 1997 and references therein). As shown in Figure 7, a sidereal day on Venus is thus longer than a Venus year. In contrast, a sidereal day on Earth lasts a few minutes less than 24 hours. Many factors—including accretionary processes, giant impacts during or after accretion, and atmospheric and solar tides—can affect the spin dynamics of Venus over geologic time. Length-of-day variations on Earth are approximately a ms (or about 1 part in 10^{11}) whereas they may be up to about 20 min (or about 1 part in 10^{5}) on Venus due to solar tides and the coupling between the fluid atmosphere and the solid surface (e.g., Margot et al. 2021). Venus's slow rotation could have been established during its accretion—or may be a recent phenomenon. Altogether, the rotation state of Venus is strikingly unique in the Solar System.

2.3.1 A Hellish Venus in Popular Culture

Popular artists did not deny the new scientific consensus about present-day Venus. However, revealing the truth about Venus caused immediate depression. Dozois (2016) describes the angst caused by discovering that Venus "was just a ball of baking-hot rock and scalding poisonous gas, [allegedly] duller than a supermarket parking lot." Science-fiction writers committed to at least a smidgen of realism could no longer place heroes on Venus and expect them to have a good (or at least damp) time. New stories about Venus, such as those in the anthology *Farewell, Fantastic Venus!* (Aldiss & Harrison 1968) were "deliberately retro" and tinged with regret that reality ultimately failed to conform to optimistic expectations (Dozois 2016). When Bradbury's *The Long Rain* was adapted for television in the 1990s, it was stripped of any reference to Venus—the setting was shunted to an unnamed exoplanet. However, artistic work eventually reflected a transition from depression about the lost dream of jungly adventure to acceptance of the real Venus.

Many fictional works now treat Venus as less interesting than virtually all other planetary bodies in the Solar System. For example, in *Rendezvous with Rama* (Clarke 1973), human settlements stretch to Mercury but skip Venus. Likewise, *The Expanse* (Figure 4) is a wildly popular series of novels, novellas, short stories, and television that concluded in early 2022 (Corey 2022). This space opera tours Earth, Mars, sundry asteroids, the outer solar system, and scores of exoplanetary systems—all home to diverse, memorable communities. In contrast, Venus is kept deserted with plans "to create a network of high-atmosphere floating cities" mired in "a labyrinth of lawsuits" (Corey 2011). Later, Venus is treated as a convenient dumping ground for a life-devouring horror—as a protagonist proclaims at a pivotal point, "Give [the life-devouring horror] Venus… it's an awful place" (Corey 2011). Inhabitants of *The Expanse* would place Venus at the bottom of any list of places to visit.

The best evocations of Venus in popular culture now embrace its superlative inhospitality. Venus provokes awe because its hostility is relatable—it is the Mr. Hyde to Earth's Dr. Jekyll. This duality echoes the symbolic tension between Venus's namesake (Aphrodite, the Greek goddess of love) and the hostility of its surface. For example, a recent, award-winning novel, *Gideon the Ninth*, leans into this tension. This bestseller depicts a consequential gathering of representatives from nine "Houses", each situated on or near nine worlds: the Solar System's eight major planets plus Pluto. The representative from Venus (a necromancer, as it happens) remarks that "[her] House loves beauty… a kind of beauty in dying beautifully" (Muir 2019). A 2020 novel, *The House of Styx* (Figure 4) is set on Venus as a proving ground for the protagonists to grow stronger through adversity. In this novel, bands of industrious, anarchist Quebecois live in atmospheric habitats, obliged to a constant "struggle to pit [their] cunning against Venus to stay alive and scrape some subsistence from the deep clouds" (Künsken 2020). Some of the characters worship Venus, although the planet demands "the same price as any goddess: she wants to be embraced," which hurts a lot (because of the acid) for the cloud-dwellers who take "embraced" literally (Künsken 2020). Life on Venus demands sacrifice—the symbolism is potent but not subtle.

2.4 Recent History of Spacecraft Exploration

Back in real life, people never stopped launching spacecraft towards Venus, either as a primary target or as a waypoint on an interplanetary trajectory to another destination. Previous reviews contain comprehensive accounts of missions that targeted Venus. For example, Table 2 in Taylor et al. (2018) from the Venus III collection lists all Venus-related launches, including both successes and failures. Even missions that do not "care" about Venus, except as a convenient mass from which to steal momentum during a gravitational assist maneuver, provide snapshots of Venus's evolution (e.g., Gray et al. 2021). For example, MESSENGER made unique measurements of Venus's upper atmosphere during its flybys (e.g., Pérez-Hoyos et al. 2018; Peplowski et al. 2020)—and BepiColombo is executing similar observations on its way to Mercury (e.g., Mangano et al. 2021). Of course, missions that orbit Venus for years and/or perform in situ measurements make scientists rewrite textbooks. In this review, we do not aim to cover the full history of spacecraft exploration at Venus. Instead, here we highlight four missions from the last three decades that are foundational to our present understanding of Venus and exemplify how spacecraft can shed new light on Venus and possible models of its evolution.

2.4.1 Magellan

The NASA Magellan Mission entered orbit around Venus in August 1990 and operated until purposefully plunging into the atmosphere and burning up in October 1994. Magellan was a scaled-down version of a concept called Venus Orbiting Imaging Radar—to save money, Magellan was designed to re-use hardware from other flight programs as much as possible (e.g., Saunders et al. 1990). Magellan's primary instrument was a large radar sensor built on a high-gain antenna with a diameter of 3.7 m. For imaging, the antenna was operated as a synthetic aperture radar (SAR) instrument with a wavelength of 12.6 cm (S-band) and a look angle of ~25° away from the vertical direction (i.e., off-nadir). A small horn antenna was nadir-pointed and collected altimetry data. In the burst-mode of data collection, the horn and high-gain antennas were operated in a careful sequence so their transmissions and the reflections from the Venus surface would not overlap (e.g., Pettengill et al. 1991). The spacecraft was placed in a polar orbit so the solid body would rotate underneath the orbital path every 243 Earth-days, which corresponded to a single "Cycle". During each orbit, Magellan alternated between collecting data and transmitting the data back to Earth with the high-gain antenna—and brief periods of spacecraft housekeeping (e.g., desaturating the reaction wheels and navigating).

Magellan achieved its primary requirements during its first Cycle—and achieved additional science during four subsequent Cycles. During Cycle 1 (1990–1991), Magellan achieved its primary objectives to acquire radar imagery of >70% of the surface with a horizontal resolution of <300 m (Saunders et al. 1992) and to determine the global topography with horizontal and vertical resolutions of ~10 km and ~80 m, respectively (Ford & Pettengill 1992). These SAR images were left-looking with incidence angles that varied from ~45° at the equator to ~16° near the poles. During Cycle 2 (1991–1992), the spacecraft was reoriented to a right-looking geometry with an incidence angle of ~25° (slightly less toward the south pole). Because the spacecraft's electronic bays overheated during data transmission to Earth, only images of ~55% of the surface were returned during this phase. For Cycle 3 (1992), the spacecraft was reoriented back to a left-looking geometry—but with a smaller incidence angle to enable stereo imagery. Unfortunately, the spacecraft's transmitters experienced failures and only ~21% of the surface was imaged in this new geometry. After Cycles 1–3, however, over 98% of the surface had been imaged at least once with a spatial resolution of ~125 m or so—still the best global radar map of the surface to the date of writing. Towards the end of the mission, the spacecraft dedicated itself to acquiring gravity data via Doppler ranging in its original, elliptical orbit (Cycle 4) and after aerobraking that circularized the orbit (Cycle 5). Ultimately, the best gravity data have a resolution approaching spherical harmonic degree 180, equating to a horizontal resolution of >250 km (Konopliv et al. 1999)—a thousand times worse than the image resolution.

Overstating the scientific importance of the Magellan datasets is likely impossible. Although the images, topography, and gravity data are now more than three decades old, they are still being mined for new scientific insights. Magellan revealed most of the properties of the surface and interior discussed below in sections 3.2 and 3.3. Globally, Magellan provided a snapshot of the planet's current geologic state, including a catalog of thousands of tectonic and volcanic features—some of which are analogous to those observed on other terrestrial planets, whereas others are superlative in the Solar System. In terms of the evolution of Venus, puzzling observations have spawned many debates. Because Magellan only operated for a few years, the rates of various volcanic and tectonic processes remain unknown—and attempts to detect changes to surface features between successive radar imaging cycles were inconclusive. Fortunately, the VERITAS and EnVision missions will serve as the spiritual successors to Magellan (e.g., Widemann et al. 2023, this issue), providing new geologic and geophysical data with orders-of-magnitude better image, topographic, and geodesic resolution over a temporal baseline of decades, which may well verify that Venus is geologically active in the present.

2.4.2 Venus Express

ESA's Venus Express (VEx) orbited Venus from 2006 until 2014 (e.g., Svedhem et al. 2007a, 2007b). Its scientific payload was mainly focused on characterizing the atmosphere, from the surface to the thermosphere, using a suite of spectrometers, imagers, and in situ instrumentation. While many of the investigations aboard VEx focused on how Venus works in the present day, much of their data informs our knowledge of how Venus has evolved.

VEx provided several indications which are indirectly suggestive of current or geologically recent volcanism. These observations build on the legacy of multiple prior missions to Venus. For example, an infrared atmospheric spectrometer (6–35 μm) onboard Venera 15 operated for two months, which demonstrated the power of such data to characterize the temperature structure (e.g., Oertel et al. 1985) as well as water and SO_2 content at the cloud tops (e.g., Zasova et al. 2004)—Pioneer Venus Orbiter also studied SO_2 in the ultraviolet (e.g., Stewart et al. 1979; Esposito 1984). Firstly, its mapping of mesospheric SO_2 abundances showed a fourfold rise in the first year of observations followed by a tenfold fall over following years, a pattern which suggests episodic injection of SO_2 into the mesosphere, due to either volcanic activity or meteorological variability (e.g., Marcq et al. 2013, 2020). Secondly, mapping of surface emissivity at 1 μm wavelength, performed on the nightside of Venus by the VIRTIS instrument, found anomalously high emissivity surrounding some hotspot volcanoes, which may indicate fresh, as yet unweathered lava flows (Smrekar et al. 2010). Thirdly, some repeated 1 μm imagery from the Venus Monitoring Camera showed apparent changes in surface radiometric brightness, which could be a direct thermal signature of volcanic activity (Shalygin et al. 2015). However, this detection was only achieved at one location and at one wavelength without correction for cloud effects, so it cannot be considered a robust detection. Taken together, these three results from Venus Express support the case for active volcanism on

Venus today—and have inspired follow-up observation on future Venus missions to search for new eruptions.

VEx also provided some first clues about compositional diversity on the surface of Venus through its 1 μm emissivity mapping—in particular, showing that tesserae highlands have low 1 μm emissivity, consistent with a felsic composition (e.g., Gilmore et al. 2015, 2017). If widespread felsic composition of highlands is confirmed, that would suggest a similarity to Earth's continental crust, whose formation required large water abundances, and would provide strong evidence of a water-rich past (see section 3.2 below).

Escape of volatiles to space is another area in which VEx contributed to our understanding of Venus's evolution. Escape rates of hydrogen and oxygen were measured. While, at first, they seemed to be roughly in stoichiometric 2:1 ratio (i.e., for H_2O), subsequent analysis found that the ratio can be as low as 1:1 in times of solar maximum, with implications for the chemical evolution of the Venus atmosphere during water escape (Persson et al. 2018). The oxygen ion escape rates were found to be lower than those from Earth, although Venus is closer to the Sun and not shielded by an internal magnetic field. This observation appears to contradict the commonly held belief that internal magnetic fields "protect" planets from atmospheric loss (e.g., Brain et al. 2016; Dong et al. 2020). Finally, Venus Express' SPICAV spectrometers showed that the HDO/H_2O ratio in the mesosphere of Venus is twice as highly enriched as in the troposphere (below the clouds), and that this enrichment factor rises by another order of magnitude above 100 km altitude (Bertaux et al. 2007; Fedorova et al. 2008; Vandaele et al. 2020). Venus' high D/H enrichment compared to that of Earth implies that Venus has lost vast amounts of water over its history (as will be discussed below in section 3.1.1)—these measurements of its vertical distribution enable better understanding of D/H fractionation processes, and therefore of its implications for understanding the history of water on Venus.

2.4.3 Akatsuki

Akatsuki was almost a failure but turned into a spectacular success. Launched in May 2010 as Japan's third planetary mission (Planet-C project), Akatsuki was supposed to enter Venus's orbit in December 2010. However, the orbit insertion maneuver failed, leaving the spacecraft in a heliocentric orbit (Nakamura et al. 2011). Subsequent analysis found that fuel was unable to pass through a critical valve into the orbital maneuvering engine—but the spacecraft could use its reaction control system to perform an orbital maneuver (Nakamura et al. 2014, 2016). The team performed clever trajectory analyses and designed a new orbit insertion maneuver that placed the spacecraft into Venus's orbit in December 2015. Originally, the spacecraft planned to enter an equatorial orbit with a period of ~30 hours and periapsis and apoapsis altitudes of <850 km and ~80,000 km, respectively (Nakamura et al. 2011). The final orbit is ~5–6 times further away from Venus than planned (e.g., with a periapsis altitude of ~1,000–8,000 km and an apoapsis altitude of 360,000 km) and has a period of ~10.5 Earth-days (Nakamura et al. 2011). However, the equatorial orbit (inclination of 3°) still allows Akatsuki to track features in Venus's atmosphere for much longer than was previously possible using instruments on spacecraft in polar orbits (e.g., Nakamura et al. 2014, 2016).

Akatsuki's instrument payload was designed to make three-dimensional movies of the atmospheric dynamics. The spacecraft carries five photometric sensors (Nakamura et al. 2014): infrared cameras at 1 μm (IR1) and 2 μm (IR2), an ultraviolet imager (UVI), a long-wave infrared camera (LIR), and a lightning and airglow camera (LAC). Atmospheric gasses, clouds, and hazes absorb different wavelengths of light at different altitudes. For example, ground-based studies have used near-infrared spectral windows to study the lower atmosphere of Venus (e.g., Arney et al. 2014). Multispectral imaging by Akatsuki thus returns multiple "slices" of the atmosphere (Figure 3). Wind speeds are inferred via tracking of morphological features (e.g., Peralta et al. 2017, 2019, 2020; Limaye et al. 2018). Images also constrain models of other cloud properties (e.g., thicker clouds block more thermal emission from the surface and thus appear darker in the near-infrared on the nightside). Akatsuki also performs radio sounding of the atmosphere, which provides vertical profiles of temperature and some molecular abundances (e.g., vertical profiles of H_2SO_4 vapor). These snapshots of the present-day atmosphere feed into models of its long-term evolution.

Akatsuki is still operating and continues to make notable discoveries. Characterizing the processes that drive the atmospheric superrotation (see section 3.1.1) is a major goal. Based on studies of the cloud-level winds, the Akatsuki team discovered that thermal tides and large-scale turbulence promote and oppose superrotation at the cloud tops (Horinouchi et al. 2020). The overall dynamics are still uncertain because the winds at lower altitudes remain unknown, but Akatsuki images recently revealed a large-scale disruption in the lower cloud decks that propagates much faster than the prevailing winds (Peralta et al. 2020). Akatsuki also studies the coupling between the surface and the atmosphere. For example, new images revealed a large stationary gravity wave in the atmosphere, probably generated by mountain topography (Fukuhara et al. 2017)—meaning that the lower and upper atmosphere may interact more than previously believed (e.g., Brecht et al. 2021). Such waves may change the rotation rate of the solid body over time (e.g., Navarro et al. 2018). Overall, scientists need to understand how regions of the atmosphere interact with each other and with the surface. Understanding those dynamics at present day is a first step towards building models of how the entire planetary system evolved over geologic time.

2.4.4 Parker Solar Probe

NASA's Parker Solar Probe (PSP) launched in 2018 to study the solar wind and sample the low solar corona for the first time (Fox et al. 2016). PSP uses several Venus gravity assist (VGA) maneuvers to gradually lower its perihelion to <10 solar radii from the Sun's center—seven VGA maneuvers are currently planned, the last scheduled for 2024. Although PSP was not designed to study Venus, many of its instruments operate during each gravity assist and make useful scientific measurements. The Solar Orbiter mission will behave similarly during its many Venus flybys (e.g., Allen et al. 2021). For example, PSP has yielded new insights into the Venus plasma and magnetospheric environment (e.g., Bowen et al. 2021; Malaspina et al. 2020; Collinson et al. 2022)—and discovered a circumsolar dust ring near Venus's orbit (Stenborg et al. 2021). During VGA2, PSP searched for but did not find radio signals from lighting on Venus (Pulupa et al. 2021)—supporting the result from Akatsuki that optical flashes from lightning (at least those visible from space) occur much less frequently, if at all, and/or more intermittently than terrestrial lightning (e.g., Lorenz et al. 2019). Finally, PSP returned some of the most striking images of Venus ever taken at visible wavelengths (Figure 3). During flybys of Venus in 2020 and 2021, the Wide-Field Imager for Parker Solar Probe (WISPR) observed the nightside of Venus (Wood et al. 2022). WISPER was designed to study the solar wind at wavelengths from ~0.5–0.8 μm. Surprisingly, their images revealed thermal emission from the surface of Venus (mostly at ~0.7–0.8 μm) and O_2 nightglow emission at the limb (mostly at ~0.45–0.55 μm). The human eye is, in principle, sensitive enough to see the O_2 nightglow—and perhaps a lucky observer could catch a glimpse of the surface emission. Overall, multi-flyby missions such as PSP and Solar Orbiter help us understand Venus's evolution by better illustrating Venus's present-day state.

2.5 Recent Advances in Venus-Related Theory and Modeling

In parallel to new spacecraft launches, scientists leveraged advances in theories, techniques, and computational power—often first applied to Earth—to develop increasingly sophisticated models of Venus. In turn, exploration of Venus fed back into building a better understanding of all planets (e.g., Lapôtre et al. 2020). Here we provide a few examples of how efforts to understand Earth's tectonics (sections 2.5.1 and 2.5.2) and early habitability (sections 2.5.3 and 2.5.4) led to advances in our understanding of Venus's evolution.

2.5.1 Theory of Mantle Convection and Plate Tectonics on Earth

The hypothesis that Earth's mantle flows and circulates has slowly developed ever since the nineteenth century. General studies on the physics of thermal convection—not specifically applied to Earth's mantle—were gradually linked to observations (see, e.g., Bercovici 2015 for a detailed historical timeline). In particular, individual observations and concepts of continental drift, seafloor spreading, apparent polar wander, and subduction, together with the growing concept of a viscously deforming mantle on geological timescales, were combined into the plate tectonics theory that revolutionized geophysics in the mid-to-late 1960s. The plate tectonic model divides the solid, outer shell of the Earth (lithosphere) into a number of thin, rigid plates that move with respect to one another and that are continuously being created and consumed at their edges (e.g., Morgan 1968; McKenzie & Parker 1967; Le Pichon 1968). Turcotte and Oxburgh (1967) applied boundary layer theory for thermal convection to Earth's mantle, associating oceanic lithosphere with the cold, upper thermal boundary layer of mantle convection; ocean ridges with ascending convection; and ocean trenches with descending convection of the cold upper thermal boundary layer into the mantle. Finally, it was broadly accepted that both viscous (fluid-like) and elastic (solid-like) behavior, depending on the timescale of deformation, shape the Earth's interior and surface. Subsequent to this plate tectonics and mantle convection revolution, a wealth of fundamental studies explored key concepts such as nonlinear convection, mantle flow with increasingly complex variable rheologies, and convection in the presence of newly-established solid-solid phase transitions throughout Earth's mantle.

Once plate tectonics was established as the fundamental framework describing Earth's present-day dynamics, it was only a matter of time before scientists went beyond this framework and explored different regimes of mantle convection and tectonics, acknowledging planetary transitions over time. With increasingly improved studies on simplified mantle flow coupled with rigid plates, different relationships between surface kinematics and convective forces were soon established (e.g., Christensen 1985; Hager & O'Connell 1981; Ricard et al. 1993; Bunge & Grand 2000). Distinct "modes" of mantle convection were proposed that establish different wavelengths of convection and surface boundary mobility. These modes of mantle convection are highly dependent on, amongst other parameters, the thermal state of the convective system and the material properties (such as density and viscosity). These dependencies imply that during the thermal evolution of a planet (e.g., as it cools down), different mantle convection regimes may be encountered, with crucial implications for the planet's surface tectonics evolution (see section 3.3.2 and Rolf et al. 2022, this issue).

Key questions related to planetary transitions that have been puzzling scientists are "When and how did plate tectonics start on Earth?" and, relatedly, "Why does Venus currently lack plate tectonics?" Roughly speaking, the fact that the surface of Venus is hot and dry—compared to the relatively cold and wet surface of Earth—is probably pivotal. However, even though we can study our own planet *in situ*, understanding of the initiation and evolution of plate tectonics on Earth is still wrapped in controversy. The lack of unambiguous data—such as pristine, unaltered, and completely contextualized rocks older than ~3.5 Ga sampling the deep interior and surface of the planet—is but one factor impeding our understanding. Despite this lack of direct evidence, more refined modeling combined with proxies for tectonic processes on the early Earth have helped us infer the nature of early tectonics on this planet. Examples include the formation of felsic rocks typical of (proto)continental crust, paired metamorphic zones typical of convergent tectonics (e.g., Hawkesworth et al. 2020), and strong, thickened crust that can support brittle breakage and the intrusion of dyke swarms (e.g., Van Kranendonk 2010; Hawkesworth et al. 2009; Cawood et al. 2013).

Suggestions for the timing of the onset of plate tectonics range from ~4–1 Ga (e.g., Van Kranendonk 2011; Hawkesworth et al. 2020). Indeed, the process appears to have been gradual—or perhaps episodic—with an initial transition from an earlier convection regime (possibly from a sluggish or more stagnant state, or already a plume-induced proto-plate tectonics) between ~3 and 4 Ga. Although the rock record shows evidence of major continental amalgamation by ~2.8 Ga (e.g., Evans 2013), there is earlier evidence of increased tectonic activity in the form of eroded continental crust (e.g., Belousova & Kostitsyn 2010; Dhuime et al. 2012). Recent modeling studies on tectono-magmatic processes on Precambrian Earth (e.g., O'Neill et al. 2007; Gerya 2014; Rey et al. 2014; Bercovici & Ricard 2014; Fischer & Gerya 2016; Rozel et al. 2017; Sobolev & Brown 2019; Hawkesworth et al. 2020; Gerya 2022) enhanced our understanding of pre-plate tectonic regime with lid evolution driven by episodic tectono-magmatic activity in the absence of subduction (e.g., Sizova et al. 2015; Capitanio et al. 2019a, 2019b). Secular cooling of the mantle potential temperature during the Archean-Proterozoic period (~3 Ga and ~0.75 Ga) likely resulted in transitional tectonics on Earth, whereby a squishy- or plume-lid regime (see Rolf et al. 2022, this issue, for details) gradually, or episodically, evolved towards the modern plate tectonics regime by combining elements of different global tectonic styles in both space and time (e.g., Fischer & Gerya 2016; Chowdhury et al. 2017, 2020; Sobolev & Brown 2019; Perchuk et al. 2018, 2019, 2020).

2.5.2 Advances in Analogue Experiments and Numerical Techniques

Most—if not all—of the above-mentioned advances in understanding Earth's tectonics go hand-in-hand with developments in geodynamic and atmospheric modeling, mainly facilitated by improved theory, advanced laboratory experiments, numerical modeling techniques, and, importantly, computational power.

Analogue modeling is an experimental approach to investigate geological phenomena and geodynamic processes in a laboratory at convenient time- and length-scales. It has a long history starting over 200 years ago (see, e.g., Ranalli 2001 for a detailed timeline). While early analogue models mainly focused on individual geological structures, e.g., folds, thrust faults, and salt domes (e.g., Daubrée 1879; Cadell 1889; Escher & Kuenen 1928; Ramberg 1967), the focus shifted to plate tectonic processes as the theory of plate tectonics became well accepted in the 1960s. Another major step forward in analogue modeling came in the 1980s, when realistic models were built to simulate both brittle and viscous behavior, mimicking a rheologically stratified crust and mantle (e.g., Faugere & Brun 1984; Davy & Cobbold 1988). Analogue modeling underwent significant advances and proved itself an effective and relatively inexpensive tool for investigating tectonic and geodynamic processes. For example, analogue models were—and still are—key in describing mantle geodynamic regimes that can occur in rocky planets (e.g., Davaille 1999; Davaille & Limare 2007). Recently, analogue models have been applied to Venus to make important hypotheses on the style of mantle dynamics and the potential of plume-induced subduction on Venus (Davaille et al. 2017).

Numerical modeling developed from the mid-to-late 1970s onwards. The first 2D numerical model of subduction was presented in 1970 (Minear & Toksöz 1970), exactly during the start of the "Plate Tectonics Era," shortly followed by the first 2D mantle thermal convection model (Torrance & Turcotte 1971). It was not long before the first 2D mantle thermal-chemical convection models (Keondzhyan & Monin 1977, 1980) and the first 3D spherical mantle convection models (Baumgardner 1985; Machetel et al. 1986) were presented. Surprisingly, the first 3D models of mantle convection were in spherical geometry—not Cartesian as one might expect! Since the 1980s, the field of numerical geodynamic modeling developed very rapidly in terms of the applications and techniques. However, as most early models treated the mantle and the lithosphere with little to no feedback, the self-consistent generation of (plate) tectonics in these models was long an issue. Only at the end of the 1990s, the improved description of pseudo-plasticity allowed for numerical modeling of mantle convection that produced, in a self-consistent way, regions with little deformation (plates) bounded by regions of localized deformation (plate boundaries) (e.g., Moresi & Solomatov 1998; Tackley 1998; Trompert &

Hansen 1998). These models opened novel perspectives on the exploration of a unified lithosphere-convective mantle system on Earth and, importantly, how the system operates on other rocky planets. Nowadays, computational power and ever-improving computational techniques (e.g., parallel high-performance computing, adaptive mesh refinement, solvers, inverse theory, etc.) allow us to obtain larger and—perhaps—higher-quality numerical data in less and less time. However, the exploration of high-resolution 3D global models of mantle convection and surface processes, potentially coupled with atmospheric dynamics, remain a computational frontier. Moreover, as numerical data gets more complex, it becomes even more important to thoroughly understand the physics behind the computations.

2.5.3 Theory and Modeling of a Runaway Greenhouse

In the last century, key developments were made in understanding the evolution of planetary climates and atmospheres which have applications to Venus. The first to recognize that an atmosphere in radiative equilibrium under an increased solar insolation would lead to an excess of infrared radiation (IR) was Simpson (1927). Plass (1961) demonstrated the role of increased anthropogenic CO_2 would have on the IR budget and the warming of the climate. Sagan (1960) was among the first to realize that the then estimated 600 K surface temperature on Venus made it “evident that a very efficient greenhouse effect is required” (see section 2.3). Sagan (1960) and Gold (1964) both realized that this “efficient greenhouse effect” would prevent Venus from having surface liquid water which Gold (1964) referred to as a “runaway process.” Subsequent 1-D radiative-convective modeling work identified what we now term the “runaway greenhouse” (e.g., Komabayashi 1967, 1968; Ingersoll 1969; Pollack 1971; Kasting 1988; Abe and Matsui 1988; Nakajima 1992).

Ingersoll (1969) was likely the first to propose that a habitable planet with oceans at the orbit of Venus could switch to an uninhabitable state when greenhouse gasses in the atmosphere block thermal radiation from leaving the planet, preventing the planet’s atmosphere from cooling, leading to a runaway greenhouse. Two years later, the first 1-D, non-grey radiative transfer simulations by Pollack (1971) demonstrated that ancient Venus could have had temperate conditions if the planet had 100% cloud cover, but with 50% it would be in a runaway state. Work by many authors over the subsequent decades discussed the possibility of an early temperate Venus that would warm up as the Sun increased in luminosity over the eons (Gough 1981), gradually increasing the atmospheric temperature and driving it into its present-day runaway greenhouse state (e.g., Bullock & Grinspoon 1996, 2001; Grinspoon & Bullock 2007). While the runaway greenhouse process has been successfully modeled in 1-D, radiative-convective models as mentioned above, it has proved to be devilishly difficult in 3-D general circulation models (GCMs) (e.g., Ding & Pierrehumbert 2020, Boukrouche et al. 2021; Chaverot et al. 2022). For example, most (but not all) Earth-derived GCMs used for planetary atmospheric modeling cannot handle multiple condensable species—or a variable atmospheric mass with more than one species—as the model moves forward in time (e.g., Fauchez et al. 2020). For the latter, as the atmosphere heats up, water becomes an ever-larger fraction of the atmosphere. This means the mean molecular weight of the atmosphere, which must be pre-set, becomes more and more inaccurate (e.g., Way et al. 2017; Appendix A). These factors will influence the accuracy of the atmospheric dynamics, including cloud convection processes. As well, most GCM parameterized radiative transfer schemes are limited in the temperature and pressure ranges allowed, although pressure is probably the easiest to accommodate.

2.5.4 Links Between Venus and (Early) Earth and Planetary Habitability

Earth has physical attributes that can be analyzed to provide information about its early habitability (i.e., rocks dating back to ~4.1 Ga, mantle zircon crystals dating back to ~4.3 Ga, and inherited geochemical signatures from erstwhile Hadean crust). However, the rarity of these attributes and the fact that the oldest rocks have been severely altered by metamorphism makes interpretation of the signatures they contain at times controversial (see Westall et al. 2023, this issue). Therefore, iteration of the rock and geochemical data with models of the geophysical and atmospheric evolution of the early Earth are essential to a better understanding of how Earth became habitable. Additionally, comparison with the early evolution of other terrestrial planets, especially Venus and Mars, is an important factor. Briefly, habitability on the early Earth during the Hadean and Eoarchean epochs (4.5–3.5 Ga) means the establishment of conditions for the emergence of life in the first place. Here, only the essential ingredients of water, organic molecules (C, H, N, O), other elements, such as P, S, and transition elements, as well as a source of energy are necessary—but only necessary for the time needed for life to emerge (which, of course, we do not know but is likely to have been relatively short, >1–2 Ma). Important is also the "scenario" for the emergence of life, whether in submarine hydrothermal environments, subaerial ones, or any other geologic setting (see review in Westall et al. 2018). If exposed land mass is a prerequisite, it needs to be stable for the length of time for life to emerge, likewise submarine hydrothermal systems. On these timescales, the geophysical situation of a planet, whether it is one plate or not, whether the planet was dominated by plume tectonics or sluggish, shallow tectonics, is not critical. The tectonic regime and plate tectonics, specifically, become relevant once life is flourishing because of the necessity of recycling nutrients used up on the surface (e.g., Korenaga 2012; Foley & Driscoll 2016; Foley & Smye 2018). This cycle only comes into play after about a couple of billion years.

Thus, in terms of Venus, the nature of the tectonic regime that dominated the early history of the planet is irrelevant for the emergence of life, providing that the initial conditions were conducive to water at the surface (the other ingredients: organic molecules, essential elements, and energy sources would have been similar to those in early Earth). Tectonics only become critical if there was a flourishing (or, eventually, flailing) biosphere on the planet that needed to access renewable resources. Nevertheless, a better understanding of the physical mechanisms responsible for Venus' geologic history will greatly advance our understanding of what makes a rocky planet habitable and, ultimately, life emerge.

3. Fundamental Properties of Venus Relevant to Its Evolution

Understanding the evolution of Venus is, by definition, a more complex task than making direct observations of its modern properties. A detailed catalog of the fundamental properties of Venus is the foundation of attempts to study its past. Table 1 compares the basic properties of Venus and Earth. Because the bulk densities of these two planets are so similar, scientists often assume that Venus and Earth have similar bulk compositions (section 1). However, measurements of key parameters for Venus are so uncertain that significant differences might await discovery. Here we describe the different parts of Venus as a planetary system and how they may have changed over time.

Table 1. Basic properties of Venus and Earth. Unless otherwise given, data are extracted from the NASA Earth and Venus Fact Sheets (Williams 2022a, 2022b). Additional sources include: [1]Simon et al. (1994), [2]Konopliv et al. (1999), [3]Konopliv and Yoder (1996), [4]nominal Love number at degree and order 2 for an anelastic Earth (Petit and Luzum 2010), [5]Margot et al. (2021), [6]von Zahn et al. (1983), Taylor et al. (1997), and de Bergh et al. (2006), [7]Lebonnois & Schubert (2017), [8]James et al. (2013), [9]Anderson & Smrekar (2006), [10]Jiménez-Díaz et al. (2015), [11]Dumoulin et al. (2017), [12]Kennett et al. (1995) (model ak135), [13]Tesauro et al. (2012).

Parameter [Units]	**Venus**	**Earth**
	Orbital and Rotational Parameters	
Semimajor Axis [10^6 km]	108.210	149.598
Sidereal Orbital Period [days]	224.701	365.256
Orbit Inclination [deg]	3.395	0.000
[1]Orbit Eccentricity	0.006772	0.0167
Sidereal Rotation Period [hrs]	5832.6	23.9345
Obliquity to Orbit [deg]	177.36	23.44
	Bulk Planetary Parameters	
[2]Mass [10^{24} kg]	4.8675	5.9722
Equatorial Radius [km]	6051.8	6378.1
Polar Radius [km]	6051.8	6356.8

Volumetric Mean Radius [km]	6051.8	6371.0
Mean Density [kg/m^3]	5243	5513
Equatorial Surface Gravity [m/s^2]	8.87	9.80
J_2 [$x10^{-6}$]	4.458	1082.63
[3,4]Tidal Love Number, k_2	0.295 ± 0.066	$0.30102 - i \cdot 0.00130$
[5]Moment of Inertia Factor	0.337 ± 0.024	0.3307
Surface and Atmosphere Parameters		
Solar Irradiance [W/m^2]	2601.3	1361.0
Average Surface Temperature [K]	737	288
Surface Pressure [10^5 Pa]	92	1.014
Mass of Atmosphere [10^{20} kg]	4.8	0.051
[6]Atmospheric constituents [by volume]	96.5% CO_2 3.5% N_2 20 ppm H_2O 70 ppm Ar 150 ppm SO_2	78.1% N_2 21.0% O_2 ~1% H_2O 9340 ppm Ar 412 ppm CO_2 and rising
Fraction of angular momentum contained in the atmosphere[7]	1.6×10^{-3}	2.7×10^{-8}
Topographic Range [km]	13	20.4
Interior Structure Estimates		
[8,12]Thickness of the Crust [km]	8–25	35
[9,10,13]Thickness of the Elastic Lithosphere [km]	<100 <20 for underneath 50% of the surface area	10–120
[11,12]Radius of the Core [km]	2940–3425	3479.5

3.1 The Atmosphere of Venus

The atmosphere is the easiest part of Venus to study—yet many of its basic properties are still unknown or poorly understood. Virtually every planetary process affects the atmosphere. Equilibration (or lack thereof) with the early magma ocean set its initial conditions—volcanic degassing and reactions with the surface control its mass and composition over time. Any intrinsic magnetic field could have affected atmospheric escape processes. To understand the evolution of the atmosphere is thus to know the history of the entire planet. Crucially, the atmosphere also helps govern the evolution of the solid body. Surface temperature is the boundary condition for mantle convection—and controls the rheological properties of lavas and rocks that govern volcanic and tectonic processes now preserved in the geologic record.

3.1.1 Basic Properties of the Atmosphere

Venus has the most massive atmosphere of any terrestrial planet in our Solar System. Its overhanging firmament comprises nearly 0.01% of the total planetary mass, compared to the factor of ~8.5×10^{-7} for Earth (Table 1). Figure 6 shows the vertical structure of the atmosphere, which is roughly consistent at low latitudes near the equator. In Earth's atmosphere, nitrogen is the most abundant gas—but Venus's atmosphere contains roughly three times as much nitrogen relative to the mass of each planet. As discussed in Section 2.2, carbon dioxide dominates the atmosphere of Venus. The total mass of gaseous CO_2 is estimated to equal or exceed the combined amounts of CO_2 present in Earth's atmosphere plus (as carbonates) in Earth's crust and mantle (e.g., Ingersoll 2013; Lécuyer et al. 2000; Donahue & Pollack 1983). However, we cannot conclude that Venus contains more carbon than Earth (or vice versa) because the carbon inventories of their metallic cores (e.g., Fischer et al. 2020) and Venus's solid body are uncertain and debated.

Not all atmospheric gasses are more plenteous at Venus than at Earth. The absolute amount of water vapor in the Venus atmosphere is about the same as on Earth, although it represents only about 30 parts per million of Venus's massive atmosphere. In Venusian water vapor, the ratio of deuterium to hydrogen (D/H) is ~157 times larger than D/H ~ 1.5×10^{-4} for Earth (e.g., Donahue et al. 1982; de Bergh et al. 2006), which may imply that large amounts of water vapor have been lost over Venus's history. Molecular oxygen, so important to us on Earth, is present on Venus at only 50 parts per million or less on Venus; this means that the absolute mass of molecular oxygen in the Venus atmosphere is at least two orders of magnitude less than on Earth. Beyond the bulk constituents of each atmosphere, scientists are quite interested in trace components such as the myriad isotopes of noble gasses (e.g., Baines et al. 2013, Chassefière et al. 2012, Avice et al. 2022, this issue). For example, atmospheric argon-40 is twice as prevalent at Earth compared to Venus at present day (e.g., von Zahn et al. 1983; Kaula 1999; O'Rourke & Korenaga 2015).

Clouds and hazes are perhaps the most interesting features in the atmosphere of Venus. The Venus I, II, and III collections each include comprehensive reviews of these clouds and hazes (Esposito et al. 1983; Esposito et al. 1997; Titov et al. 2018). Clouds on Venus are found between altitudes of ~48–70 km above the surface. Recent studies divide the cloud deck into three layers—all dominated by concentrated droplets of sulfuric acid with <25% water by weight and water-activity values ≤0.004 (Hallsworth et al. 2021). As described in Titov et al. (2018), the upper clouds (~57–70 km) include both submicron- and micron-sized particles—and the mysterious UV absorber. A kilometer-thick gap separates the upper clouds from the middle and lower clouds. The boundary between the middle and lower clouds is (figuratively and literally) cloudy—both layers contain large particles (mean diameters of ~7–8 μm) that may be a separate "mode 3" population or simply the tail-end of a distribution of the ordinary particles. Hazes of fine aerosols are found both above and below the clouds up to altitudes of ~100 km and down to altitudes of ~33 km, respectively. A thin haze layer may also exist at the surface.

Atmospheric gases participate in complex chemical cycles that are most active in and near the clouds (e.g., Mills & Allen 2007; Marcq et al. 2017). Roughly speaking, photochemistry dominates the chemistry of the upper clouds where the temperatures are <300 K (e.g., Titov et al. 2018). Photochemical processes depend on the amount of incident sunlight and thus vary spatially and temporally across the atmosphere based on the local time of day. The middle and lower clouds become more reliant on processes such as condensation and convective mixing with the lower atmosphere. Below the clouds, temperatures exceeding ~400 K enable relatively rapid reactions that enable gases to approach thermochemical equilibria. Sulfur and water (and many other species) cycle through all these regions. For example, photochemistry forms sulfuric acid (H_2SO_4) from sulfur oxides and water in the upper atmosphere, which condenses with water vapor to form the cloud droplets. At the base of the clouds, H_2SO_4 evaporates and, at lower altitudes, decomposes into water vapor and SO_3, which is highly reactive on its way to forming SO_2 (e.g., Dai et al. 2022). At the surface, volcanism may inject SO_2 into the lower atmosphere, explaining its elevated abundance relative to model predictions (e.g., Esposito 1984) and thus, perhaps, the existence of the clouds themselves (e.g., Bullock & Grinspoon 2001). However, existing models of these chemical cycles leave many questions unanswered (e.g., Bierson & Zhang 2020), including what surface reactions buffer the composition of the lower atmosphere (e.g., Gillmann et al. 2022, this issue) and why SO_2 and H_2O are depleted in and above the clouds of Venus relative to models that predict rapid fluxes of SO_2 through the clouds (e.g., Rimmer et al. 2021). Future missions that traverse or dwell in the clouds should help solve these puzzles.

Venus, like Earth, also features different atmospheric layers defined by vertical variations in temperature. The Venus International Reference Atmosphere (VIRA) provides temperature, density, pressure, and thermodynamic gas properties for the atmosphere at different altitudes and latitudes (Seiff et al. 1985). Roughly speaking, the atmosphere is hottest at the surface, above which temperatures decrease with altitude at nearly the dry adiabatic lapse rate of ~10 K/km. Convective equilibrium usually prevails in the troposphere, although stable stratification may exist at some altitudes. Recent work has focused on the (in)stability of the atmosphere near the surface, which is poorly understood because only the VeGa-2 probe provided a reliable temperature profile within <12 km of the surface (e.g., Lebonnois & Schubert 2017). The base of the upper clouds typically defines the tropopause, above which the UV absorber (whatever it is) absorbs roughly half of the incoming solar energy. The layer above the troposphere is often called the stratosphere by analogy to Earth because radiative equilibrium sets the vertical thermal profile (e.g., Taylor et al. 2018)—although other studies prefer “mesosphere” instead because, unlike Earth, temperature continues to decrease with altitude in this layer (e.g., Pätzold et al. 2007; Lebonnois & Schubert 2017). Temperature does increase with altitude from ~120–150 km in the thermosphere due to ionization and dissociation caused by solar radiation (e.g., Taylor et al. 2018). The outermost, ephemeral layers of the atmosphere are the exosphere, where collisions between molecules are so rare that they can easily escape, and the magnetosphere induced by the solar wind (but maybe not entirely, see section 3.3.3).

Wind speeds vary dramatically with altitude in the Venusian atmosphere. Famously, Venus has one of the only super-rotating atmospheres in the Solar System—moving in the same direction as the solid body, but with a shorter period (e.g., Read & Lebonnois 2018). However, many exoplanets may have similar atmospheric dynamics (e.g., Imamura et al. 2020; Lee et al. 2020). In 1985, radio tracking of two balloons—a highlight of the VeGa mission—at altitudes near ~54 km provided the first in situ measurements of cloud-level wind speeds (Sagdeev et al. 1986; Crisp et al. 1990). Four Pioneer Venus entry probes measured zonal wind speeds (Figure 6) that were near-zero below altitudes of ~10 km but rose pseudo-linearly to ~65–90 m/s at altitudes of ~60 km (e.g., Schubert et al. 1980). The rotation period of the atmosphere thus ranges from ~7 to 4 Earth-days from the bottom to top of the clouds, respectively. The angular momentum density of the atmosphere peaks at altitudes of ~20 km, although >70% of the total atmospheric mass lies at lower altitudes. Sub-cloud altitudes contain >90% of the total mass and angular momentum (e.g., Peralta et al. 2019; Schubert et al. 1980). In tandem with the zonal super-rotation, the atmosphere features Hadley cells at the cloud levels that extend north and south from the equator to cloud-top polar vortices. Because of the huge mass and thermal inertia of the atmosphere and the rapidity of zonal and meridional transport, changes in elevation cause the biggest changes in surface temperature with a >100 K difference between Maxwell Montes and Diana Chasma—the highest and lowest elevations on Venus, respectively. In contrast, latitude, longitude, and local time cause temperature fluctuations of less than ±10 K. Solar insolation peaks at the equator and local noon, but excess heat is swiftly redistributed.

3.1.2 How the Atmosphere May Have Evolved

Before they learned the composition of the clouds (e.g., Sagan 1960), scientists speculated that the atmosphere of Venus underwent dramatic changes over time. Imagine that Venus once had an Earth-like climate with water oceans on the surface. Excess sunlight due to Venus's relative proximity to the Sun can drive the atmosphere into a “runaway greenhouse” state (Ingersoll 1969) as described in section 2.5.3. Briefly, a post-accretion steam atmosphere above surface oceans can only radiate a certain amount of energy away to space. Because the saturation vapor pressure of water increases exponentially with temperature, a hotter troposphere has greater opacity. This feedback between temperature and opacity imposes an upper limit to the upward flux from a steam atmosphere in equilibrium. Only the evaporation of the oceans can provide an energy sink to balance any excess incoming radiation. With insolation above the critical value, thermal equilibrium is not achieved until the surface is dry and the relative humidity of the troposphere can decrease. One-dimensional models indicate that the radiation limit is ~280–300 W/m^2 (e.g., Ingersoll 1969; Abe & Matsui 1988; Kasting 1988; Nakajima et al. 1992; Marcq et al. 2017)—although different assumptions about the structure and composition of the atmosphere can change the exact value.

In any case, Venus probably absorbs less solar radiation than it can re-radiate away at present due to its bright clouds. However, the solar insolation would have exceeded that limit if Venus ever had fewer clouds and thus an Earth-like albedo. Clouds can help promote or prohibit the stability of surface oceans, depending on where they occur (e.g., Way et al. 2020; Turbet et al. 2021). Clouds on the dayside reflect solar radiation, but clouds on the nightside act as a thermal blanket. Regardless, the Sun has brightened over time, so a simple story for the evolution of Venus features an Earth-like climate that was eventually forced into a runaway greenhouse state (Figure 1), producing today's dry atmosphere as mentioned in sections 1 and 2.5.3.

Several chapters in this topical collection discuss how the atmosphere of Venus may have evolved—and how its evolution influences the rest of the planetary system. First, two chapters explore the possible histories and scientific value of trace gasses in the atmosphere. Salvador et al. (2023, this issue) investigate the role of water in the early atmosphere of Venus and the processes that may have caused volatile loss at early times. Avice et al. (2022, this issue) focus on how measurements of isotopes of volatiles and noble gasses can constrain models of Venus's evolution. Two other chapters discuss the myriad connections between the atmosphere and solid body. Wilson et al. (2023, this issue) tackle the hypothesis that magmatic degassing affects the composition of the present-day atmosphere. They also describe how mapping of anomalous plumes of gas (e.g., elevated concentrations of a wide array of possible species) or particulate matter (e.g., ash particles or sulphate aerosols) could help identify regions of the surface with active volcanism. Gillmann et al. (2022, this issue) present fully coupled models for the atmosphere, crust, mantle, and core of Venus that include feedbacks between surface temperature, the regime of mantle convection, and even the connections between an internal dynamo and atmospheric escape. Finally, the atmosphere is the easiest part of a Venus-like exoplanet to observe. Way et al. (2022, this issue) review the prospects for characterizing such distant worlds—and how studies of exoplanets and the Earth/Venus dichotomy inform and feed into each other.

3.2 The Surface of Venus

Venus has a surface unlike any other world in the Solar System except, perhaps, parts of Earth. The Venus surface is relatively young, probably active, but not operating in an Earth-like regime of plate tectonics (likely because of its temperature and the lack of surface water now). Scientists vigorously debate how the surface has evolved recently and over geologic time. Does the surface preserve signs of a clement past? Or has recent, planet-wide volcanism erased the geologic "memory" of most of the history of Venus?

3.2.1 Basic Properties of the Surface

Scientists have used various techniques to peer through the atmosphere of Venus and unveil the surface. Since the 1960s, missions (e.g., Pioneer Venus Orbiter, Venera 15 and 16, and Magellan) and Earth-based facilities (e.g., Arecibo and Goldstone) have observed Venus with radar to which the atmosphere is transparent. So far, Magellan has provided the highest-quality, global imagery and topographic data so far from mapping cycles conducted over three Venus-years from 1990 to 1992 (detailed in section 2.4.1 above). The radar images have a horizontal resolution of ~125 m per pixel (Saunders et al. 1992; Ford et al. 1993). The global topographic data has a horizontal resolution no better than ~10–20 km per pixel (Ford & Pettengill 1992). Recently, Herrick et al. (2012) processed stereo imagery acquired during Cycles 1 and 3 (section 2.4.1) to create digital elevation models with horizontal and vertical resolutions of ~1 km and ~100 m, respectively, that cover ~20% of the surface. In comparison, the Venera 15 and 16 orbiters performed SAR mapping with a horizontal resolution of ~1 km and a swath width of ~10–40 km—and delivered some altimetry data with an accuracy of ~50 m. The two Soviet spacecraft operated up to spring of 1985 at coordinated orbits and mapped the northern hemisphere, corresponding to around 25% of the surface. Pioneer Venus Orbiter and then Venera 14 and 15 discovered many of the types of features described below (e.g., Barsukov et al. 1986), which Magellan revealed in sharper detail and found to be distributed across the entire surface.

Thermal radiation from the surface can penetrate the atmosphere in several "spectral windows" in the near infrared (e.g., Allen & Crawford 1984; Allen 1987; Carlson et al. 1991; Crisp et al. 1991). Although not all surface radiation is absorbed, escaping surface radiation is inevitably scattered with blurring at horizontal scales of >50 km when observed remotely from above the cloud layer (i.e., from orbit). The VIRTIS (Visible InfraRed Thermal Imaging Spectrometer) instrument on Venus Express (see section 2.4.2) observed Venus in three of these spectral windows (e.g., Drossart et al. 2007). Scientists used VIRTIS data to place coarse bounds on the infrared emissivity of surface units (e.g., Mueller et al. 2020), which provoke hypotheses about their rock type as discussed below (e.g., Gilmore et al. 2017; Gilmore et al. 2023, this issue). Ultimately, radar and near-infrared image data have shown that all major geologic processes—volcanism, tectonics, mass wasting, erosion, and impacts—have operated on Venus (Figure 8). However, scientists debate the relative importance of these processes in shaping the present-day surface and the sequence(s) in which they may have occurred.

In the aftermath of the Venera, Pioneer Venus, and Magellan missions, mappers classified myriad types of named features on the surface of Venus. The United States Geological Survey (USGS) produced a handy guide to the official nomenclature (Tanaka et al. 1993). Some features are huge—the first things someone would notice when presented with a map of the surface. For example, the most extensive land masses on Venus are called “terrae” (singular “terra”). These terrae are often compared to Earth’s continents, although the hypsometry of Venus is unimodal, not bimodal as for Earth (and weakly on Mars). Near the north pole, Ishtar Terra hosts four mountain ranges (termed “montes”), including the superlative Maxwell Montes. The lower plain inside these ranges is Lakshmi Planum—“planum" being the general term for a plateau or high-standing plain. Near the equator, Aphrodite Terra is divided into two main “Regiones” (regions): Ovda Regio and Thetis Regio. Along the southeastern edge of Aphrodite Terra is Artemis Corona, the prime example of the more than 500 quasi-circular features that range from ~60 to over 1,000 km in diameter, and which are associated with a variety of tectonic and volcanic features (e.g., Barsukov et al. 1986, Smrekar & Stofan 1997, Stofan et al. 1992; McGovern et al. 2013). Artemis Corona is the largest with a diameter of >2,000 km. Another superlative feature is Baltis Vallis—a thin (~1–3 km) channel, almost certainly volcanic, that is the longest (~6,800 km) found anywhere in the Solar System. Not every named feature on Venus is gigantic. The surface is littered with smaller landforms both tectonic—e.g., “dorsae” (ridges), “fossae” (long, narrow depressions), “lineae” (elongated features)—and volcanic (Figure 8), such as “tholi” (small domes or hills) and “fluctūs” (flow features). Merely cataloging the surface is the work of many lifetimes.

One of the few uncontroversial facts about the surface of Venus is that it is relatively (geologically) young on average. Venus hosts a unique and enigmatic population of impact craters (e.g., Herrick et al. 2023, this issue). Fewer than 1,000 craters have been identified on the surface (e.g., Phillips et al. 1991, Schaber et al. 1992). On airless bodies like the Moon, Mercury, and Mars, the size–frequency distributions of impact craters obey power laws. Smaller impactors (e.g., asteroids and comets) are more common than large ones, so smaller craters form more frequently than larger ones. However, the size–frequency distribution of impact craters on Venus is log-normal. One might suspect that available imagery prevents scientists from identifying small craters. However, the thick atmosphere is the real culprit behind their absence (e.g., Zahnle 1992)—as was predicted before any images were obtained (e.g., Tauber & Kirk 1976; Kahn 1982). Impactors that would otherwise form craters smaller than a kilometer or so across burn up or explode before reaching the surface. We can derive an approximate age for the surface on the basis of a production function for impactors that are large enough to plow through the atmosphere and actually reach the surface. Such impactors are expected to hit Venus every half a million years or so, meaning that 1,000 craters correspond to an age of ~0.5 Gyr. Careful calculations yield estimates for Venus ranging from ~240 Myr to ~1 Gyr (e.g., McKinnon et al. 1997; Le Feuvre & Wieczorek 2011). Crucially, this cratering age need not be the actual age of the surface. With so few craters, obtaining statistical constraints on the relative ages of different terrains is difficult (e.g., Hauck et al. 1998), if not impossible. Many areas of the surface could be many times older than the cratering age (e.g., Hansen & Lopez 2010). Finally, craters are not always atop their local stratigraphic sequence (e.g., Herrick & Rumpf 2011).

The USSR delivered the only successful landers to the surface of Venus in the 1970s and 80s. Venera 7, the first probe to reach the surface, measured the surface temperature and the rigidity of the rocks—but did not survive for long. Venera 8 was the first design able to operate for more than an hour on the surface. Its gamma-ray K-Th-U measurements suggested a more evolved rock rather than the broadly basaltic composition found for all sites subsequently visited. Suggested explanations for the Venera 8 measurements include there being older terrain at the landing site or a specific kind of K-rich basalt (Surkov et al. 1983; Treiman 2007). Their success and the failures of the 1973 Mars campaign pushed the USSR to put Mars on standby as they proceeded with sustained Venus exploration. From Venera 9 to VeGa, a heavier Proton launcher allowed for much higher complexity and capacity of Venus missions. Venera 9 and Venera 10 (1975) delivered the first panoramas of the surface (Florenskiy et al. 1983), supplemented with in situ composition (gamma-ray and photometry) measurements (Surkov et al. 1983). The basaltic composition revealed by these missions confirmed the past differentiation of Venus into a mantle and crust, and presumably an iron-rich core. The density of the surface was measured at 2.7–2.9 g cm^{-3}. Venera 11 and 12 (1978) attempted the analysis of the surface samples via X-ray fluorescence. However, the newly developed drilling device failed—and the panoramic cameras' openings remained closed. By 1981, having solved technical problems encountered by Venera 11 and 12, the USSR launched the Venera 13 and 14 landers (e.g., Moroz 1983). These later landers returned two color panoramas of the landing site—and analyzed two surface samples acquired by drilling from ~3 cm depth and transferred into the protected lander volume. The samples from two geologic units, a hilly upland and a flat lowland near the eastern extension of Phoebe Regio in the planet's western hemisphere, were attributed to weakly differentiated alkaline gabbroids (Venera 13) and oceanic tholeiitic basalts (Venera 14). Overall, the legacy of Soviet Venera and VeGa landers consists of four panoramas and in-situ analysis of seven (Venera 8–10, 13, and 14 and VeGa 1 and 2) landing sites, five revealing a predominantly tholeiitic basaltic lavas and two (Venera 8 and 13) sites indicating more alkalic, lamprophyre-like lavas or ash beds (e.g., Weitz & Basilevsky 1993; Treiman et al. 2007). In the context of Magellan radar images, the composition of Venus rocks compared with analogues on Earth suggested a different formation history of the two planets' crusts.

3.2.2 How the Surface May Have Evolved

Other chapters in this topical collection address three key questions related to the evolution of the surface: Are any geologic features relics of or otherwise related to the putative transition from clement to hellish conditions? Does the present surface record evidence of so-called "catastrophic resurfacing? And what are the feedbacks between the evolution of the surface and the rest of Venus as a planetary system?

Tesserae are units on Venus proposed to record evidence that water was once stable on the surface of Venus. Firstly, VIRTIS data provide tantalizing hints that at least some tesserae are felsic due to their low infrared emissivity (e.g., Mueller et al. 2009; Gilmore et al. 2015). Large volumes of felsic rock are most efficiently formed in the presence of oceans (e.g., Campbell & Taylor 1983). Secondly, tesserae have complex patterns of topography (Figure 8), which has been compared with valley patterns that fluvial erosion can produce (e.g., Khawja et al. 2020). Gilmore et al. (2023, this issue) provide a general overview of available constraints on models of the composition of the surface. Carter et al. (2023, this issue) discuss how sedimentary processes, which are often assumed to play a minor role on Venus, may have shaped the surface—and perhaps confused our interpretations of many features. Finally, Westall et al. (2023, this issue) teach us what the present surface can tell us about the evolving habitability of Venus.

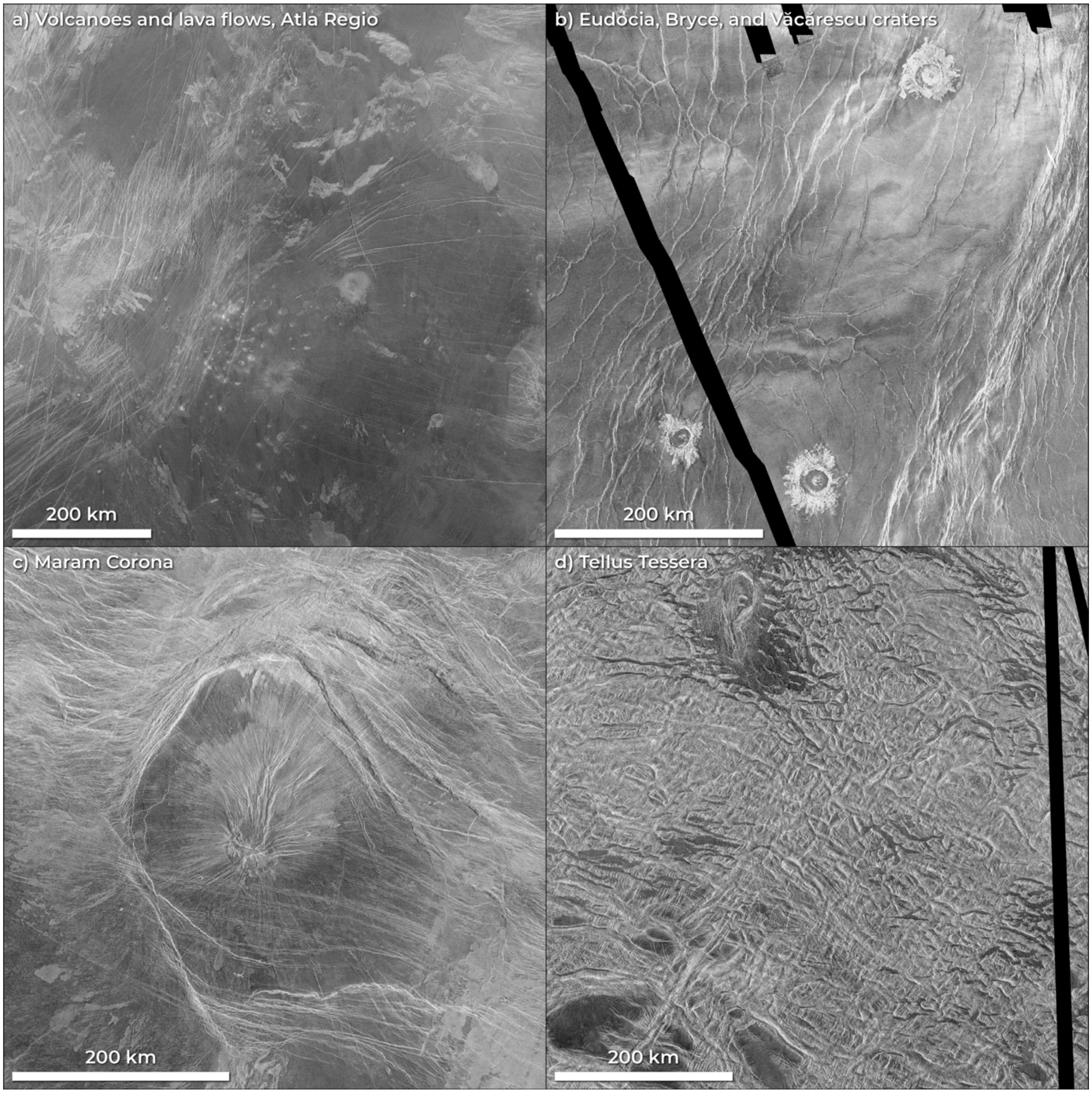

Figure 8. Four types of geologic features—shown here in left-looking radar imagery overlain on inverted right-looking imagery from Magellan—exemplify how observations of Venus can constrain models of its evolution. (a) A field of volcanoes and lava flows near Atla Regio, in the planet's southern hemisphere. The morphology and distribution of volcanic landforms reflect the processes and compositions of magmas in the subsurface. (b) A cluster of three craters—Eudocia, Bryce, and Văcărescu—at high southern latitudes; impact craters can provide information on the age of the surface. (c) Coronae probe the properties of Venus's lithosphere, including its elastic thickness and heat flow. This example is Maram Corona, centered near 7.5°S, 221°E. (d) A portion of Tellus Tessera (centered at 37°N, 81°E), one of Venus' enigmatic and highly tectonically deformed surface units. North is to the top in all frames; the scale bars show 200 km. Black areas are gores (missing data) in the Magellan global radar image mosaic.

If temperate conditions existed in an earlier Venusian epoch, then any climatic catastrophe on Venus should probably have a geologic counterpart. A huge amount of the mantle would have needed to undergo partial melting to degass >90 bars of carbon dioxide (e.g., Way & Del Genio 2020; Way et al. 2022). Such massive melting would presumably cover the vast majority of the surface in thick lava flows. Scientists have long debated whether catastrophic resurfacing (i.e., an episode of planet-wide volcanism lasting <100 Myr that covers >80% of the surface in flows with thicknesses of ~1 km or more) is the most parsimonious interpretation of the cratering record (e.g., Strom et al. 1994; Nimmo & McKenzie 1998; Ivanov & Head 2013). Alternatively, Venus could preserve a uniformitarian history where a variety of geologic processes have operated on a variety of scales at a variety of times (e.g., Guest & Stofan 1999). Herrick et al. (2023, this issue) delve into all the facets of the impact record and the history of attempting to explain them with models both simple and complicated. Ghail et al. (2023, this issue) survey all the volcanic and tectonic features on Venus as the foundation for building realistic models of their geologic evolution.

Ultimately, processes that originate in the deep interior of Venus govern the age and appearance of its surface. On Earth, plate tectonics started as a kinematic theory to describe the rotation and translation of the surface. Linking simple models of plate boundaries to a three-dimensional conception of mantle convection was a scientific revolution (see sections 2.5.1 and 2.5.2, above). Likewise, ongoing efforts attempt to link straightforward models for the resurfacing of Venus (e.g., Herrick et al. 2023, this issue) to theories about the long-term evolution of the lithosphere and mantle. Rolf et al. (2022, this issue) review different conceptions of Venus's mantle dynamics at present day (e.g., stagnant- versus episodic- versus squishy-lid). As noted in section 3.1.2, Gillmann et al. (2022, this issue) discuss how atmospheric evolution can lead to changes in the tectonic regime on Venus over time via the feedbacks between volcanic degassing, surface temperature, and rock rheology.

3.3 The Interior of Venus

Little is known about the interior of Venus now—let alone how the interior has changed over time. Most models assumed that Venus, like all terrestrial planets, was initially hot due to the release of gravitational energy during accretion (e.g., Stevenson et al. 1983). Even without invoking late energetic impacts, Venus is expected to start with a core that is fully molten and a mantle that was at least partially liquid, like Earth. Radioactive decay of isotopes of uranium, thorium, and potassium provides additional heat over geologic time. Once Venus formed, it started losing heat to the void of space. Depending on the regime of mantle convection and atmospheric properties, the rate at which heat is lost to space might roughly exceed, equal, or pale in comparison to the rate of internal, radiogenic heat production. Consequently, the interior temperature of Venus can increase, stay roughly constant, or decrease at different periods during its history. Figure 9 shows how the present-day internal structure of Venus reflects its bulk temperature. Thus, the modern state of the core and mantle will tell us the extent to which Venus has cooled down from its putative hot start.

3.3.1 Basic Properties of the Interior

Venus is a differentiated planet, but the sizes, compositions, and physical states of its different layers are unknown. The Pioneer Venus Orbiter and Magellan missions used the Doppler tracking method to determine the planetocentric constant *GM*, where *G* is the gravitational constant (Konopliv et al. 1999). As is common for planetary bodies, these data are high-quality enough that only the fundamental uncertainty about the value of *G* limits the precision of our estimate of *M* for Venus. The radial distribution of Venus's internal mass is still largely putative because it is mainly based on models and comparisons with Earth (e.g., Shah et al. 2022, Smrekar et al. 2018). The first surface analyses from the Venera landers revealed that Venus has a crust that was derived from partial melting of its silicate mantle (e.g., Surkov 1983; Treiman 2007). However, available data do not discriminate between a wide range of models for the thicknesses of its crust, lithosphere, mantle, and core. The surface is obviously solid, but the state (liquid and/or solid) of the deep interior are largely unconstrained (Dumoulin et al. 2017). Future measurements of these parameters (e.g., Widemann et al. 2023, this issue) will be vital to constrain thermal evolution models.

At present, three tools provide access to the structure and internal properties of Venus: measurements of the moment of inertia, the tidal deformation, and the gravity field. The moment of inertia (MoI) is calculated by accurately determining the precession rate of the spin axis. If Venus were in hydrostatic equilibrium, the MoI could also be derived from its degree-2 gravity field. However, the polar flattening of the planet does not correspond to its current rotation (Van Hoolst 2015), so hydrostatic equilibrium is not applicable. The long precession period of Venus (~29,000 Earth-years) and the small obliquity of its rotation axis have long prevented the estimation of its MoI. A recent study by Margot et al. (2021) estimated for the first time the MoI with an uncertainty of ~7%. They precisely measured the precession rate of the rotation axis through the analysis of radar echo speckles measured at ground-based antennas over the period 2006–2020. This result, although pathbreaking, does not allow us to determine the size of the core with useful accuracy (e.g., ~3,500 ± 500 km). Fortunately, future Venus missions should improve this measurement of Venus's MoI thanks to radio science alone (e.g., Rosenblatt et al. 2021) or radio science coupled with radar imagery (e.g., Cascioli et al. 2021).

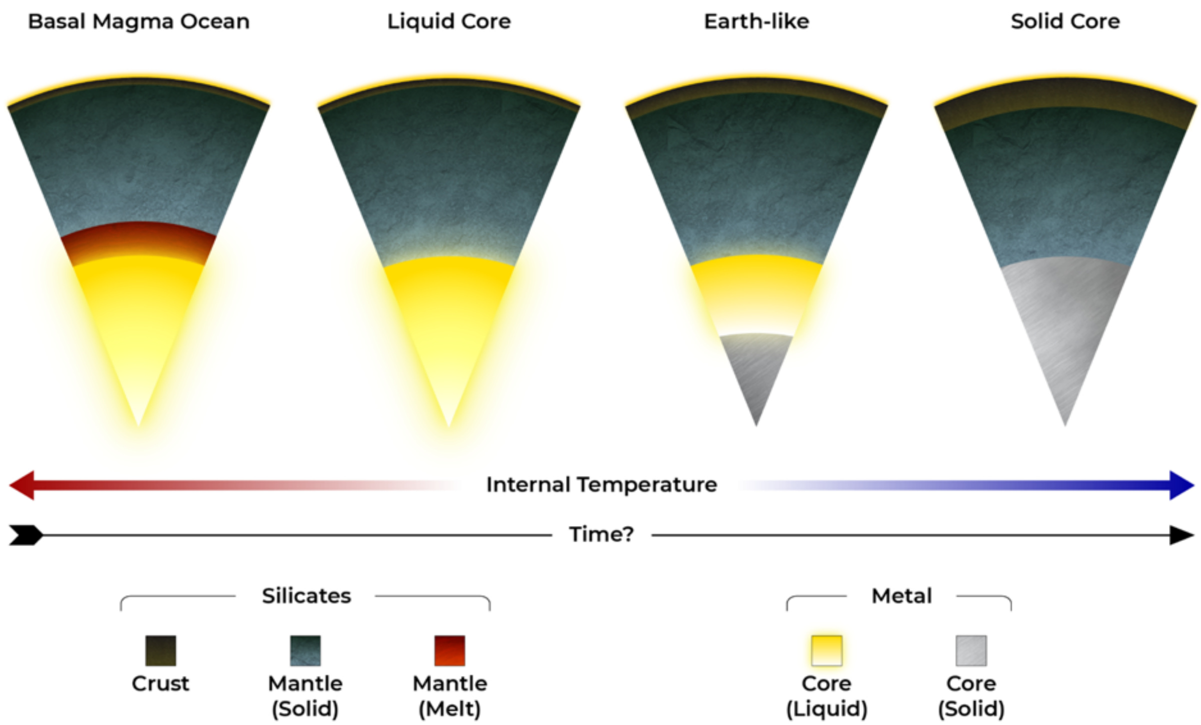

Figure 9. The internal structure of Venus at present is unknown. Four possibilities are shown, corresponding to internal temperatures that decrease from left to right. First, Venus may be hot enough that the lowermost mantle is still molten. Next, the core could remain fully molten after the mantle completely solidifies. However, Venus may have an Earth-like internal structure with a partially frozen core. Finally, observations do not exclude the (unlikely) possibility that Venus is so cold that the core is entirely solid. Venus probably formed hot and cooled down over time (albeit the mantle may not cool monotonically due to radiogenic heating)—so the internal structure could evolve from left to right over geologic time.

The deformation of the planet under the gravitational attraction of the Sun (solar solid body tide) is a source of information on the internal structure and also on its rheological parameters, such as the viscosity of the mantle or the state of the core. Indeed, the changes in the mass distribution during the tidal deformation generate a variable term in the gravity potential field, of degree 2. The proportional coefficient between the potential due to mass redistribution and the external potential due to solar tide is called the potential Love number and is denoted k_2. The first estimate of the potential Love number was made using tracking data from the PVO and Magellan probes by Konopliv & Yoder (1996). The value found (k_2 = 0.295 ± 0.066) was then used to rule out the presence of a solid core based on elastic tidal deformation modeling results (Yoder 1995). However, if viscosity is taken into account, making solid interior layers more deformable, the current uncertainty on the value of k_2 does not rule out this possibility. Dumoulin et al. (2017) showed, for instance, that a model with a solid core having a low viscosity (i.e., less than 10^{17} Pa s) can account for the current estimate of k_2. Radio-science experiments onboard future missions orbiting Venus will also considerably reduce the uncertainty on k_2 (e.g., Rosenblatt et al. 2021, Cascioli et al. 2021). The imaginary part of the potential Love number, which is equal to k_2/Q, Q^{-1} being the global dissipation function of the planet, reflects the phase lag of the tidal bulge and therefore particularly provide a quantification of the mantle viscosity (c.f., Dumoulin et al. 2017). Again, the estimation of this parameter by future space missions (Rosenblatt et al. 2021, Cascioli et al. 2021) could therefore allow an estimate of the mantle viscosity, and consequently of the mantle temperature, which is crucial to constrain thermal evolution models. These new constraints could also be useful for constraining the rotational evolution of the planet via solid body tidal dissipation (e.g., Way et al. 2020, Section 5).

The planet's gravity field can also be used in conjunction with the global topography data to estimate crustal and lithospheric thickness. These studies require assumptions about crustal density and type of topographic support (e.g., Wieczoreck 2015). Overall, recent work suggests that the crustal thickness of Venus is ~5–70 km, depending on the region, with a mean of ~15–30 km, depending on the study (e.g., Nimmo & McKenzie 1998; Anderson & Smrekar 2006; James et al. 2013; Jimenez-Diaz et al. 2015; Yang et al. 2016; Maia & Wieczoreck 2022). Broadly speaking, exploitation of the low spherical harmonic degrees of the geoid and topography allows for estimation of global and/or regional lithospheric thickness. Scientists also apply models of lithospheric flexure to the topography of individual volcano-tectonic features (e.g., Johnson & Sandwell 1994; Russell & Johnson 2021; Borrelli et al. 2021; Smrekar et al. 2022a; Ghail et al. 2023, this issue) and impact craters (e.g., Ivanov et al. 1986; Grimm & Solomon 1988; Brown & Grimm 1996), which provide local estimates. Depending on the study, the lithospheric thickness of Venus has been reported as ~0–600 km (but usually <100 km), depending on what isostatic equilibrium models are assumed and/or what types of features are studied (e.g., Anderston & Smrekar 2006; Moore & Schubert 1997; Orth & Solomatov 2011).

The bulk composition of the mantle has been estimated using accretion models of the protoplanetary disc. Because of the lack of constraints on these accretion scenarios, models of Venus's internal structure have been generally terrestrial models scaled to Venus to account for the slightly smaller radius and hence lower pressure (e.g., Zharkov et al. 1983; Yoder 1995; Mocquet et al. 2011; Aitta 2012). However, accretion models can lead to different iron oxide contents in the mantle depending on the cosmochemical assumptions (e.g., Lewis 1972; Weidenschilling 1976; Ringwood & Anderson 1977; Morgan & Anders 1980; Rubie et al. 2015). Recent models of solar nebula condensation seem to favor a somewhat smaller Venusian mantle than that of the Earth, implying a larger core-to-mantle volume for Venus than for the Earth (e.g., Tronnes et al. 2019). Various radial structures have also been proposed to account for the variability of the mantle composition with respect to the accretion model hypothesis (e.g., Dumoulin et al. 2017; Zharkov & Gudkova 2019). If the FeO content of the mantle increases (or decreases), then the core should be smaller (or larger). In models, the size of the core varies by several hundred kilometers depending on the assumed interior composition (e.g., Shah et al. 2022). Depending on the core's exact radius, the mantle may or may not have a perovskite to post-perovskite phase transition at its base, similar to the one that can occur in the few hundred km above Earth's core (e.g., Dumoulin et al. 2017; Xiao et al. 2021; Margot et al. 2021). Once again, VERITAS and EnVision will sharpen the tools we use to study Venus's interior (e.g., Widemann et al. 2023, this issue), allowing us to make realistic models of its present structure.

Overall, the relative sizes of the core and mantle provide proxies for Venus's redox state. Redox state (or oxygen fugacity) is a central parameter in models of the evolution of Venus. In this collection, Gillmann et al. (2022) describe how the oxygen fugacity of the bulk mantle helps control the long-term evolution of the atmosphere. Because the properties of iron alloys change with pressure and temperature, the proportion and nature of light elements in Venus's core govern its eventual solidification history (e.g., Xiao et al. 2021; Shah et al. 2022). The DAVINCI mission aims to measure the oxygen fugacity of the lower atmosphere to constrain models of the surface mineralogy and atmosphere-surface interactions at present-day (e.g., Garvin et al. 2022). Broadly speaking, oxygen fugacity is also critical to measure for rocky exoplanets, since it is key to the formation and evolution of planetary interiors, surfaces, and atmospheres.

3.3.2 How the Lithosphere and Mantle May Have Evolved

The evolution of a planetary body is strongly controlled by its thermal history. The vigor of convection and extent of partial melting of the mantle determine processes like volcanism and tectonics—which translate in turn to crustal production and the evolution of the atmosphere. Hypotheses about how the lithosphere and mantle of Venus may have evolved developed in tandem with the advances in understanding plate tectonics on Earth, which were detailed in sections 2.5.1 and 2.5.2 above. Ultimately, recent studies establish that Venus may provide a modern example of the lithospheric and mantle dynamics of early Earth. However, many first-order questions about Venus's mantle dynamics, and how they have evolved over time, await answers from new missions and modeling studies.

Comparisons between the terrestrial planets in our Solar System suggest that Earth is currently unique as it operates within a plate tectonic regime. Perhaps consequently, Earth has had a habitable climate over geologic time scales. Plate tectonics (as defined on Earth) is characterized by a coherent network of fractured lithosphere, which self-organizes the surface into a series of rigid surface plates. Motion of these discrete plates is accommodated by localized failure along relatively narrow plate boundary zones. The cold surface plates of a plate tectonic regime participate in mantle overturn and in turn are associated with the cooling of the planetary interior. As a result, plate tectonics is considered to be a specific example of the mobile-lid style of mantle convection. Earth is the only body in the Solar System for which a large and robust dataset of its thermal, geologic, and tectonic evolution is accessible. However, our understanding of Earth's evolution remains contentious despite (or perhaps because of) this expansive dataset. For example, the onset time of plate tectonics and thus its duration—and the mechanisms that initiated it—are far from certain (e.g., O'Neill et al. 2007; Debaille et al. 2013; Gerya 2014; Foley et al. 2014; Weller & Lenardic 2018). The starting condition for Earth is uncertain. However, a long-standing consensus, from a thermal standpoint, is that plate tectonics will eventually wane as Earth cools—and Earth will eventually move into stagnant-lid regime, perhaps not dissimilar to Mars today.

In contrast to the current day Earth, observations of Mars suggest a planet operating within a stagnant-lid tectonic regime (e.g., Nimmo & Stevenson 2000). Within this regime, the cold and stiff outermost rock layer does not participate in mantle overturn. Unlike the fractured network of plates in a plate tectonic planet, the surface is made up of a single plate. Single-plate surfaces lack significant horizontal or vertical motions, which largely segregates the surface from the interior. The thick lithosphere of the single-plate, stagnant lid inhibits conductive heat loss, which in addition to the lack of chilling from down going slabs, leads to a warmer interior. Similar to Earth, there exists suggestions of an early mobile or plate tectonic phase for Mars (e.g., Sleep 2000*;* Zhang & O'Neill 2016). However, evidence of such a phase remains elusive. The tectonic history of Venus is even more elusive.

How Venus loses its heat remains a major unanswered question. Pure conduction through a stagnant lithosphere is unlikely to account for all the heat transfer from its interior (e.g., Reese et al. 1999). Several other tectonic regimes have been proposed for Venus, which are described in more detail in Rolf et al. (2022, this issue). A popular proposition is that the planet experiences episodical overturns of a lithosphere that is usually a stable stagnant lid, leading to an "episodic lid" regime (e.g., Turcotte 1993; Moresi & Solomatov 1998). This regime would account for global recycling of crust that is subducted during ephemeral bursts of activity. Such a crustal overturn event could produce a global resurfacing event favored by some, but certainly not all, catastrophic models for the evolution of the surface discussed in section 3.2.2 above (e.g., Strom et al. 1994; Nimmo & McKenzie 1998; Armann & Tackley 2012; Gillmann & Tackley 2014; Bercovici & Ricard 2014). The episodic-lid regime, however, does not account for intrusive or extrusive magmatism on the planet. The recently proposed "plume-lid" (Sizova et al. 2010; Fischer & Gerya 2016) or "plutonic-squishy lid" (Lourenço et al. 2018, 2020) regime emphasizes the importance of intrusive magmatic processes and is characterized by a set of strong plates separated by warm and weak regions generated by plutonism. Instead of lithospheric subduction, lithospheric material is recycled into the mantle by delamination and dripping. This squishy lid regime has also been applied to early Earth in the Archean Eon (4–2.5 Ga) (Fischer & Gerya 2016), when temperature conditions on Earth were thought to be similar to those on Venus today (e.g., Anderson 1981; Head et al. 2008; Van Kranendonk 2010; Harris & Bédard 2014).

The "kick-start" of subduction, a key element of modern-style plate tectonics, has been attributed to various factors. Perhaps most relevant for Earth—and Venus—is the hypothesis that the interaction of a buoyant mantle plume with oceanic lithosphere may have initiated subduction (e.g., Ueda et al., 2008). According to this scenario, under certain circumstances, a long-lived, buoyant mantle plume can overcome the strength of the lithosphere and penetrate through it, pushing the lithosphere downward into the asthenosphere, eventually initiating self-sustained subduction (e.g., Ueda et al. 2008; Stern & Gerya 2017). Numerical explorations of this theory in 3D were undertaken to investigate the initiation of subduction by a thermal plume on Archean Earth (Gerya et al. 2015), by a thermal-chemical plume on modern Earth (Baes et al. 2016) and on Venus (Gülcher et al. 2020). A combination of three key physical factors was proposed to be needed to trigger self-sustained plume-induced subduction (Gerya et al. 2015): 1) a strong, negatively buoyant lithosphere; 2) focused magmatic weakening and thinning of the lithosphere above the plume, and 3) lubrication of the slab interface by hydrated crust. The first and third factor may be (partially) absent on Venus (e.g., Smrekar et al. 2007; Huang et al. 2013). Furthermore, laboratory experiments undertaken by Davaille et al. (2017) advocate a limited plume-induced subduction regime in Venusian environments (see section 2.5.2).

3.3.3 How Prospects for Intrinsic Magnetism May Have Evolved

Spacecraft missions have not yet provided clear evidence that Venus has any intrinsic magnetism. There are at least two types of intrinsic magnetism: 1) an active dynamo that relies on modern motions of electrically conductive fluid in the planetary interior and 2) crustal remanent magnetism that signals the past existence of a dynamo as found on Mars, Mercury, Earth, and Earth's Moon. Many relevant measurements have been made, but the detection limits for Venus are poor relative to those for other terrestrial planets. Specifically, magnetometers have been carried on at least 11 missions to Venus: Mariner 2 and 10; Venera 4 and 9–12; Pioneer Venus Orbiter; VeGa 1 and 2; and Venus Express (e.g., Russell 1993; Russell et al. 2007). Only Venera 4, PVO, and Vex made measurements at close enough distances to address the intrinsic magnetism of Venus (Figure 10). The other missions established that Venus lacks an Earth-like magnetosphere and tackled science questions related to space physics and the solar wind.

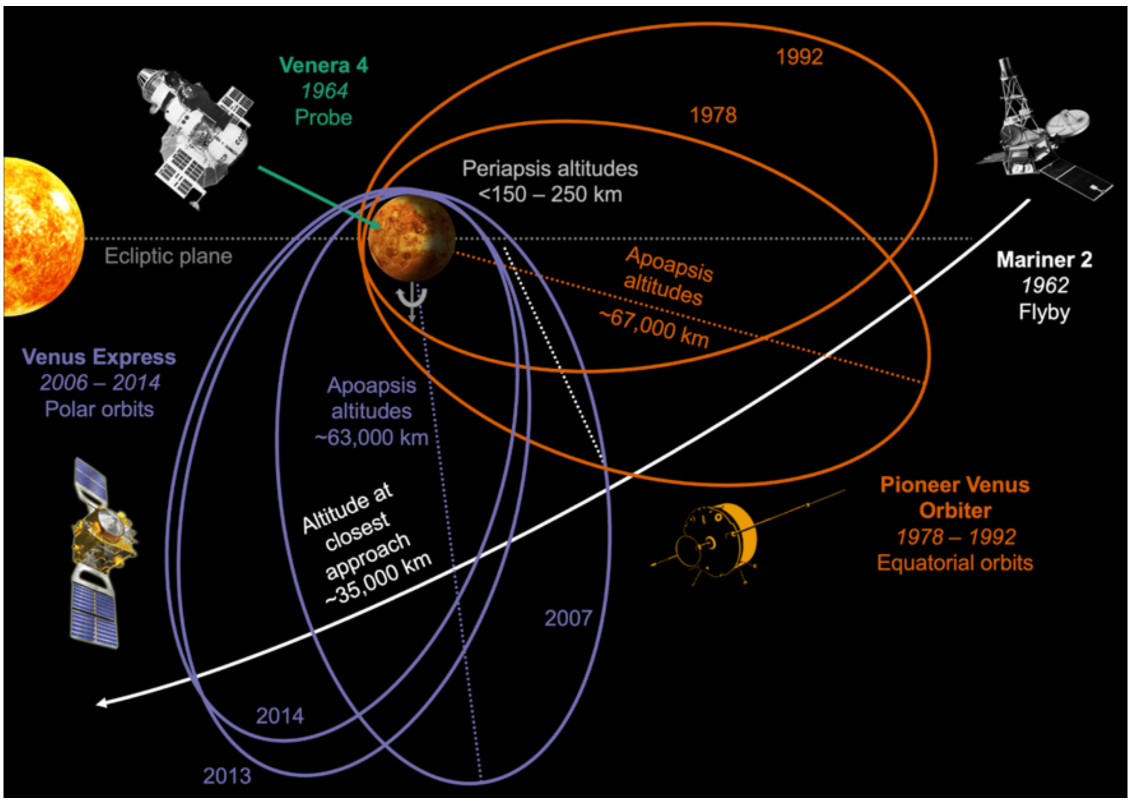

Figure 10. No intrinsic magnetism has yet been discovered at Venus. This cartoon shows the orbits and trajectories (approximately to scale, following Futaana et al. 2017) of the first magnetometer flyby by Mariner 2 and of the three missions (Venera 4, Pioneer Venus Orbiter, and Venus Express) that supplied the most stringent constraints currently available on our models of Venus's intrinsic magnetism. Pioneer Venus Orbiter and Venus Express placed the most precise upper limit so far on the total magnetic moment of Venus, which is at least ~10^5 times lower than Earth's modern magnetic moment. Venera 4 collected magnetometer data until ~25 km above Eistla Regio (19°N 38°E)—but no other mission made relevant magnetometer measurements below the ionosphere. The southern hemisphere is unexplored magnetically—strong, horizontally coherent magnetization there is possible. Crustal remanent magnetization at horizontal scales smaller than orbital altitudes could exist almost anywhere on the surface.

Pioneer Venus Orbiter provided the most stringent detection limit on (the putative lack of) Venus's dynamo. Measurements taken in orbit implied that the total magnetic moment of Venus is <10^{-5} times Earth's magnetic moment (Phillips & Russell 1987). Lowering this detection limit with a future orbiter is difficult because the thick atmosphere precludes operating at lower altitudes. Weaker magnetic fields would also interact with the solar wind and the ionosphere in complicated ways that require numerical simulations to interpret. In any case, the current limit from PVO is widely considered proof that no dynamo exists because most existing theories predict that a dynamo would be stronger if it existed (e.g., Stevenson 2003, 2010). For example, the "weak" dynamo of Mercury is still ~10^3 times stronger than the detection limit for Venus. However, some scientists argue that current models and observations are not stringent enough to exclude the possibility that a feeble dynamo exists (e.g., Luhmann et al. 2015). In fact, a very small intrinsic field, near the detection limit from PVO, has been proposed to explain observed structure in the nightside magnetosphere of Venus (e.g., Knudsen et al. 1982).

Crustal remnant magnetism could await discovery on Venus and explain any weak intrinsic magnetism. Intuitively, preserving crustal magnetism on Venus might seem difficult because Venus has the hottest surface on average of any terrestrial planet in the Solar System. However, temperatures in the top few kilometers of the crust should be low enough for common minerals such as magnetite and hematite to retain thermal remanent magnetism from a past dynamo for billions of years (O'Rourke et al. 2019 and references therein) unless the surface was much hotter in the past (e.g., Bullock & Grinspoon 1996). In principle, the upper limit on the magnetic moment of Venus of PVO is consistent with the entire surface of Venus being magnetized with an intensity of ~1 A/m down to a depth of ~1 km (i.e., a total dipole moment of ~5×10^{17} A m^2 versus ~8×10^{22} A m^2 for Earth). For reference, the average value for magnetized regions in smoothed maps from orbital data of crustal magnetization on Mars is ~1 A/m (e.g., Langlais et al. 2019). Crustal magnetization on Venus could also be sparse with local regions having high magnetization intensities, as on Mars at the InSight landing site where the magnetization intensity could be ~10 A/m or higher locally (e.g., Johnson et al. 2020). In models, the structure of the nightside magnetosphere of Venus is governed by the total sum of the magnetization, not its spatial distribution (e.g., Knudsen et al. 1982).

New missions are required to search for weak intrinsic magnetism and, if successful, to characterize the source as either a weak dynamo or crustal remanence. As mentioned above, only Venera 4 measured magnetic fields below orbital altitudes—down to an altitude of ~25 km above Eistla Regio (Dolginov et al. 1969; Russell 1976). No crustal magnetism was detected at this particular location. Crustal magnetization is not apparent either in the PVO and Vex datasets. Orbital missions are only able to search for magnetization that is spatially coherent at length scales comparable to orbital altitudes (≥150 km above the equator and north pole). No mission has yet made magnetometer measurements at low orbital altitudes over the south pole. Magnetometer surveys below the ionosphere (e.g., from an aerial platform as in O'Rourke et al. 2021) are best suited to searching for intrinsic magnetism. Any low-altitude survey should be able to definitively test the dynamo hypothesis, which would produce global, albeit weak, fields. A non-detection of crustal magnetism is more equivocal because of the possible spatial variability. As an extreme analogy, the question of whether Earth's crust preserves a record of a Hadean dynamo is not yet settled (e.g., Borlina et al. 2020; Tarduno et al. 2020)—and will only be answered via small-scale, laboratory measurements of individual mineral crystals.

Because the magnetic history of Venus is so uncertain, the extent to which magnetism constrains models of the evolution of Venus is unclear. In other words, perhaps only a "small" difference between Earth and Venus can explain the absence of an Earth-like magnetosphere. Slow rotation of Venus is occasionally proposed as the culprit (e.g., Luhmann et al. 2015) but most modern scaling laws for the intensity of a dynamo-generated field do not depend on rotation rate above a critical threshold that Venus exceeds by several orders of magnitude (e.g., Stevenson 2003, 2010; Christensen 2010). Perhaps a more popular idea is that the deep interior of Venus cools slowly relative to Earth. Driving a dynamo with convection in an electrically conductive fluid—either in the metallic core or, perhaps, a basal magma ocean (e.g., O'Rourke 2020)—requires that fluid to cool at a certain rate. Slow cooling leads to stagnation and the rapid ($<10^4$ years) dissipation of any magnetic fields (as happened on Mars). Because Venus has slightly lower pressure than Earth at its center, Venus may lack an inner core even if it has the same core-mantle boundary temperature as Earth. Thus, even if Earth and Venus were cooling at comparable rates, Venus would be less likely to host a dynamo (Stevenson et al. 1983). In general, the critical heat flow required to produce a dynamo in terrestrial planets is close to the actual heat flows expected in planetary interiors. This marginal criticality is why not all terrestrial planets have dynamos, whereas dynamos are basically universal in ice giants, gas giants, and stars. In the absence of plate tectonics, the operative mode of mantle convection may extract relatively less heat from the deep interior (e.g., Nimmo 2002; Driscoll & Bercovici 2013, 2014; O'Rourke et al. 2018).

Alternatively, a dramatic difference in the accretion of Earth and Venus would predict that Venus never had an intrinsic magnetic field. If Venus experienced a "gentle" accretion without any late energetic impacts, then primordial chemical stratification of the core would preclude convection and thus a dynamo from ever existing (Jacobson et al. 2017). At an extreme case, which would be contrary to all expectations, Venus could have accreted so gradually that internal temperatures were low enough for the deep interior to fully solidify. Ultimately, Venus is the only planetary body in the inner Solar System that lacks either an internal dynamo today (as in Earth and Mercury) or strong evidence that a dynamo existed in the past (as for Earth's Moon and Mars). Improving our understanding of magnetic fields at Venus would help us understand terrestrial planets in general.

4. How Understanding the Evolution of Venus Motivates the Future of Planetary Exploration

Nations invest in space exploration to advance scientific knowledge, to understand humanity's place in the universe, and to advance their prestige amongst the family of nations. National space agencies prioritize science missions based on the perceived importance and feasibility of answering different sets of questions. Historically, the popularity of Venus as a mission target has waxed and waned over the last several decades. As detailed in section 2, interplanetary missions often targeted Venus at the start of the Space Age because it was relatively accessible from Earth and because scientists had long believed that it was habitable today. Other worlds—for example, Mars and myriad icy satellites—soon seemed more appealing once spacecraft became capable enough to reach and explore them—and when they were recognized as perhaps the most likely places to find life beyond Earth at present day. However, the popularity of Venus has recently rebounded from its post-Magellan nadir.

New missions to Venus happen when scientific desires converge with technological advances. The scientific desire to explore Venus has only grown in recent years. As detailed in section 3, all the available observations of Venus are compatible with radically different stories about its evolution over time—a habitable past or a perpetual hell. Starting roughly in the 2000s, increasing awareness of anthropogenic climate change on Earth highlighted the importance of understanding the extreme greenhouse effect on Venus, motivating concepts such as the Venus Climate Mission (Grinspoon et al. 2012). As studies of exoplanets have exploded over the past decade, Venus has gained increasing prominence as the archetype of a hot, rocky planet. The field of noble gas isotope geochemistry developed over the past few decades and demonstrated the power to diagnose the formation and evolution of planetary systems (e.g., Baines et al. 2013, Chassefière et al. 2012). This broad-based interest in Venus recently aligned with mission proposals that had relatively low technical risk. Geophysical orbiters like VERITAS (e.g., Smrekar et al. 2022b) and EnVision are analogous to Magellan but will return orders-of-magnitude better data after thirty years of instrument development. The DAVINCI mission will use geochemistry instruments that would have been exotic in the 1990s but now have high heritage from recent Mars missions (Garvin et al. 2022). Future missions to Venus will benefit from technology development efforts that are happening now—focused on, for example, enabling long-lived aerial platforms and surface stations.

Here we review how open questions about the evolution of Venus fit into the strategic plans of space agencies in Europe and the United States. Ultimately, the next few decades of Venus exploration are guaranteed to be fruitful and exciting due to VERITAS, DAVINCI, and EnVision. However, both ESA and NASA are laying the groundwork for an even more ambitious sequence of follow-up missions to understand why Venus and Earth are so different—and what Venus can teach us about the evolution of terrestrial planets in general. Although not discussed here, space agencies in many other countries, including India, Japan, and Russia, also plan to explore Venus. We encourage interested readers to consult Widemann et al. (2023, this issue) in this collection to learn about the science goals and planned measurements for these upcoming and possible future missions.

4.1 Importance of Venus's Evolution to ESA

ESA's planetary exploration in the early 21st century has been based largely on its "Cosmic Vision" strategy (ESA 2005). This poses four big questions, the first two of which are "What are the conditions for planet formation and the emergence of life?" and "How does the Solar System work?" The first of these themes explicitly calls for a study of planetary formation and evolution, and the emergence of habitable environments, and then of life itself. These themes are clearly addressed by the EnVision orbiter that in 2021 was selected to be the next mission in ESA's space science program—and would also be addressed by cloud-level balloon missions like the European Venus Explorer concept proposed to ESA in 2007 and 2010 (Wilson et al. 2012). The second top-level question posed in the Cosmic Vision strategy deals with the role of the Sun in the solar system, and its interactions with the planetary systems. This question would support a mission focused on measurement of escape processes and solar wind interaction—or, equally, a mission focused on the radiation budget of Venus, monitoring ingoing and outgoing radiative fluxes and studying its greenhouse balance.

The two previous missions selected in ESA's space science program, PLATO and Ariel, both due for launch in the late 2020s, focus on exoplanet detection and characterization. Their search for, and study of, terrestrial exoplanets will inevitably lead them to confront questions of the diversity of evolutionary outcomes for terrestrial planets and refinement of habitable zones for terrestrial planets; in this their goals will be quite complementary to those of the solar system missions which allow study of a few nearby planets in great depth.

Cosmic Vision is now being succeeded as a strategy document by a new one called *Voyage 2050*. This new report identifies themes for both large- and medium-class missions for the next three decades. One of the large-class mission themes called for is the "characterization of temperate exoplanets." Venus's exploration will play an important role in informing what we know about planetary habitability and its evolution through time, and about what observations can be used to constrain these factors. *Voyage 2050* calls out "Venus Geology and Geophysics" as a key theme for understanding why Venus took an evolutionary path so different from that of Earth—a theme largely addressed by the EnVision mission. No further Venus-specific mission themes are singled out in the Voyage 2050 document. However, ESA's calls for medium-class mission ideas are open to mission concepts that would address Venus's evolution.

4.2 Importance of Venus's Evolution to NASA

In the United States, the National Academies of Sciences, Engineering, and Medicine provide strategic advice to NASA via the decadal survey process. For the last ten years, NASA has operated under the guidance of "Vision and Voyages for Planetary Science in the Decade 2013–2022" (National Academies 2011). Recommendations from the community of scientists interested in Venus, especially via the Venus Exploration Analysis Group (VEXAG), helped shape the recommendations in that survey. As described in a previous review (Glaze et al. 2018), Venus was central to the prioritized scientific objectives for the exploration of the inner solar system planets. At the end of the applicable decade, NASA decided to achieve many of these objectives by selecting the VERITAS and DAVINCI missions for the Discovery Program (Widemann et al. 2023, this issue).

Planning the next decade of Venus exploration began with a grassroots effort organized through VEXAG. In 2018 and 2019, VEXAG produced three strategic documents (Figure 11): the Goals, Objectives, and Investigations (GOI) for Venus Exploration (O'Rourke et al. 2019); the Venus Technology Plan (Hunter et al. 2019); and the Roadmap for Venus Exploration (Cutts et al. 2019). The GOI document identified three high-priority scientific goals (unprioritized):

1. Understand Venus's early evolution and potential habitability to constrain the evolution of Venus-sized (exo)planets.
2. Understand atmospheric composition and dynamics on Venus.

3. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

The technology plan lauded the successes of existing programs such as the Heatshield for Extreme Entry Environment Technology (HEEET) and High Operating Temperature Technology (HOTTech)—and described the new technologies required to support ambitious missions in the extreme conditions found at Venus's atmosphere and surface. Finally, the Roadmap document recommended an ambitious program of Venus missions, starting with an orbiter and an atmospheric-entry probe in the near term—exactly what NASA selected in VERTIAS and DAVINCI. The new decadal survey considered other types of missions to Venus, including additional orbiters, probes, landers, and aerial platforms—all motivated by scientific questions that the triad of now-selected missions may not fully answer.

A new decade brings new opportunities to explore Venus to advance planetary science. Recently, the National Academies released "Origins, Worlds, Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032" (National Academies 2022). This survey was organized around 12 priority science questions. These questions centered on three high-level scientific themes:

1. Origins: How did the solar system and Earth originate, and are systems like ours common or rare in the universe?
2. Worlds and processes: How did planetary bodies evolve from their primordial states to the diverse objects seen today?
3. Life and habitability: What conditions led to habitable environments and the emergence of life on Earth, and did life form elsewhere?

Future exploration of Venus is central to all three themes. Table 2 lists the priority science questions and sub-questions that are directly tied to Venus. The decadal survey lists the research activities that would help answer these (sub-)questions—and elaborates on the technological developments that would enable these activities.

Table 2. Priority questions from the new Planetary Science and Astrobiology Decadal Survey 2023–2032 (National Academies 2022) that relate to the evolution of Venus. Studying Venus also helps us understand the evolution of Earth (e.g., Q3.3) and rocky planets writ large (e.g., Q12). The VISE mission concept for the New Frontiers program would mostly address questions 3, 5, 6, 10, and 12. Venus-targeting missions in the Discovery and/or SIMPLEx programs could address any question(s).

Scientific Theme	Priority Science Questions Related to	Sub-Questions Involving Venus

	Venus	
Origins	Q1. Evolution of the protoplanetary disk.	Q1.1 What were the initial conditions in the Solar System? Q1.2 How did distinct reservoirs of gas and solids form and evolve in the protoplanetary disk? Q1.3 What processes led to the production of planetary building blocks?
	Q3. Origin of Earth and inner solar system bodies.	Q3.1 How and when did asteroids and inner Solar System protoplanets form? Q3.2 Did giant planet formation and migration shape the formation of the inner solar system? Q3.3 How did the Earth-Moon system form? Q3.4 What processes yielded Mars, Venus, and Mercury and their varied initial states? Q3.5 How and when did the terrestrial planets and Moon differentiate? Q3.6 What established the primordial inventories of volatile elements and compounds in the inner Solar System?
Worlds and processes	Q4. Impacts and dynamics	Q4.2 How did impact bombardment vary with time and location in the Solar System? Q4.3 How did collisions affect the geological, geophysical, and geochemical evolution and properties of planetary bodies?
	Q5. Solid body interiors and surfaces.	Q5.1 How diverse are the compositions and internal structures within and among solid bodies? Q5.2 How have the interiors of solid bodies evolved? Q5.3 How have surface/near-surface characteristics and compositions of solid bodies been modified by, and recorded, interior processes? Q5.4 How have surface characteristics and compositions of solid bodies been modified by, and recorded, surface processes and atmospheric interactions? Q5.5 How have surface characteristics and compositions of solid bodies been modified by, and recorded, external processes? Q5.6 What drives active processes occurring in the interiors and on the surfaces of solid bodies?
	Q6. Solid body atmospheres, exospheres, magnetospheres, and climate evolution.	Q6.1 How do solid-body atmospheres form and what was their state during and shortly after accretion? Q6.2 What processes govern the evolution of planetary atmospheres and climates over geologic timescales? Q6.3 What processes drive the dynamics and energetics of atmospheres on solid bodies? Q6.4 How do planetary surfaces and interiors influence and interact with their host atmospheres? Q6.5 What processes govern atmospheric loss to space? Q6.6 What chemical and microphysical processes govern the clouds, hazes, chemistry, and trace gas composition of solid-body atmospheres?
Life and habitability	Q10. Dynamic habitability.	Q10.1 What is “habitability”? Q10.2 Where are or were the Solar System’s past or present habitable environments? Q10.3 What controls the amount of available water on a body over time? Q10.4 Where and how are organic building blocks of life synthesized in the Solar System? Q10.5 What is the availability of nutrients and other inorganic ingredients to support life? Q10.6 What controls the energy available for life? Q10.7 What controls the continuity or sustainability of habitability?
	Q11. Search for life elsewhere	Q11.1 What is the extent and history of organic chemical evolution, potentially leading toward life, in habitable environments throughout the Solar System?

		Q11.2 What is the biosignature potential in habitable environments beyond Earth? What are the possible sources of false positives and false negatives? Q11.3 Is or was there life elsewhere in the Solar System?
Cross-cutting	Q12. Exoplanets	Studies of Venus's evolution would help address the exoplanetary analogues to all the priority science questions listed above.

Figure 11. During the three years in the run-up to the new decadal survey in the United States, the Venus community produced several reports and mission concept studies that expressed a consensus vision of Venus exploration—highlighting the importance of Venus science to cross-cutting questions in planetary science and astrobiology. The top and bottom rows show the covers of the 2019 VEXAG strategic documents and three recent mission concept study reports, respectively.

NASA will likely select its next missions to Venus (after VERITAS and DAVINCI) through competitions. What NASA calls small-cost missions are commonly led by a single Principal

Investigator (PI) and designed to achieve a focused set of science objectives. These missions are typically developed and launched within ~3–5 years after their selection. The new decadal survey endorsed continuing three successful programs of competed, PI-led missions that include Venus as a possible destination. First, the Small Innovative Missions for Planetary Exploration (SIMPLEx) program includes very small, low-cost missions with a PI-managed mission cost cap of $55 million in 2018, which the decadal survey recommended raising to roughly $80 million (in fiscal year 2025 dollars, not including the launch). Similarly, ESA's Fast (F) mission opportunities support relatively small, low-cost spacecraft that launch along with a primary mission but then address any area of space science. NASA's Discovery Program enables more sophisticated (and less risky) missions with a PI-managed mission cost cap an order of magnitude above the cost cap for SIMPLEx (e.g., ~$800 million or so), comparable to ESA's Medium (M-class) missions. Both the SIMPLEx and Discovery Programs are open to any mission that advances planetary science—obviously including Venus-targeting missions.

Higher-cost NASA missions are typically chosen from a restricted list. Venus is on the list of allowed targets for the New Frontiers program, which includes missions that are more scientifically ambitious (and thus technically challenging) than Discovery-class missions. Specifically, the new decadal survey described a New Frontiers mission called the Venus In Situ Explorer (VISE), which must address at least two of these three scientific objectives:

- Characterize past or present large-scale spatial and temporal (global, longitudinal and/or diurnal) processes within Venus's atmosphere.
- Investigate past or present surface-atmosphere interactions at Venus.
- Establish past or present physical and chemical properties of the Venus surface and/or interior.

VISE is anticipated to collect data that is not obtainable from an orbiter alone (e.g., VERITAS and EnVision) or a single descent probe (e.g., DAVINCI).

Innovative teams can design missions with a wide range of modalities that are responsive to the VISE concept in the decadal survey. For example, missions proposed to the New Frontiers program under a previous definition of VISE have included landers (targeting the plains or tesserae) and a combined orbiter plus descent probe. This decadal survey commissioned a study at NASA's Goddard Space Flight Center of a new concept called ADVENTS (Assessment and Discovery of Venus's Past Evolution and Near-Term Climatic and Geophysical State, Figure 11), which included an orbiter, a variable-altitude aerobot, and a dropsonde (O'Rourke et al. 2021). The Steering Committee of the decadal survey ultimately decided that ADVENTS overlapped with the VISE concept—and thus an ADVENTS-like mission is eligible for the New Frontiers program to satisfy the listed VISE objectives. The Panel on Venus for the decadal survey suggested several other mission concepts, including Venus In Situ Seismic and Atmospheric Network, Venus Sub-Cloud Aerobot, the Venus Life Potential, and Venus Investigation of Dynamics From an Equatorial Orbit. These mission concepts were not studied in detail through the decadal survey process, but future teams could develop them under the umbrella of VISE (National Academies 2022, Appendix E).

The new decadal survey did not prioritize a Flagship mission to Venus. Flagship missions are directed by NASA—not led by a PI nor chosen by competition—and must have exceptional scientific merit. In preparation for the decadal survey, NASA commissioned a concept study for a Venus Flagship Mission (Figure 11). This ambitious mission would deliver an orbiter, two small satellites, a lander, and a variable-altitude aerobot on a single launch to simultaneously study Venus with remote observations and in situ measurements (Beauchamp et al. 2021). The full version of this mission was estimated to have a total cost above $7 billion and relatively high technical risk. A descoped version of the mission could include only an orbiter and a lander—but was still judged to have relatively high cost and technical risk (National Academies 2022). Mission teams could consider designing a lander that targeted the plains instead of a tessera to reduce risk and cost while still answering priority science questions. As technology matures, increased lander lifetime, mobility, and/or autonomy will enable more advanced scientific investigations (e.g., Kremic et al. 2021).

Beyond missions, the new decadal survey recognized that investments in facilities and technology are vital to Venus's exploration. NASA currently supports at least two facilities that can recreate some of the conditions at the surface of Venus. For example, scientists have used the Planetary Aeolian Laboratory at NASA Ames Research Center to study aeolian processes at extreme pressures relevant to Venus (e.g., Greeley & Iversen 1985). The NASA Glenn Extreme Environments Rig (GEER) is a newer, highly capable facility that can conduct scientific measurements and test equipment at the temperature, pressure, and chemical conditions applicable to Venus's surface (e.g., Lukco et al. 2018). The GEER facility is the staging ground for the team building the Long-Lived In Situ Solar System Explorer (LLISSE), which is a small lander that could serve as a technology demonstration on future Venus missions (e.g., Beauchamp et al. 2021). LLISSE uses electronics built with silicon-carbide integrated circuits that can survive near-indefinitely on Venus's surface (Hunter et al. 2020). Further work on LLISSE over the next ten years should enable the next decadal survey to treat a long-lived lander as technically feasible—capable of achieving the scientific promise intrinsic to such a mission modality.

Increased investment in other NASA infrastructure is also needed to support future exploration of Venus—and planetary science in general. Spacecraft missions return data to scientists on Earth via the Deep Space Network (DSN), the international collection of giant radio antennas. The decadal survey identified a clear need to expand the DSN to support the communications requirements of future missions, including human missions that involve huge amounts of video transmissions. Although one radio band (Ka) offers the best downlink speeds, the decadal survey endorsed maintaining the DSN's ability to transmit in other bands. In particular, S-band transmissions can penetrate Venus's atmosphere and are thus vital to any in situ Venus mission (National Academies 2022). Finally, the Goldstone Solar System Radar (GSSR) is a productive facility that works in tandem with the DSN. GSSR is key to Venus exploration via its ability to map the surface in the L- and S-bands—and to measure the spin state of Venus over a long temporal baseline (e.g., Margot et al. 2021).

5. Conclusions

Scientists have more questions than answers about the evolution of Venus. Unlike at the dawn of the Space Age, we now know that the surface of Venus is inhospitable—scorched under a thick blanket of CO_2 whose most visually striking feature is the global cloud layer made of concentrated sulfuric acid. National space agencies will soon spend billions of dollars to answer one question: Has Venus always been like this? Our uncertainty is the best motivation for continued exploration. Without understanding the Earth/Venus dichotomy, we cannot claim to understand rocky (exo)planets in general. Scientists can publish many articles supporting the "habitable hypothesis:" the idea that Venus once was as we once imagined it to be now. A time traveler might have found two "blue marbles" in our Solar System only a billion years ago. However, these optimistic models could be wrong. Perhaps Earth and its sister planet trod divergent evolutionary paths from the start. Venus may have toured only the gradations of hell over its lifetime. This review aimed to explain the key turning points in the evolution of our study of the evolution of Venus—and to arm the reader with enough background knowledge to tackle the other manuscripts in this topical collection. Ultimately, we will rediscover Venus over the next few decades. Some of our current ideas about Venus might seem as silly as the old "Seltzer ocean" hypothesis seems now. But one prophecy is secure: We will soon have satisfying answers to some of our most pressing questions—and be able to ask new questions that cannot yet congeal in our ignorant minds.

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