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Venus Evolution Through Time: Key Science Questions, Selected Mission Concepts and Future Investigations

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Abstract
In this work we discuss various selected mission concepts addressing Venus evolution through time. More specifically, we address investigations and payload instrument concepts supporting scientific goals and open questions presented in the companion articles of this volume. Also included are their related investigations (observations & modeling) and discussion of which measurements and future data products are needed to better constrain Venus' atmosphere, climate, surface, interior and habitability evolution through time. A new fleet of Venus missions has been selected, and new mission concepts will continue to be considered for future selections. Missions under development include radar-equipped ESA-led EnVision M5 orbiter mission (European Space Agency 2021), NASA-JPL's VERITAS orbiter mission (Smrekar et al. 2022a), NASA-GSFC's DAVINCI entry probe/flyby mission (Garvin et al. 2022a). The data acquired with the VERITAS, DAVINCI, and EnVision from the end of this decade will fundamentally improve our understanding of the planet's long term history, current activity and evolutionary path. We further describe future mission concepts and measurements beyond the current framework of selected missions, as well as the synergies between these mission concepts, ground-based and space-based observatories and facilities, laboratory measurements, and future algorithmic or modeling activities that pave the way for the development of a Venus program that extends into the 2040s (Wilson et al. 2022).

Keywords Venus · Planetary system formation · Geological processes · Atmospheric dynamics · Atmospheric chemistry · Space instrumentation · Surface processes · Interior structure · Thermal state · Synthetic aperture radar · Subsurface sounder · Radio-science · Multispectral imager · Ground and space-based observatories

1 Introduction

Each of the companion articles in this collection has identified key open questions about the evolution of Venus' atmosphere, climate, surface, interior and habitability through time, as well as the measurements or approaches that are needed to address them. To capture the

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wide variety of scientific domains and fields covered in this collection, and before describing current and future investigations to address these questions, we provide a summary of their conclusions as well as open questions regarding the dynamical properties and various processes of the present-day atmosphere.

VERITAS (Smrekar et al. 2022a), DAVINCI (Garvin et al. 2022a), and EnVision (European Space Agency 2021) will greatly advance our understanding and lead to new questions about the evolution of Venus through time. Key advances will come from new types of data to better constrain the interior, such as improved crustal thickness and structure, mantle viscosity/temperature from seismology, lithospheric thickness from electromagnetic sounding, in-situ heat flow to constrain thermal lithospheric thickness and radiogenic heat budget and distribution. Over the next 15 years, these three missions will work together to answer many of the outstanding questions in Venus science and rocky planet evolution described above (Fig. 2; Table 1).

In addition, several Venus missions are under consideration on in development: Russia's Venera-D orbiter, descent module and lander mission (Zasova et al. 2020); an Indian radar-equipped orbiter, Shukrayaan-1 (Antonita 2022); a Chinese radar-equipped orbiter, VOICE (Dong et al. 2023); Rocket Lab's private, low-cost "Morning Star" concept mission to Venus (Seager et al. 2021). Their science observation strategy is under competitive study or development. Furthermore, various mission concepts, whether from landers, from aerial platforms or from orbit require further technology development beyond the current framework of selected missions to enable long-term surface science (seismic, compositional, heat flow investigations); missions that take advantage of mobility in the surface, near-surface, and atmospheric environments; and collection and return of atmospheric samples to Earth (Wilson et al. 2022; Limaye and Garvin 2023). Therefore, the current definition phase is an ideal time to collate knowledge of Venus long-term evolution scenarios and the observations needed to distinguish between them. These questions are left for future investigators to address through a wide range of research approaches, including Earth-based observations, laboratory and modeling studies based on existing data, and future new spacecraft missions.

Section 2 presents an overview of conclusions and open questions from the companion papers in the following order: (1) Comparison of Venus with exoplanets; (2) Venus initial conditions; (3) Venus surface processes, surface age and evidence for volcanic and tectonic activity; (4) Interior regime through history, water and other volatiles.

Sections 3-8 outline the science objectives of upcoming and future missions, in addition to their observational strategy, including expectations for addressing the conclusions summarized in Sect. 2. In June 2021, NASA selected two missions in its Discovery program: VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) (Smrekar et al. 2022a) and DAVINCI (Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging), a descent chemistry/imaging probe coupled with a carrier, relay and imaging spacecraft (Garvin et al. 2022a). EnVision has been selected as ESA's 5th Medium-class mission in the agency's Cosmic Vision plan, and is targeted for launch in the early 2030s. The mission is a partnership between ESA and NASA, with NASA providing the Synthetic Aperture Radar (European Space Agency 2021). In this Section, mission design proposals Venera-D (Zasova et al. 2020) and Shukrayaan-1 (Antonita 2022) are also described in some detail.

Sections 9-12 address future mission concepts and measurements that require further technology development beyond the current framework of selected missions, future mission concepts, the synergies between currently selected missions and future laboratory measurements in different experimental setups, and expected modeling activities to address the evolution of Venus' climate, surface, interior and habitability through time. Complementarity with non-Venus missions (e.g., exoplanet observatories) is also addressed. The review concludes with a Summary and Conclusions (Sect. 13), which discusses key questions about Venus' evolution can be answered convincingly with the current and next-generation mission concepts, and which fundamental questions will remain open for future investigations.

2 Open Science Questions and Required Investigations to Address Venus Evolution Through Time

This section presents an overview of conclusions and open questions from the companion articles, organized along the following science themes:

Comparison of Venus with Exoplanets, summarizes conclusions and open questions about how Venus' ancient evolution can inform exoplanet studies regarding the importance of primordial & basal magma oceans and their evolution toward habitability, and, conversely, how terrestrial exoplanet studies can inform Venus' evolutionary history. We summarize conclusions of Way et al. (2023, this collection) and Westall et al. (2023, this collection) regarding water inventory, early tectonics, and volatile cycling between the interior and atmosphere of Venus, and whether liquid water ever existed on the surface at temperatures conducive to the emergence of life. We explore the longevity of a habitable Venus, the divergent paths for planets in the Venus Zone (Kane et al. 2014), and the conditions of Venus evolution from a habitable to an inhospitable planet.

Initial Conditions, Accretion, and Early Venus, discusses modeling and observational constraints on early Venus based on different accretion scenarios. How did the accretion of Venus and Earth differ? Is Venus a more primordial or primitive body than Earth? Was there a late giant impact and to what extent it could have affected its initial thermal state and differentiation? What are the processes driving the thermal evolution of the latter and the concurrent early atmosphere formation, volatile trapping in the solidified mantle and water distribution? (Salvador et al. 2023, this collection). How does the elemental abundances and isotopic compositions of noble gases (He, Ne, Ar, Kr, Xe) and stable isotopes (H, C, N, O, S) constrain the budget of volatile elements outgassed in the atmosphere, the timing and mechanisms of volatile transport between planetary reservoirs, and the geodynamical history of Venus through time? (Avice et al. 2022, this collection).

Surface Processes, Age of the Surface and Evidence for Current Activity, addresses key open science questions about the resurfacing history and volcanic activity of Venus and their relationship to present-day volcanism and tectonism. Upcoming orbital missions will improve our understanding of the resurfacing history of Venus in crucial ways for a better understanding of the sequence of events that occurred in producing the geologic landscape: how are impact features and their associated deposits (ejecta, haloes, parabolas) altered over time, has the nature of volcanism and tectonics changed over time, and how does this compares with global resurfacing models and constrain the global evolution of Venus through time? (Herrick et al. 2023, this collection; Ghail et al. 2023, this collection). Sediments and sedimentary rocks are also critical to understanding surface modification processes and how Venus works today, but are also extremely important for determining how Venus's climate has changed through time and whether it was once a habitable planet (Carter et al. 2023, this collection). Furthermore, mineralogy of the Venus surface provides a critical record of geologic and climatologic history and the current chemical exchanges between the atmosphere and solid body (Gilmore et al. 2023, this collection).

Interior Regime Throughout History, Water and Other Volatiles, discusses open science questions regarding dynamics and evolution of Venus' mantle: how did mantle cooling history control the state of Venus' core and the tectonic regime; and constraints on the variability of heat flow through time by Rolf et al. (2022, this collection); what was the evolution of the atmosphere-interior of Venus, including its core (Gillmann et al. 2022, this collection)? What are the signatures and potential detectability of present-day volcanically emitted material in the atmosphere of Venus by incoming Venus missions, is there a non-gaseous component of volcanic plumes? Could these measurements shed light on the compositional history of magmatic volatiles and their reservoirs? (Wilson et al. 2023, this collection).

In addition to open questions along the previous science themes, this section also addresses investigations and open questions based on the recent analysis and exploitation of ESA's Venus Express and JAXA's Venus Climate Orbiter (Akatsuki) - in addition to recent ground-based observations, on how to better constrain the dynamical variability and couplings from surface to cloud tops in present day's atmosphere. Important variability on all time scales, in latitude, in local time of the main dynamical and photochemical tracers at all altitude levels, such as CO, SO or SO_2, variability of the cloud convective layer, atmospheric structure and turbulent processes, and large bow-shaped topography-driven stationary waves above the main equatorial highlands, all contribute to the study of the complex dynamical structure and properties of the Venusian atmosphere, and their relation to the long-term evolutionary path of Venus.

2.1 Comparison of Venus with Exoplanets

2.1.1 Synergies Between Venus and Exoplanetary Observations (Way et al. 2023, this collection)

a) ***The importance of magma oceans***: Exoplanetary observations of planets in the Venus Zone (VZ), defined by Kane et al. (2014) as part of the Habitable Zone (HZ) in which an Earth-sized planet is more likely to be a Venus analog than an Earth analog, can help us to constrain the magma ocean (MO) lifetime of Venus. Constraining the magma ocean lifetime prior to solidification is extremely important in understanding the likelihood of water ever condensing on the surface of a Venus-like world. The reason lies in 1-D calculations by Hamano et al. (2013), who demonstrated that Venus may sit at a boundary between a world that receives so much solar insolation that the magma ocean lifetime is long ($\sim$100 Myr), providing ample time for photodissociation and escape of the overlying steam atmosphere, and effectively drying out Venus (classified in Hamano et al. 2013 as a Type II world). On the other hand, Venus may lie on the other side of this boundary with a short-lived magma ocean with a steam atmosphere lifetime of $\sim$1 Myr (i.e., comparable to Earth's, see e.g., Salvador et al. 2017, 2023, this collection) that allows the planet to condense water on the surface (a Type I world). Work by Turbet et al. (2021) suggests that it is more likely that Venus ended up as a Type II world because their 3-D model generates clouds that appear to efficiently trap heat at the poles and night side. However, both the Hamano and Turbet models use CO_2-H_2O or N_2-H_2O atmospheres. It is not clear from recent work by Gaillard et al. (2022) and Bower et al. (2022) that these combinations of gases are adequate. For this reason, exoplanetary observations of young planets around G-stars in the Venus Zone will be critical, in addition to selected Venus missions, to discerning early Venus' history (see Sect. 11.2).
b) ***Are there divergent evolutionary paths for exoplanets in the Venus Zone?*** As indicated above, the magma ocean lifetime is critical to understanding the likelihood of water ever condensing on the surface of a world in the Venus Zone. At the same time, 3-D General Circulation Modeling (GCM) by Yang et al. (2014), Way et al. (2016) and Way and Del

Genio (2020) has demonstrated that slow rotation is key to keeping a planet temperate within the Venus Zone. Moving present-day Earth into the Venus Zone will rapidly move the planet into a moist and then runaway greenhouse state, as 1-D models have shown that Earth is already at the inner edge of the habitable zone (Kopparapu et al. 2013, Fig. 8). The 3-D GCM modeling studies have shown that if Earth were rotating as slowly as modern Venus does, an efficient, large-scale cloud-albedo feedback at the substellar point would generate high enough albedos for a significant portion of the incident solar radiation to be reflected back to space, keeping the surface of the planet temperate. Most observable habitable-zone exoplanets are terrestrial exoplanets orbiting M dwarfs, with rotation periods of order of 10-30 days; such planets close to their star are expected to become tidally despun into a synchronously rotating state; atmospheres of typical tidally locked terrestrial exoplanets are expected to superrotate (Imamura et al. 2020, and references therein). Examining planets in the Venus Zone of exoplanetary systems will determine whether these 3-D GCMs are correct, and whether Venus-like worlds ever have temperate surface conditions and the role that rotation rate may play. Even if water condenses early on the surface of a Venus-like world, its later evolution may diverge, depending upon its rotation rate.

c) ***What is the longevity of habitability of an Earth-sized planet in the Venus Zone?*** If Venus had a temperate period, its longevity may be difficult to constrain, but Earth-size worlds in their Venus Zone will help us to bound the problem. Conversely, new data from upcoming Venus missions should give us a constraint on the longevity of water on Venus and encourage the planetary and exoplanetary science communities to search for such worlds in exoplanet databases in the coming decades. Yet the latter is not unambiguous; for instance, key observations that the DAVINCI descent probe analytical instruments within and below the clouds (Sect. 5.3) and the EnVision VenSpec-H spectrometer (Sect. 6.3) are related to the D/H ratio and the heavy noble gas isotopes. Work by Avice et al. 2022 (this collection) demonstrates that the D/H ratio in itself is insufficient to determine when Venus lost its water and the time-scale of that loss, as implied in the published Pioneer Venus D/H measurements by Donahue et al. (1982). The heavy noble gas isotope measurements by DAVINCI will be crucial to understand the epoch and timescale of the loss on Venus (Garvin et al. 2022a; this review, Sect. 5.3). If Venus had a habitable period, what constraints can interior, tectonic, and atmospheric escape models provide to understand the likelihood of long-term volatile cycling? Here again, exoplanetary observations of planets in the Venus Zone will be a unique opportunity to test our models and their application to Venus' long-term evolution.

2.1.2 The Habitability of Venus (Westall et al. 2023, this collection)

a) ***What was Venus' water inventory and was there liquid water on its surface at temperatures conducive to the emergence of life?*** Did water condense after crystallization of the magma ocean? Given the lack of direct access to the ancient history of the planet, this question is best addressed by refining models and through eventual comparisons with exoplanets exhibiting characteristics such as rotation speed of the planet that may have similarities with early Venus. Important requirements for habitable conditions would be a slow rotation of early Venus and a corresponding weak Coriolis force to allow for a large and reflective cloud cover (e.g., Way and Del Genio 2020). Liquid water on the surface may allow silicate weathering and thereby maintain a low atmospheric pressure of CO_2, protecting a subaqueous habitable environment.

b) ***If there was once water on the early planet's surface, how long was the transition from habitable to uninhabitable planet?*** This question is closely related to the tectonic state of early Venus. With active plate tectonics, a carbonate-silicate cycle similar to that on Earth could have allowed for a substantial habitable period until the proposed resurfacing event accompanied by catastrophic mantle outgassing some several hundred million years ago (e.g., Way and Del Genio 2020; Krissansen-Totton et al. 2021). In contrast, without plate tectonics but with liquid surface water, recycling of carbonates into the mantle would have been rare, limiting the long-term habitability on Venus (Höning et al. 2021). Knowledge of Venus is currently insufficient to rule out any but the most extreme scenarios, but further observation should yield important evidence to constrain Venus' evolution. In particular, constraints on ancient plate tectonics, which could be derived from future seismic measurements as well as from a more detailed exploration of surface features such as the tesserae and their compositions, would shed light into the early habitable period of Venus.

c) ***How habitable is the Venusian cloud environment, and are there signs that it was ever inhabited?*** Conditions at today's 55-70 km altitude range are juxtaposed with the observed limits for terrestrial life. By these metrics, hypothetical life in Venusian aerosols may be within required bounds of temperature, pressure, and pH, and energy sources (Grinspoon and Bullock 2007; Nicholson et al. 2010; Limaye et al. 2021; Westall et al. 2023, this collection, Fig. 8); is the purported phosphine signature (Greaves et al. 2021; Encrenaz et al. 2020b; Villanueva et al. 2021) real and is it really a biosignature? The odds against there being life in the clouds of Venus today are high due to extreme conditions in terms of water activity (which takes extreme acidity and aridity into account), and the lack of permanent habitability (for Earth-like life in any case). Venusian life would have to be quite different from that on Earth to not just survive but thrive in its clouds. This does not mean that the hypothesis should be completely disregarded, but it remains just a hypothesis, awaiting further boundary conditions from missions including DAVINCI and EnVision. If Venusian cloud life exists, and if it is indeed very different from terrestrial life, then could it be identified as living and viable? If the answer to these speculations is yes, then this would answer our first question of Venus habitability. This question requires an in-depth characterization of the cloud-level environment: gas and cloud composition, available light levels, cloud droplet microphysics (droplet size, formation / precipitation cycles), UV & ionizing radiation levels. A detailed investigation of how these environmental factors vary with altitude, latitude and local time would require sustained measurements from an aerial platform such as a balloon or powered aircraft (Limaye and Garvin 2023).

2.2 Initial Conditions, Accretion, and Early Venus

2.2.1 The Accretion and Differentiation of Venus

Venus and Earth contain 41% and 51% of the remaining mass of the inner protoplanetary disk vs 3% and 5% for Mercury and Mars; based on this comparison, we might expect the smaller planets to be outliers and Venus and Earth to be similar and represent good averages of the composition of the inner solar system. Yet Earth and Venus appear fundamentally different. The dynamical causes and timing of this globally-important difference are a topic of active work and debate, with broad implications for planet accretion models, early solar system dynamical stability, volatile delivery to the terrestrial planet region, and the early impact rate throughout the solar system (e.g., Bottke et al. 2017).

a) ***When, from where, and how many volatiles were accreted by Venus?*** Venus and Earth are expected to have formed over several million years by accretion of planetesimals and planetary embryos originating from various heliocentric distances, with the majority coming from a narrow annulus near 1 AU (O'Brien et al. 2006). Did Venus accrete as an average body as the protoplanetary disk was rapidly cooling, or did proto-Venus components emerge from distinctive regions? The fundamentally different isotopic compositions of non-carbonaceous (NC) and carbonaceous (CC) meteorites reveal the presence of distinct reservoirs in the solar protoplanetary disk that were likely separated by Jupiter. However, the extent of material exchange between these reservoirs, and how this affected the composition of the inner disk, are not known or strongly underconstrained (e.g., Spitzer et al. 2020; Morbidelli 2020). A variety of different processes such as thermal processing in the primordial atmosphere and atmospheric escape must have had a dramatic impact on the bulk and isotopic compositions of planetary embryos accreting to form Venus, being possibly a major factor in volatile depletion (Lammer et al. 2020).
b) ***Was the accretion of Venus Earth-like with a late giant impact?*** The final stages of planetary accretion involve collisions between the forming planet and leftover bodies such as large planetesimals or planetary embryos. Earth suffered from a final major collision at the end of its accretion and the Moon is the witness of this event. For Venus, it remains unknown if the planet ever suffered from an impact energetic enough to create a moon (Brooks and Jacobson 2019; Jacobson and Dobson 2022). Medium or large impactors on early Venus affect the primordial atmosphere through impact erosion and might trigger further degassing through energy deposition in the mantle and crust. High temperatures generated in the upper mantle and the spreading of the thermal anomaly lead to partial melting and the formation of new basaltic crust. Yet, giant impacts are not the only potential interactions. Alternative scenarios involving smaller and successive multiple impacts have also been proposed to explain the Moon's formation (Rufu et al. 2017). Whether the energy deposition was then sufficient to melt the entire mantle depends primarily on impact parameters (e.g., Nakajima et al. 2021) and on their frequency. Finally, the accretion sequence of the Earth and Venus may significantly differ, with Venus possibly experiencing more hit-an-run collisions (Emsenhuber et al. 2021). To what extent these alternatives apply to Venus and how they affected its initial thermal state and differentiation remains unclear. Is Venus therefore a more primordial or primitive body than Earth, if there was no giant impact in its early history? How might these be related to a plausible water-rich past?

2.2.2 Magma Ocean, Water, and the Early Atmosphere of Venus (Salvador et al. 2023, this collection)

a) ***What proportion of initial mantle volatile inventory is outgassed and escaped?*** Water and its distribution between the different planetary reservoirs are of fundamental importance in controlling the processes and feedbacks at play, from the deep interior to the upper atmosphere, during the entire evolution of the planet (e.g., Crowley et al. 2011; Tikoo and Elkins-Tanton 2017). Furthermore, surface conditions and thus the potential habitability of the planet are direct outcomes of the evolutionary pathways followed (e.g., Hamano et al. 2013).

   The earliest stages of planetary evolution, and in particular the so-called magma ocean stage, are crucial in distributing water between the different reservoirs (e.g., Salvador et al. 2017; Nikolaou et al. 2019). During this phase, the surface is molten and the absence of a thick, long-lasting boundary between the molten mantle and the atmosphere allows for free and extremely efficient thermal and chemical exchanges between the interior and the atmosphere. Volatile species initially dissolved within the molten mantle are thought to concentrate readily into the melt during the crystallization of the magma ocean until melt saturation is reached. At that point, volatiles in excess of saturation likely exsolve out of the melt, form gas bubbles, and rise up to burst at the surface and be expelled out, forming the atmosphere. Magma ocean outgassing and therefore (secondary) atmospheric formation have been thought to be efficient because of the vigorous convection at play in the melt, believed to bring the entire melt volume close to the surface, where outgassing occurs rapidly enough.

In part because of the extreme P, T conditions of the magma ocean, which are far out of reach of current numerical models and experimental setups capabilities, many processes affecting the thermo-chemical evolution of the magma ocean, such as the crystallization scenario and the convection regime, remain highly unconstrained. In addition, the initial state of the magma ocean itself is highly uncertain. For instance, the mantle redox state or the initial volatile abundance and their evolution with time are still unsettled. Yet these processes are thought to significantly affect the type and timing of outgassed volatiles and thus their evolving distributions between the interior and the atmosphere. Further investigations considering the range of uncertainties and the interplays between these mechanisms are needed to draw a consistent picture of the early volatiles outgassing and escape processes and reconcile the early evolution with the current state of Venus. Any measurable constraint on the timing and amount of early outgassing, volatile loss, and on the amount and type of remaining volatiles in the present-day mantle could be used in evolution models and would help in choosing among the different scenarios, thereby improving our understanding of the processes at play.

b) ***What is the timing of silicate / metal differentiation?*** Several parameters of primary importance for the early evolution stages remain highly unconstrained, for instance including the initial water content, and the initial mantle state. These two aspects are tightly linked to the outcomes of the accretion sequence. While it seems reasonable to assume, given their vicinity, that the Earth and Venus experienced similar accretion histories with similar volatiles delivery, the absence of a moon and associated late Moon-forming giant impact challenges the assumptions regarding the timing and extent of large-scale melting episodes on early Venus. Indeed, a moon-forming impact on early Earth (e.g., Canup 2004) is thought to induce a global-scale mantle melting that is generally assumed to be the initial state of coupled magma ocean-atmosphere models. However, it is important to note that this event is not the only heat source that can support large-scale mantle melting. Other plausible scenarios than the single giant moon-forming impact hypothesis, i.e., smaller multiple-impact models, have been proposed and may better explain the compositional similarities of the Earth and Moon (Rufu et al. 2017). These scenarios would not ultimately discard the likelihood of deep and global magma oceans but constraining the timing and timescale of Venus formation/accretion would help clarify the initial state of planetary evolution. This could be achieved using the ^{182}Hf ^{182}W chronometer to constrain the timing of silicate/metal differentiation and thus core formation (e.g., Lee and Halliday 1995; Harper and Jacobsen 1996). This ultimately relates to the molten state of the mantle and thus to the timescale and intensity of the accretion phase (e.g., Zahnle et al. 2007). Knowing the amount of accretionary energy delivered within a constrained time frame would help test the global magma ocean hypothesis and provide clues for the initial state of the early evolution of Venus.

c) ***Could the mantellic water content be constrained through the geodynamic regime (and present-day volcanic outgassing)?*** Because of the influence of water on mantle melting and viscosity (and thus rheology) (e.g., Lange 1994; Hirschmann 2006; Ohtani 2020), information on current mantle convective regime and dynamics might provide indirect clues about its current and therefore past water content. The mantle present-day outgassing rate and composition might be another way to sample the planetary interior state and water content and inform models of early and long-term planetary evolution. Estimates of the Venusian mantle water content would indeed provide constraints for evolutionary models to match with and thus help deciphering which paths and associated mechanisms are most likely to match with these constraints.

d) ***Are there hints for the existence of liquid water in the past? Can they be inferred through Venus surface mineralogy, mantle present-day rheology, outgassing and composition?*** Hints for the existence of liquid water in the past would provide significant constraints for the early evolution scenarios. If liquid water ever existed at the surface of Venus, it would be strong evidence that enough water has to be retained, either in the planetary interior or in the atmosphere, for a substantial amount of time and that temperate climates were plausible in Venus' past. It would discard all scenarios where water is lost in Venus' early history due to desiccation via a slowly ($\sim$100 Myr) cooling magma ocean (Hamano et al. 2013 type II planets), and can thus never sustain habitable conditions (Turbet et al. 2021). Conversely, it would favor scenarios where the early evolution of the magma ocean allows for a rapid ($\sim$1 Myr) solidification (type I planets according to Hamano et al. 2013 classification). For instance, this could either be due to an inefficient magma ocean outgassing (e.g., Ikoma et al. 2018; Salvador and Samuel 2023) and reduced atmospheric greenhouse effect, or due to mechanisms reducing the incoming solar flux and allowing for temperate climates at Venus orbital distance, such as the presence of highly reflecting clouds. In the latter case, temperate surface conditions would directly be inherited from the early magma ocean stage evolution while in the former, habitability would be related to the subsequent long-term evolution of Venus (e.g., Way and Del Genio 2020; see also Gillmann et al. 2022, this collection).

2.2.3 Volatiles and Noble Gas Isotopes (Avice et al. 2022, this collection)

The elemental and isotopic compositions of volatile elements (H, C, N, O, S, P and noble gasses) contained in the Venus atmosphere hold clues to the origin and evolution of the entire planet and can provide decisive answers to three major fundamental questions:

a) ***Did Venus acquire its volatile elements from the protoplanetary solar nebula, asteroids, comets, or a mix of these sources?*** Classical views, supported by geochemical constraints and outcomes of models of the formation of terrestrial planets, propose that Earth, and by extension Venus, accreted relatively dry and acquired most volatile elements later by bombardment of volatile-rich material (asteroids/comets) during the final stages of planetary formation (Marty 2012; Halliday 2013). These late events could also have delivered chemical elements and/or compounds conducive to the emergence and development of life. The detection of solar-derived gasses in the interior of Earth (e.g., Williams and Mukhopadhyay 2018) and on Mars (Swindle 2002) also leaves room for an early contribution of gasses from the solar nebula, or from solar wind implanted at the surface of grains (Péron et al. 2018), to the budget of volatile elements on terrestrial planets. Recent investigations propose that the Earth's building blocks did contain significant water (Piani et al. 2020). Estimating the delivery mix of volatile elements to Venus would thus help to constrain the timing of the formation of Venus and the building blocks of the planet, also contributing to placing Venus in the context of the formation of the entire Solar System. For example, the isotopic composition of Venus' atmospheric xenon could carry the signature of a delivery of cometary material to the atmosphere of Venus (Avice et al. 2017; Marty et al. 2017). This cometary contribution is visible in the isotopic composition of Earth atmospheric xenon as a marked depletion in ^{134}Xe and ^{136}Xe isotopes relative to Solar or Meteoritic end-members (Avice et al. 2022, this collection, and references therein). In addition to Ar/Ne and ^{20}Ne/^{22}Ne, detecting (or not) cometary xenon on Venus would thus be a key constraint for models attempting to understand the late delivery of volatile-rich bodies originally formed in the outer Solar System to the terrestrial planets. A list of key measurements of noble gases and of their associated maximal uncertainties required to answer the scientific questions is summarized in Avice et al. 2022, this collection, Table 1. DAVINCI's Descent probe quadrupole mass spectrometer instrument VMS is described in Sect. 5, Sect. 5.3.1 (see also Garvin et al. 2022a, Table 3.2).

b) ***How was Venus' atmosphere shaped by early impacts and atmospheric escape?*** On Earth, the Moon-forming impact likely removed the primitive, possibly solar-derived, atmosphere and set the stage for the emergence of a secondary atmosphere. Loss of water has been a key driving mechanism for the evolution of Venus (Baines et al. 2013), but the extent of water loss and the history of atmospheric escape, including of other atmospheric species, remain largely unconstrained. Measurements of the isotopic composition of nitrogen and precise determinations of the elemental and isotopic compositions of noble gasses in the atmosphere of Venus would provide constraints on the presence or absence of remnants of primordial solar gasses, on the regime of atmospheric escape (thermal vs. non-thermal) but also on its timing in the planet's history. For example, elevated ^{38}Ar/^{36}Ar and ^{15}N/^{14}N ratios measured in Mars' atmosphere demonstrate that non-thermal escape processes have been active on Mars (Atreya et al. 2013). Knowing the abundance and isotopic composition of xenon in the atmosphere of Venus would also clarify if Venus suffered from joint hydrogen-xenon escape processes (Zahnle et al. 2019; Avice and Marty 2020) like Earth and Mars. Determining the ^{129}Xe/^{132}Xe ratio, which might have recorded contributions of radiogenic ^{129}Xe from the decay of now extinct ^{129}I ($T_{1/2} = 16$ Ma), would also help evaluate the relative timing of atmospheric escape and outgassing processes (see next paragraph). NASA's DAVINCI mission will address these issues directly via *in situ* sampling and measurements of Xe isotopes.

c) ***What is the outgassing history of Venus?*** Although Venus is currently in a quiet stagnant-lid regime, the planet is not "dead" and there is evidence for recent activity including recent hotspot volcanism (Smrekar et al. 2010a). Several models propose that Venus might have been in a much more active regime in the past and even that plate tectonics was active on ancient Venus. Radioactive decay of extinct (^{129}I, ^{244}Pu) and extant (^{238}U, ^{40}K) nuclides present in silicate portions of Venus have been producing excesses of radiogenic and fissiogenic isotopes of noble gasses (e.g., ^{40}Ar, $^{129,131\text{-}136}$Xe) relative to primordial compositions. Given the wide range of half-lives of the parent nuclides (ranging from Ma to Ga), the relative proportions of these excesses measured in a reservoir should vary with time. Magmatic-driven outgassing contributes to the progressive degassing of these radiogenic isotopes from Venus' interior to its atmosphere. Measuring the elemental and isotopic composition of noble gasses in the atmosphere of Venus would thus help to refine current estimates on the relative proportions of radiogenic noble gasses degassed in the atmosphere versus those still retained in the planet's interior (Kaula 1999). Such measurements will also allow a coherent picture to be built of the geodynamical history of Venus through time.

Two broad types of science investigations are envisaged for gathering data on the elemental and isotopic compositions of noble gasses and stable isotopes (H, C, N, O, S) in the atmosphere of Venus. One would be an in-situ mission carrying a scientific payload to sample and measure the abundances and isotope ratios of the chemical elements of interest below the homopause such as DAVINCI (Garvin et al. 2022a, see Sect. 5). Another would be a sample mission during which a portion of the Venus atmosphere would be sampled below the homopause, which corresponds to a pressure level of 10^6 mbar (approximatively 135 km, see Mahieux et al. 2015), such as JPL Cupid's Arrow concept (Sotin et al. 2018a,b; Rabinovitch et al. 2019), with collected sample(s) possibly returned to Earth for characterization with state-of-the-art technologies available in international laboratories (Shibata et al. 2017; see also Sect. 10, Sect. 10.3.2).

2.3 Surface Processes, Age of the Surface and Evidence for Current Activity

2.3.1 Resurfacing History and Volcanic Activity of Venus (Herrick et al. 2023, this collection)

Upcoming orbital missions will improve our understanding of the resurfacing history of Venus in crucial ways. We will have a better understanding of the sequence of events that occurred in producing the geologic landscape. Placement of craters within that sequence will provide a timeline for that sequence, and constraints on the current level of volcanic and tectonic activity will provide a present-day "boundary condition" on that history. Advances in understanding will be achieved by upcoming missions for three critical science questions, including the following:

a) ***How are impact features and their associated deposits (ejecta, haloes, parabolas) altered over time?*** Key to establishing the absolute timing of geologic events is evaluating whether impact craters largely postdate the volcanic and tectonic activity observed on the Venus surface, or whether they are a population of features that are in various stages of being obliterated. It is expected that improved resolution in imaging and topography, along with SAR polarimetry and imaging at multiple wavelengths (e.g., by the VERITAS and EnVision radar orbiter missions), will enable the processes altering the appearances of impact craters over time on the Venusian surface to be distinguished. If aeolian or chemical weathering processes are the dominant mechanisms for removing the emissivity and backscatter signatures associated with distal impact deposits such as dark haloes and parabolas, and sediment fill is responsible for creating low-backscatter floor deposits, then most of the craters can be viewed as being at the top of the stratigraphic column. In such a case, the surface would have formed from a relatively rapid sequence of events several hundred million years ago. If large portions of the craters have deposits that have been altered by one or tectonic or volcanic events, then the timeline of geologic activity spreads, and much of the surface, are probably younger than 100 My.
b) ***Has the nature of volcanism and tectonics changed over time?*** Improvements in imaging and topography from the upcoming missions will enable seeing key geologic contacts, individual volcanic flows, fault blocks, and other details of surface geology. Considerable advancements in our knowledge of compositional information will come from both infrared and SAR imaging. This information will allow us to build an understanding of the sequence of events on the surface and evaluate whether or not fundamental changes in the nature of geologic activity have occurred over the past several hundred million years.
c) ***What is the current level of volcanic and tectonic activity?*** Magellan images compared against changes observed during the upcoming orbital missions (VERITAS and EnVision), will constrain where and how much current geologic activity is occurring on the

surface. Most of this work will simply involve change detection among images taken at different times to search for new flows, landslides, new fractures or faults, etc.. Repeat pass SAR interferometry will also provide information regarding cm-scale movement in tectonic zones, caldera inflation and deflation, and other active small-scale deformation. The near-infrared descent imaging by the DAVINCI probe will search for signs of mass wasting in 3D using very high resolution imaging and topography acquired under the clouds for a region within Alpha Regio to complement the orbital SAR observations.

2.3.2 Volcanic and Tectonic Constraints on the Evolution of Venus (Ghail et al. 2023, this collection)

a) ***What stresses and thermal, mechanical and geochemical parameters are responsible for the formation of Venus' extremely diverse volcanic features?*** Venus hosts an enormous diversity of volcanic features: direct analogs and those whose formation mechanisms are extremely challenging to understand, such as narrow lava channels that extend many 1000s of km. Large volcanic rises termed hotspots are directly linked to mantle plumes, probably arising at the core-mantle boundary. But where do smaller plumes that are likely to form at least some coronae originate? Why are coronae arguably unique to Venus? What processes are responsible for Venus' many enigmatic volcanic features? Are differences in features due to spatial or temporal differences in crust/lithosphere/mantle conditions? These questions will be addressed by NASA-JPL's VERITAS orbiter mission (Smrekar et al. 2022a), NASA-GSFC's DAVINCI mission (Garvin et al. 2022a) and by the ESA-led EnVision M5 orbiter mission (European Space Agency 2021), but better understanding of crust/mantle/core composition and rheology will be needed to take the next steps in understanding.
b) ***What are the driving forces and mechanisms for stress accommodation that produce the variable scales and apparent strains seen in Venus complex tectonic terrains?*** Extensional and compressional features on all spatial scales dominate deformation, with limited evidence for strike-slip faulting. In some environments, the origin of stress is clearly linked to mantle plumes or volcanic processes. In most feature types, there are multiple possible origin hypotheses. For example, what causes the ∼major 5000-10,000 km rifts? There is no apparent compressional zone of accommodation for the displaced, extended lithosphere. Local scale (<150 square km) studies using fine-scale topography from the DAVINCI probe's sub-cloud imaging will provide boundary conditions for strain within Alpha Regio at scales < 30 m.
c) ***What is the mechanism of tesserae formation?*** Tesserae are characterized by highly elevated topography, small-scale surface roughness and multiple sets of cross-cutting tectonic structures and appear to represent areas of intense, past tectonism. Tessera terrain covers about ∼8% of the surface of Venus and is morphologically clearly distinct from the volcanic plains that dominate the remainder of the planet. Detailed study of the type, number, spacing, distribution, and stratigraphic position of tessera structures will yield insight into the geodynamics of Venus before the production of the plains. Are tessera structures compressional or extensional in nature? Does their formation require a different strain rate, heat flow, or composition than in the plains? Is there evidence of lateral accretion of materials to form tessera plateaus? Do the tesserae underlie the plains across Venus? Are the tesserae dynamically compensated? The formational models to explain such high, complex and strained terrain are still the subject of much debate and uncertainty: horizontal convergence, extension, mantle upwelling, sub-crustal flow, crustal underplating, sub-crustal rejuvenation, crustal plateau formation, diapiric

intrusion, gravitational sliding and relaxation, or all of these? (Hansen and Willis 1996; Ivanov and Head 2011).

d) ***Absent Earth-like plate tectonics, what is Venus' overall geodynamic system that links mantle convection, surface deformation and volcanism, and volatile history?*** Venus' interior heat engine provides ample energy to the geologic activity that creates Venus' young surface and massive atmosphere. But fundamental questions remain. Why does Venus lack a dynamo? How does Venus lose its heat? Have processes changed with time? What is the extent of lithospheric recycling? Is Venus, with its hot lithosphere, a good analog for Earth's Archean? Are current tectonic processes the precursors of plate tectonics and continent formation? Can up- and downwelling plumes produce all surface features? Numerous hypotheses have been put forward, but additional data are needed to discriminate between them.

2.3.3 Mineralogy of the Venus Surface (Gilmore et al. 2023, this collection)

The Venera, VeGa, and Magellan missions found that Venus is dominated by basaltic rocks associated with widespread volcanism (Basilevsky and Head 2003a). Near-infrared observations from Venus Express and Galileo first detected variations attributed to mineralogy. They suggest that there is diversity in the FeO content of materials, including relatively high FeO content consistent with less weathered rocks, and low FeO content consistent with differentiated, non-basaltic compositions.

The stratigraphically oldest material on Venus are found among the major tessera terrains. They record an extinct geodynamic regime and have a near-IR emissivity signature that is different from the basaltic plains. The nature of the tesserae is critical to our understanding of Venus prior to the emplacement of the plains. Several major questions about Venus history are recorded in tessera terrain. Near-IR observations from VERITAS, EnVision, and DAVINCI (including below the cloud deck at spatial scales < 100 m) will provide the first global assessment of surface composition, which is critical to addressing the following questions:

a) ***What is the composition and diversity of Venus surface materials?*** What are the primary rocks and minerals recorded on the surface of Venus? How do these compositions spatially correspond to morphological units? How do these units vary with time and location? What do these differences tell us about the ancient and modern geologic history of Venus?
b) ***What is the style of weathering recorded in surface rocks over the history of Venus?*** Thermodynamic models of Venus weathering make predictions about the products of surface-atmosphere weathering under current Venus conditions, but there is a lack of consensus over exactly which phases might form from bulk versus diffusion-constrained reactions between surface and atmosphere and the timing of their formation. Weathering reactions depend upon the composition and crystallinity of the surface rocks, which are unknown. Do we detect these predicted phases? Can the presence or absence of these phases be used to constrain the age of surface units? Do we see weathering products that are consistent with weathering under an extinct atmosphere? Can we constrain the composition of the high radar reflectivity materials found across Venus?
c) ***Is there compositional evidence for aqueous or hydrous minerals?*** Is the near-IR signature of the tesserae consistent with Fe-poor magmas, clay minerals, or primary sedimentary phases? Is there evidence for Fe-poor phases in other regions of Venus?
d) ***Are the tesserae felsic?*** The near-IR emissivity of the tesserae may be consistent with Fe-poor materials, which, if igneous, could be consistent with the production of felsic lavas

(Hashimoto et al. 2008; Mueller et al. 2008; Gilmore et al. 2015) or of granitic rocks. If confirmed, these would require a planet with abundant water and a plate-recycling mechanism. Such a discovery would be critical evidence of a once-habitable Venus and elevate the targeting of tessera for future *in situ* study.

e) ***Are the tesserae compositionally, morphologically, and stratigraphically heterogeneous?*** Is there compositional variation across and within the tesserae? What is the detailed stratigraphic relationship between the tesserae and the plains? Is there evidence of unrecognized craters in the tesserae? Is there evidence of sedimentary materials in the tesserae?

Each of these questions requires laboratory work to examine the near-IR signatures of rocks and minerals and their weathering products expected under Venus conditions (see also Sect. 12.1.2 below).

2.3.4 Sediments, Regolith / Sediment Supply, Evolution (Carter et al. 2023, this collection)

a) ***What are the nature, distribution, and range of sedimentary surface modification processes?*** How has the surface of Venus been modified since it was formed? In particular, what are the processes that have modified and partially filled impact craters? What are the causes of the lower emissivity material in some highlands, and what do they imply about weathering processes and possible volatile transport? On Venus, sediments are likely produced by impact cratering and weathering (Garvin 1990). Even if these are not volumetrically large, sediments are likely widespread, covering a large fraction of the surface. Thus aeolian erosion and deposition may be important processes at the Venus surface. Local-scale evidence from Venera lander panoramas indicates possible sedimentary processes that would need connection to regional and global scale models to place them in a proper context (Garvin et al. 1984).

b) ***Is there evidence of active physical and chemical landscape change?*** Landscape evolution refers to processes that modify the morphology of a planet's surface, such as gravity-driven mass-wasting landslides and slumps. Mass-wasting is a ubiquitous geomorphological process operating on any planetary body large enough to have gravity; such features are observed on Earth, the Moon, Mercury, Venus, Mars, icy satellites, comets, and asteroids. Magellan's low-resolution radar imagery provided the first evidence of mass movement on Venus in the form of large-scale slope failures: rock slumps, rock and/or block slides, rock avalanches, debris avalanches, and possibly debris flows are seen in areas of high relief and steep slope gradients (Malin 1992).

c) ***Understanding the range and scope of mass-wasting processes.*** Although impact cratering is likely the main process behind sediment production on Venus, the planet's hot, dense and highly oxidizing atmospheric conditions may cause chemical weathering of surface materials. In the absence of near-surface water which, on Earth, affects material bulk density, shear strength and pore-pressure, and thus lead to slope instability, the mechanisms of slope instability and failure on Venus are unclear, and it is likely that landslides require triggering by external forces, such as earthquakes. Magellan imagery (Malin 1992) revealed a very strong spatial relationship between the locations of large-scale mass-wasting features and steep slopes related to rift zones and volcanic edifices, which may in turn point to them being geodynamically active in the recent geological past. Wind-streaks and debris-fans (downwind of impact craters) are relatively large-scale features on Venus (kilometer to tens of kilometers in length) and are also commonly observed in Magellan images (Greeley et al. 1992, 1995; Kreslavsky and Bondarenko 2017; Neakrase et al. 2017).

2.4 Interior Regime Throughout History, Water and Other Volatiles

2.4.1 Dynamics and Evolution of Venus' Mantle Through Time (Rolf et al. 2022, this collection)

a) ***How did mantle cooling control the state of Venus' core?*** The state and size of Venus' core are largely controlled by the cooling efficiency of the mantle and thus provide constraints for the evolution of Venus' mantle convection and surface tectonics. Available observations (MoI, k_2) do not pin down these important characteristics of the core well enough (see Gillmann et al. 2022, this collection), though they will be addressed by the upcoming VERITAS and EnVision missions. A smaller Venus core implies a thicker mantle that experiences high pressures at the core-mantle boundary, possibly high enough for the occurrence of post-perovskite that is known to influence lowermost mantle and core dynamics on Earth. Current estimates of Venus' core size (Margot et al. 2021) seem inconsistent with the occurrence of this high-pressure phase, but further refinement is necessary. Next to core radius, the state of the core remains a fundamental unknown. A completely solidified core would imply efficient cooling through time and a cold state of the mantle. Compared to present-day, such a scenario would point to more efficient cooling during parts of Venus' evolution, possibly expressed as mobile lid tectonics with more large-scale horizontal surface motion than inferred for the present day. The opposing end member of a fully liquid core would in contrast point to smaller core cooling rates and reduced heat loss across the core-mantle boundary. In such a case, remnants of a basal magma ocean may be preserved inside Venus' mantle today, with implications for the planets' magnetic field history (O'Rourke 2020). The explained end members may be extreme scenarios, but they emphasize the importance of further pinning down the properties and state of Venus' core and deep mantle.
b) ***How much heat does Venus lose today?*** Heat loss from the mantle to the atmosphere and its efficiency through time are crucial for understanding Venus' interior evolution. Venus loses its interior heat via thermal conduction through the lithosphere and via volcanism, but how these fluxes vary through time and across Venus' surface and how they are linked to the various geological and tectonic features on Venus' surface remains to be established. Conductive heat flux has not been measured in-situ, but is indirectly determined from flexural modeling of elastic thickness. Strong lateral variations are indicated, yet insufficiently mapped out. Improving this knowledge gap could provide key information on local differences in lithospheric and crustal thickness as well as in the temperature of the uppermost mantle. The latter is important for the rheology of the uppermost mantle and lower crust, both of which are key aspects for interior-surface coupling on Venus (see Ghail et al. 2023, this collection).
c) ***Has Venus' surface preserved anomalously old regions; are these felsic tessera?*** The crucial question of Venus' mean surface age and its lateral uniformity links back to the debate of whether Venus' crust is renewed via catastrophic events or by more equilibrium processes. These different options have contrasting implications for the regime of mantle convection inside Venus. Venus' sparse crater distribution provides some constraints (Herrick et al. 2023, this collection), but the degree of age uniformity across the surface has been questioned. Refined surface age characteristics would further pin down the rates and scales with which tectonism and volcanism renew the surface. An important issue is how to link this to underlying mantle patterns, such as up- or downwellings? Tesserae may form some of the oldest regions on Venus, but whether they are substantially older-than-average as proposed by some and perhaps even predate a

phase of near-global resurfacing is challenging to answer without knowing their formation mechanism. This relates to their composition, which if felsic as indicated for some tessera (see Gilmore et al. 2023, this collection) would demand a relatively wet environment during formation and thus a tectonomagmatic regime that can maintain enough water in the shallowest interior.

2.4.2 Atmosphere-Interior Evolution of Venus and Evolution of the Core (Gillmann et al. 2022, this collection)

a) ***Was there ever liquid water on the surface of Venus?*** The presence or absence of water in any form, but especially liquid water on the surface of Venus, is a major unknown in the scenarios for the planet's evolution. Currently, investigated evolutionary pathways range from a Venus that desiccated early and never harbored any substantial water inventory after the magma ocean phase to possibly habitable scenarios until recently, with a full spectrum of intermediate cases. Water in the atmosphere or on the surface could potentially make a huge difference for the evolution of climate, volatile exchanges, and general planetary evolution. It affects weathering, surface reactions, outgassing conditions, atmosphere structure, escape mechanisms, and possibly volatile recycling and interior dynamics. Vague clues to the accretion of Venus and its very early history (about 4 Ga and older) come from comparisons with Earth, modeling, impact hypothesis (Gillmann and Tackley 2014; Gillmann et al. 2016) and noble gas measurements. We also have Venus' present/recent state, because the majority of its surface formed from ∼0.3-1 Ga ago. However, no data points lie in between to identify a most likely scenario, define an intermediate state in the planetary evolution (ideally, with time constraints), or help find criteria to refine scenarios. Knowing if liquid water was present on Venus at any point in its history would be an important starting point, followed by estimating the amount of water necessary to explain those observations. Having an idea of the time period for that wet past then defines a basic succession of eras. Definite proof of a liquid water surface could finally constrain a tighter set of evolution scenarios. Lack of proof could mean that Venus was dry or that evidence was just lost. If ancient material is still present at the surface of Venus, it could offer a window into the planet's past. Likewise, the presence and abundance of granite-like rocks (see Gilmore et al. 2023, this collection) could yield information on the conditions during their formation and on the availability of liquid water. VERITAS will distinguish unequivocally the difference between granite and basalt based on their distinctive emissivity signatures near 1 micrometer, resolving this controversy at last. Additionally, new km-scale topography of Alpha Regio developed from analysis of Arecibo polarimetric imaging and radargram-based reanalysis of Magellan altimetry showcases possibilities of stream networks in this region when compared to Earth (Garvin et al. 2022b).
b) ***When was the thick CO_2 atmosphere formed?*** Another way to look at the situation is to understand when the current state of Venus' atmosphere came to be. The distinctive 90 bar CO_2 atmosphere is in itself an interesting limitation for many processes, from outgassing to climate modeling. Based on the lack of small craters on the surface of Venus, the atmospheric pressure has likely been high at least since the formation of the current surface. Little is known for sure beyond that. Radiogenic argon suggests that Venus is less outgassed than Earth, but re-constructing the entire outgassing history relies on under-constrained models. The timing and means of the CO_2 atmosphere formation can inform evolution models. Is it a recent feature (formed just before the change to present-day conditions, 500-1000 Myr ago), a relic from the magma ocean freezing, or the result

of a long term build-up? If it is a recent feature, there would be strong implications for the planet's past climate, under a thin atmosphere. A catastrophic transition could point either to the destabilization of carbonate deposits or mantle-related massive volcanic outgassing. The mineralogy of the surface can help us understand if the CO_2 in the current atmosphere of Venus is buffered by solid-gas reactions.

c) ***What is the dominant volatile exchange process on the surface (buffering reactions, outgassing, oxidation…)?*** A key to understanding the past is to understand how volatile species are exchanged between the interior and the atmosphere of the planet, and how they can be trapped or recycled. Recent work has shown that quantifying the volatile exchanges could provide invaluable insights into the evolution of the planet, and help understand how various processes and feedback mechanisms have shaped Venus. However, such investigations rely on the ability to constrain volatile flux reasonably well and identify all the processes involved. Because the planet is a complex system that changes with time, the relative importance and even the existence of those processes will also vary, depending on specific conditions such as climate affecting surface reactions for example, or liquid water affecting recycling, thus mantle conditions and finally outgassing. This makes the modeling of fully consistent evolution scenarios a daunting task, with widely different mechanisms operating under different states of the planet on a variety of time scales and domains (from the core to the upper atmosphere). We still do not know if a single exchange process dominates the others at the surface of Venus or if its atmosphere is close to a steady state. Is it slowly evolving due to volcanic outgassing or are surface-gas reactions buffering the atmosphere to a stable level? It has been suspected that water cannot be outgassed beyond marginal concentrations due to the surface pressure (Gaillard and Scaillet 2014): do the observations support this idea? What does it mean for surface lava flow composition? The volatile species may be trapped in the flow during the ascent of the magma and its extrusion. Does this imply high gas fractions and generate explosive volcanism for which there is only very limited evidence on recent Venus? How would it have changed with time? Does it mean that volcanic activity actually is a trap for water due to oxidation processes, rather than being a source?

d) ***Where is the oxygen?*** This question is perhaps the corollary to all the previous ones. If Venus had water at any time (and it did, at least initially), where did its constituents (two hydrogen and one oxygen atoms) go? Oxygen is especially critical because hydrogen could be lost to space and removed from the atmosphere efficiently, while oxygen mostly remains. Atmospheric escape of oxygen species has been recently suggested to be extremely low, which indicates that either some other process has been involved or that there was very little oxygen in the atmosphere in the first place. Can that be verified with recent instruments that have proved themselves on Mars, with the MAVEN mission? Does it mean the O is in the solid planet instead? If so, is it in the mantle (either not outgassed or recycled), or in the crust? Both confirmation of atmosphere measurements and surface investigation will be needed. NASA's DAVINCI mission will address the oxygen within the clouds and deep atmosphere directly via its VfOx student collaboration experiment (see Sect. 5, Sect. 5.3.5), and the detailed measurements of oxygen-bearing trace gas species by its Venus Mass Spectrometer and Venus Tunable Laser Spectrometer (Garvin et al. 2022a).

2.4.3 Magmatic Volatiles and Effects on the Modern Atmosphere (Wilson et al. 2023, this collection)

a) ***What is the rate and style of volcanic outgassing in the present era?*** Were the radically different evolutionary paths of Earth and Venus driven solely by distance from the Sun, or did internal dynamics, geological activity, volcanic outgassing, and weathering also played an important part? What types of volcanism may be expected on Venus in light of its unique interior-surface coupling history described in companion articles (Avice et al. 2022; Gillmann et al. 2022; Ghail et al. 2023; Gilmore et al. 2023; Herrick et al. 2023, this collection)? To understand the long-term climate evolution of Venus, we need to establish (1) whether there is any morphological and compositional evidence of an epoch with abundant liquid water on the surface; (2) whether Venus is geologically active now, and whether this is a continuous or episodic style, to constrain interior-atmosphere exchange throughout history; (3) if there is atmospheric evidence of present day volatile sources and sinks at the atmosphere of Venus, including potential active volcanic sources; (4) whether and how sulfur- and water-related volatiles are transported through the atmosphere and how they interact with cloud layers (Bullock and Grinspoon 2001; Wilson et al. 2008; Titov et al. 2018).

b) ***How are tropospheric and geological processes coupled on Venus?*** Do exchanges take place from direct outgassing of volatiles into the lowermost atmosphere, buffering of atmospheric species with surface reservoirs, or aeolian/chemical alteration of surface minerals? The high surface pressure of Venus is maintained through surface-atmosphere chemical buffering reactions that are, as yet, unidentified. Buffer systems proposed have included calcite-anhydrite (Fegley and Treimann 1992; Fegley et al. 1992, 1997) and pyrite-magnetite (Hashimoto et al. 1997; Hashimoto and Abe 2005) systems, but there is little evidence constraining these claims because several of the relevant minerals including pyrite are unstable in Venus surface conditions (Hashimoto and Abe 2005). Latitudinal variability of minor species in the troposphere is thought to arise either from non-uniform vertical profiles, or from planetary-scale meridional transport through global convection cells, not restricted to cloud layers where most of solar energy is deposited, but extending deeply into the troposphere where latitudinal contrasts are observed. Because latitudinal gradients have already been observed in CO and OCS, these species act as tracers for the meridional circulation and provide glimpses into some of the chemical cycles of the troposphere. The water vapor vertical gradient in the deep atmosphere is not known and may be a steep gradient due to surface-atmosphere reactions (Ignatiev et al. 1997). Studying how trace gas abundances change over terrain of different compositions and/or elevations may yield insights into the surface-atmosphere exchanges and coupling (Zolotov 2018; Zolotov and Garvin 2020; Garvin et al. 2022a).

c) ***Does present day atmospheric chemistry involve volcanic trace gasses?*** Sulfur dioxide variations in the present day mesosphere have been used as possible evidence of volcanic activity (Esposito 1984). The proximate cause for these variations is related to spatial and temporal fluctuations of the SO_2 supply through vertical mixing within the cloud region. However, the origin of these vertical mixing fluctuations is barely understood. Purely atmospheric phenomena such as momentum deposition from upward propagating atmospheric gravity waves induced by topography (Kouyama et al. 2019; Kitahara et al. 2019) or diurnal variations of cloud top convection through solar absorption certainly play a role. Thermal destabilization of the atmospheric column through hot volcanic outgassing has also been suggested (Esposito 1984). SO_2 exhibits the most dramatic variations at Venus' cloud top, both spatially and temporally (Esposito 1984; Esposito et al. 1988; Marcq et al. 2013; Vandaele et al. 2017a,b, Encrenaz et al. 2016, 2019, 2020a), spanning more than two orders of magnitude on timescales ranging from a few days up to several decades. The greater range of SO_2 variations compared to H_2O is currently explained by the fast photochemical destruction of SO_2 by UV sunlight at cloud top level, making this species a much more sensitive tracer of the atmospheric circulation and vertical mixing between its lower atmospheric source and its cloud top photochemical sink. The variations of the vertical mixing are poorly understood. Conditions at which a buoyant plume could reach an altitude of 40-50 km are very narrow and require volatile-rich eruptions at higher elevation, their signature depending on the flux of volcanic gases, mixing rate with the air through eddy diffusion and turbulence (Lefèvre et al. 2018, 2020; Morellina and Bellan 2022), and wind velocities at different altitudes (Lorenz 2016; Bengtsson et al. 2012). Deep atmosphere gradients (i.e., every 140-200 m) associated with trace gas species involving SO_2 and other sulfur-bearing species will be obtained by the DAVINCI mission together with altitude resolved measurements of pressure, temperature (p, T) to address this issues regionally (Garvin et al. 2022a).

2.5 Global and Mesoscale Atmospheric Processes: Short Term and Long-Term Variability

a) ***How to better constrain dynamical variability and couplings from surface to cloud tops?*** The present-day surface of Venus is permanently obscured by a layer of optically thick clouds between 45 and 70 km altitude. The atmosphere at cloud level is in retrograde superrotation with a period of 4-7 Earth days in the zonal direction, i.e., parallel to the equator, relative to the solid surfacesurface, a motion driven by its thermal structure (Grassi et al. 2010, 2014). The sidereal day of Venus, by comparison, is 243.02 Earth days, also retrograde. The clouds have been studied *in situ* and are mostly composed of sulfuric acid droplets described as populations with lognormal size distributions with mode diameters of 0.15, 1.0, 1.3, 3.4 mm, called mode 1, 2, 2', and 3 (Knollenberg and Hunten 1980; Ragent et al. 1985). Several structures visible in UV and IR wavelengths at different altitudes indicate a dynamically active atmosphere as well as a significant geodynamic coupling with the surface: huge bow-shaped structures extending from northern to southern latitudes have been detected by the Longwave Infrared Camera (LIR) and the Ultraviolet Imager (UVI) on board JAXA's Akatsuki (Fukuhara et al. 2017, and references therein). The extension of wave trains in both upstream and downstream directions was also observed (Fukuya et al. 2022). Vertical wind oscillations attributed to topographic gravity waves have also been observed by the VeGa balloons over Aphrodite Terra, which has a top height of 3-4 km (Blamont et al. 1986).

   One of the remaining questions about the dynamics of the Venusian atmosphere is how the convective cloud layer and topographically generated waves mix momentum, heat, and chemical species (Lefèvre et al. 2022). Radio occultation can be used to monitor the main cloud constituent, H_2SO_4, in both vapor and liquid form, near the cloud base, providing clues to cloud formation and convection processes. Using direct imaging or high frequency (HF) radar, electromagnetic signatures of lightning could be considered (Lorenz 2018), an investigation that would also contribute to the understanding of chemical and microphysical processes at work in the cloud layer. It should also be noted that the complex dynamics of the Venusian atmosphere produce a periodic mass redistribution pattern that generates a time-varying modulation of the Venusian gravitational field (Cascioli et al. 2023).

b) ***How variable is the upper atmosphere?*** The Venusian mesosphere (65-120 km) is a transition region between the lower atmosphere (from the surface to the cloud layer near 60 km), where the circulation is mainly zonal, and the upper thermosphere (above 120 km), where the wind pattern is mainly driven by diurnal pressure contrasts and flows from the sub-solar to the anti-solar point (the so-called SSAS flow). The zonal component decreases with altitude above the clouds, probably due to the deceleration caused by momentum transport by atmospheric waves (Sánchez-Lavega et al. 2017). Global structure of thermal tides in the upper cloud layer has been studied by the LIR camera on board Akatsuki (Kouyama et al. 2019). Monitoring of thermal profiles and winds in the mesosphere has shown that this transition region, where the two types of circulation coexist, is also characterized by important temporal variability. Large-scale images from Venus orbiters (e.g., VMC/VEx, UVI/Akatsuki) lacked spectroscopic capabilities, while orbiter-borne spectrographs (e.g., VIRTIS-H/VEx, SPICAV-UV/VEx) lacked extensive spatial coverage. Because mesospheric composition varies on time scales ranging from hours to years, measurements over a wide range of latitudes, local times, longitudes, and time scales are needed, including atmospheric airglow at 1.27 μm (Hueso et al. 2008; Soret et al. 2014), measurements of the spatial and temporal variability of albedo and UV absorber (Lee et al. 2019), ionospheric electron density, and temperature, pressure, and density of the neutral atmosphere by radio-occultation (Peter et al. 2023). HF sounding radar can be used to constrain the ionosphere, as routinely performed by MEx/MARSIS (Picardi et al. 2005). The DAVINCI mission will carry a technology demonstration instrument (CUVIS) that will acquire UV (200-400 nm) spectra at 0.2 nm spectral resolution on two Venus dayside flybys in 2030 with up to one million new spectra of the upper clouds, as well as a near UV frame imaging camera (VISOR UV) that will acquire "movies" during these periods to quantify cloud feature motions (Garvin et al. 2022a).

Venus is particularly important to our understanding of terrestrial planets' habitability, providing a natural laboratory to understand its evolution in time. Many significant questions remain on the current state of Venus, suggesting major gaps in our understanding of how Venus's evolutionary pathway diverged from Earth's (Fig. 1). Venus is the only spatially resolvable, Earth-sized world other than the Earth, where a diversity of geophysical envelopes, their interactions and evolution at several time scales and spatial scales, may be monitored from a variety of mission and instrumental concepts and support long-term evolutionary models of Earth-sized planets. Venus exploration offers therefore unique opportunities to answer fundamental questions about the evolution of terrestrial planets and the habitability within our own solar system.

Comparing the interior, surface and atmosphere evolution of Earth and Venus is essential to understanding what processes have shaped our planet, and is particularly relevant in an era where we expect thousands of terrestrial exoplanets to be discovered. Compelling recent insights, and the planet's relevance to exoplanetary systems (Kane 2022), have opened up new questions about the evolution and dynamic nature of Venus and its atmosphere. In Sects. 3-8, we explore how recently selected investigations and payload instrument concepts support the scientific goals and open questions presented in the accompanying papers of this collection. VERITAS (Smrekar et al. 2022a), DAVINCI (Garvin et al. 2022a), and EnVision (European Space Agency 2021) will greatly advance our understanding as well as lead to new questions about geologic evolution. In Sects. 9-12, we also address what key advances would come from new types of data to better constrain the interior, such as improved crustal thickness and structure, mantle viscosity/temperature from seismology, lithospheric thickness from electromagnetic sounding, in-situ heat flow to constrain thermal lithospheric thickness and radiogenic heat budget and distribution. In-situ geochemistry would help constrain rock rheology, mantle conditions, accretion considerations, and the source and history of specific rock types. Information on age of specific features will be very valuable; the detailed composition of weathering products will tightly constrain weathering rates and, if feasible, rock age dating would provide valuable absolute age information. Section 10 addresses, in particular, key areas and investigations at Venus not covered by the fleet of missions under development described in previous sections.

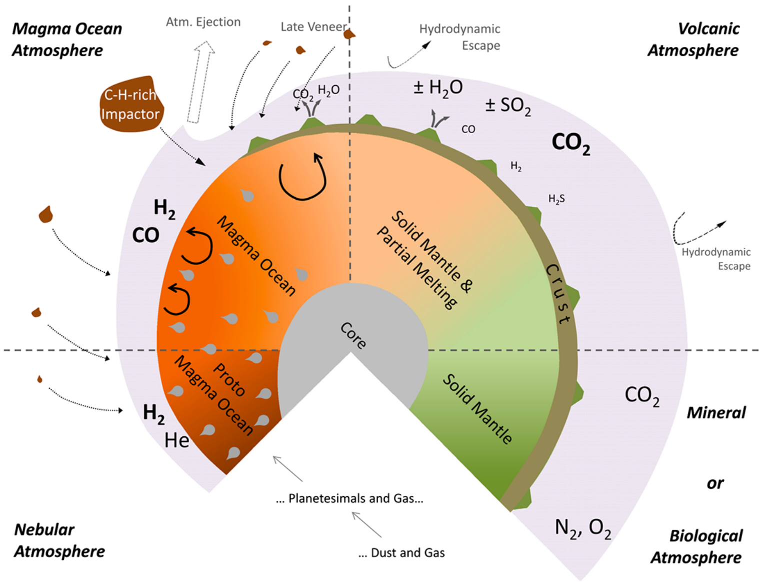


Fig. 1 Venus is essential to our understanding of the habitability of terrestrial planets, providing a natural laboratory for understanding their evolution throughout the history of our solar system. This clockwise helicoidal projection illustrates the parallel growth of an Earth-sized planet's interior, surface, and atmosphere (Gaillard and Scaillet 2014). In companion papers, Way et al. (2023), this collection, and Westall et al. (2023), this collection, discuss ongoing studies of the habitability of Earth-size planets, how they can inform the evolutionary history of Venus, and conversely, how the ancient evolution of Venus can serve as ground truth for studies of the divergent paths for Earth-size planets and the longevity of a habitable Venus-size or Earth-size body. The initial thermal state of the planet, which is closely related to its accretion sequence, determines the amount of energy the planet will dissipate over its history and the initial mantle inventory to be outgassed (Avice et al. 2022; Salvador et al. 2023; this collection), while later stages affect the extent, nature, and distribution of surface modification processes (Herrick et al. 2023, this collection; Ghail et al. 2023, this collection; Gilmore et al. 2023, this collection; Carter et al. 2023, this collection) and interior, surface, and atmosphere exchanges over time (Rolf et al. 2022, this collection; Gillmann et al. 2022, this collection; Wilson et al. 2023, this collection)

3 Overview of Mission Concepts and Observation Strategies to Address Venus Evolution Through Time

3.1 Selected Missions in 2021

On June 2, 2021, NASA announced the selection of two new missions to Venus, VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy, Sect. 4) and DAVINCI (Deep Atmosphere Venus Investigation of Noble gasses, Chemistry, and Imaging, Sect. 5) as part of the Agency's Discovery 2019 competition. On June 10, 2021, the European Space Agency (ESA) announced the selection of EnVision as its newest Medium-Class science mission in the framework of ESA's Cosmic Vision program (Sect. 6). VERITAS, DAVINCI and EnVision will greatly advance our understanding as well as lead to new questions about Venus evolution through time. Key advances will come from new types of data to better constrain the interior, such as improved crustal thickness and structure, mantle viscosity/temperature from seismology, lithospheric thickness from electromagnetic sounding, in-situ heat flow to constrain thermal lithospheric thickness and radiogenic heat budget and

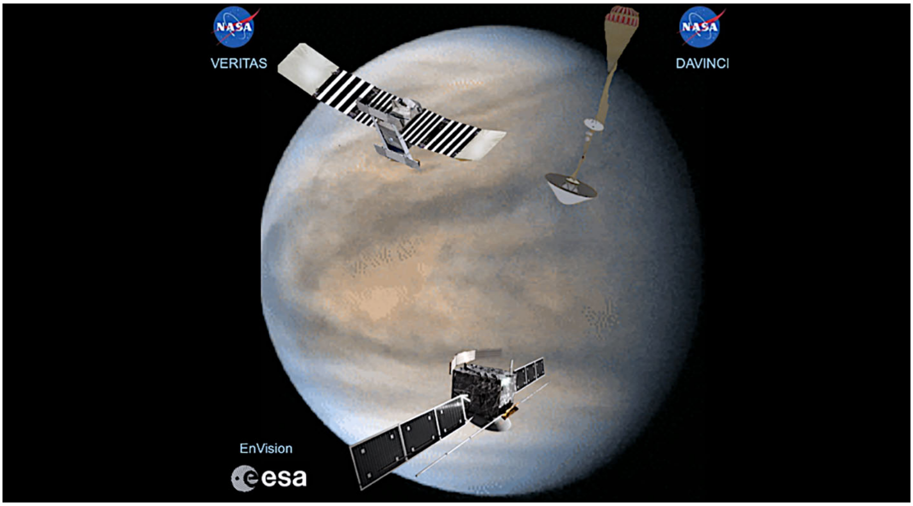


Fig. 2 A new fleet of elements of a Venus exploration program is now under development. These include two radar-equipped orbiters (ESA-led EnVision orbiter and NASA-JPL's VERITAS orbiter), and NASA-GSFC's DAVINCI entry probe with flyby remote sensing mission. Credit NASA / ESA / JAXA / Paris Observatory / VR2Planets

distribution. Over the next 15 years, these three missions will work together to answer many of the outstanding questions of Venus science and rocky planet evolution described above (Fig. 2; Table 1).

NASA's VERITAS orbiter will map the topography of the planet, create a compositional map, search for surface properties indicative of formation during a water-rich period, search for thermal and chemical signatures of volcanic activity, constrain interior structure, and look for surface change using a combination of radar imagery and differential interferometric techniques (Smrekar et al. 2022a). NASA's DAVINCI probe/flyby mission will measure atmospheric chemistry (noble gas isotopic abundances to constrain Venus' formation and early evolution) and physical properties (including wind speed, pressure and lapse rate) down to the surface and collect multi-scale near-infrared (sub-cloud deck) images of composition and topography at scales from $\sim$200 m down to $\sim$25 cm of the ancient tessera terrain where an oceanic past may be recorded (Garvin et al. 2022a). ESA's EnVision orbital mission will follow with a range of observation modes including multi-resolution radar imaging, radar polarimetry and radiometry, a suite of infrared and UV spectrometers for sensing the atmosphere and surface, and conduct the subsurface sounding (European Space Agency 2021). EnVision's combination of surface and atmospheric measurements will characterize ongoing volcanic processes though an extended-timeline, search for their thermal, morphologic, and gaseous signatures, while also tracing key volatile species from the surface up to the mesosphere (Table 1). EnVision is an ESA-led mission in partnership with NASA, providing its Synthetic Aperture Radar instrument, VenSAR and Deep Space Network support for critical mission phases.

Both NASA and ESA orbital missions will provide global context to understand DAVINCI's local, high-resolution near-IR imaging (with topography and band-ratio composition) of its entry ellipse descent corridor within western Alpha Regio (Sect. 5.3.4), which in turn provides 'ground truth' for radar and near-IR VERITAS and EnVision data interpretation (Sects. 5.5 & 6.4). The scientific results of these three synergistic missions will

Table 1 A comparison of missions VERITAS, DAVINCI and EnVision payload instruments as developed in the following Sects. 4-6, their synergies and complementarity; mission design and driving requirements at time of publication (Smrekar et al. 2022a; Garvin et al. 2022a; European Space Agency 2021). VISAR, Venus Interferometric Synthetic Aperture Radar (§4.3.1); VEM: Venus Emissivity Mapper (§4.3.2); VMS: Venus Mass Spectrometer (§5.3.1); VTLS: Venus Tunable Laser Spectrometer (§5.3.2); VenDI: Venus Descent Imager (§5.3.4); VISOR UV: Venus Imaging System for Observational Reconnaissance (§5.4.1-5.4.2); VISOR near-IR: Venus Imaging System for Observational Reconnaissance (§5.4.1); CUVIS: Compact Ultraviolet Imaging System (§5.4.2); VenSAR, Venus Synthetic Aperture Radar (§6.3.1); SRS: Subsurface Radar Sounder (§6.3.2); VenSpec-H, -M, -U: Venus Spectrometer Suite (§6.3.3)

Parameter	**VERITAS** (Section 4)	**DAVINCI** (Section 5)	**EnVision** (Section 6)
Launch date / Duration (at time of publication)	Not earlier than 2031 / 4 cycles (2.7 years beginning ~2 yr after launch) + extended mission opportunities	June 2029: 2 flybys (Jan. 2030, Nov. 2030) + 1 entry, descent, science for chemistry, imaging & physical properties (June 2031)	Dec 2031, May 2032, or Nov 2032 / 6 cycles (4 years beginning ~4 yr after launch) + extended mission opportunities
Orbit / Inclination	180 × 255 km / 85.5 deg	Flybys from 180,000 km to 5,000 km; optional post-probe Venus Orbit Insertion (Jan 2032)	220 x 520 km / ~88 deg
Radar Imagery	**VISAR:** Global X-band (7.9 GHz) Imaging: 30 m;15 m 25% of surface	N/A	**VenSAR:** S-band (3.2 GHz) Imaging: 30 m ~30% of surface; 10 m ~2% of surface
Topography at high resolution	**VISAR:** Single Pass Interferometry Global Topography; 250 m horiz., 5 m vertical	**VenDI:** Sub-cloud near-IR Structure-from-Motion processed images from 60 m at < 4 m vertical to 25 m at < 3 m vertical; other options include ~90 m at < 7 m vertical & 5 m at 1 m vertical	**VenSAR:** Stereo, 25% surface, 300 m horiz. 30-50 m vertical Radar Altimetry, 75% surface, 3 km footprint, 2 m vertical precision; SRS Altimetry, 68% of surface
Subsurface boundaries	**VISAR:** indirect inference from synthetic aperture radar	N/A	**SRS:** penetration depth up to 1000 m; 20 m resolution
Microwave Radiometer brightness temperature and emissivity maps	N/A	N/A	**VenSAR:** Dual Polarization HH-HV 7% of surface nadir and off-nadir microwave radiometry, 75% surface. Short-term Temp. var. < 1K
Repeat Pass Interferometry for Deformation	**VISAR:** Targeted 12-18 200 × 200 km sites; 1.5 cm deformation accuracy	N/A	Not in current baseline; may recover some opportunistic capability depending on ΔV
k_2 tidal Love number and Moment of Inertia Factor (MoIF)	k_2 accuracy 0.2% at 3-sigma, moment of inertia at 0.3% at 3-sigma using two-way Ka-band Doppler tracking and radar tie points	N/A	**RSE**: k_2 accuracy 1.2% at 3-sigma, moment of inertia at 1.2 % at 3-sigma w/capability to combine Doppler tracking and radar tie points
Gravity field	Two-way Ka/Ka-band and X/X-band tracking; gravity field resolution < 105 km globally with <4 mGal RMS accuracy	N/A	**RSE:** Two-ways X / X-Ka band tracking; gravity field resolution < 200 km globally and < 170 km on at least 40% of planet with < 10mGal RMS accuracy
Noble gases, trace gases & their isotopic ratios; loss mechanisms and past outgassing	N/A	**VMS; VTLS:** in-situ probe-based analytical chemistry of S, O species and He isotopes Isotopic ratios for Ne, Ar, Kr, Xe H, S, C, and O & their isotopic ratios including D/H	**VenSpec-H:** D/H in tropospheric H_2O, HDO
Detect current and recent surface volcanism	**VEM**: thermal signature 1020 nm, unweathered flows: 6 near IR bands 860 to 1180 nm. **VISAR**: Surface changes within mission and between Magellan and EnVision	N/A	**VEM**: thermal signature 1020 nm, unweathered flows: 6 near IR bands 860 to 1180 nm. **VenSAR**: Surface changes vs Magellan, within mission, vs. VERITAS
Surface composition	**VEM:** 6 near IR bands 860 to 1180 nm	**VISOR**: 3 NIR bands from 900 to 1030 nm for Alpha, Ovda, Maat **VenDI**: sub-cloud near-IR band-ratios at scales from 150 m down to 12 m (740 to 1030 nm)	**VenSpec-M**: 6 near IR bands 860 to 1180 nm
Current volcanism using water vapor, S-bearing gas detection, and cloud top UV absorber	**VEM:** water vapor bands at 960 and 1160 nm; cloud bands at 1195, 1310, 1510 nm	**CUVIS**; hyperspectral UV spectroscopy (0.2 nm resolution) on two dayside flybys; **VISOR**: near IR emissivity mapping of Maat, Alpha, Ovda on 2 nightside flybys **VMS; VTLS:** Probe-based analytical chemistry of S, O species and He isotopes	**VenSpec-M:** water vapor bands 960 & 1160 nm; cloud bands at 1195, 1310, 1510 nm **VenSpec-H**: 1000-2700 nm: H_2O, HDO, CO and SO_2 **VenSpec-U**: SO, SO_2 variations 190-380 nm
p, T vertical structure of atmosphere	X/X+Ka/Ka-band radio occultation sounding, SO_2 and H_2SO_4 liquid and gaseous content at 45-55 km, p, T profiles at 45-90 km	p, T, winds, accelerations every 15-50 m from 70 km – surface; for lapse rate (T vs. z). Trace gases every 140 m from 40 km – surface for masses from 8 to 272 *Da* with gradients in key species (SO_2, OCS, H_2O, CO_2)	**RSE:** One-way X-Ka band radio occultation sounding, SO_2 and H_2SO_4 liquid and gaseous content at 45-55 km, T profiles at 35-90 km, at all local time, lat./long., 4 soundings / day

answer fundamental questions about the early period of Venus history, how the transition to its current forbidding environmental state came about, where volcanic eruptions are reshaping the surface today, and what the differences from Earth can tell us about possible pathways of extrasolar rocky planet evolution.

3.2 Missions Considered for Selection

In addition to the three selected missions, several international space agencies have developed mission concepts. This collection is based on the papers presented at the Space Science Series of the International Space Science Institute (ISSI) workshop ‘Venus: Evolution through Time’ held in Bern, Switzerland, on September 13-17, 2021. It therefore captures the discussions that took place among the participants during the workshop. At that time, two large mission concepts were discussed for launch before the end of the current decade and possibly before the planned launch period of the currently selected VERITAS, DAVINCI, and EnVision missions: Venera-D (Zasova et al. 2020) and Shukrayaan-1 (Antonita et al. 2022). We therefore decided to describe extensively these two mission concepts in Sects. 7 and 8.

In conclusion to Sect. 3, we add a brief description of the Chinese radar-equipped VOICE orbiter mission proposal (Dong et al. 2023); and of Venus Life Finder “Morning Star”, Rocket Lab’s private low-cost concept mission to Venus (Seager et al. 2021; Limaye and Garvin 2023).

Venus Volcano Imaging and Climate Explorer (VOICE) is a Chinese orbiting mission to investigate Venusian geological evolution, atmospheric thermal-chemical processes, surface-atmosphere interactions, and habitable environment and life in the clouds. Three state-of-the-art scientific payloads, the Polarimetric Synthetic Aperture Radar (PolSAR), the Microwave Radiometric Sounder (MWRS) and the Ultraviolet-Visible-Near Infrared Multi-Spectral Imager (UVN-MSI), will be flown on a polar-circular orbit of $\sim$350 km. VOICE is currently proposed to Strategic Priority Program (SPP) on Space Science of the Chinese Academy of Sciences (Dong et al. 2023).

Venus Life Finder “Morning Star” Mission, Rocket Lab’s low-cost, small entry probe mission to Venus is intended to be the first in a series (Seager et al. 2021). After the cruise phase, the Photon platform, designed for launch on the Electron small launch vehicle, will target an entry interface to deploy a small ($\sim$20 kg) probe directly into the atmosphere with a flight path angle (EFPA) between -10 and -30 degrees, communicating direct-to-Earth through an S-band antenna, containing up to 1-kg of science payload (French et al. 2022; Seager et al. 2022).

4 Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS)

The Venus Emissivity, Radio Science, InSAR, Topography And Spectroscopy (VERITAS) mission will address key science objectives about the geologic and volcanic history of Venus; it will elucidate how Venus’ evolution differs from Earth’s with three overarching Science Goals: 1) constrain Venus’ geologic evolution; 2) determine which geologic processes are active; and 3) search for evidence of past and present water. VERITAS is a partnership between scientists and engineers at NASA/JPL and with the German, Italian and French Space Agencies. DLR provides the Venus Emissivity Mapper (VEM) instrument and VISAR interferometric processing support, ASI, which provides the Integrated Deep Space

Transponder, the lower power RF portion of the VISAR radar and the high gain telecommunications antenna, and CNES, which provides VEM optics and filter array subsystems, and the Ka-band TWTA. Equipped with an interferometric synthetic aperture radar and infrared imaging spectrometer VERITAS will globally map the surface of Venus producing imagery, rock type, topographic, and gravity maps. Following its selection by NASA, and according to the best information available at the time the manuscript is revised, VERITAS is programmed for launch no earlier than 2031 (Table 1).

4.1 VERITAS Science Objectives

4.1.1 Overview

VERITAS is structured to answer three essential science questions about the processes that have shaped and continue to shape the surface today:

1. What processes shape rocky planet evolution?
2. What geologic processes are currently active?
3. Is there evidence of past and present interior water?

These questions are organized into a series of specific investigations that can be addressed with two instruments and a radio science investigation.

VERITAS intends to definitively answer whether volcanism has been steady or catastrophic, why it lacks terrestrial-style plate tectonics, how it loses its heat, and if its plateaus are analogs of Earth's continents. It will also extend our knowledge of Venus with numerous firsts, including constraints on the core size and state (relevant to dynamo formation), high resolution topography and radar imaging, and a search for active surface deformation and active or recent volcanism.

Without an understanding of Venus' geologic evolution through time, we cannot fully test hypotheses for how Earth and other terrestrial planets evolve. Our knowledge of Earth in particular forms the basis for understanding habitability (Way et al. 2023, this collection; Westall et al. 2023, this collection). One of the central issues regarding the potential habitability of extrasolar planets is the extent to which plate tectonics is required to maintain habitability (e.g., Southam et al. 2015). A planet's interior is the engine for geologic activity, which drives climate and atmospheric evolution, thus setting the conditions for its long-term habitability. Because exoplanet surfaces cannot be spatially resolved, only indirect information on planetary radius, interior density, and atmospheric composition is available to predict habitability, in addition to radiative constraints to allow water to condensate in liquid phase (Hays et al. 2015; Meadows et al. 2018). Knowledge of the interior, including the size and state of the core, is critical to understanding how a planet loses its heat and evolves. Habitability models, such as that of Tosi et al. (2017), cannot predict the circumstances leading to habitability of a Venus-like planet, due to a lack of knowledge of Venus' geologic history and evolution.

Plate tectonics is Earth's defining geologic process. For billions of years, distinct lithospheric plates have moved above the upper mantle as they spread apart at undersea volcanic regions (the mid-ocean ridges), sink at subduction zones, and slide past each other at transform faults. Continental crust formed largely via melting of subducting slabs in the presence of water (Campbell and Taylor 1983; Arndt 2013). Earth's continents drift apart and crash together, but are never dragged into the interior because their Si-rich composition is lower in density.

Many new hypotheses linking plate tectonics to Earth's habitability are emerging, including the origin of the great oxygenation event (Duncan and Dasgupta 2017). Processes

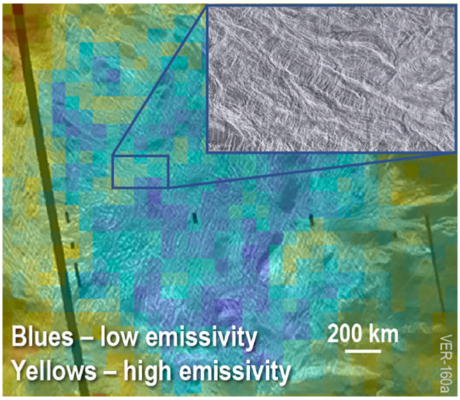


Fig. 3 VEM's 6 channel, high signal-to-noise ratio (SNR) spectra will determine definitively if tessera plateaus are felsic (low iron) like Earth's continents. The lower 1000 nm VIRTIS emissivity for Alpha Regio (color overlay) suggests low iron content (Gilmore et al. 2015; Dyar et al. 2020; Helbert et al. 2021). An example of the complex deformation that characterizes tesserae is shown in the Magellan SAR image inset

that link volcanism (that releases volatiles such as H_2O, CO, and SO_2 from the interior to the atmosphere) and subduction (that cycles volatiles back into the mantle) help maintain a stable climate and hydrosphere (Kasting and Catling 2003; Driscoll and Bercovici 2013). In fact, the vast majority of Earth's present-day oceans and atmosphere came from interior degassing (Pearson et al. 2014; Marty et al. 2016, 2017). Interior heat loss maintains our planet's magnetic dynamo, protecting complex organic compounds from radiation damage by magnetically deflecting the solar wind. On Earth, plate tectonics is the dominant heat loss mechanism. Is there evidence of these processes on Venus? VERITAS looks for evidence of "continents," past geologic processes, volcanic history, and subduction—the first step in initiating plate tectonics.

4.1.2 What Processes Shape Rocky Planet Evolution?

Global Rock Type, Terrains, and Tesserae. - Venus surface geology is controversial and geochemistry is largely unconstrained. What little we know about surface composition comes from a handful of Venera and VeGa geochemical analyses (Grimm and Hess 1997; Treiman 2007), laboratory experiments (Shellnutt 2013), thermodynamic modeling (Tef-feteller et al. 2019), and conclusions drawn from Magellan radar and limited (single-band) emissivity data from VEx (Mueller et al. 2008; Helbert et al. 2008; Smrekar et al. 2010a; Gilmore et al. 2015; Mueller et al. 2020). Landed measurements suggest geochemically distinct volcanic plains units, but the large uncertainties preclude definitive interpretations (Gilmore et al. 2017). New Magellan emissivity analysis suggests variability among tessera plateaus (Gilmore et al. 2019).

The composition of tessera terrain provides critical constraints on Venus geochemistry, geodynamics and the history of water on the planet. Containing what may be the oldest surface rocks on Venus (Ivanov and Head 1996), they are extremely complex geologic terrains (Figs. 3 and 4). Tesserae occur as both large plateaus with diameters of 1000–4000 km, and as smaller, isolated 100s-km-scale areas embayed by plains volcanism. They have been proposed to be continent-like based on their morphology, gravity signature, and inferred low-Fe, high-Si composition (Hashimoto et al. 2008).

Surface emissivity data from the VIRTIS on VEx, as well as from Galileo, suggest that tesserae are more felsic (lower in iron) than basaltic plains (Hashimoto et al. 2008; Helbert et al. 2008; Gilmore et al. 2015; Helbert et al. 2021) and thus possible analogs of terrestrial continents. Tessera composition and formation are key to assessing the role that volatiles play in shaping Venus' evolution. Large uncertainty in Magellan topographic height (Fig. 4)

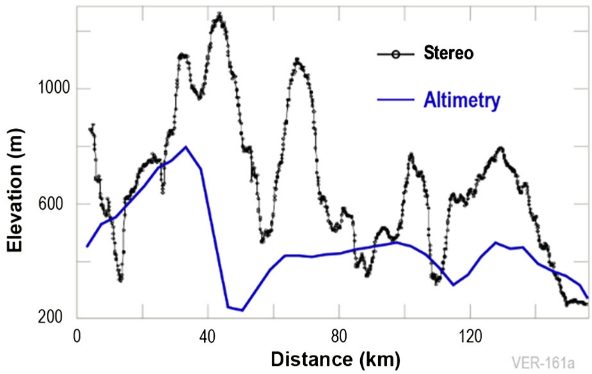


Fig. 4 Constraining tesserae composition requires both VEM data and the VERITAS digital elevation model (DEM) to provide the elevation-dependent temperature correction. Tessera heights are not fully resolved in either the spatially limited Magellan stereo DEM data (black) or Magellan global altimetry resolution (blue)

and thus in the altitude-dependent temperature correction for emissivity, as well as lack of spectral data, together preclude an answer to whether Venus has continents.

Two main hypotheses have been proposed for the origin of tesserae: downwelling and upwelling mantle flow. Deciding between these has significant implications for the crustal strength, volatile content, thermal gradient and evolution, and formation timescale (Lenardic and Kaula 1995; Ghent et al. 2005). According to the downwelling scenario, plateaus form as the crust thickens above regions where the cold mantle sinks (Bindschadler and Parmentier 1990; Bindschadler et al. 1992). Downwelling and remelting of basaltic crust could produce more Si-rich compositions, similar to those produced at some of Earth's subduction zones (Elkins-Tanton et al. 2007; Romeo and Turcotte 2008; Gilmore et al. 2017). Alternatively, plateaus may have formed over upwelling mantle plumes, with crustal thickening caused by profuse mantle melting (Phillips and Hansen 1994) that should produce a basaltic composition. Discriminating between these formation models requires distinguishing between Fe-rich, Si-poor basaltic rocks and more Si-rich continental rock types, as well as ascertaining the detailed shape of the small-scale graben that are diagnostic of specific deformation sequences (Bindschadler and Parmentier 1990; Bindschadler et al. 1992; Hansen and Willis 1998). If intermediate rock types are present, they are expected to have intermediate emissivities.

The primary mountain belts on Venus encircle Lakshmi Planum, and may be similar in composition to tesserae. However, there are no VIRTIS emissivity or landed data in that location. If the plains' compositional differences (tholeiitic and highly alkaline basalts) suggested by landed data can be validated by VERITAS' near-global rock type mapping, they would provide evidence of varying depths of melting and fractionation and thus geologic setting (Gilmore et al. 2017).

In addition, gravity data also inform our understanding of rock types and global terrain. Global gravity and topography data can be used to estimate the elastic thickness/thermal gradient, which constrains mechanisms of formation, and can identify processes such as subduction, localized delamination/ upwellings, and fossilized rifts. Other fundamental questions also remain: Did all tesserae form the same way? Are they all the same composition?

Prior Geologic Regimes: Buried Features. - Global high-resolution surface topography, images, and gravity data can provide critical windows into the past. On Mars, high-resolution topography shows subtle signatures of buried impact craters, only revealed by MGS' Mars Orbiter Laser Altimeter (MOLA) instrument (Frey et al. 2002; Buczkowski and McGill 2002; Frey 2006). These demonstrate that an ancient cratered surface was buried

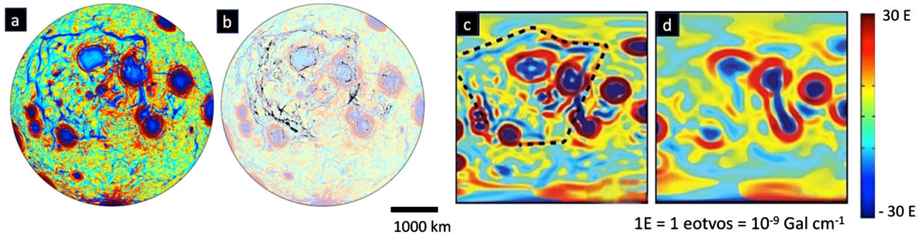


Fig. 5 Bouguer gravity anomalies and gravity gradients reveal a pattern of narrow linear anomalies that border Procellarum associated with buried lunar subsurface structures (a, b; data from the GRAIL mission). VERITAS' high-resolution gravity can reveal such subsurface structures. Gravity gradient maps at VERITAS' resolution (c) would reveal buried rifts (outlined in dots); map at Magellan resolution (d) is insensitive to these features. Figure after Andrews-Hanna et al. 2014; 1 Eotvos (E) $= 10^{-9}$ Gal cm$^{-1} = 10^{-9}$ s^{-2})

beneath plains material, disproving theories of resurfacing by plate tectonics and supportive of lowlands formation via a giant impact (Andrews-Hanna et al. 2008). MESSENGER images of Mercury show volcanically flooded ghost craters (Head et al. 2011). On the Moon, GRAIL gravity data reveal ancient rifts for which no surface signature exists (Fig. 5, Andrews-Hanna et al. 2014), as well as buried impact craters (Evans et al. 2016; Sood et al. 2017).

What lies beneath Venus' volcanic plains? Evidence for buried impact craters would shed new light on the history of volcanism and age of the underlying terrain. Venus may have had plate tectonics earlier in its history, perhaps continuing until the most recent resurfacing event (Armann and Tackley 2012). Interconnected lineations in the gravity or topography could reveal the sites of past spreading centers or subduction zones. Alternatively, tesserae may underlie the plains.

Tesserae inliers are common and could be the gravitationally relaxed remnants of ancient tesserae plateaus (Ivanov and Head 1996; Hansen and López 2010). The topographic or gravity signature of tesserae under the plains would show that tesserae were widespread, and may have formed during a prolonged wet period on Venus.

Impact and Volcanic History. - Venus' impact crater population holds the key to the planet's integrated time history of volcanism. The small number of craters (less than 1000 observed) implies a young surface age, but there is uncertainty in the number of modified craters. The "Catastrophic Resurfacing" hypothesis postulates that a huge pulse of volcanism rapidly covered Venus ~1 Ga ago, followed by limited activity. This theory was based on two observations: 1) The distribution of craters cannot be distinguished from a random one; and 2) few craters appear to be modified by volcanism or tectonism (Schaber et al. 1992; Strom et al. 1994).

Numerous models derive a resurfacing rate by comparing the rates of crater formation and removal or modification. Many models are more consistent with an equilibrium rather than catastrophic resurfacing rate (Basilevsky 1993; Bjonnes et al. 2012; O'Rourke et al. 2014; King 2018). In all cases, the critical parameter is how many craters are modified. The two primary modes of crater modification are volcanic infilling and weathering removal of distal crater ejecta (halos and parabolas). In the catastrophic resurfacing model, major crustal resurfacing is confined to a discrete pulse, and consequently only a small number of craters, preserved from this time, should show volcanic modification. The equilibrium theory suggests resurfacing processes occur continuously, and the majority of craters should display some form of modification, although the degree of modification should vary regionally (Herrick and Rumpf 2011).

Studies investigating crater modification have found evidence of craters with varying levels of modification, however, these results remain controversial. If all dark-floored craters (∼80% of craters) have been partially flooded, then volcanism has persisted over 100s of millions of years (Herrick and Sharpton 2000; Herrick and Rumpf 2011). However, the resolution of the Magellan stereo data (∼100 m) casts the robustness of this interpretation into doubt.

The study of fine-grained distal crater ejecta (halos and parabolas) argues against catastrophic resurfacing. Analysis of variations in halo retention combined with regional crater density, suggest that the surface of Venus is divisible into three major age groupings (Basilevsky et al. 2003b). These include those superposed on wrinkle ridges on regional plains, those superposed on units younger than regional plains, and "other." However, their study relies on the assumption that the processes removing the extended ejecta deposits operate at a uniform rate across the planet, despite no direct observations of the actual mechanisms, and the natural difficulty in mapping the morphology of the dark, diffuse deposits.

Radically different implications follow from the various resurfacing models. The "catastrophic" resurfacing hypothesis suggests that planets may behave episodically, with cycles of plate tectonics or mantle overturn and massive melting (Parmentier and Hess 1992; Reese 1999; Armann and Tackley 2012) separated by periods with no plate motion (a "stagnant lid" regime). These models predict the spike in volcanism implied by catastrophic resurfacing. Volatiles outgassed by volcanism in a catastrophic event could have a significant effect on climate, perhaps changing temperature enough to cause detectable thermal expansion of the surface (Anderson and Smrekar 1999). In contrast, the equilibrium resurfacing model implies more Earth-like rates of volcanism without a need for episodic plate tectonics (O'Rourke et al. 2014).

All resurfacing models are constrained by the number of modified craters and extended ejecta deposits, which remains controversial. Thus, the distribution of volcanism in space and time, the relative age of different locations, and implications for the history of Venus' evolution are uncertain. One method to assess resurfacing history is to model the gradual removal of fine-grained crater ejecta (Phillips and Izenberg 1995; Ghail et al. 2023, this collection). Relatively old regions, without any volcanism for an extended time, would have both high crater density and relatively few halos, since aeolian or chemical weathering can also remove halos and not high-standing crater rims or rocky ejecta. A high-resolution Digital Elevation Model (DEM), gravity measurements, and surface imagery are needed to discriminate between models: to characterize subduction and extension zones, fault patterns, flexed terrains and their margins, elastic thickness anomalies, and the distribution, nature and extent of impact crater modification (Herrick et al. 2023, this collection). VERITAS will provide a new and detailed view of global tectonics, potentially revealing strike-slip faults, extensional zones and other deformation features (Fig. 6).

What Are the Major Tectonic Processes? Is Subduction Currently Active? - Venus does not currently have recognizable Earth-like plates bounded by spreading centers, subduction zones, and transform faults (Solomon et al. 1991). On Earth, plate formation at spreading centers and subduction of old plates dominate heat loss and drive geologic activity. Without global plate tectonics, how does Venus lose its heat?

One clue is that Venus' internal heat engine has created abundant tectonic deformations including >40,000 km of fractured troughs, possible subduction zones, and huge mountain belts. Among the terrestrial planets, only Earth and Venus have such massive deformation zones. Could Venus represent a transitional tectonic state between active (plate tectonic) and stagnant (no plate motion) regimes? Although not globally interconnected, Venus may have key elements of plate tectonics: subduction, major extensional zones, and even transform faults.

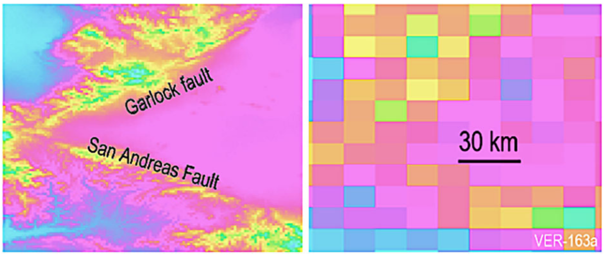


Fig. 6 VERITAS' Digital Elevation Model (DEM) has the needed resolution to discover narrow deformation zones such as strike-slip plate boundaries not apparent in image data. Shuttle Radar Topography Mission (SRTM, Rodriguez et al. 2005; Farr et al. 2007) Earth's topography data (blue = low, purple = high), reduced to VERITAS resolution (left, 240 m horizontal, 5 m vertical noise) clearly show major tectonic boundaries. Such faults are invisible at Magellan resolution (right, 15 km horizontal, 100-m noise)

Subduction is a necessary first step in initiating plate tectonics. Whether it occurs on Venus is vigorously debated (Hansen and Phillips 1993; Sandwell and Schubert 1992a,b; Hansen and Olive 2010; Baes et al. 2016; Crameri and Tackley 2016). Venus' huge trough systems (termed chasmata) are typically interpreted as extensional zones, based on numerous long, linear fractures that can sometimes be identified as graben. However, some chasmata have characteristics of subduction. Specifically, some troughs have the same asymmetric shape, with a ridge on the concave side and a trough on the convex side, as observed at some arcuate terrestrial oceanic subduction zones including the South Sandwich Islands trench (Sandwell and Schubert 1992a; Fig. 7).

Because proposed Venusian subduction zones have estimated elastic thicknesses and bending moments similar to their terrestrial analogs (Sandwell and Schubert 1992a,b), their mechanical behavior should also be similar. If Venus' asymmetric chasmata are produced by subduction, their gravity signature should be asymmetric, in contrast to the symmetric signature of extension (Smrekar et al. 2010b).

A recent theoretical development (Bercovici and Ricard 2014) assesses the likelihood of plate tectonics on exoplanets: subduction evolves into plate tectonics when reductions in lithospheric strength from breakage (due to microcracks and grain-size dependent deformation) dominate over lithospheric healing via grain growth. This suggests that Venus may have a hot lithosphere that anneals too rapidly to allow subduction to develop into full plate tectonics. Global estimates of elastic thickness will allow us to assess whether it indeed has a hot, thin lithosphere, similar to early Earth's. Finding unequivocal evidence for subduction on Venus would elucidate the conditions and mechanisms for subduction initiation on terrestrial planets. Evidence of other major tectonic boundaries (extensional zones like mid-ocean spreading centers or major transform faults) would suggest that Venus could even transition to an Earth-like plate tectonic regime, as predicted by modeling (Armann and Tackley 2012).

Interior Structure and Thermal State. - Our knowledge of the internal structure of Venus is based on limited data for mass, radius, gravity, and topography. One direct existing constraint is provided by the tidal Love number k_2, or gravitational potential modification due to the tidal deformation of the planet.

Lack of a magnetic field at this stage of Venus' evolution does not provide any constraint (Stevenson 2003). Thus, interior structure models use a core size that is simply rescaled from Earth. Published temperature profiles for Venus' interior differ by up to 1000 K and 500 K in the lower and upper mantle, respectively (Steinberger et al. 2010; Armann and

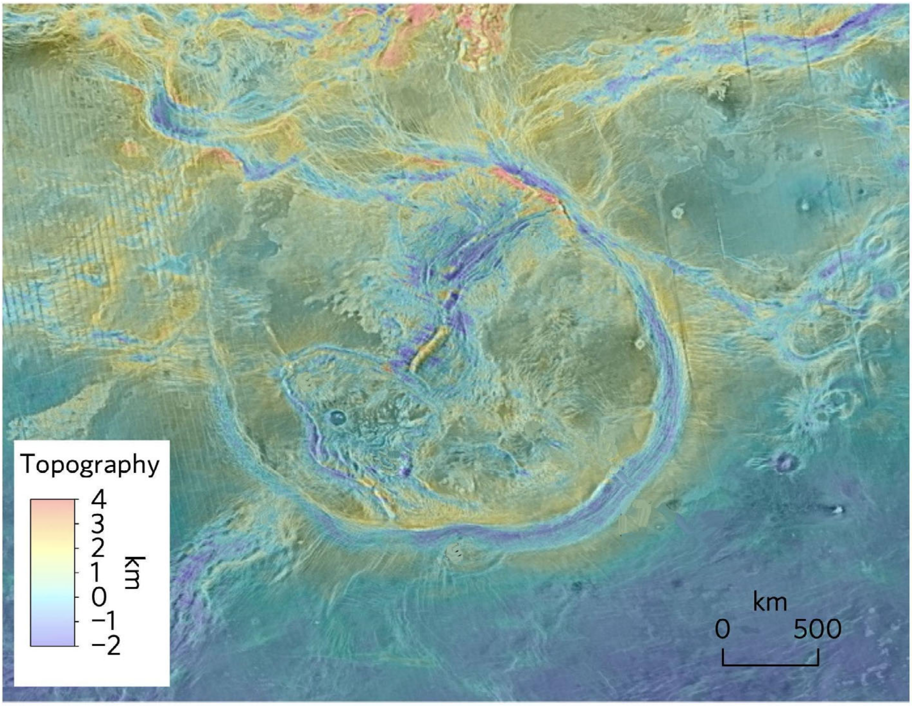


Fig. 7 VERITAS determines whether Venus has subduction. The surface of Venus hosts a variety of different features - volcanoes, rifts, mountain belts - that are typically on the scale of hundreds of kilometers, set within globally extensive regional lowland plains. Many features resemble Earth's arc-shaped oceanic subduction zones, such as the trenches at Artemis Corona, shown in this overlay of Magellan SAR data on altimetry (vertical scale at lower left): troughs have the same asymmetric shape, with a ridge on the concave side and a trough on the convex side (after Davaille et al. 2017)

Tackley 2012) with different implications for its cooling and volcanic history. Gravity and topography (Konopliv and Yoder 1996; Steinberger et al. 2010; Huang et al. 2013; Rolf et al. 2018) are linked at long wavelengths to the structure and dynamics of the sub-lithospheric mantle.

Precise measurements of the Moment of Inertia factor (MOIF) through the pole precession rate, the tidal Love number, k_2 and the tidal phase lag, e, will permit the first useful comparisons between the interior of Venus and other terrestrial planets (see also this Section, Sect. 4.3.3). The state of the core, its size (if liquid), and the tidal phase lag have already been determined by space missions with different accuracy for Mercury, Mars, and Moon. These previous studies demonstrate that knowledge of Venus' interior structure and therefore constraints on its long term evolution, can be derived from the moment of inertia, Love number k_2, and phase lag e.

As an example of results obtained for other Solar System bodies, Moment of Inertia factor constrains the core size of Mercury (Genova et al. 2019) and Mars (Smrekar et al. 2019), and the measured Love number k_2 is indicative of a liquid (or partially liquid) core for the Moon (Williams et al. 2014), Mercury (Margot et al. 2018), and Mars (Yoder et al. 2003). k_2 for Venus has been estimated from Doppler tracking of Magellan and Pioneer Venus Orbiter ($k_2 = 0.295 \pm 0.066$; Konopliv and Yoder 1996), but the large uncertainty does not allow distinguishing between a liquid vs. solid core (Dumoulin et al. 2017). Use of the Martian phase lag (Plesa et al. 2018) constrains core size and volatile components such as sulfur (Rivoldini et al. 2011), as well as mantle viscosity.

4.1.3 What Geological Processes Are Currently Active?

Multiple observations suggest that Venus is geologically active. Magellan topography and gravity data analysis indicate the likely presence of low density, hot mantle plumes under large volcanic rises, or "hotspots," similar to those on Hawaii (Smrekar 1994). Atmospheric sulfur variations imply active volcanic outgassing (Marcq and Lebonnois 2013). The average sulfur content corroborates ongoing volcanism because SO_2 breaks down over time (Fegley and Prinn 1989; Fegley et al. 1997). Campbell et al. (2017) presented evidence for relatively recent pyroclastic volcanic flows based on their radar properties and lack of erosion. Finally, the 2011 Planetary Science Decadal Survey named the case for recent volcanism (Smrekar et al. 2010a) from near-IR emissivity anomalies to be one of the ten major discoveries of the last decade. Enhanced 1020 nm emissivity correlates with stratigraphically young flows at three areas classified as hotspots based on their broad topographic rises and large positive gravity anomalies (interpreted as mantle plumes). The emissivity increase between these areas and the surrounding plains is consistent with that between unweathered and weathered basalt, implying recent volcanism on timescales of years to decades, based on new laboratory data (Knafelc et al. 2019; Berger et al. 2019). But VEx VIRTIS data cover only the southern hemisphere with only a single band.

Are the six hotspots not observed by VIRTIS also active? Is there evidence for recent volcanism in other geologic settings? If present-day volcanism is restricted to hotspots, this may imply a shift from radiogenic internal heating to basal heating at the core-mantle boundary, allowing hotspot formation (Choblet and Parmentier 2009). Alternatively, restriction of volcanism to hotspots could arise from upper mantle heating under an insulating stagnant lid, leading to shutdown of widespread plains volcanism through desiccation of the upper mantle. In this scenario, hotspot volcanism occurs where water-bearing material from the lower mantle melts (Smrekar and Sotin 2012). Identifying the origin of current volcanism will dramatically change our understanding of interior dynamics.

If Venus remains volcanically active, it is also deforming. For the first time on another planet, we will have the ability to detect active tectonic deformation through repeat pass interferometry. Finding active deformation, and identifying the mechanism(s) responsible, would provide unprecedented insights into the geologic evolution of Venus, and by extension to terrestrial planets.

4.1.4 Is There Evidence of Past or Present Water?

Geochemical Fingerprints of Past Water. - Venus may have once had a shallow ocean's worth of water at the surface, based on the D/H ratio of the atmosphere (Donahue et al. 1982; Kumar and Taylor 1985; de Bergh et al. 1991). Its interior may still hold ~75% of its original volatiles (O'Rourke and Korenaga 2015). Its surface composition could retain a fingerprint of past water. Recent VIRTIS emissivity data at 1020 nm from a limited number of tesserae suggest a composition lower in iron than the plains, implying they formed in the presence of water (Mueller et al. 2008; Gilmore et al. 2015; Campbell et al. 2017). With an additional five emissivity bands and more accurate altimetry data to correct for altitude-dependent temperature (as well as detailed T vs z lapse rate boundary conditions from DAVINCI), VERITAS can fully confirm or refute this.

VERITAS uses VEM to map the distribution of FeO contents and relates them to geologic features. If continental-scale low-Fe silicic crustal regions on Venus are confirmed, this will indicate past hydrated source regions. Determining that tesserae are in fact continent-scale silica-rich regions would illuminate the processes that shaped our home planet.

Is Interior Water Being Volcanically Outgassed Today? - Pioneer Venus and VEx (Marcq et al. 2013; Esposito 1984; Esposito et al. 1988) observed strong SO_2 variability at the cloud tops, suggestive of plumes of rising gas from active volcanoes. Recent ground-based observations using Infrared thermal mapping have continuously evidenced such rapid variations (Encrenaz et al. 2013-2020a, see also Sect. 11, Sect. 11.1.3). Plumes must include substantially lighter elements than SO_2, including ~2–5% H_2O, to have sufficient buoyancy to reach heights of tens of kilometers (Airey 2015). Terrestrial volcanoes emit large quantities of H_2O, CO, and SO_2 (e.g., Gerlach 1980). Thus, volcanically outgassed water will only be observed on Venus if there are large, Earth-like concentrations remaining in the interior. Radar-derived evidence for relatively recent pyroclastic flows implies significant outgassing (Campbell et al. 2017). VERITAS observes near-surface water vapor through near-IR atmospheric absorption bands. Unlike higher altitude VEx H_2O measurements, the association of near surface water vapor with volcanism can be confirmed with additional surface observations.

4.2 VERITAS Mission Overview

The VERITAS mission is an orbiter carrying an X-band Interferometric SAR and the VEM instrument to perform global SAR mapping at 30 m resolution; and to acquire topography, gravity, InSAR, and NIR emissivity data. Its indicative mass budget including all margins is 1450 kg (dry mass). After nominal launch VERITAS has a ~7-month cruise to Venus. Following Venus Orbit Insertion (VOI), VERITAS performs a maneuver to reduce the orbit period from 120 hrs to 13 hrs. Aerobraking is then used to place the flight system in its initial and final science orbits. VERITAS has two planned science phases: Science Phase I (SP1) and Science Phase II (SP2). Science Phase I uses a 6.1-hour, highly elliptical orbit, and Science Phase II has a 91-minute orbit period at a mean orbit altitude of 217 km. Both have a nearly an orbit inclination of 85.5°.

The planned aerobraking campaign begins about two weeks after the Period Reduction Maneuver. The aerobraking campaign is divided into two segments: Aerobraking I (AB1, 7 months) and Aerobraking II (AB2, 9 months), with the 4-month SP1 embedded between them. During aerobraking, the spacecraft lowers periapsis into the upper atmosphere, using the additional drag to reduce its apoapsis altitude from over 40,000 km to 400 km. In SP2, which consists of four Venus cycles (roughly equal to a sidereal day of 243 Earth days), all instruments, VEM and VISAR, as well as the gravity science observations are conducting observations. Science Phase II begins with a 60-day VISAR calibration phase after the post-Aerobraking Exit maneuver (post-ABX) 200 × 400 km orbit is reshaped into the final science orbit. Venus rotates so slowly that the ground track moves only 10 km per orbit at the equator. Venus is so spherical, with an equatorial bulge three orders of magnitude smaller than Earth, that the spacecraft's ascending node precesses extremely slowly. These effects create a ground-track repeat cycle slightly longer than the 243-day Venus sidereal day; this causes the orbit to experience the same gravitational perturbations repeatedly over every orbit, which leads to significant eccentricity vector evolution, similar to that experienced by low lunar orbiters such as GRAIL. The mean inclination of 85.5° has been selected to cause this evolution to bend back upon itself, yielding a near-frozen orbit with altitude variation of 182.6 km to 252.5 km that repeats with the topography. A small radial Eccentricity Control Maneuver (ECM) at the end of each cycle corrects the slight mismatch.

Repeat-Pass Interferometry (RPI) enables cm-scale change detection of the surface and requires that the spacecraft fly within 160 m of its previous path over the targeted site. In

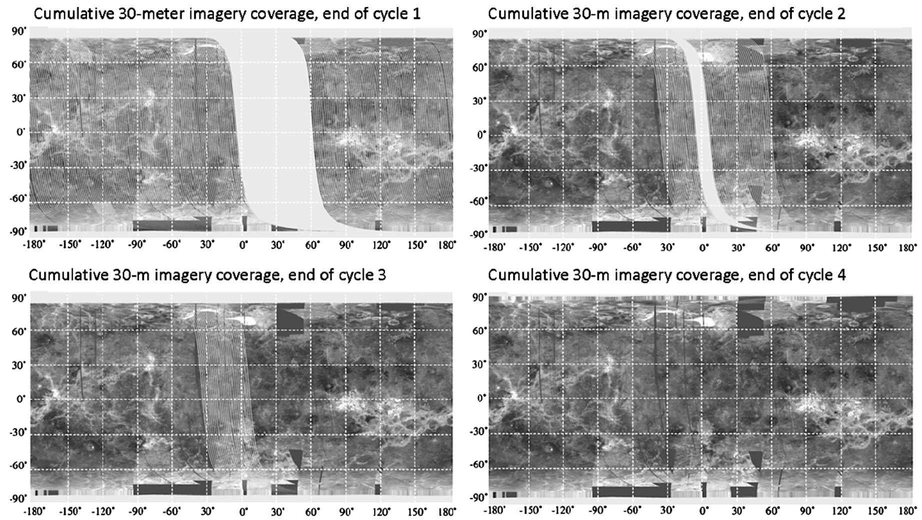


Fig. 8 Map of cumulative 30-meter VISAR radar images over the 4-cycle VERITAS ∼3.5 Earth years mission Science Phase II (SP2). SP2 starts after further aerobraking has placed VERITAS in a near-polar, circular, low-altitude orbit. For 57% of each 224-day Venus year, science mapping will cover the entire orbit

addition to maneuver execution errors and differential solar tidal torques, the uncertainty in the rotation period of Venus affects repeatability. To compensate, VERITAS will process radar tie points on the ground, as demonstrated with Magellan data, to improve orbit reconstruction (Chodas et al. 1992, 1993), and modeled for VERITAS (Cascioli et al. 2021).

The VERITAS mission design for SP2 enables a flexible orbit plan that balances 11 science mapping orbits with five downlink orbits each day. For 57% of each 224-day Venus year, science mapping will encompass the entire orbit. In the remainder, eclipses are long enough that additional power management is required. VISAR mapping occurs on a fraction of these orbits selected to optimize coverage within available power balance. Figure 8 shows the build of the 30 m radar imagery over the 4 cycle mission.

4.3 VERITAS Science Payload

VERITAS's payload is composed of two instruments crafted to study Venus' surface coupled with a radio science investigation to measure the gravity field. The two instruments are an X-band interferometric synthetic aperture, VISAR, and a fourteen-band infrared spectrometer, VEM.

4.3.1 Venus Interferometric Synthetic Aperture Radar (VISAR)

Persistent optically opaque cloud cover of Venus necessitates the use of synthetic aperture radar techniques to obtain high resolution imagery and topography of the surface. The Venus Interferometric Synthetic Aperture Radar instrument (VISAR) instrument is an X-band single pass radar interferometer designed to acquire high resolution imagery and topography of Venus as well as to make repeat pass interferometric measurements of surface deformation.

VISAR Specifications. - VERITAS requires a Digital Elevation Model (DEM) with 300 m horizontal postings over 90% of the Venus surface, with height accuracy $\leq$10 m for

Table 2 Key VISAR radar design and performance parameters

VISAR Parameters	
Instrument Parameters	Value
Platform Altitude Range (km)	182–252
Polarization	VV
Peak RF transmit power (dBW)	26.0
X-band Wavelength (m)	0.038
Antenna azimuth × elevation dimensions (m)	3.9 × 0.65
Range bandwidth (MHz)	20
Slant Range/Azimuth Resolution (m)	7.5, 2.3
Incidence Angle at swath center (°)	32
Pulse Repetition Frequency (PRF) (Hz)	5500
Pulse length (μs)	35
Baseline length (m), and orientation angle (°)	3.1, 30
Range, Azimuth Ambiguities (dB)	−36, −25
Atmospheric Losses (dB)	−9.5 dB

95% of the mapped surface. Global imagery with resolution less than 30 m is also required with radiometric resolution better than 3 dB.

VISAR Design Considerations. - VISAR operates at a center frequency of 7.9 GHz (0.038 m wavelength), which optimizes topographic mapping accuracy by balancing the effects of atmospheric attenuation with baseline and antenna size constraints to fit within the spacecraft fairing. A 20 MHz bandwidth provides ∼15 m ground resolution at the VISAR 30° angle of incidence. The radar must map a swath width greater than 14 km, spanning the 10 km of surface rotation at the equator during an orbital period with 2 km overlap with adjacent orbits. Table 2 lists key radar design and performance parameters.

VISAR Onboard Processing. - VISAR would include an On-board Processing (OBP) element to meet downlink constraints. Key processing steps in the OBP data flow are range compression, motion compensation, azimuth compression, interferogram formation and look averaging of imagery and interferograms.

VISAR Modes of Operation. - The radar has one science-mapping mode with several data downlink options that would accommodate different interferometric and imagery resolutions. For nominal science operations during SP2, we would upload a command table twice weekly specifying, as a function of S/C clock time, the radar parameters needing adjustment.

VISAR Calibration. - Preflight VISAR instrument calibration activities would include measurements of the Solid State Power Amplifier (SSPA) power output, pulse shape, receiver gain, ADC characteristics, Tx-cal-loop phase and amplitude over temperature, and antenna composite waveguides phase and amplitude variation over temperature. For in-flight radar calibration the radar would collect raw data from the two antennas to be downlinked for ground analysis. These data would be used to update calibration parameters needed for the proper collection and onboard processing of the radar data. Primarily, these data would be residual differential time delay between the two radar receive channels any yaw or pitch angle bias adjustments needed for the S/C pointing control to achieve zero-Doppler steering.

VISAR Data Acquisition. - Topography data would be acquired on ascending and descending passes with at least two observations (also called revisits) for 95% of Venus' surface, with more than 80% acquired 3–6 times. Revisits would provide the opportunity to detect surface changes. During descending passes for the VISAR left-looking sensor, matching the dominant East-Looking data acquired by Magellan, data would be acquired to obtain a combination of MedRes (30 m resolution) imagery for nearly 100% coverage and HiRes (15 m resolution) imagery with 27% coverage. VERITAS would be capable of targeting between 12 and 17 200 × 200 km sites with RPI, covering approximately 0.1% of the surface, acquiring each site at least twice to form a repeat pass interferogram. The deformation accuracy including atmospheric variations, mostly due to SO_2 variations, at 50 m posting is about 1.5 cm. These data would be the first deformation SAR interferometry at another planet (Hensley et al. 2022). Potential surface activity areas included those that are likely to have recent volcanism, possible subduction zones and areas of gravitational relaxation; If active regions of Venus experience similar levels of activity as Earth analogs the VERITAS project predicts detection of 3–7 events on a total of 17 RPI acquisitions.

VISAR Expected Performance. - We developed a comprehensive model to evaluate radar performance at Venus including imaging, radar stereo, single and repeat pass interferometric modes (Hensley 2009; Hensley et al. 2018). The radar performance model elements specify the observing geometry and scenario, the instrument configuration and product specification parameters, propagation and scattering parameters that are used to determine radar performance depending on mode, time and location of measurement. Backscatter information is derived from Magellan S-band data using a physical scattering model to convert S-band backscatter measurements to the desired radar frequency and incidence angle. The impact of atmospheric attenuation as a function of terrain height is derived from a model described in Duan et al. (2010). Two-way losses at X-band as a function of elevation (in km) relative to the 6051 km reference sphere is roughly −9.5 dB. In assessing the interferometrically derived height accuracy we have assumed a "bundle adjustment" procedure to remove residual cross-track tilts due to baseline and phase errors. Bundle adjustment uses tie points between adjacent orbits and between crossing ascending and descending passes in a least squares procedure to estimate cross-track tilt and elevation bias between the swaths.

The expected elevation mapping accuracy of the VISAR instrument is shown in Fig. 9. Backscatter contributions to SNR and attenuation losses are factored in the overall performance. Elevation accuracy is computed every 10 km based on the orbital geometry. Phase noise limited elevation accuracy (in green in Fig. 9c) is compared to elevation accuracy before and after bundle adjustment (red and blue in Fig. 9c). The cumulative elevation accuracy is shown in Fig. 9d and shows that 95% of the surface is mapped with elevation accuracy better than 5.9 m.

4.3.2 Venus Emissivity Mapper (VEM)

The permanent cloud cover of Venus prohibits observations of the surface with traditional imaging techniques over much of the electromagnetic (EM) spectral range. Therefore, it was once thought that information about the surface composition of Venus could only be derived from lander missions. Given the harsh environmental conditions on the surface, any type of landed mission will have high complexity and therefore a higher associated risk than orbiting missions. In addition, mission concepts for Venus landers typically focus on one landing site instead of a global reconnaissance, forcing difficult choices to be made between different types of surface units.

The mapping of the southern hemisphere of Venus with VIRTIS instrument on Venus Express using the 1.02-μm thermal emission band can be viewed as a proof-of-concept for an orbital remote sensing approach to surface composition and weathering studies for Venus (Mueller et al. 2008; Helbert et al. 2008; Smrekar et al. 2010a; Gilmore et al. 2015). Thermal emission from the surface is observed on the night side at spatial scales > 50 km.

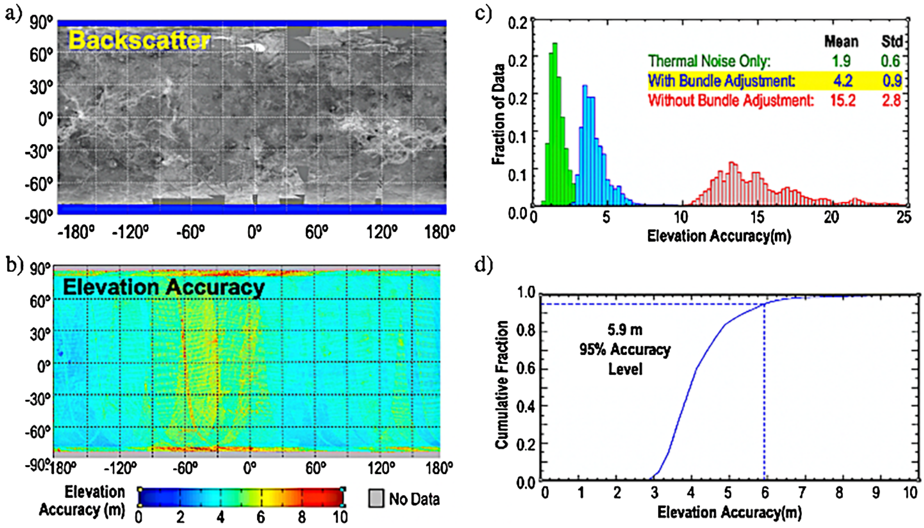


Fig. 9 (a, b) Map of the VISAR elevation mapping backscatter/accuracy, (c) histograms of elevation mapping accuracy with the bundle adjustment and (d) cumulative elevation accuracy showing a 5.9 m 95% accuracy level

Recent advances in high-temperature laboratory spectroscopy at the Planetary Spectroscopy Laboratory at DLR show that the atmospheric windows in the CO_2 clouds of the Venus atmosphere, ranging from 0.86 µm to 1.18 µm, are highly diagnostic for surface composition (Dyar et al. 2020, 2021; Helbert et al. 2021). Night-side observations at shorter wavelengths (<0.80 µm) from the Wide-Field Imager WISPR instrument on board Parker Solar Probe (PSP), allowed to extend measurements of this thermal emission into the optical regime (Wood et al. 2021).

The Venus Emissivity Mapper (Helbert et al. 2016, 2020) builds on these recent advances. It is the first flight instrument specially designed with a focus on mapping the surface of Venus using the narrow atmospheric windows around 1 µm. By observing with six surface bands centered at 0.86 µm, 0.91 µm, 0.99 µm, 1.02 µm, 1.11 µm, 1.18 µm coupled with 8 atmospheric and calibration bands, VEM will provide a global map of surface composition (Dyar et al. 2020, 2021, Table 3 and Fig. 10). Continuous observation of Venus' thermal emission would also provide tight constraints on current day volcanic activity (Smrekar et al. 2010a; Mueller et al. 2017). Measurements of atmospheric water vapor abundance as well as cloud microphysics and dynamics would permit accurate correction of atmospheric interference.

VEM is a pushbroom multispectral imaging system. The telecentric optics images the scene onto a filter array, and the image is relayed by a three-lens objective onto the detector. VEM's optical sub-system sits on top of the electronics compartment and the power supply. A two-stage baffle protects VEM from scattered light. A 45° FOV yields a swath width of 207 km at an altitude of 250 km, providing a thorough sampling of surface emissivity and orbit-orbit repeat coverage.

Scattering at the cloud particles limits the achievable spatial resolution at the surface to approximately 50-100 km (Moroz 2002, 1990; Hashimoto 2003). The VEM optical system has a theoretical on-ground resolution of 300 m from a 250-km orbit. Using digital TDI, the data are reprocessed in the instrument at a spatial resolution of 1 km, providing a significant

Table 3 The 14 bands of the identical VEM instrument on VERITAS and the VenSpec-M instrument on EnVision, fall into four categories depending on the altitude range from which the near-IR radiation originates (Helbert et al. 2016, 2020, 2021). (1) Radiation for the surface bands at 0.86, 0.91, 0.99, 1.02, 1.11, 1.18 μm originates at the surface. Surface bands are used to determine rock types and to monitor the thermal signature of active volcanism. (2) Radiation in the water vapor bands originates in a layer near the surface (0.96, 1.15 μm) and is sensitive to the abundance of water vapor that may be produced by active volcanic plumes. (3) In the cloud bands at 1.195, 1.31, and 1.51 μm, the radiation originates in an atmospheric layer above the surface but below the clouds. Because the signal in the cloud bands has no surface or water vapor contributions, measurements in these bands can be used to remove cloud-induced contrast variability from the other bands. (4) The background bands at 0.79, 1.06, and 1.37 μm correspond to an atmosphere that is opaque, allowing the removal of background signal on the detector. The spectral widths of the bands, approximately ±10 to ±20 nm, are optimized to cover the full range of atmospheric windows based on radiative transfer modeling while minimizing out-of-band radiation

	Mineralogy & active volcanism	Clouds	Water	Background
Central wavelength (μm)	0.86 0.91 0.99 1.02 1.11 1.18	1.19 1.31 1.51	0.96 1.15	0.79 1.06 1.37

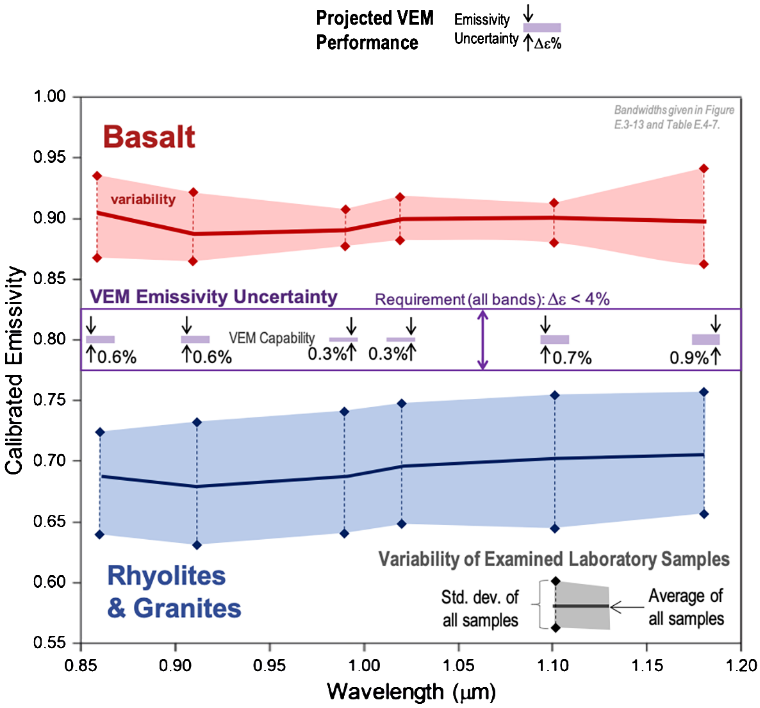


Fig. 10 The projected VEM performance in all surface bands far exceeds the 4% requirement and will enable creation of the first global map of composition on the surface of Venus, and distinguish between felsic and mafic rocks (Dyar et al. 2020, 2021). The 14 bands of VEM fall in four categories depending on the altitude range from which the near-IR radiation is originating. Bands at 0.86, 0.91, 0.99, 1.02, 1.11, 1.18 μm originate at the rocky surface (Helbert et al. 2016, 2020, 2021). See Table 3

gain in signal-to-noise ratio (SNR). Due to the low orbit required for the radar, the wide field of view of the VEM instrument would allow every spot on the surface to be viewed between 5 and 10 times in consecutive orbits. This would allow short-term variability in the atmosphere of Venus to be accounted for. To distinguish between surface and atmospheric contributions, VEM would use an updated version of the extensively tested data pipeline developed to process VIRTIS surface data (Helbert et al. 2008), combined with a radiative transfer model (RTM) (Kappel et al. 2012; Kappel 2014; Kappel et al. 2016). Data would be processed at 10 km spatial resolution and the data from consecutive orbits would be stacked. Both provide an additional increase in the SNR.

Of VEM's total of 14 bands, six would see the surface through all Venus atmospheric windows; three compensate for stray light; three measure cloud transparency; and two measure water abundance. The water vapor and cloud opacity channels would be used as RTM inputs to constrain near-surface water vapor abundance and cloud particle distributions. Observations at 1.16 μm have sufficient accuracy and precision to enable a search for active volcanic outgassing from retrievals of the water concentration in the atmosphere. Multiple observations over the duration of the mission would be used to account for additional unknown atmospheric variability not accounted for in the RTM. This would reduce both atmospheric and instrument noise by averaging image swaths acquired at different times. Applying an updated analysis (Dyar et al. 2020) of atmospheric error for VEM parameters, and taking multiple look averaging into account, our capability for emissivity precision is between 0.3 and 1.2%.

4.3.3 Radio Science / Gravity Experiment

The gravity investigation of VERITAS aims to fill the large knowledge gap on the internal structure of Venus as compared to the other terrestrial planets and the Moon. This investigation addresses Venus evolution science goals involving interior structure of thermal state (Sect. 4.1.2). Geophysical models of the interior are based on limited data for mass, radius, gravity, and topography. Work by Dumoulin et al. (2017) indicates that the state of the core and its size, as well as the viscous response of the interior, can be well constrained by the VERITAS requirements, that is a determination of k_2 to ± 0.01 and of e to $0.25°$ accuracies. These accuracies will be further improved through the use of radar tie points from VISAR (Cascioli et al. 2021).

As introduced in Sect. 4.1.2, precise measurements of the Moment of Inertia factor (MOIF) through the pole precession rate, the tidal Love number, k_2 and the tidal phase lag, e, will permit the first useful comparisons between the interior of Venus and other terrestrial planets. VERITAS will measure the precession rate with an accuracy of 50 arcsec/cycle (1 cycle equals 1 Venus sidereal day or 243.02 Earth days). Information derived from the moment of inertia is crucial to model the thermochemical evolution of Venus' interior including differentiation, as well as key surface processes; e.g., core size which is a key parameter in predicting vigor of mantle convection and the size and number of hot mantle plumes. Recent determinations of the pole precession and the Moment of Inertia factor (MOIF) at 0.337 ± 0.024, using Earth-based observations of radar speckles tied to the rotation of Venus in 2006–2020, find a core radius of approximately 3500 km (58% of the planetary radius) with large (>500 km) uncertainties due to both model limitations and current uncertainties on normalized moment of inertia C/MR^2 (Margot et al. 2021). VERITAS will determine core to $\pm$ 20 km using both the gravity field and radar tie points (Cascioli et al. 2021). Additionally, loading of the surface by the atmospheric thermal tides can be extracted from the gravity field, providing further constraints on both interior structure and atmospheric circulation (Cascioli et al. 2023).

The knowledge of crustal processes, essential to determine why and how Venus and Earth diverged, will greatly benefit from high fidelity mapping of the gravity field. As discussed in

Sect. 4.1, global gravity and topography data are linked at long wavelengths to the structure and dynamics of the sub-lithospheric mantle, and therefore can be used to estimate the elastic thickness/thermal gradient, which constrains mechanisms of formation and how different Venus' evolution processes are from Earth's (Mazarico et al. 2023). Doppler measurements are the primary observables for reconstructing the orbit of the spacecraft and recovering the gravity field of a planet. These measurements are collected by recording the Doppler shift of a radio signal sent from the ground station to the spacecraft, which then coherently retransmits it back to the Earth by means of an onboard transponder. The estimation of Venus' gravity field and VERITAS orbit will rely on the use of advanced orbit determination codes built on accurate mathematical models of the solar system dynamics and of the observables. The 2-way Ka-band radio tracking data are analyzed to reconstruct the VERITAS trajectory and estimate model parameters. The gravity field harmonic coefficients up to an average degree strength of 130 ($\sim$145 km) are generated together with corrections to the spin rate and to the pole right ascension and declination.

By combining global high-resolution gravity and topography VERITAS would look for possible subduction, buried features (e.g., as observed on Mars and the Moon) and unrecognized deformation. In addition, the improved uniformity of the gravity field knowledge would provide precise estimates globally of the elastic thickness, a proxy for heat flow.

4.4 Summary / Outcomes Revealing Venus Evolution

NASA's VERITAS mission is designed to study the geologic evolution of Venus and the processes that affect the habitability of terrestrial planets. Venus most likely had elements essential for habitability because its present conditions can be seen as a geodynamic analog to early Earth, when the lithosphere was hotter and thinner, plate tectonics and continents began to form, and life emerged.

VERITAS will carry two instruments: VISAR and VEM. The Venus Interferometric Synthetic Aperture Radar (VISAR) X-band measurements will provide: 1) a global digital elevation model (DEM) with 250 m postings, 5 m height accuracy, 2) Synthetic aperture radar (SAR) imaging at 30 m horizontal resolution globally, 3) SAR imaging at 15 m resolution for targeted areas, and 4) surface deformation from RPI at 2-centimeter vertical precision for $>$12 200 $\times$ 200 km potentially active area targets. Community input would be solicited for both RPI and high-resolution imaging targets. VEM will produce surface coverage of most of the surface in 6 near-IR bands located within five atmospheric windows and of eight atmospheric bands for calibration and water vapor measurements. VERITAS will also conduct radio science. Magellan spherical harmonic gravity field has an average resolution of only 550 km. Rigorous modeling shows that VERITAS data, with an average resolution of 155 km, would enable estimation of elastic thickness-a proxy for thermal gradient and resolution of specific geologic processes. Measurements of the moment of inertia factor and k_2 will constrain core size and state (Cascioli et al. 2021). The reader may refer to Smrekar et al. (2022a) for a full mission overview.

The VERITAS mission profile consists of two phases. Science Phase I (SP1) occurs while aerobraking is paused, about 6 months after insertion into a polar elliptical orbit. Science Phase II (SP2) starts after further aerobraking has placed VERITAS in a near-polar, circular, low-altitude orbit that allows global observations throughout the mission. Over $\sim$3.5 Earth years, the mission will return synergistic, global datasets with unprecedented coverage, resolution, and accuracy to meet its science goals: high resolution topography, X-band radar imagery, targeted surface deformation, near-IR spectroscopy and gravity. The VERITAS spacecraft downlinks a total of 20.9 terabits of data to the DSN stations using

CCSDS packets. The total volume of science data products to be archived (raw, reduced, and derived) is estimated to be 134 terabytes. These rich datasets will allow VERITAS to meet key required investigations and science objectives.

VERITAS' rich global datasets will provide an invaluable resource for a new generation of Earth, planetary, and exoplanet scientists, and reveal the truth about how Earthlike Venus really is. These datasets are highly synergistic with DAVINCI (Sect. 5) and EnVision (Sect. 6), providing information about Alpha Regio and identifying key targets for EnVision exploration. These missions also enrich VERITAS contributions by, for example, providing high resolution visual and near-IR images of Alpha Regio (i.e., DAVINCI flyby near-IR emissivity and sub-cloud near-IR imaging and high-resolution local topography before the VERITAS launch) and continuing the search for volcanic activity (EnVision).

5 Deep Atmosphere Venus Investigation of Noble Gasses, Chemistry, and Imaging (DAVINCI)

DAVINCI inherits the legacy of the successes of previous atmospheric probe missions, connecting definitive analytical chemistry of Venus' deepest and bulk atmosphere with new surface compositional constraints linked to the history of water. It provides critical measurements about the evolution of the atmosphere via noble gas isotopes, isotopes of hydrogen (D/H), and other species all in a highly detailed physical context while also imaging the surface in the near-infrared from under the clouds at spatial scales not possible from orbital altitudes.

5.1 DAVINCI Science Objectives

Compelling recent insights (e.g., Garvin et al. 2022a), and the planet's relevance to exoplanetary systems (Kane 2022; Way et al. 2023, this collection), have raised new questions about Venus' atmosphere, climate, and habitability evolution through time. Since 1978, six orbiting missions have comprehensively mapped Venus' surface and upper atmosphere. Despite the success of these reconnaissance missions and prior missions to the surface (Venera and VeGa landers), significant knowledge gaps about Venus' early state and overall evolution remain that can only be addressed through state-of-the-art *in situ* analytical and flyby remote sensing measurements. The international scientific community is now asking key questions about a possible long-lived oceanic state and considering past and present life on Venus, posing new hypotheses that are directly testable by measurements of the local surface and atmosphere.

5.1.1 Overview

The Deep Atmosphere Venus Investigation of Noble gasses, Chemistry, and Imaging (DAVINCI) mission is one of several needed next steps in Venus' exploration, originally suggested by Morrison and Hinners (1983) in their summary of solar system exploration priorities. DAVINCI will be the first mission to Venus to incorporate science-driven Venus dayside and nightside flybys and an instrumented descent sphere (DS) into a unified architecture. The mission will deliver both a deep atmosphere probe and a flyby remote-sensing carrier relay imaging spacecraft (CRIS) to Venus; it will assess the habitability of Venus over time, establishing how the planet evolved from upper atmosphere to the surface. Its complement of *in situ* and remote sensing measurements will reveal the processes that may

Table 4 The DAVINCI mission traces its primary science goals and objectives through the operation of its 7 instruments to specific outcomes related to Venus' evolution and connections to exoplanets like Venus. Each of the Key Science questions (Left column) is linked to Planetary Decadal Survey questions including # 3, 6, 10, and 11 (NASEM 2022) with specific measurement strategies listed (middle column). Color codes map instruments shown at far right (column) to key questions at the far left. The CUVIS technology demonstration instrument will provide 0.2 nm UV (200-400 nm) spectral observations of the Venus dayside at favorable solar phase angles on both flybys (January, November 2030), providing raw spectra as well as AI/Machine Learning analysis on-board (see Sect. 5.4.2)

DAVINCI Goals Address Key Questions		VMS	VTLS	VASI	VfOx	VenDI	VISOR	CUVIS
Key Science Questions	*Traceability of DAVINCI Measurements*							
What is the origin of the Venus atmosphere and how has it evolved? How and why is Venus different from Earth and Mars, and how does it compare to Earth-sized exoplanets?	**VMS**: noble gas abundance and isotope ratios to test current hypotheses of origin and evolution **VMS & VTLS**: atmospheric and isotopic composition, search for exotic chemistry, constrain mineralogy by constraining surface-atmosphere exchange **VfOx**: oxygen abundance near the surface **VISOR & CUVIS**: UV absorbers in the upper clouds and dynamics from flybys							
Was there an early ocean on Venus? If so, when and where did it go? What is the rate of volcanic activity on Venus?	**VMS, VTLS, & VASI**: D/H and other key trace gases above and below the clouds down to the surface; history of water **VMS**: radioactive decay products ^{40}Ar and ^{4}He to determine long-term and recent volcanism rate **VenDI & VISOR**: compositional insights into past water-rock interaction							
What exactly are the tesserae highlands? What is their origin and history? How do they compare with major highlands?	**VenDI**: high-resolution morphology, composition, and role of crustal water in igneous rock formation and erosional processes at Alpha Regio **VfOx**: constrain surface redox state through oxygen measurements near the surface-atmosphere interface **VISOR & VenDI**: IR emissivity for composition at scales of 5-200 m (VenDI) and ~70 km (VISOR) to constrain regional composition of mountains on Venus							

have allowed surface water to persist and then dissipate. DAVINCI will further establish new bounds on planetary habitability and enable-improved interpretation of biosignatures in our solar system and beyond (Garvin et al. 2022a; VEXAG 2019; U.S. National Academies of Sciences, Engineering, and Medicine/NASEM 2022).

DAVINCI fully addresses its three overarching science goals (Table 4), which are described in the next three subsections: (1) Atmospheric origin and evolution (Sect. 5.1.2); (2) Atmospheric composition and surface interaction (Sect. 5.1.3); (3) Venus surface properties (Sect. 5.1.4). The results will further catalyze years of productive follow-on scientific analysis that will quantitatively connect Venus to exoplanets and place its evolution into the context of recently selected orbiter missions VERITAS (Sect. 4) and EnVision (Sect. 6).

5.1.2 What Is the Origin of Venus' Atmosphere and How Has It Evolved?

Atmospheric Origin and Evolution. - DAVINCI answers questions about atmospheric formation and evolution of habitable zone planets, including the timing and rate of volcanic outgassing in the past and present that can only be addressed through *in situ* measurements of key noble gasses (including Xe) and nitrogen, never before adequately measured for Venus. DAVINCI unambiguously quantifies atmospheric noble gasses deeply enough (below ∼60 km) to avoid strong compositional dependencies on time of day, latitude, and molecular mass prevalent higher in the atmosphere. This information will help us understand similar evolutionary processes for exoplanets of various ages, many of which are expected to be Venus-like.

Enticing Earth-based remote sensing data have suggested the presence of phosphine, a possible biosignature, in the atmosphere of Venus (Greaves et al. 2021), an evidence later questioned (Encrenaz et al. 2020b; Villanueva et al. 2021). Modern life detection science strategies summarized in framework reports by the USA National Academies of Sciences requires that putative biosignatures be evaluated within the systems-level chemical context of the environment – presently poorly constrained at Venus. Investigating its past and present habitability through a definitive analysis of chemical reservoirs and cycles would revolutionize our understanding of Venus, its place in our solar system, and its prospects as a future astrobiology target (Limaye and Garvin 2023).

5.1.3 Was There an Early Ocean on Venus?

Atmospheric Composition and Surface Interaction. - DAVINCI tests hypotheses of when and how Venus lost its putative early oceans, plus chemical processes in the cloud and sub-cloud atmosphere down to the surface. The descent profile enables vertically resolved (i.e., at altitude scales as fine as 100-200 m) measurements of chemical species across a broad mass range combined with high-precision abundances and isotopes of targeted trace gasses. The highest cadence measurements focus on the deep atmosphere (<16 km), which contains 66% of the atmospheric mass, where no definitive *in situ* data exist and orbiting remote sensing techniques are largely blind. Such precision and broadband analysis is critical to reveal unknown chemical cycles. Cross-calibrated descent and flyby surface emissivity mapping in the near-infrared ($\sim$1 μm) will connect the deep atmosphere chemistry measurements to compositional maps of Alpha Regio and other tesserae.

5.1.4 What Are the Tesserae Highlands, Their Origin and History?

Surface Properties. - Analysis of the near-IR radiance of Alpha Regio tessera using VEx VIRTIS data shows that the tessera material differs from the plains materials in a manner that is consistent with a lower FeO (more felsic) content (Gilmore et al. 2015), corroborating earlier measurements by Galileo NIMS during its Venus flyby (Hashimoto et al. 2008). During the descent above western Alpha Regio, which is also the largest (1600×1300 km) known exposure of tessera terrain, the DAVINCI probe distinguishes felsic rock (i.e., formed in association with water) from others, such as primitive basalt, at new spatial scales (<100 m) not accessible from orbit via multi-band near-IR descent imaging in 3D context. Alpha Regio is considered an ideal, representative example of tesserae terrain unique to Venus. Compositional constraints from the high-sensitivity 3D views produced by the near-IR descent imaging system will be developed at unprecedented resolution (5-200 m) to connect with $\sim$60-km scale emissivity mapping from the DAVINCI CRIS remote sensing flybys, as well as previous (VEx) and future orbital data (e.g., from Venus emissivity mapping to be accomplished by VERITAS and EnVision in the 2030's). Existing orbital radar (SAR) and near-IR emissivity data have insufficient spatial resolution to characterize such geomorphology definitively without ground-truth from DAVINCI from beneath the clouds, including meter-vertical resolution imaging and derived topography.

5.2 DAVINCI Mission Overview

DAVINCI inherits the legacy of the successes of previous missions, connecting definitive analytical chemistry of Venus' deepest atmosphere with new surface compositional constraints at regional scales from flyby near-infrared remote sensing. DAVINCI probes the composition and physical structure of Venus' atmosphere from an altitude of $\sim$67 km (in the upper clouds) to the surface, addressing terrestrial planet formation, evolution, and the boundaries of habitability (Table 4). During its robust operational phase, including two science-guided Venus flybys, a $\sim$1-hour descent probe *in situ* investigation, and options for extended mission operations (Fig. 11), the DAVINCI mission acquires up to 500 Gbits of uncompressed data about Venus in <2.1 years.

Fig. 11 DAVINCI offers definitive measurements from the top of the Venus cloud deck to the surface, while observing cloud dynamics and regional composition of key highlands including Alpha Regio. The Figure shows the nominal launch in June 2029; after a ∼6-month cruise, the spacecraft would fly by Venus in January 2030 for initial remote sensing in the UV and near-IR, then the trajectory returns 9 months later for a second flyby in November 2030. Both flybys will include dayside UV imaging and spectroscopy, as well as night side near-IR surface emissivity mapping of multiple tesserae including Alpha Regio. After an additional 7-month cruise, the flight system will deliver the probe in June 2031 for its entry, descent, and science campaign above western Alpha Regio at very high solar illumination conditions

DAVINCI nominally launches in June 2029 (Garvin et al. 2022a). - After a ∼6-month cruise, the Carrier Relay Imaging spacecraft (CRIS) flies by Venus for unique remote sensing science (i.e., near UV cloud motion videos, near-IR surface emissivity of tesserae and volcanic centers), before setting the spacecraft on a trajectory to return for a second science flyby, followed by delivery of the *in situ* probe to Alpha Regio, with favorable solar illumination (Figs. 11, 12). DAVINCI's imaging target area within western Alpha Regio has been comprehensively mapped by prior missions (and Arecibo radiotelescope, see Sect. 11, Sect. 11.1.1) and is large enough to avoid complex controlled descent. DAVINCI's entry-descent-touchdown ellipse (∼348 × 160 km) fits within this area with large margin and high-resolution near-IR descent images will assess its relevance to the history of Venus water in association with rock units and geomorphology.

In June 2031, two days before arrival at Venus, the Probe Flight System (PFS) is released. The Carrier-Relay Imaging Spacecraft (CRIS) observes PFS release (via imaging using the VISOR camera system) then conducts a divert maneuver to communicate with the descent sphere (DS) throughout the *in situ* science mission (i.e., by flying overhead with its 2 m HGA for two-way S-band telecommunications). The DAVINCI descent sphere is a hermetically sealed titanium pressure vessel with dimensions (1.1 m × 0.85 m; 250 kg) similar to the Pioneer-Venus Large Probe (PVLP). After DS atmospheric entry and parachute deployment (∼70 km altitude), the heat shield is released and the DS-based instruments begin to collect and transmit altitude-resolved, high-fidelity measurements of noble, trace gas, and isotopic abundances; atmospheric temperature, pressure, and winds; and high-resolution broadband and ∼1 µm narrow-band images (Fig. 12). Although not required to function following touchdown, the DS has sufficient resources to conduct science and relay data for an additional ∼18 minutes from the surface, if it survives the ∼13 m/s touchdown. After the CRIS spacecraft has recorded the required probe *in situ* data, it turns toward Earth and transmits those data to the DSN. Via an optional extended science mission, six months after the DS entry-descent-science phase, the CRIS spacecraft conducts a Venus orbit-insertion (VOI) maneuver and enters a 5-day, 60-degree inclined science orbit for most of a Venus year (∼6 months), mapping dayside cloud dynamics and nightside near-IR surface emissivity potentially at the same time as VERITAS observes the surface with its powerful payload to evaluate synergies including those associated with different observational times.

DAVINCI delivers definitive atmospheric chemistry measurements, coupled to unprecedented 3D views of ancient tesserae at local scales (5-60 m horizontally) that will transform

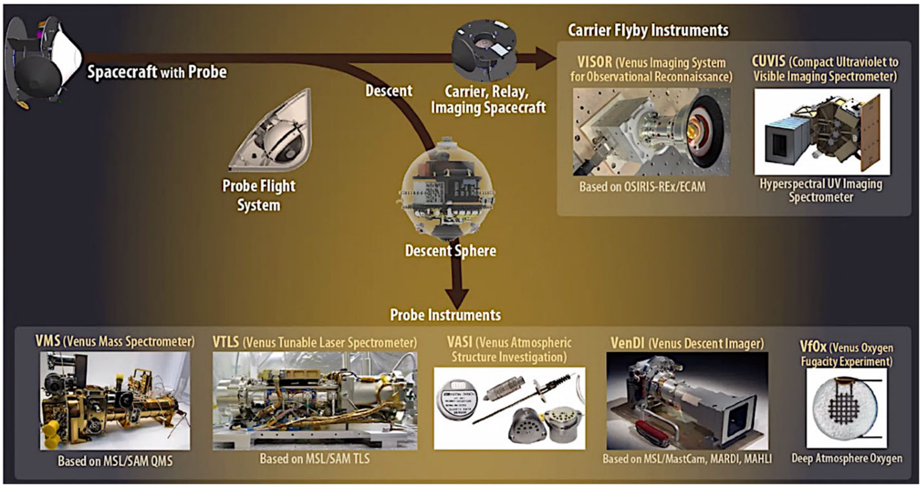
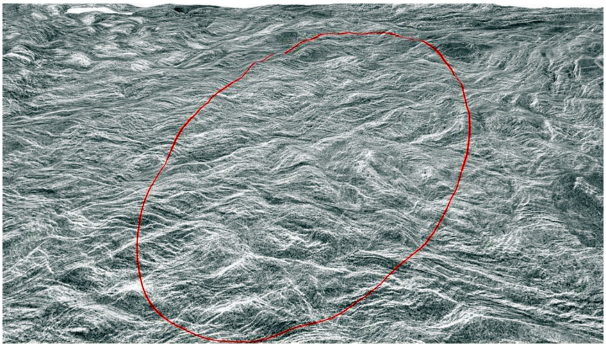


Fig. 12 DAVINCI delivers critical science using five descent sphere (DS)-based instruments, and two remote-sensing instruments on the carrier relay imaging spacecraft (CRIS) (Figure from Garvin et al. 2022a). The probe instruments will operate during its ∼59 minute long descent from the upper clouds (∼67 km) to the surface over an entry-descent-science corridor with a landing error ellipse located within western Alpha Regio (see Fig. 13)

Fig. 13 DAVINCI entry error ellipse with Magellan S-band SAR mosaic draped over new 1 km scale Digital Elevation Model (DEM) of Alpha Regio based on combined Arecibo polarimetric radar & Magellan radar altimeter datasets (Garvin et al. 2022b, 2023, in preparation)



our understanding of the planet next door and serve as the foundation for future exploration. Given the recent unexpected but contentious discovery of phosphine at Venus (Greaves et al. 2021; Encrenaz et al. 2020b; Villanueva et al. 2021), *in situ* measurements are required to uncover new chemical cycles, including those involving oxygen, sulfur, phosphorus, and others. Enabled by DAVINCI's quantitative investigation of Venus' lower atmosphere and its pathfinding high-resolution near-infrared views of enigmatic tesserae, future missions can follow to accomplish additional 2022 Planetary/Astrobiology Decadal Survey objectives (NASEM 2022). DAVINCI's measurements can also be tied to JWST investigation of Venus analogue exoplanets around M-dwarf stars as "planetary atmosphere ground truth", which is underway at the time of this writing by the JWST observatory (see also Sect. 11, Sect. 11.2).

5.3 DAVINCI Descent Probe Instruments

Five descent probe instruments and two carrier-relay-imaging spacecraft instruments leverage highly successful partnerships between NASA/Goddard Space Flight Center (GSFC), NASA/Caltech Jet Propulsion Laboratory (JPL), NASA/Johns Hopkins University Applied Physics Laboratory (JHU/APL), and Malin Space Science Systems (MSSS), see Table 4; Fig. 12. These include the pairing of a quadrupole mass spectrometer and tunable laser spectrometer evolved from the SAM (Sample Analysis at Mars) suite on MSL/Curiosity rover now in its eleventh year of operation on Mars in Gale Crater. A flyby camera suite based upon imaging systems on the OSIRIS-REx mission provides sensitive nightside NEAR-IR mapping and dayside UV cloud imaging (with movies) from new vantage points over Venus. The *in situ* and flyby observations combine to define the DAVINCI mission baseline.

5.3.1 Venus Mass Spectrometer (VMS)

DAVINCI's Venus Mass Spectrometer (VMS) provides the first comprehensive survey of Venus' noble gasses, as well as detailed analysis of trace gas species – both those expected and those yet to be discovered. Employing mature, tested operational modes, VMS definitively measures isotope ratios for Ne, Ar, Kr, and Xe, and collects hundreds of measurements of each trace species to constrain fine variations with altitude. The VMS is a Quadrupole Mass Spectrometer (QMS) with a gas-enrichment system and pumping system that will provide a comprehensive *in situ* survey of the planet's noble gases. It has significant heritage from the Mars Science Laboratory/MSL (Curiosity) Sample Analysis at Mars/SAM QMS (Webster and Mahaffy 2011; Atreya et al. 2013) and with a broad mass range from 2 to 550 Dalton (Da), VMS has the capability to discover new trace gas species (Garvin et al. 2022a, Table 3.2) within the deep atmosphere where non-equilibrium chemistry is suspected.

VMS measurements will occur every $\sim$200 m or better below 61 km, particularly in the lowest 30 km of the atmosphere (Fig. 12), where it will probe the supercritical CO_2 boundary and properties of the CO_2/N_2 mixture in the temperature and pressure conditions of the deep atmosphere of Venus (Lebonnois & Schubert 2017), and profile new species, including CHNOPS-bearing molecules (including, potentially, P_4O_6 and PH_3) and those trace gases expected to be tied to surface mineralogy and the thermochemical cycle of sulfur-bearing species.

5.3.2 Venus Tunable Laser Spectrometer (VTLS)

DAVINCI's Venus Tunable Laser Spectrometer (VTLS) answers major questions about the Venus atmosphere by providing the first precise abundance and isotopic measurements of key gasses containing hydrogen, sulfur, carbon, oxygen, and potentially phosphorus. VTLS provides a series of ten definitive measurements of the D/H ratio in water vapor throughout the atmosphere (i.e., from 67 km to $\sim$2 km), critical to understanding the longevity, and loss mechanisms of past oceans (Way et al. 2023; Salvador et al. 2023, this collection). The instrument consists of a multipass Herriott cell with three laser channels at 2.64, 4.8, and 7.4 µm, specifically targeting key science questions that discriminate chemical processes in the upper clouds and near-surface environment. VTLS draws heritage from the MSL/SAM tunable laser spectrometer (e.g., Webster and Mahaffy 2011; Pla-Garcia et al. 2019).

VTLS is specifically tailored to answer critical questions about the long-term evolution of Venus' atmosphere by providing the first highly sensitive *in situ* measurements of key gas species containing H, S, C, and O, as well as their high-precision isotope ratios including

D/H (Garvin et al. 2022a, Table 3.2). It should be noted that VTLS offers the possibility to directly measure trace species at different heights in the clouds with a sensitivity of ∼1 ppbv, allowing to set new upper limits for PH_3 at the 1 ppbv level discussed in Villanueva et al. (2021) or Encrenaz et al. (2020b).

5.3.3 Venus Atmospheric Structure Investigation (VASI)

DAVINCI's Venus Atmospheric Structure Investigation (VASI) characterizes the fine-scale vertical structure and dynamics of the Venus atmosphere during descent, including wind speed, pressure, and the first detailed profile of the deep atmosphere temperature (e.g., the lapse rate, dT/dz). The instrument consists in a suite of sensors that measure atmospheric pressure, temperature, and dynamics. Internally mounted accelerometers and gyroscopes combined with Doppler tracking via the spacecraft-to-DS communications link enables detailed reconstruction of the descent probe trajectory. VASI provides thermodynamic context for the composition measurements and enables reconstruction of the detailed descent profile and precise landing position, with most measurements every 15-50 m, as well as a final measurement set within ∼100 m of the local surface.

5.3.4 Venus Descent Imager (VenDI)

DAVINCI's Venus Descent Imager (VenDI) is a near-IR descent-imaging system with a nadir orientation. It will deliver clear, high contrast, high SNR images (>100:1), providing the first geologic constraints on the highland surface environment at 2-200 m length scales from reflectance imaging below the cloud-deck (and sub-cloud hazes). A narrowband, near-IR channel delivers 1.02 μm albedo maps with sensitivity to felsic rocks or alteration products when ratioed against broadband images (0.74 to 1.02 μm). Topography can be derived using machine-vision algorithms via Structure-from-Motion (SfM), an expansion of Scale-Invariant Feature Transform (SIFT) algorithm to construct a Digital Elevation Model (DEM) from multiple overlapping images with varying vertical and horizontal baselines (Garvin et al. 2018, 2022a). SfM processing of bundles of descent images produces first 5 - 60 m scale topography of tesserae and establishes boundary conditions for tectonic and erosional models. Final imaging scales from VenDI below ∼1.5 km produce unblurred images at scales finer than 1 m, permitting feature-identification resolution of key indicators of sedimentary processes at scales that connect to those observed by prior Venera landers (e.g., Garvin et al. 1984). Evaluation of Earth-based analogue datasets (Pilbara, Zagros mountains) that emulate VenDI near-IR bandpasses and spatial scales have demonstrated discrimination of felsic surfaces at <100 m (down to 5-10 m) providing confidence that sub-cloud descent imaging will complement 50-100 km scale orbital near-IR emissivity mapping by multiple missions (see Sects. 4.3.2; 6.3.3).

5.3.5 Student Collaboration Experiment VfOx; DAVINCI's Engineering Science Investigation (ESI)

The oxygen cycle on Venus, like those involving sulfur, hydrogen, phosphorus, and carbon, is incompletely resolved on the basis of current data and DAVINCI's quadrupole mass spectrometer (VMS) and tunable laser spectrometer (VTLS) measurements of altitude-resolved species will extend beyond extrapolated equilibrium models of likely chemistry to measured abundances across the deep atmosphere all the way to the surface just about the complex ridged terrain in Alpha Regio.

Student Collaboration Experiment VfOx obtains independent measurements of the oxygen fugacity (fO_2) in the lowermost scale height of the Venus atmosphere to compare with indirect (and independent) measurements of oxygen-species retrieved by VTLS. DAVINCI's Student Collaboration Experiment partners with Johns Hopkins University (and others), engaging students to implement an *in situ* sensor that measures oxygen partial pressure, also known as fugacity (V*f*Ox).

DAVINCI's Engineering Science Investigation (ESI) meets high priority NASA measurement objectives for Venus entry with measurements tied to improving future Venus Entry, Descent and Landing (EDL) activities. Measurements that document the entry conditions after Atmospheric-Entry-Interface below 140 km will be obtained via support from NASA's Space Technology Mission Directorate in partnership with the Science Mission Directorate. Final instrument selection is in progress as DAVINCI advances toward its mission confirmation by NASA.

5.4 DAVINCI Carrier/Flyby Instruments

5.4.1 Venus Imaging System for Orbital Reconnaissance (VISOR)

VISOR is an integrated system of four cameras that provides global dayside coverage of Venus in the UV and nightside coverage in the near-IR (0.93–1.03 μm). Each of the VISOR cameras has a field of view of 11.3 degrees by 8.9 degrees which can be converted to a spatial sampling scale as a function of distance to target. Three cameras image night-side Venus in three independent near-IR bands, from 930–938 nm, 947–964 nm, and 990–1030 nm. They will deliver night-side surface emissivity mapping (three near-IR bands to properly characterize clouds and scattered light) to constrain regional composition at $\sim$60 km scales, unveiling new regional patterns associated with highlands during 2030 flybys prior to global mapping by two future orbiters.

DAVINCI first and second Venus gravity-assist flybys, with a closest approach on the night-side hemisphere near Equator at 00:00 LT, are scheduled on January 30 and November 15, 2030 for the planned June 2029 Launch Readiness Date (Table 1). Thousands of images are acquired during the two flybys, potentially identifying felsic regions, "calibrated" by local-scale, sub-cloud VenDI band-ratio mapping at Alpha Regio, as well as with VASI lapse rate information. The fourth VISOR camera will provide global, dayside coverage of Venus in the unknown UV absorber band (355–375 nm). Dayside UV imaging (single band) will measure cloud dynamics as the spacecraft approaches and recedes from pericenter, allowing ultraviolet feature tracking at 355-375 nm at a frequency that exceeds any existing Venus orbital imaging dataset.

5.4.2 CUVIS (Compact Ultraviolet Imaging System)

Technology Demonstration Opportunity (TDO) experiment CUVIS (Compact Ultraviolet Imaging System) acquires 0.2 nm resolution spectra and hyper-cubes of images from 0.2 to 0.4 μm, concurrent with VISOR UV imaging on the dayside flybys of Venus, in a technology demonstration of a new class of small planetary instruments. This UV hyperspectral sensor (CUVIS) will perform upper atmosphere SO_2 and SO chemistry and gather spectral information on the unknown UV absorbing species at a spectral resolution of 0.2 nm in the UV from 0.20 μm to 0.40 μm (Pollack et al. 1980; Wilson et al. 2023, this collection). CUVIS can be accommodated on the CRIS spacecraft and is implemented in a fully separable, *do no harm* fashion. It will further employ Machine Learning to identify key species and test approaches to accommodate effective data transmission for rich datasets such as those delivered by CUVIS. All of its observations will be coupled to VISOR near UV dayside observations which will provide wider field-of-view context (and multi-frame "movies").

5.5 Summary / Outcomes Revealing Venus Evolution

The overall DAVINCI mission, scheduled for launch in June 2029, will provide up to 500 Gbits (uncompressed) new data about the atmosphere and near surface, as well as the first unique characterization of the deep atmospheric environment and chemistry. DAVINCI returns to the Venus atmosphere at a time of heightened interest in understanding terrestrial planet evolution, habitability, and astrobiology in our solar system and beyond (NASEM 2022; Garvin et al. 2022a). Understanding the evolutionary pathways of Venus necessarily involves the interplay between the time-variable atmosphere-climate system, the lithosphere, and the interior. The NASA DAVINCI mission addresses several questions about such components of evolution as they relate to five of the key priorities (as questions) recently published in the US National Academies Planetary and Astrobiology Decadal Survey including for example numbers 3, 4, 5, 6, 10, and 12 (NASEM 2022).

DAVINCI's *in situ* analytical chemistry measurements of noble gasses in the bulk atmosphere will distinguish between current models by resolving the isotopic ratios of xenon, which is currently unmeasured. As for Mars, the full suite of noble gasses and their isotopes will provide chemistry boundary conditions for models that range from early impact blow-off of an initial atmosphere to the consequences of catastrophic volcanic resurfacing on the evolved atmosphere, as well as others. Coupled to these noble gas measurements are ten altitude-resolved observations of D/H in water from as high as 67 km down to the near surface at $\sim$2 km altitude.

A suite of 10 such measurements by means of DAVINCI's tunable laser spectrometer will expand upon Pioneer Venus Large Probe based measurements in the cloud deck (above 38 km) and those from remote sensing retrievals from ESA's Venus Express in the upper atmosphere, and connect to the state of D/H in the deep atmosphere, where surface-atmosphere interactions may have affected the history of water. Near surface quantification of the oxygen fugacity by means of multiple experiments (i.e., including the DAVINCI Student Collaboration experiment "VfOx", as well as VTLS and VMS) will resolve the state of oxygen species in the atmosphere and mineral stability near the surface in the tesserae highlands where DAVINCI will come to rest after its atmospheric transect. The oxygen cycle on Venus, like those involving sulfur, hydrogen, phosphorus, and carbon, is incompletely resolved on the basis of current data and DAVINCI's quadrupole mass spectrometer (VMS) and tunable laser spectrometer (VTLS) measurements of altitude-resolved species will extend beyond extrapolated equilibrium models of likely chemistry to measured abundances across the deep atmosphere all the way to the surface just above the complex ridged terrain in Alpha Regio.

Mineral stability assessments associated with rocks containing Fe, S, and other elements will be conducted to infer possible weathering pathways within $\sim$2 km of the surface, with direct connections to near-infrared band-ratio descent imaging in the 740 to 1200 nm spectral region at scales as fine as a few meters for potential identification of water-related rock units. Connections between the near-IR descent imaging of possible felsic rock compositions at scales from 100 m down to a few meters and the analytical chemistry of trace gas species potentially relevant to rock formation or modification processes will provide local ground-truth for global assessments of rock unit compositional patterns at 50-100 km scales across Venus. DAVINCI will further address aspects of evolution of the Venus deep atmosphere over time by directly measuring gradients in key species involving S, O, H, P, and

C as often as every 150-200 m in the deepest atmosphere where connections to local rock compositions can be made.

By the time DAVINCI completes its *in situ* transect of the atmosphere (late June 2031), new information of the vertical stratification of the atmosphere from 67 km to the surface as well as a resolved lapse rate (temperature vs altitude at 0.1 K precision every 15-50 m down to the surface) will enable systems-level modeling of Venus evolution that connect the history of the atmosphere to that of the lithosphere, with linkages to Venus tectonic evolution via connections with VERITAS observations. Ultimately the possible evolutionary signatures of water in the Venus system over time will be resolved, preparing the way for future landed experiments that make use of mineralogical signatures in the context of the massive Venus atmosphere that is clearly a major factor in Venus evolutionary divergence from Earth (i.e., see Kane 2022). For further details, see the mission overview in Garvin et al. (2022a).

6 EnVision: Understanding Why Earth's Closest Neighbor Is so Different

On June 10, 2021, the European Space Agency (ESA) announced the selection of EnVision as its 5th Medium-class science mission, targeting a launch in the early 2030s. EnVision is an ESA-led mission in partnership with NASA, providing its Synthetic Aperture Radar instrument, VenSAR and Deep Space Network support for critical mission phases. EnVision will use an array of payload instruments to perform holistic observations of Venus from its inner core to upper atmosphere to better understand how Earth's closest neighbor in the Solar System evolved so differently (European Space Agency 2021).

EnVision's overarching science questions are to explore the full range of geoscientific processes operating on Venus. It will investigate Venus from its inner core to its atmosphere at high resolution, characterizing the interior, signs of past geologic processes, and looking for evidence of past liquid water. As developed in companion articles, recent modeling studies strongly suggest that the evolution of the atmosphere and interior of Venus are coupled at all stages of the planet's long-term evolution (Way and Del Genio 2020; Weller and Kiefer 2020), emphasizing the need to study the atmosphere, surface, and interior of Venus as a system. EnVision's combination of surface and atmospheric measurements will characterize ongoing volcanic processes through an extended-timeline, search for their thermal, morphologic, and gaseous signatures, while also tracing key volatile species from the surface up to the mesosphere.

The mission is scheduled for launch in the fourth quarter of 2031 (see Table1); the final schedule will be agreed between ESA and NASA at Mission Adoption in January 2024, with back-up launch readiness dates every 6 months in 2032 and 2033, on Ariane 62. Following orbit insertion and periapsis walk-down, orbit circularization will be achieved by aerobraking over a period of several months, followed by a nominal science phase lasting at least 6 Venus sidereal days (4 Earth years). The EnVision payload consists of five instruments provided by European and US institutions (Fig. 14). The five instruments comprise a comprehensive measurement suite spanning infrared, ultraviolet-visible, microwave and high frequency wavelengths. This suite is complemented by the Radio Science investigation exploiting the spacecraft Telemetry, Tracking and Command (TT&C) system. All instruments in the payload have substantial heritage and robust margins relative to the requirements with designs suitable for operation in the Venus environment. This suite of instruments has been selected to meet the wide range of measurement requirements in support of EnVision science investigations.

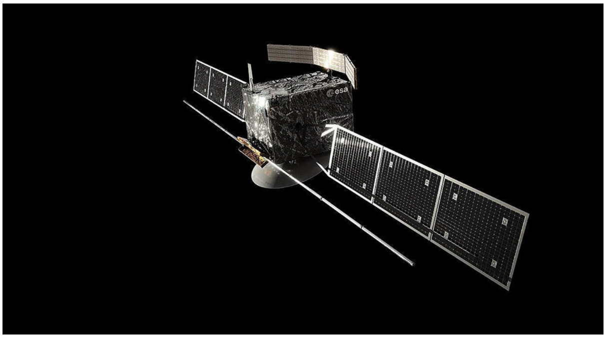


Fig. 14 Rendering of the generic concept EnVision spacecraft orbiting Venus, with the SRS, VenSAR feeder and reflectarray antennas deployed. Credit ESA / NASA / Paris Observatory / VR2Planets

6.1 EnVision Science Objectives

EnVision will deliver new insights into geological history through complementary imagery, polarimetry, radiometry and spectroscopy of the surface coupled with subsurface sounding and gravity mapping. It will search for thermal, morphological, and gaseous signs of volcanic and other geological activity; and it will trace the development and transport of key volatile species from their sources and sinks at the surface through the clouds up to the mesosphere. Following the same approach through which our understanding of Earth and Mars has been developed, EnVision will combine global observations at low or moderate spatial resolution (e.g., surface emissivity and atmosphere composition) with regionally targeted observations of higher spatial resolutions from a dual polarization S-band synthetic aperture radar (SAR) and subsurface sounding radar profiles.

6.1.1 Overview

EnVision will investigate both present and past geological activity on Venus, and how its atmospheric, surface and interior processes are linked. The background for EnVision's scientific investigations and strategic knowledge gaps is presented in this Section following the lines of three top-level science questions:

1. History - How have the surface and interior of Venus evolved?
2. Activity - How geologically active is Venus?
3. Climate - How are Venus' atmosphere & climate shaped by geological processes?

6.1.2 How Have the Surface and Interior of Venus Evolved?

Geologic Mapping of Volcanic Features and Their Surface Morphology. - Geologic mapping of volcanic features and their surface morphology and dielectric constant is a cornerstone of Magellan data interpretation (Campbell and Campbell 1992; Campbell 1994). There is a need to carry this work to finer spatial scales and into the subsurface to answer fundamental questions of localized stratigraphy (from subsurface profiles and geologic mapping from images), magma composition (from morphology, roughness, and dielectric properties), surface mineralogy, order-of-magnitude eruption rates and volumes (from morphologic features and subsurface profiles), and post-emplacement weathering (from morphologic features and dielectric properties). In a complementary approach to VERITAS, EnVision will accomplish this objective in part through SAR imaging at 10 m resolution and polarimetric imaging at 30 m resolution (Fig. 15), along with VenSpec-M surface investigations. EnVision 30-m SAR imagery will dramatically enhance our understanding of volcanic surface

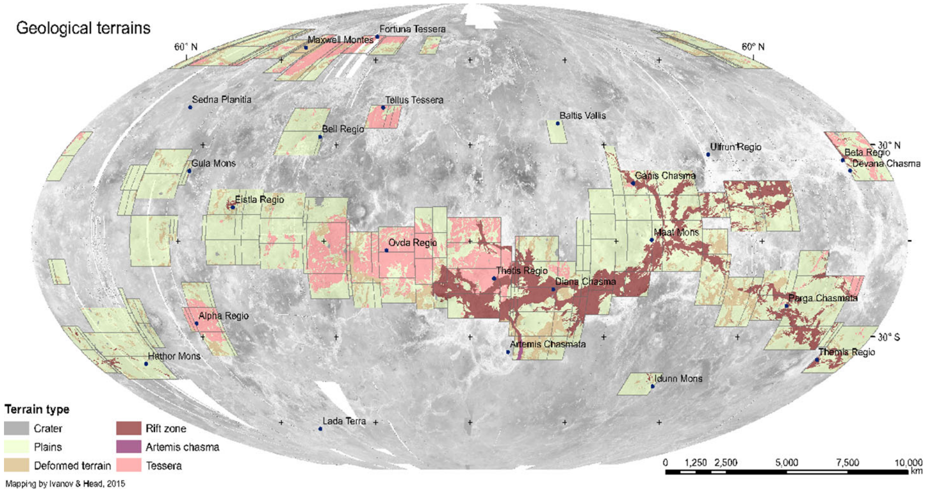


Fig. 15 Map of geological terrains and named landmarks covered by the Regions of Interest (RoIs) defined in EnVision's Science Operations Reference Scenario. The RoIs are chosen to include representative samples of all major geological terrain and feature types. These different features are not distributed at random but are in specific, known locations. EnVision's approach is to define roughly thousand-kilometer square RoIs covering most of the highlands and a representative selection of the lowland features. This strategy allows to progressively build up along the 6 cycles the required global and targeted measurements dataset, in particular over all pre-selected regions of interest, which represent a fraction of about 30% of Venus surface. Definitions of geological terrain types are as mapped by Ivanov and Head (2015)

features. At the >120 m resolution of Magellan (120 m azimuth resolution and 93 m best case range resolution), features like flow channels are visible only where they are at the highest end of those typically seen in terrestrial flow fields, vent locations and associated ash or rugged clinkers are too small to observe, and collapsed tubes or skylights are unseen. Within any single major shield volcano, there are often a wide range of features indicative of magma storage beneath calderas, rapid eruptions that form rugged, channelized flows, fine-grained pyroclastic ash from volatile-rich eruptions, and steep-sided constructs linked with higher-viscosity magma (Campbell and Rogers 1994). Targeted observations at 10 m resolution will bring out crucial details in the stratigraphic relationship between flows, their likely thickness, and the range of scales in flow fields (i.e., short high-volume eruptions or long-term, tube-fed complexes).

Variations in Morphologic Characteristics, Stratigraphic Relationships, and Dielectric Properties of Plains. - The volcanic plains cover around 80% of Venus. Far from being uniform, they exhibit signs of extensive geological activity, from volcanic and tectonic to aeolian and weathering processes. Did the plains form rapidly, with few flow boundaries (like lunar mare) or are they constantly reformed by small-scale volcanism, below the resolution of Magellan? Understanding and mapping stratigraphic boundaries is important in distinguishing geologically old and young units, and between directional and equilibrium surface histories.

The Subsurface Radar Sounder (SRS) will be used to look for layering in the plains and elsewhere on Venus, as has been successfully done on both the Moon and Mars (Fig. 16, and Sect. 6.3.2 below). Analyses of this type enable a far better understanding of Venus's recent geological past and reveal vital information about the character, thickness and mode of resurfacing on Venus. For example, catastrophic resurfacing models for Venus (Strom

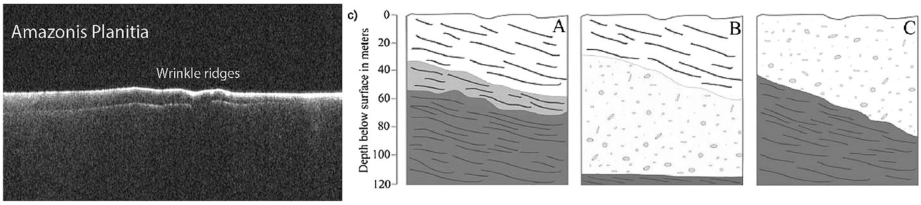


Fig. 16 (a, left): A SHARAD radargram showing layering about 100 meters thick in Amazonis Planitia warped by wrinkle ridges. The image is 400 km across (Campbell et al. 2008). (b, right): Schematic representation of the three potential scenarios of subsurface stratigraphy interpreted from SHARAD radar sounding of volcanic layering in the Arsia Mons caldera (A - stacked lava flows with vesiculated and less dense flows overlying very dense lava, B - less dense lava-flow and a thick tephra deposit overlying denser bedrock, C - pyroclastic or other low-density material deposited over dense lava- flows in the southern part of the caldera, adjacent to the wall (Ganesh et al. 2020; Watters et al. 2006)

et al. 1994) predict that the plains were resurfaced in a brief epoch several hundred million years ago. In such a model, there might not be sufficient time between lava flows to develop thick weathering layers that would produce discrete layered returns in SRS data. If SRS does detect clear layering in the plains, it would tend to favor more gradual resurfacing models for Venus.

Mapping of Tectonic Structures. - Magellan observations provide a valuable overview of tectonic processes on Venus (Solomon et al. 1991), but are limited by the resolution of the radar images and especially the topography (10-30 km). Complementing observations by VERITAS, EnVision's much higher horizontal resolution: 10-30 m imagery, 300 m horizontal resolution of the SAR stereo Digital Elevation Model (DEM) will enable much clearer definition of the styles of tectonic deformation and of the superposition and cross-cutting relationships used by geologists to map the sequence of deformation in a given region.

High resolution radar data are particularly essential in understanding the tesserae of Venus, which contain fine-scale, complex patterns of deformation. We expect that tesserae represent the oldest terrain, locally, but they may not have all formed at the same time; better understanding of their structure and arrangement, their relationship with volcanic terrains and their correlation from one place to another would help to unravel these temporal and structural conundrums. Magellan imagery revealed very varied tesserae interiors often with complex arrangement of solid and deformed rocks, blanketed by finer grained or smoother materials (Hansen and Willis 1996; Ivanov and Head 2011) but without greater spatial resolution and better topographic detail, the nature of the materials and their origins could not be resolved. Multi-polarimetry observations (HH and HV) are needed to better understand their surface textures and physical structures, to reveal emissivity variations of solid lithologies and to discriminate them from unconsolidated materials.

Impact Crater Modification. - The only method for determining the absolute age of a surface, in the absence of measurement of radioactive isotopes, is through the use of crater counts. Because Venus has so few craters it is difficult, or impossible, to distinguish the age of different geological units using craters alone. However, craters on Venus are modified to varying degrees, first by loss of radar-dark halo, and then by infilling, causing dark floors. Some are also modified volcanically or tectonically (Izenberg et al. 1994). Because initial crater depth depends on crater diameter, the extent to which a particular crater deviates from the expected depth-diameter relationship provides a guide to post-impact infilling by lava or sediments at that crater. The height of the crater's rim above the surrounding terrain similarly provides a guide to the thickness of post-impact fill in the crater's ejecta blanket. Initial estimates of crater fill with Magellan data (Herrick and Rumpf 2011) were limited by the accuracy of the available stereo topography digital elevation model. In contrast, VenSAR observations will be optimized to produce high resolution DEMs and nadir altimetry profiling will provide global topographic data. Possible direct measurements of crater infilling with sounding radar will be complementary to topography-based estimates of crater fill thickness. Craters are globally distributed, so such measurements can provide important new information about the global resurfacing history of Venus.

The Heat Engine in Venus' Interior: What Are the Driving Forces for Volcanism and Tectonism? - While Venus and Earth have similar bulk geophysical properties, they have clearly followed divergent geodynamic paths – the former apparently characterized by a strong continuous lithosphere and stagnant lid convection, and the latter characterized by plate tectonic recycling of the lithosphere (Rolf et al. 2022, this collection; Gillmann et al. 2022, this collection; Herrick et al. 2023, this collection). At the root of these distinctions, it is interior dynamics that essentially governs the cooling of a planet. Stagnant lid convection represents a heat transport mechanism much less effective than mobile lid convection. It shows different tectonic characteristics than the plate tectonic regime on Earth. Internal dynamics can therefore cause surface stresses and thus tectonic structures on the planetary surface. Different convection regimes will lead to different tectonic characteristics. As a result, it is expected that planetary surfaces reflect their inner dynamics: a number of features on Venus are tantalizingly similar to structures on Earth, including continent-like tesserae plateaus, chasmata interpreted as rift zones, and some coronae that are surrounded by troughs resembling subduction zones.

6.1.3 How Geologically Active Is Venus?

Detecting Volcanic Activity in Repeated SAR Images. - Detecting and characterizing of relatively large eruptions over the past 40 years will come from three sources in the SAR image data: i) any new, large lava flows (>200 m wide and 100s m long) erupted since the Magellan mission and within EnVision's mapped area will be revealed in the imaging cycles of the EnVision mission; ii) any large scale changes in the morphology of volcanic edifices will also be revealed within EnVision cycles; and iii) any new, small lava flows (>60 m wide and at least a few hundred meters long) erupted in the 4-year duration of the EnVision mission. Detected changes (or non-detection) will be used to place bounds on the volcanic activity rate as described in Lorenz (2015).

Searching for Surface and Near-Surface Temperature Changes. - In addition to SAR imaging, temperature signatures associated with volcanic activity from both hot lava and hot volatile gasses will be detected and monitored in the infrared (IR) and microwave domains. Temperatures associated with volcanic eruptions can range from only 500 °C for low viscosity carbonatite lava to well over 1000 °C for ultramafic lavas. Such young, hot lavas will be directly detectable by their signature in IR emissivity data, (provided lava outflows cover an area of at least 0.1 km^3). Cooling rates at the surface are estimated to be on the order of hours (Mueller et al. 2017), but microwaves offer the prospect of sensing the shallow subsurface and thus may detect warmth from old lava flows, i.e., lava flows which have cooled at the surface possibly years ago and thus have no more IR emission signature but are still hundreds of K above ambient at depth (Lorenz et al. 2016). Polarimetric radiometry measurements (used to determine whether candidate areas have anomalous emissivity rather than high physical temperature) and a better knowledge of the topography (and therefore of the altitude-dependence of the surface physical temperature) will greatly enhance the reliability of the volcanic detection and monitoring.

Understanding the Range and Scope of Mass-Wasting Processes (Landslides). - Though Magellan imagery showed us evidence of mass-wasting and aeolian features, it was not able to reveal their temporal changes during the mission's lifetime, so their geomorphological and temporal properties remain unknown, and we have almost no information about weathering, surface alteration or other aeolian processes. Since there is currently no constraint on the mechanisms and rates at which these processes might be occurring, better topography and nested imaging at multiple resolutions, and repeated imaging during the mission, are needed.

Landscape evolution refers to processes that modify the morphology of a planet's surface, in particular gravity-driven mass-wasting processes such as landslides and slumps. Mass-wasting is a ubiquitous geomorphological process operating on any planetary body with gravity (such as those observed on Earth, the Moon, Mercury, Venus, Mars, icy satellites, comets and asteroids). Malin (1992) provided the first evidence of mass movement on Venus in the form of large-scale slope failures. Magellan's imagery also provided evidence for two dune fields (Greeley et al. 1992, 1995) and indirect evidence for putative 'micro-dunes' (Weitz et al. 1994) that were not resolved by the 100 - 200 m spatial resolution of Magellan's imagery. The surface winds evidenced by these dune fields and by wind streaks and debris fans (downwind of impact craters) are likely to be important agents of aeolian geomorphological change, but data of higher spatial and temporal resolution, and the ability to distinguish loose from consolidated surface materials, are needed to characterize them. Higher resolution, VenSAR observations, with consistent geometry, should reveal many smaller features and better resolve the morphology of features that were not resolved by Magellan. Repeated observations of regions expected to be active, e.g., along rifts, will help to characterize processes operating at decadal (Magellan-VERITAS-EnVision comparison over 40 yrs) and yearly (EnVision inter-cycle comparison) time scales. Local scale DEM's at 5-60 m spatial sampling within the Alpha Regio tesserae will complement the EnVision measurements at scales as wide at 150 km^2.

In the absence of near-surface water which, on Earth, affects material bulk density, shear strength and pore-pressure, and thus leads to slope instability, the mechanisms of slope instability and failure on Venus are unclear, and it is likely that landslides require triggering by external forces, such as earthquakes. Magellan imagery revealed a very strong spatial relationships between the locations of large-scale mass-wasting features and steep slopes related to rift zones and volcanic edifices, which may in turn point to them being geodynamically active in the recent geological past. EnVision's proposed Regions of Interest and higher resolution imaging offer excellent coverage of known mass-wasting features and increase the likelihood of imaging new or previously undetected smaller features. The planned VenSAR investigations will include detailed characterization of mass-wasting geomorphological properties and features with stereo imagery, and of their surface conditions with multi-polarimetry.

6.1.4 How Are Venus' Atmosphere & Climate Shaped by Geological Processes?

Detection of Volcanogenic Gas and Particulate Plumes. - Sulfur dioxide variations in the mesosphere have been attributed as possible evidence of volcanic activity (Esposito 1984), but they also could be due to intrinsic dynamic variability of the atmosphere, associated with temporal changes in transport of SO_2 from troposphere (where it is highly abundant) to mesosphere (where it is detected). On the other hand, volcanic gas plumes in the troposphere (below the clouds) would have quite a distinct signature, with distinct plumes advecting with the prevailing East-to-West winds (Fig. 17). Water vapor is likely to be a better tracer of volcanic activity than sulfur dioxide, because it is less abundant in the Venus atmosphere than SO_2, and because it can be mapped at three different altitudes in the troposphere using different spectral bands on the nightside. Analyses of Venus Express data found no evidence of

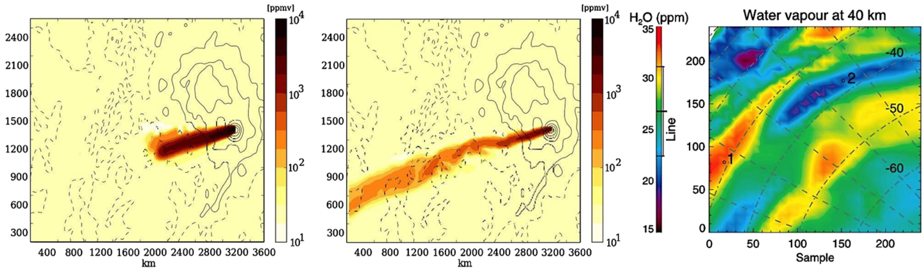


Fig. 17 Simulated advection of a volatile gas plume emitted from Imdr Regio. Black contours represent topography. Colors show excess water vapor (in arbitrary units) after 72 hours of outgassing, at (a, left:) 10 km altitude and (b, center:) 35 km altitude. (Wilson and Lefèvre 2020). (c, right): Variations of water vapor at 40 km altitude (Tsang et al. 2010). This result was later found to be potentially attributed to degeneracies between cloud and water vapor retrieval. The higher spectral resolution of VenSpec-H, compared to VIRTIS-M, will enable unambiguous disentangling of these signals

tropospheric water vapor variations (Bézard et al. 2009, 2011), but these analyses represent data only from a few days and, due to low spectral resolution, could only determine water vapor to a fairly wide range of 25 – 40 ppmv.

The nominal column mass of volcanic gasses in the Venus atmosphere, integrated from surface to space, is $\sim$200 kg m^{-2} for SO_2, $\sim$10 kg m^{-2} for H_2O and $\sim$0.1 kg m^{-2} for HDO. If the composition of Venus volcanic gasses is the same as on Earth - provided that plume dispersion does not exceed 10 km, the limiting spatial resolution induced by cloud scattering - then a large, Pinatubo-size eruption would change H_2O abundance, D/H ratio, and SO_2 abundance, respectively, by $\sim +30\%$, -30%, and $+1\%$. The latter effect may be underestimated with respect to the others, both because the Venusian interior may be much drier than Earth's, and because the outgassed SO_2/H_2O ratio is expected to be higher for a given magma volatile content due to Venus' high atmospheric pressure (Gaillard and Scaillet 2014). The frequency of occurrence, and the ratio of gasses and particulates in any volcanic plumes detected would provide constraints on the upper mantle properties.

Explore the Main Constituent of the Cloud, H_2SO_4, in Both Vapor and Liquid Form. - The main constituent of the clouds, H_2SO_4, in both vapor and liquid form, can be monitored near the cloud base altitude, yielding clues as to cloud formation and convection processes. Geological activity can affect clouds in several ways: (1) volcanic ash can contribute to cloud and haze layers; (2) volcanic sulfur dioxide emissions can contribute to formation of sulfate cloud & haze layers and to the as-yet unidentified UV absorber seen at cloud-tops; (3) volcanically emitted volatiles can form condensate layers; (4) heat from volcanic activity can cause changes in atmospheric circulation (Esposito 1984); (5) near-surface winds in Venus' dense atmosphere can lift dust & other particulates from the surface into airborne suspension. Understanding the dependence of the cloud layer on outgassed mantle volatiles is critical for understanding the long-term climate evolution of the planet. All of these effects can be studied by monitoring the spatial and temporal variations of clouds and hazes. Characteristic timescales of cloud formation and dissipation are expected of the order of hours to days, therefore observations on such timescales are properly addressed from a Venus low polar orbit.

6.2 EnVision Mission Overview

EnVision will be launched on an Ariane 62 in the fourth quarter of 2031 (current working assumption, the final schedule will be agreed together with NASA at Mission Adoption), with back-up launch dates every 6 months until mid 2033. Indicative mass budget including all margins is 1350 kg (dry mass); estimated total wet mass including launch adapter at the time of mission selection is 2500 kg. An interplanetary cruise of 15 months (to be confirmed and pending final launch date) is followed by orbit insertion and then circularization by aerobraking over a period of about 16 months to achieve the nominal science orbit, a low quasi-polar Venus orbit with inclination between 87 and 89 deg, altitudes varying from 220 to 510 km and orbital period of about 92 min. The nominal science phase of the mission will last six Venus sidereal days (four Earth years). The choice of science orbit around Venus is mostly driven by a need for global VenSpec, SRS, and VenSAR altimeter and radiometer coverage, stereo topography, polarimetric and repeated VenSAR imaging, and for high-resolution gravity mapping. The spacecraft is approximately rectangular, 3 m in height $\times$ 2 m in depth and width in stowed configuration, with chemical propulsion and powered by two deployable solar arrays. EnVision will downlink $\sim$210 Tbits of science data, using a Ka-/X-band comms system with a fixed high-gain antenna (HGA) of diameter $>$ 2.5 m.

The communication subsystems relies on X-band uplink for simultaneous telecommand and ranging reception, on X-band downlink for simultaneous spacecraft telemetry and ranging transmission, and Ka-band (32 GHz) downlink for high data rate transmission of science data or alternatively for ranging. The HGA is the primary antenna used for spacecraft communication in X and Ka-band, and is completed by several Low Gain Antennas (LGA) used for X-band communications only, during Launch and Early Operations Phase (LEOP) and spacecraft safe modes. To maximize the data return, the Ka-band communications subsystem relies on a powerful Travel Waveguide Tube Amplifier (TWTA) with a radio frequency power output of 120 W. This architecture, together with daily communication passes with 35 m Deep Space Antennas of 9.3 hours in average, allow to downlink the required science data return whatever the Earth to Venus distance.

6.3 EnVision Science Payload

EnVision's science payload consists of VenSAR, a dual polarization S-band radar also operating as microwave radiometer, three spectrometers VenSpec-M, VenSpec-U and VenSpec-H designed to observe the surface and atmosphere of Venus, and the Subsurface Radar Sounder (SRS), a High Frequency (HF) sounding radar to probe the subsurface. These are complemented by a radio science investigation which achieves gravity mapping and radio occultation of the atmosphere, for a comprehensive investigation of the Venusian surface, interior and atmosphere and their interactions. This extensive suite of instrumentation and experiments work together to comprehensively assess surface and subsurface geological processes, interior geophysics and geodynamics, and atmospheric pathways of key volcanogenic gasses, which together illuminate how and why Venus turned out so differently to Earth. The synergistic and holistic way in which the payload instruments collaborate to investigate processes at different altitudes, depths and spatial scales is characteristic of the EnVision mission (European Space Agency 2021).

6.3.1 VenSAR on EnVision

A **Synthetic Aperture Radar, VenSAR**, will image pre-selected regions of interest at a resolution of 30 m/pixel, and subregions at 10 m/pixel. An order of magnitude better than Magellan and with a better sensitivity, these images are the key to understanding geological processes from local to global scale, discriminating relationships between units of different age, and identifying the changes caused by geological activity. Topographic information at 300 m spatial and 20 m vertical resolution across these regions, derived from stereo imaging at two different incidence angles, is complemented by a global network of altimetry mode tracks with a vertical resolution of 2.5 m. This enables to map the surface at a better resolution than any previous dataset, essential for resolving the geometry of faults, folds and other features, and enabling the quantitative analysis of geological processes. Surface properties such as roughness will be derived from active imaging in both HH and HV polarizations – a first for a Venus orbiter - and passive radiometry at a range of angles, which also permits the detection of surface temperature anomalies. Repeated observations and comparisons with Magellan imagery allow for the detection of volcanic, tectonic and geomorphic changes over periods of months, years and decades.

EnVision will acquire dual-polarization SAR imagery at 30 m resolution for about 7% of the surface after 6 cycles, which aids surface characterization by exploiting the polarimetric reflection properties of the surface. SAR polarimetry is essential for differentiation of surface types and properties, because it is sensitive to surface roughness and structure (e.g., consolidated vs fine-grained material). VenSAR employs a dual polarization mode (transmitting H and recording H and V polarizations) to enable differentiation between terrain types and first-order surface properties characterization. Dual polarization was chosen for data rate and swath width considerations and H polarization to match the Magellan data enhancing change detection studies. Passive radiometry will be carried out in a near-nadir (with an incidence angle of 14°) or nadir viewing geometry, in parallel with other EnVision instruments. The surface microwave brightness temperature will be recorded globally ($>$75% of the surface) with repeated observations (at least 2 times) and a final resolution likely better than 10 km when using all overlapping near-nadir observations.

Surface Topography. - Surface topography is integral to many of the EnVision science investigations, either as the primary data source for inferring the type and magnitude of geologic processes that shape the surface, or as ancillary data necessary for proper interpretation of other data. The resolution and vertical accuracy required depends on the investigation and varies from several kilometer scale resolution to roughly quarter kilometer with vertical accuracy of 10s of meters. Magellan global topographic data with its 15-20 km resolution and vertical accuracy of 50-100 m is insufficient to support these investigations (Ford et al. 1992). Quantitative modeling of faulting and folding requires knowledge of topography with a vertical resolution of 25-50 m. Such models can constrain the physical processes that produce the observed tectonic landforms, the magnitude of the deformation, and the mechanical structure of the crust and lithosphere in the vicinity of the tectonic feature.

Topography from SAR stereo data for impact craters, at horizontal resolutions less than a quarter to a third of a crater diameter, i.e., less than 10 km, and vertical resolutions better than 20 m, will enable the measurement of the thickness of post-impact crater fill. Still finer spatial- and vertical-accuracy topography measurements will reduce the uncertainty in crater depth-diameter measurements and more accurate crater fill thickness estimates. Moreover, the plains of Venus are under-represented in the RoIs, and a globally distributed set of topographic measurements will be particularly important for understanding the plains resurfacing history.

Topography data are also needed for investigations other than those of the SAR. The Subsurface Radar Sounder (SRS) requires topographic information to identify likely off-nadir echoes (“clutter”) that may confuse subsurface feature identification. Knowledge of the absolute surface temperature is needed for calculation of the absolute surface emissivity from near-IR nightside observations. The variation of surface temperature is primarily dependent on surface altitude; reducing the accuracy of the surface altitude determination to $\leq$10 m also reduces the uncertainty in the absolute determination of surface emissivity.

Surface Properties: Nadir and Near-Nadir Radiometry, Surface Polarimetry, Microwave Emissivity. - Used in passive radiometry mode, EnVision SAR will map the thermal emission emanating from Venus surface with significantly better precision and accuracy than the Magellan radar (0.7 K against 1-2 K and 1.7 K against 15 K, respectively). Emission maps, in the form of surface brightness temperature maps, will then be used to search for thermal anomalies or, if the surface temperature is known, to map the emissivity of the surface which, in turn, provides insight into its composition (through the dielectric constant) and physical properties (roughness, density).

Passive nadir and near-nadir radiometry SAR modes are primarily designed for the search of thermal anomalies but will also be used, based on assumptions on the physical temperature, to build a mosaic of the surface emissivity at 9.5-cm by dividing the measured brightness temperatures by an estimate of the surface temperature. At nadir or near-nadir the microwave emissivity of a surface is largely controlled by its dielectric constant and the surface roughness only has a second order effect. In turn, the dielectric constant is related to the bulk composition and density of the surface material and the dielectric map inferred from radiometry measurements will be used to distinguish surface units. More specifically, for dry materials, the relationship between dielectric constant and the density is generally well described by a power-law function and, with some assumptions, the dielectric map can be readily converted into a global near-surface density map (Campbell and Campbell 1992; Campbell and Rogers 1994).

In addition to near-nadir and nadir observations, polarized radiometry measurements will be acquired in an off-nadir geometry (with a viewing angle of 25-30°) in selected regions. As aforementioned, the main advantage of nadir radiometry is to be less sensitive to roughness than off-nadir radiometry. However, the average of two orthogonally polarized emissivity values (or the polarization ratio) is also less sensitive to roughness than either individual component and can be used to provide an even more reliable estimate of the dielectric constant, requiring no assumption on the physical temperature. Such measurements will be primarily performed in Venus highlands to confirm or inform their unusually high dielectric constant and put new constraints on their composition candidates. Recording of both H and V polarization in an off-nadir geometry will distinguish between the effects of dielectric constant and roughness/volume scattering, thus offering an additional powerful tool for surface characterization (European Space Agency 2021).

By collecting microwave emissivity data at a higher resolution than the radar of Magellan, with better precision and especially accuracy (by a factor $\sim$10) and geometries (targeted off-nadir polarized measurements) relevant to the science objectives, the EnVision radar operating as a radiometer combined with the instrument high-resolution topography and polarimetric imaging will refine the mapping of Venus surface in terms of composition and physical properties. It will thus provide key information to retrieve the geological history and age of its terrains. In particular, it will help unravel the nature and rate of alteration in Venus high-altitude low-emissivity regions, investigate impact modification in crater ejectas and maybe unveil deeply weathered regions, thick sedimentary layers or signatures of recent resurfacing. By the end of the EnVision mission (6 cycles) we should be able to produce a radiometry map of $>$90% of the surface, with a resolution of about 10 km using all overlapping measurements.

6.3.2 EnVision Subsurface Radar (SRS)

A **Subsurface Sounder, SRS**, will characterize the vertical structure and stratigraphy of geological units including volcanic flows. Geological inferences from Magellan data point to

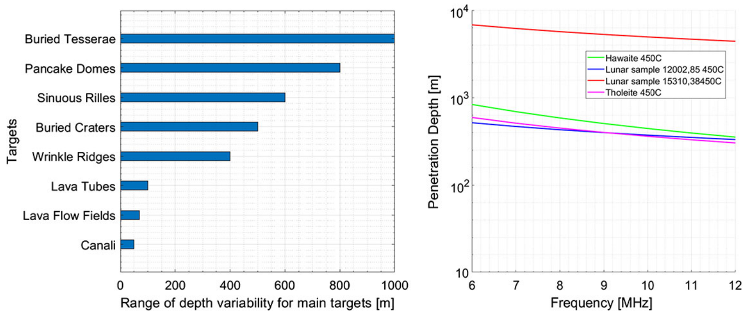


Fig. 18 (a, left): Typical range of subsurface sounding depths in which different geological targets of the EnVision Subsurface Radar (SRS) can be identified; (b, right:) SRS average penetration depth calculated for different Venus-like samples (from measurements on Moon and Earth analogue materials at Venus temperature) in the SRS bandwidth.

a range of subsurface structures and geometries that are as yet unquantified. The SRS provides a unique opportunity to sound the great variety in geologic and geomorphic units. It will also provide unprecedented information on the surface in terms of roughness, composition and permittivity (dielectric) properties at wavelengths completely different from those of VenSAR, thus allowing a better understanding of the surface properties (Fig. 18). SRS observation will also result in altimetry measurements by providing low-resolution profiles of the topography that can be integrated with the altimetric data of VenSAR.

EnVision is the first mission to Venus with a confirmed sounding instrument (ISRO's proposed Venus mission is also considering a sounder, see Sect. 8.3.2) that will allow for the direct measurement of subsurface features. Despite some geological surface investigations that provide hints about possible existence and nature of subsurface structures, no direct measures exist. In this context the Subsurface Radar Sounder (SRS) onboard EnVision mission represents a unique opportunity to sound the great variety of geologic and geomorphic units. SRS will investigate stratigraphic and structural patterns, to test hypotheses related to the origin of structures at the surface and in the shallow subsurface and their relationships. This will enable investigation of interaction processes between surface and subsurface structures as well as subsurface structures not directly linked with surface ones.

There are many geological investigations for which the detection of subsurface boundaries may provide invaluable constraints. They include impact craters and their infilling, buried craters, tesserae and their edges, plains, lava flows and their edges, and tectonic as well as volcanic features. For those features subsurface characteristics are crucial for: the relative dating of surfaces by the analysis of stratigraphic relationships, the modeling of three-dimensional structure, the identification of boundaries between units/edges. The subsurface material boundary delineation by sounding will improve the understanding of Venus resurfacing history and geologic evolution.

These investigations will be performed Venus wide (with an average observation density of 2 per degree of longitude at Equator) and on selected RoIs which include the mentioned features (with an average observation density of 10 per degree of longitude at Equator). The scientific investigations call for a penetration down to a few hundreds of meters (up to 1000 m) and about 20 meters of vertical resolution. The typical depth needed for sounding of different subsurface feature types is shown in Fig. 18a. Calculations of SRS penetration depth, shown in Fig. 18b, determine that the SRS will be able to investigate a wide variety of geological targets. The SRS penetration depth has been calculated using a large variety

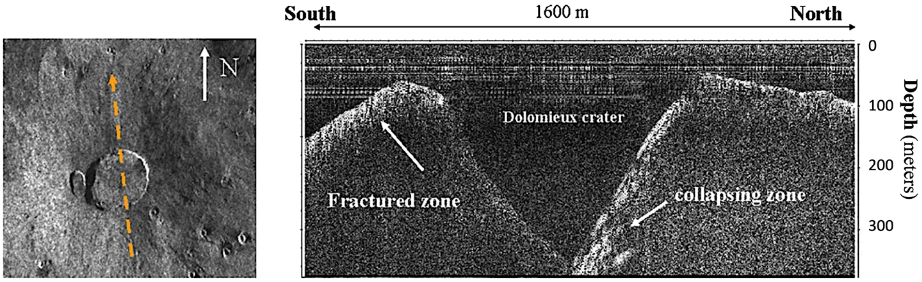


Fig. 19 Airborne radar sounder profile at 40 MHz central frequency (more than four times higher than the SRS one) over the Dolomieu Crater on the top of the Fournaise Volcano in the reunion Island in the Indian Ocean. Fournaise is a hot spot effusive volcano with geomorphological features and magma dynamic very similar to several Venusian volcanoes (Anderson 2005). The radargram crossing from South to North the main crater on the top of the volcano show the fractured areas (white areas before and after the crater) that are materialized by the strong signal scattering resulting from the fractures. Inside the crater the radargrams shows the layering that is on the crater northern wall arising from the succession of debris flowing from the collapsing northern part. The crater depth is approximately 100 m and its width 1 km. The lava temperature ranges from 40 C at the surface to 600 C beyond the 10 m level, demonstrating the viability of HF sounding through rocks at these elevated temperatures

of different rock types and surface topologies; for a quick demonstration of the viability of HF subsurface sounding through rocks at Venus temperatures, Fig. 19 shows an example of sounding through lava at >600 °C of a volcanic crater floor on Earth.

6.3.3 EnVision Spectrometer Suite (VenSpec)

A **Spectrometer suite, VenSpec**, will obtain global maps of surface emissivity in six wavelength bands using five near-infrared spectral transparency windows in the nightside atmosphere, to constrain surface mineralogy and inform evolutionary scenarios; and measure variations of SO_2, SO and linked gasses in the mesosphere on the dayside, to link these variations to tropospheric variations and volcanism. In combination of its three instruments, detailed below, VenSpec will provide unprecedented insights into the current state of Venus and its past evolution. VenSpec will perform a comprehensive search for volcanic activity by targeting atmospheric signatures, thermal signatures and compositional signatures, as well as a global map of surface composition.

VenSpec-M, like the identical VEM instrument on-board VERITAS (Sect. 4.3.2), is a pushbroom multispectral imager optimized to map thermal emission from Venus' surface using six narrow bands ranging from 0.86 to 1.18 µm, and three bands to study cloud microphysics and dynamics. VenSpec-M will provide near-global compositional data on rock types, weathering, and crustal evolution by mapping the Venus surface in five atmospheric windows. VenSpec-M will use the methodology pioneered by VIRTIS on Venus Express but with more and wider spectral bands, the NASA VERITAS VISAR and Envision VenSAR-derived Digital Elevation Models (DEMs) and EnVision's lower orbit compared to Venus Express to deliver near-global multichannel spectroscopy with wider spectral coverage and an order of magnitude improvement in sensitivity. It will obtain repeated imagery of surface thermal emission, constraining current rates of volcanic activity following earlier observations from Venus Express (Smrekar et al. 2010a; Mueller et al. 2017). In combination with the observations provided by the identical VEM instrument on the NASA VERITAS mission VenSpec-M will provide more than a decade of monitoring for volcanic activity, as well as search for surface changes (Fig. 10).

VenSpec-M uses the same 14 bands filter array as VEM on board VERITAS (Helbert et al. 2016, 2020, see also Table 3 and Fig. 10). Those 14 bands fall in four categories depending on where the radiation is originating. The radiation for the six surface bands at 0.86, 0.91, 0.99, 1.02, 1.11, 1.18 µm originates at the surface. Surface bands are used to determine rock types (Dyar et al. 2020, 2021; Helbert et al. 2021) as well as monitor for the thermal signature of active volcanism. The radiation in the two water vapor bands originates in a layer close to the surface and is sensitive to the abundance of water vapor which may see changes due to volcanic exhalations, complementing the H_2O and HDO measurements by VenSpec-H in the middle atmosphere. In the three cloud bands, radiation originates at an atmospheric layer above the surface but below the clouds. Because the signal in the cloud bands has no surface or water vapor contributions, the measurements in these bands can be used to remove cloud-induced contrast variability from the other bands. Finally, the three background bands are sensitive in spectral regions where the atmosphere is opaque, thus allowing the removal of background signal on the detector. The high density of cloud particles results in multiple scattering of the radiation, reducing the spatial resolution to 50–100 km.

VenSpec-H is dedicated to high spectral resolution atmospheric measurements in the near-infrared. It will focus on the volcanic and cloud forming gases and search for composition anomalies potentially related to the volcanic activity. The instrument, designed to measure H_2O, HDO, CO, OCS, and SO_2 on both the night and day side, is a nadir-pointing, high-resolution (R$\sim$8000) infrared spectrometer that will perform observations in different near-IR spectral windows between 1 and 2.5 µm. Spectra in these bands will be recorded sequentially as the EnVision spacecraft moves along its quasi-polar orbit, and will allow the sounding of different layers in the Venusian atmosphere: close to the surface (1.17 µm), 15-30 km (1.7 µm), 30-40 km (2.4 µm) and above the clouds (1.38 & 2.4 µm). Two additional polarization filters will be used during dayside observations to better characterize the clouds' properties.

The instrument will include a total of four spectral bands: 1.165 - 1.180 µm (B#1), 2.34 - 2.48 µm (B#2), 1.72 - 1.75 µm (B#3) and 1.37 - 1.39 µm (B#4). B#2 is further divided into two ranges: 2.34 - 2.42 µm (2a) and 2.45 - 2.48 µm (2b). Bands 1, 2a, 2b and 3 are observed on the night side, bands 2a, 2b and 4 on the day side. In this near-IR region, the high spectral resolution combined with the high sensitivity of the instrument will allow to clearly identify the absorption features of the targeted species. Spectral band selection is performed in part by a filter wheel mechanism with stringent lifetime requirements and a filter-slit-assembly that allows sequential measurements in the 4 spectral bands of interest. Design measures are taken to make the VenSpec-H observations insensitive to polarization, while exploiting the polarization information contained in the light reflected from Venus.

VenSpec-U, a dual-channel ultraviolet spectrometer, will monitor minor sulfur species (mainly SO and SO_2) and investigate the complex and highly variable upper atmosphere and its relationship with the lower atmosphere. VenSpec-U will search for atmospheric effects of geological activity, in order to determine how much outgassing is occurring, and how the atmospheric chemistry is coupled with surface/subsurface geochemistry and weathering cycles; study how mesospheric gas variations are linked to volcanism, in order to identify the causes of variability in the mesospheric sulfured gases (SO, SO_2); and finally how cloud and particulate variability is linked to volcanism, in order to detect plumes of volcanic ash or sulphate clouds caused by volcanism, and to understand any link between the Venus sulfuric acid clouds and volcanism.

Observations can be conducted in a strict nadir geometry (null emission angle), or in near-nadir geometry (emission angle $< 30°$) thanks to a UV imaging spectrometer operating in the 190 – 380 nm spectral range. Spectral resolutions shall be better than 0.3 nm in the 205 – 235 nm range (typical SNR of 100 at 220 nm) in order to distinguish SO and SO_2 spectral lines, and better than 2 nm in the 190 – 380 nm range (typical SNR of 200 at 220 nm) which encompasses the unknown UV absorber peaking near 365 nm. Spatial sampling shall range from 3 km to 24 km, depending on spectral resolution and orbiter altitude. The narrow-slit axis of the instrument contains the spectral information, whereas the long-slit axis contains the spatial information along the 20° field of view. The remaining spatial direction is provided through orbital scrolling.

6.3.4 EnVision Radio Science / Gravity Experiment (RSE)

A **Radio Science Experiment** uses the spacecraft-Earth radio link for gravity mapping and atmospheric profiling. Measurements of the lateral variations in the strength of a planet's gravity field is an important tool in probing the subsurface structure of a planet. Regional differences in elevation can be supported by differences in crustal thickness, by flexure of the elastic lithosphere, or by convective flow in the mantle. These mechanisms can in turn be distinguished by their expected gravity signatures, resulting in estimates of the thickness of the crust and lithosphere in different regions of Venus. As discussed previously (Ghail et al. 2023; Herrick et al. 2023; Gilmore et al. 2023, this collection), we need to understand whether the tesserae, which contain fine-scale, complex patterns of deformation, represent thick, ancient remnants of deformed and deep-rooted continental crust. The tesserae may also hold clues to the nature of past resurfacing; particularly whether there have been periods of enhanced crustal mobility, or whether Venus has been in its current state for most of its history.

Crustal thickness affects the stratification of mechanical strength in the lithosphere and thus can also affect the style of tectonic deformation (Dumoulin et al. 2017). Magellan gravity data are consistent with an organized pattern of mantle convection broadly similar to Earth; but it lacks the resolution necessary to understand its connection with geological-scale features, such as individual coronae or mountain belts. EnVision can measure the integrated amount of volcanism over time and thus provide tests of thermo-chemical evolution models, but can also sometimes be the product of extensional or compressional tectonism. Determining lithospheric thickness with gravity data is particularly sensitive to data with wavelengths less than 500 km. Higher spatial resolution than the Magellan solution of the Venus gravity field is required to better constrain the crustal and lithospheric structure variations. Combining Magellan and EnVision gravity data will allow determination of the gravity field over at least 95% of the planet, with an average spatial resolution better than 200 km, and an accuracy better than 20 mGal (Rosenblatt et al. 2021; European Space Agency 2021).

Venus' moment of inertia, Love number, and tide-induced phase lag also characterizing the signature of the internal structure in the gravity field will be extensively constrained during the six cycles of the EnVision mission (one cycle equals one Venus sidereal day or 243.02 Earth days). EnVision will constrain the size of the main internal layers crust, lithosphere, mantle and core, and whether or not the core is fluid, will help to understand fundamental differences or even possible similarities between Venus and Earth. Indeed, the overall size of the chemical reservoirs (crust, mantle, core) gives information about the composition of Venus; the average thickness of the crust about the rate of magmatism; the average thickness of the lithosphere about the mechanisms of heat transfer at the surface; and the state of the core about the long-term cooling rates. The EnVision spacecraft-Earth radio link will measure the gravity field of the planet with spatial resolution better than 270 km, and accuracy of <0.2 mm/s^2 globally, with an improved higher spatial resolution of <200 km and accuracy of <0.1 mm/s^2 in most of the Southern hemisphere (40% of the planet) and k_2-Love number with an accuracy of ± 0.01. As discussed before, the potential Love number helps to determine the state of the core and, in the case of a liquid core, also its size. A Love number k_2 lower than 0.27 would indicate the presence of a fully solid iron core, while for larger values, solutions with an entirely or partially liquid core are possible (Dumoulin et al. 2017).

Furthermore, the EnVision radio-occultation experiment aims at sounding of the temperature structure of the Venus atmosphere in the altitude range 90-35 km and abundance of sulfuric acid in gaseous and particulate phases. The experiment relies on the observation of the radio-link propagation (frequency and amplitude) through the atmosphere of Venus during radio-occultation. The radio ray path changes in the ionosphere and neutral atmosphere are induced by a change in the refractivity profile. This leads to a shift in the measured frequency at the ground station. These frequency changes can be used to retrieve the neutral number density, temperature and pressure profiles as a function of the planetary radius at a high vertical resolution. Thanks to the use of the dual X-Ka band, the cloud contents in both gaseous and liquid phase of sulfuric acid, and its spatial and temporal variability, will be estimated for the first time at 35-55 km, with an accuracy of 1 mg/m^3 (liquid) and 1 ppm (gaseous) on time scales from hours to years, with vertical resolution of $\sim$100 m. (European Space Agency 2021). In addition to H_2SO_4 content in both gaseous and liquid phase within and below the clouds, static stability profiles retrieved from temperature, pressure and number density profiles (35-90 km), provide valuable information about small-scale fluctuations in the thermal profiles and the latitudinal dependence of gravity wave activity. Understanding the dependence of the cloud layer on outgassed mantle volatiles is critical for understanding the long-term climate evolution of the planet, and Venus would be indeed the first planet beyond the Earth where we could relate the dynamics of gravity waves and small-scale turbulence and temperature fluctuations, and the cloud composition.

Both VERITAS and EnVision VISAR and VenSAR will produce repeated imaging of surface features throughout their mapping cycles, allowing to create radar tie points, thus tying the inertial position of the probe to the planetary body-fixed frame. Leveraging on the combination of tracking data and radar tie points, both VERITAS and EnVision will be able to measure the precession and monitor the variable spin rate of the planet with a much-improved precision.

6.4 Summary / Outcomes Revealing Venus Evolution

EnVision was selected as ESA's 5th M-class mission, targeting a launch in the early 2030s. The mission is a partnership between ESA and NASA, where NASA provides the Synthetic Aperture Radar payload. The scientific objective of EnVision is to provide a holistic view of the planet from its inner core to its upper atmosphere.

The mission is scheduled for launch on an Ariane 62 in the fourth quarter of 2031 (current working assumption, the final schedule will be agreed together with NASA at mission adoption), with backup launch dates every 6 months until mid-2033. It will provide new insights into geologic history through complementary imaging, polarimetry, radiometry, and spectroscopy of the surface, coupled with subsurface sounding and gravity mapping; search for thermal, morphological, and gaseous signs of volcanic and other geologic activity; and follow the fate of key volatile species from their sources and sinks at the surface through the clouds to the mesosphere. Following the same approach that has advanced our understanding of Earth and Mars, EnVision will combine global observations at low or medium spatial resolution (e.g., surface emissivity & atmospheric composition) with regionally focused observations at higher spatial resolution.

VenSAR, a dual-polarization S-band radar that also operates as a microwave radiometer, builds on NASA-JPL's experience with planetary radars since the Magellan mission; the Subsurface Radar Sounder (SRS), a high-frequency (HF) sounding radar to probe the subsurface, inherits from the RIME instrument on JUICE. These will be complemented by a radio science investigation that will provide gravity mapping and radio occultation of the atmosphere. The three VenSpec spectrometers build on the heritage of ESA's suite of planetary missions, in particular ESA's Venus Express from 2006 to 2014, will also highly benefit from complementarity with DAVINCI and VERITAS measurements.

To achieve its science objectives, EnVision must return 210 Tbits (26.25 Terabytes) of science data to Earth, using a Ka/X-band comms system with a fixed diameter hight-gain antenna, with a large dynamic range of distance to Earth (from 0.3 to 1.7 AU), from a low Venus polar orbit, in the hot Venus environment (exacerbated by the operation of highly dissipative units), while operating three spectrometers in a near cryogenic environment. Achieving the science objectives under these multiple constraints without oversizing the spacecraft requires careful planning of the science operations, making the science planning strategy a critical driver in the overall mission design against which the spacecraft and ground segment are then sized (Sect. 6.2 and Fig. 15).

EnVision science operations strategy is to obtain the widest range of data types that enables us to put the highest resolution datasets into regional and global context. characterize the sequence of events that generated the regional and global surface features of Venus, determine crustal support mechanisms, mantle and core properties, and the geodynamics framework that controls the release of internal heat over Venus history, by determining the styles of volcanic processes which have occurred on Venus, studying the sources, emplacement styles, magma properties and relative ages of different volcanic flows; assessing the styles of tectonic deformation that have operated on Venus by studying their surface expression and gravity signatures, and determining their role in planetary heat loss. It will also characterize surface modification processes - such as impact crater modification, low emissivity/radar bright highlands - to improve our understanding of Venus geochronology and constrain Venus' internal structure, through measurements of gravity field and tidal response, to study the properties and thicknesses of Venus' crust, mantle and core. It will better assess whether Venus once had condensed liquid water on its surface and was thus perhaps hospitable for life in its early history, and therefore fully support the scientific goals and open questions presented in the companion papers of this collection.

7 Venera-D: A Comprehensive Exploration of Venus' Atmosphere, Surface, Interior and Plasma Environment

Since the discovery of Venus' atmosphere by Mikhail Lomonosov in 1761 (Marov 2005), and further observations of the Venus transits, Venus has always been a celestial object of interest among Russian astronomers. It is not surprising that the multistage studies of Venus became the central and most successful part of the Soviet robotic space program. was the site of the first entry probe in any solar system atmosphere in 1967 (Venera-4), first soft landing in Dec. 1970 (Venera-7), first image from the surface of another planet in 1975 (Venera-9). The Soviet series of Venera & VeGa missions were phenomenally successful, not only in their technologically advanced landers which returned color pictures from Venus and successfully analyzed drill samples, but also successfully deployed balloons in the atmosphere in 1985. The Venera-D concept is the logical next step in the highly successful series of Venera and VeGa missions of the 1970s and 1980s (Marov et al. 1973; Marov 1978; Avduevskii et al. 1977; Florensky et al. 1977; Barsukov et al. 1982, 1986; Garvin et al. 1984; Surkov et al. 1984; Moroz 1990; Moroz et al. 1985, 1996; Sagdeev et al. 1986a, 1992).

The Russian Venera-D (Венера-Д) flagship mission concept has been under development with the goal of advancing the investigation of Venus' atmosphere, surface, and interior and the processes that link them as a system. Intense discussions about Venus began in 2013 as part of the Joint Science Definition Team (JSDT) established by NASA and Roscosmos with the goal of shaping a collaborative project. The JSDT developed a full Venera-D mission scenario (Venera-D Joint Science Definition Team 2019; Venera-D Venus Modeling Workshop proceedings 2018; Glaze et al. 2018; Zasova et al. 2020), but as of 2021, for a variety of (mostly non-scientific) reasons, Venera-D has been developed as a national program for Venus. Science objectives of the Venera-D mission concept currently address key questions about atmospheric dynamics, emphasizing atmospheric superrotation and radiative balance; the processes that have formed and modified Venus' surface, highlighting the mineralogical and elemental composition of surface materials; and the chemical processes occurring at the interface of the surface and the atmosphere. The Venera-D lander would not only perform descent phase measurements but would also analyze surface composition. This would of course provide invaluable "ground truth" for VERITAS, DAVINCI and EnVision's surface composition mapping, as well as contributing to understanding of geophysical evolution (Venera-D Joint Science Definition Team 2019).

7.1 Venera-D Science Objectives

Venera-D is designed to study the atmosphere, surface, internal structure and properties of plasma surrounding Venus at new scientific and technological levels. As we discussed in Sect. 2, Venus is an Earth-sized terrestrial planet that has taken a different evolutionary and habitability path. To examine the reasons for this difference is very important to understand the divergent Earth and Venus evolutionary pathways. This is of particular relevance for the study of exoplanets and conditions for their habitability (O'Rourke et al. 2023; Way et al. 2023; Westall et al. 2023; Gillmann et al. 2022, this collection). Among these key aspects and objectives of the Venera-D mission, we can formulate those high-level objectives that directly address the long-term history and evolution of Venus through time, as well as those that are not addressed by currently selected missions:

Coupling Between Geologic and Climate History. - Current and past rates of volcanic outgassing are unknown, as is an understanding of how volcanoes have affected the atmosphere and climate. More fundamentally, the role of water in geodynamics and petrogenesis must be constrained. As on Earth, the geology and climate of Venus are linked (Bullock and Grinspoon 2001). The causes and effects of rapid changes in geologic expression can be studied in detail with a capable surface payload and remote sensing techniques (Helbert et al. 2008; Mueller et al. 2008; Gilmore et al. 2015). To address key geologic questions, it is necessary to characterize the geochemistry, mineralogy, emplacement, sediment supply, and petrology of surface features and terrains (Herrick et al. 2023; Gilmore et al. 2023; Carter et al. 2023, this collection); obtaining this information for the tesserae would provide insight into the oldest exposed rocks. These data will allow us to constrain the history of volatiles, especially water, on Venus and provide a basis for direct comparison of crustal evolution on Earth and Mars. In addition, isotopic measurements of the composition of the Venusian atmosphere and an improved understanding of atmosphere-surface interactions will help constrain the outgassing history, in particular the current and past volcanic outgassing rates (Avice et al. 2022, this collection).

Abundance of Light Elements, Rare Elements and Their Isotopes. - To characterize Venus' origin and evolution through time, accurate assessment of the composition of the atmosphere's composition is essential. Like Earth and Mars, the atmosphere of Venus seems to have substantially evolved from its original composition. Whether the major processes that shaped the atmospheres of Earth and Mars—such as impacts of large bolides and significant solar wind erosion—also occurred on Venus is largely unknown. Detailed chemical measurements of the composition of the atmosphere—in particular, the noble gases and their isotopes along with light elements and isotopes—will aid in understanding if the modern (secondary) atmosphere is a result of degassing from the interior or if it formed from comet or asteroid impacts (Avice et al. 2022; Salvador et al. 2023, this collection). Likewise, it is imperative to determine how the atmospheric abundances of water, sulfur dioxide, and carbon dioxide change under the influence of the exospheric escape of hydrogen, outgassing from the interior, and heterogeneous reactions with surface minerals.

Venus Surface Geochemistry. - The only means by which the geochemical data from Venus' surface can be obtained are the landers. Several landers visited the planet in a period from 1972 (Venera-8) to 1985 (VeGa-1 and 2) and reported the only data on the chemical composition of soils on the surface of Venus. Chemical measurements were made at seven sites that are concentrated in the Beta-Phoebe region and in Rusalka Planitia to the north of Aphrodite Terra. Selection of the landing sites were based purely on the interplanetary ballistic constraints because no knowledge on the surface geology existed when the Venera-VeGa missions were implemented. At four landing sites (Venera-8, -9, -10, and VeGa-1), concentrations of the three major thermal- generating components, K, Th, and U, were determined by gamma spectrometry (Surkov 1997). The mean values of their concentrations on Venus are well within the range that is typical of terrestrial basalts (Kargel et al. 1993; Nikolaeva 1995, 1997). However, enhanced concentrations of K, Th, and U in soils at the Venera-8 landing site raises the possibility for the presence of a non- basaltic material on Venus (Nikolaeva 1990). In two landing sites (Venera-13, and -14), the concentrations of major oxides (without Na_2O) were measured by the X-ray fluorescence (XRF) method. At the VeGa-2 site, both methods (gamma spectrometry and XRF) were used separately and the concentrations of the thermal-generating elements and major oxides were measured (Surkov 1997). The XRF data also suggested that rocks of basaltic composition make up the landing sites (Surkov et al. 1984, 1986; Kargel et al. 1993). Two important factors, unfortunately, strongly limit the value of the Venera and VeGa data and prevent their robust interpretation: (1) we do not know the exact position of the landers. All stations landed somewhere within their own landing circle, which is $\sim$300 km in diameter and usually embraces terrains of different origin and age; (2) past accuracy of measurements. A new generation of lander instruments (Sect. 11.1.4) will determine the mineralogy and chemistry of terrain to ascertain rock type, and look for evidence of past water.

Role of Solar Absorbers and Near-IR Opacity Sources in Venusian Clouds. - The Venusian disk in reflected light is practically featureless in the visible and near-IR spectral regions (contrasts maximum 2 to 3%), but in the UV they reach or exceed 30% at 365 nm. The albedo of Venus decreases from a value of $\sim$0.8 at wavelengths $>$550 nm to as low as 0.3 at UV wavelengths. Cloud contrast peaks at 365 nm. UV contrasts observed between 0.33 μm and 0.5 μm are the result of absorption by a species of unknown origin. UV absorption at 0.32 to 0.5 μm was observed to disappear below 58 to 60 km by the Pioneer Venus spacecraft (Tomasko et al. 1985). Thus, absorption by the UV-absorbing species of Venus was primarily associated with the upper clouds. However, measurements taken by the VeGa lander during descent show that absorption of UV radiation (220 to 400 nm) occurs down to 47 km altitude, indicating the presence of absorbers whose identities are still unknown (Bertaux et al. 1996). Spatial variations in this absorption produce contrasts in daytime images and are a means of inferring bulk motions in the cloud top atmosphere. Measurements of small-scale feature motions over latitude and longitude provide information about the superrotation of the Venusian atmosphere at the level of cloud contrasts. Both the vertical distribution and the composition of UV-absorbing species are poorly known. The few available profiles of Venus' UV flux obtained between the cloud top and the surface indicate that the UV absorber is present in the middle and upper clouds (between ∼47 and 72 ± 2 km), but may be occasionally found in the upper haze (∼70 and 80 km) (Lee et al. 2015). It is currently unclear whether the cloud-level abundance of the absorber is solely the result of material upwelling from below, or whether it depends on chemical reactions between upwelling and downwelling species (see also Sect. 7.3.2).

Solar Wind-Venus Interaction and Venus Magnetosphere. - Plasma and magnetic field experiments on Venera-9 and Venera-10 in the 1970s provided the first data on the solar wind interaction and magnetosphere formation of Venus (Vaisberg et al. 1976). Important subsequent studies of the magnetic barrier and tail were performed by the Pioneer Venus Orbiter (Russell and Vaisberg 1983). Based on these experimental data, a model of the induced magnetosphere was developed (Vaisberg and Zelenyi 1984; Zelenyi and Vaisberg 1985). To further advance the field, Venus Express also performed investigations of the solar wind interaction with Venus (Barabash et al. 2007; Futaana et al. 2017). The discovery of the comet-like planetary plasma interaction and the processes leading to atmospheric losses allowed us to estimate how these losses vary with solar and interplanetary conditions, and their potential to cause significant changes in the chemical composition of the Venusian atmosphere over time. Despite the significant progress made by previous Venus missions, there are still outstanding problems in the study of the solar wind-Venus interaction and Venusian escape processes on recent and geological time scales.

Many of outstanding questions in Venus exploration are therefore both synergistic and complementary to the new generation of missions discussed above. Venera-D consists of a VeGa-like lander targeting the plains and an orbiter observing the atmosphere at several wavelengths, including near-IR. Beyond its surface science capabilities, the descent module is synergistic and complementary to the currently selected missions EnVision, DAVINCI and VERITAS because it will be conducting similar investigations on a different terrain type—the Venusian plains (Venera-D Joint Science Definition Team 2019). The combination of chemical and mineralogical data from both the plains and tesserae would significantly advance our understanding of the Venusian crust, mantle and igneous processes, the evolution of volcanism with time and the range of surface-atmosphere interactions on modern Venus. Atmospheric measurements from the Venera-D orbiter would complement the volatile mapping carried out by EnVision, in complement to the geophysical studies and atmospheric descent probe measurements which are at the heart of EnVision, DAVINCI and VERITAS science questions (Sects. 4-6).

7.2 Venera-D Mission Overview

The Venera-D mission architecture is composed of orbiting, landing and atmospheric modules. This mission structure provides the opportunity to make measurements in the Venus-induced magnetosphere, in the planetary atmosphere, and at the planetary surface. Figure 20 shows a general view of the mission.

7.2.1 Mission Requirements and Design Drivers

Mass budget of the spacecraft includes: 4800 kg total mass, which includes 1920 kg orbital module (OM), 2660 kg descent module (DM) and 50 kg OM/DM adapter. In addition, the

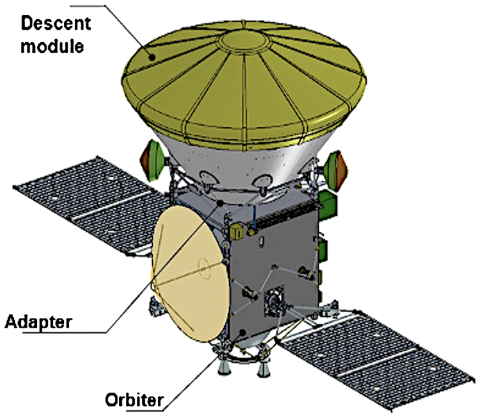


Fig. 20 Venera-D composite spacecraft consists of orbiting, landing and atmospheric modules. The orbiter module (OM) is designed for Earth-Venus transit, delivery of the lander and payload equipment (PE) to Venus, functioning while in orbit, collecting data, transmitting collected data to Earth and data from the lander (Sect. 7.2.2); The descent module (DM) is designed for performing scientific measurements during the descent and on Venus' surface (Sect. 7.2.3)

mass of the OM/upper stage adapter is 70 kg. The launch vehicle currently planned for the Venera-D mission is the new Angara-A5 LV launch vehicle with the DM-03 upper stage.

7.2.2 Orbiter Module (OM)

The Orbiter Module (OM) will carry out its science program from a highly elliptical polar orbit with a pericenter of 500 km, located above the Southern Pole, and an apocenter of 69,000 km, with an orbital period of 24 hours. Compared to Venus Express' pericenter of 250 km above the Northern Pole, and apocenter of 60,000 km, the Venera-D Orbiter Module is, essentially, symmetrical to Venus Express' orbit. The expected lifetime of the OM is 7 to 8 years. Figure 21 shows a general view of the orbiter module with a few selected instruments and subsystems. The OM will carry a complex set of science instruments to study the atmosphere of Venus from the surface to the ionosphere. Orbital studies will clarify the climate history of Venus and hopefully reveal the hidden mechanisms of water escape and the extreme greenhouse effect.

The set of imagers operating from UV to longwave IR will monitor dynamics of the atmosphere in the cloud layer on various levels. A combination of a Fourier spectrometer, a mm-radiometer, a long-IR imager and a radio science experiment will allow the construction of a three-dimensional thermal map of Venus atmosphere and the monitoring of its temporal variations. The suite of UV-to-IR spectrometers will provide new insights into minor species of the atmosphere and cloud aerosol properties.

The highly elliptical orbit of OM provides very good opportunities for plasma science. Venus has an extended magnetotail produced by the trapping of planetary ions at interplanetary magnetic field lines. The details of the interactions between the solar wind and the planetary ionosphere, and the corresponding plasma wave excitations, will hopefully be resolved by the charged particle and electromagnetic wave instruments of OM.

7.2.3 Descent Module (DM)

The Descent Module includes

- a ∼800-kg Lander Module (LM)
- a ∼420 kg Aerial Platform (AP).

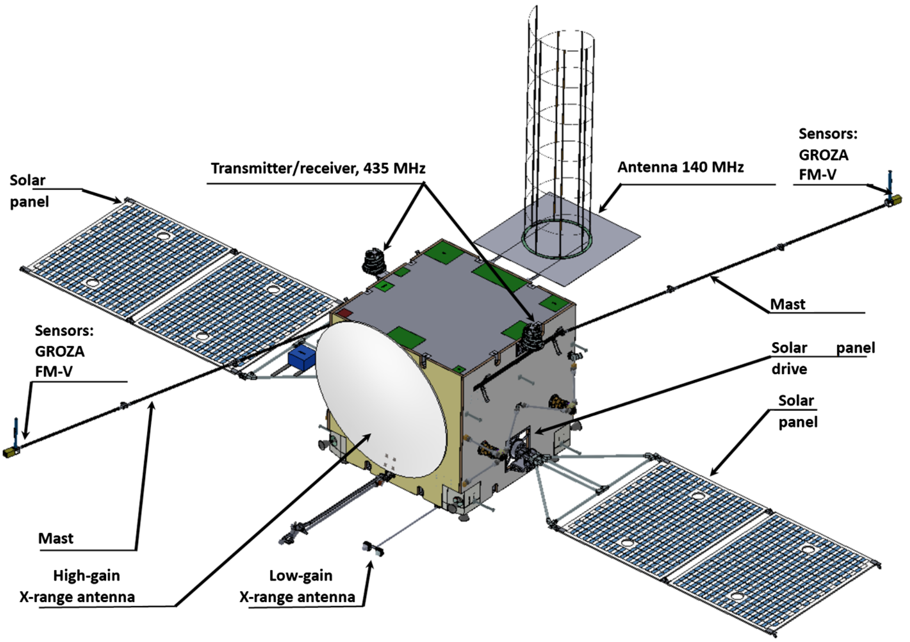


Fig. 21 Venera-D Orbiter Module (OM). OM will carry out its science program from a highly elliptical polar orbit with a pericenter of 500 km and an apocenter of 69,000 km. The orbital period is 24 hours

Landers have always been a key component of Russian missions to Venus. The Venera-D lander will be the first since the successful descent and landing of the Soviet VeGa spacecraft in 1986. The fleet of recently selected Venus missions, described in Sects. 4-6, do not include specific surface components.

Lander Module (LM). - The Venera-D Lander Module (LM) concept resembles in shape the Soviet landers that successfully operated on the surface for 1.5-2 hours, equipped with a modern scientific payload and a much more powerful data transfer system. The design of the lander includes a titanium structure developed for accommodation of onboard avionics equipment (OE); instrument container with OE, including a temperature-resistant cover that allows the LM to operate on Venus' surface for not less than 3 hr; the landing device with the damper, designed to absorb vibrations of the LM during atmospheric entry and to land on the surface; and a separable structure with a parachute system, designed to aerobrake the lander.

High resolution camera system TVS-VD (Table 6) will provide panoramic stereo imaging of the surface around the landing site with the best possible quality. The cameras will use a visible range color imaging system consisting of one landing, four to five panoramic and one close range cameras, providing detailed stereo imaging of the surface with the spatial resolution better than 0.2 mm. See also Sect. 7.3.2 - Lander science, and Fig. 24.

Harsh conditions at the surface of Venus require significant resources to extend the expected lifetime of spacecraft after landing. This lifetime should be sufficient to conduct all planned experiments and upload the obtained data to the Orbiter. As our analysis has shown, the optimum duration of the surface operations in this case is at least 2, maximum 3 hours. Lander descent time in the atmosphere: $\sim$50 min (from 125 km to the surface).

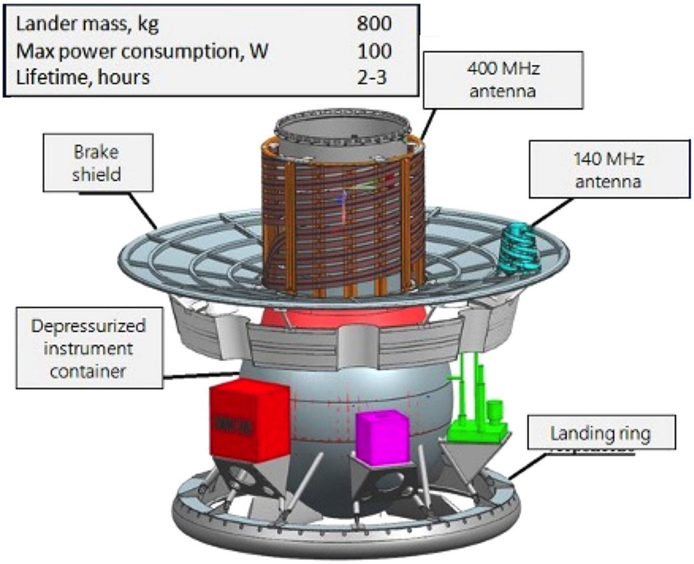


Fig. 22 Venera-D Lander Module conceptual design

Lander instrumentation will be operative during the descent and will collect both meteorological data and information about composition of atmospheric gasses and cloud aerosols. The ISKRA-V spectrometer (see Sect. 7.3.2, and Table 6) will study chemical composition of the atmosphere including abundances of gases SO_2, CO, COS, H_2O, NO_2, HCl, and HF, and their isotopologues and isotopic ratios D/H, $^{13}C/^{12}C$, $^{18}O/^{17}O/^{16}O$, and $^{34}S/^{33}S/^{32}S$ during descent from 65 km and after landing; a suite of sensors (MTK-V) will determine temperature, pressure, wind speed, temperature gradient, acceleration from 120 km altitude to the surface and at the surface; at the surface, the package measures chemical composition of rocky sample (which must be delivered inside the lander) and continues measurements of chemical composition of the atmosphere: abundance and isotopic ratio of noble gases in the atmosphere (Sect. 7.3.2, and Table 6). General view of the Venera-D Lander is shown in Fig. 22.

An important event for the planning of the Venera-D mission was the International Landing Site Selection Workshop held in Moscow in October 2019. After intense debate, the collective wisdom of 43 participants prioritized terrain types based on scientific importance and landing safety (see also Ivanov et al. 2017a,b). The results of this analysis are presented in Fig. 23. Regional plains (rp1) were identified as the currently preferred terrain type, as they are considered representative (∼30% of the Venus surface), morphologically uniform, and may represent a good sample of the fertile/depleted upper mantle. Last, but not least, is that the regional plains are relatively smooth, which increases the chances of a safe landing. The baseline mission scenario (Eismont et al. 2020), with direct DM insertion, offers a limited choice of accessible landing sites. Alternatively, landing can be achieved virtually anywhere, using gravity assist and resonant trajectories (Eismont et al. 2021a,b), at the cost of a longer transfer.

Aerial Platform (AP). - Another sub-system of the Venera-D descent module is an aerial platform, the design of which is currently less advanced than the other mission elements. The aerial platform (balloon) will have operational altitudes of 54-58 km and will offer very

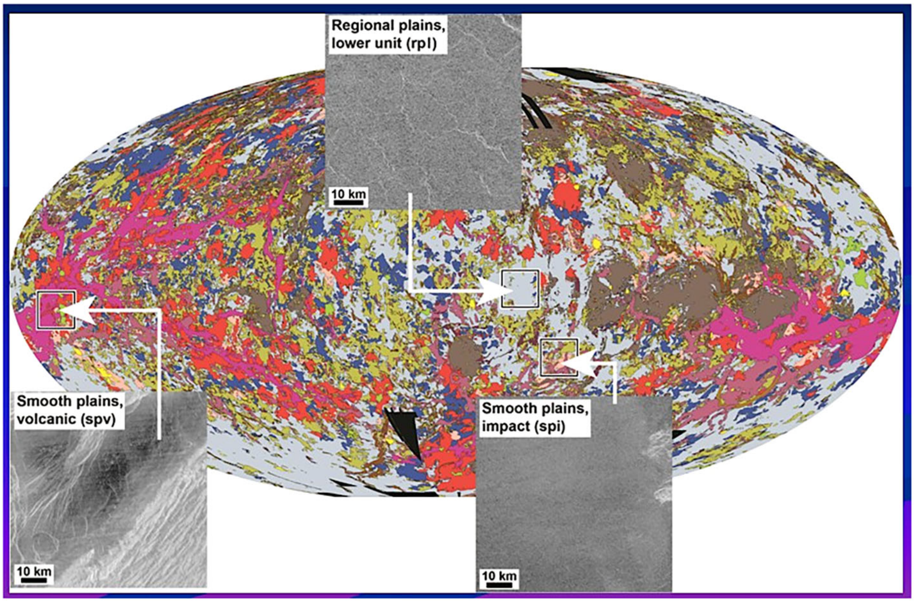


Fig. 23 Potential landing sites for the Venera-D Lander

significant opportunities to make long-term continuous measurements in the planetary atmosphere and in particular in the cloud layer. The preliminary estimate of the mass allocated to the scientific payload is about 30 kg and the set of instruments for the balloon is currently under study.

7.3 Venera-D Science Payload

7.3.1 Orbiter Science

The Orbital Module (OM) investigations aim to clarify the climate history of Venus, the mechanisms of water escape and the characteristics of the greenhouse effect. The potential suite of instruments under study includes 16 scientific instruments to perform studies of Venus atmosphere, ionosphere and magnetosphere, among which a dedicated suite of 7 instruments to analyse plasma spectra and electromagnetic field fluctuations (Table 5).

A set of monitoring cameras (VMC, LIR, IR2R) will allow to follow the dynamic trends of the Venus atmosphere and to improve the general atmospheric circulation models. The synergy of the long-wavelength IR camera (LIR), the Fourier IR thermal spectrometer (SVET) and the radiometer (MM-R) will provide an unprecedented 3D model of the thermal structure of the atmosphere. The heterodyne spectrometer IVOLGA will measure the mesosphere structure and winds, resolving CO_2 lines. UV and IR spectrometers (VOLNA, SVET, VENIS and VIKA) operating both in nadir and solar occultation modes will explore the Venus mesosphere, the cloud layer and possibly identify as yet unknown minor constituents. VIKA includes a nadir channel for the 1.05-1.65 μm range to access the atmosphere below the clouds.

The orbital experiments target to answer many outstanding questions of Venus climate evolution including the role of Solar wind direct interactions with its atmosphere. The OM instrument list is developed in Table 5.

Table 5 Table of Venera-D Orbital Module (OM) instruments under study. Notes: (1) instrument provisionally provided by INAF/ASI; (2) instruments provisionally provided by ISAS/JAXA. A dedicated suite of 7 instruments for measurements of particles (neutral and charged) and electromagnetic fields

Venera-D Orbiter Module (OM)			
Instrument		**Description**	**Scientific goals**
SVET		Thermal IR Fourier transform spectrometer 5-40 μm (2000 – 250 cm–1, Δv=1 cm–1)	3-D thermal structure 55-100 km, SO2 and H20 and clouds composition 55-75 km, dynamics, thermal tides, thermal balance
VOLNA		UV mapping nadir and limb spectrometer (190 – 590 nm, Δλ =0.2-0.3 nm)	UV absorber, SO, SO2, cloud composition, dynamics, night glow emissions
VENIS *(1)*		IR grating spectrometer 2 – 5 μm and Imager, 2 channels, Δλ=13 nm	Atmospheric structure , composition, dynamics
VIKA		IR spectrometer suite 1.05 – 1.65 μm (λ/Δλ = 20 000, nadir and occultations), 2.3 – 4.3 μm (λ/Δλ = 40 000, occultations)	Atmospheric composition, thermal structure (vertical), aerosols
IVOLGA		Hi-res heterodyne spectrometer in 1.58 and 2.05 μm CO2 lines (solar occultation)	Dynamics above clouds, meso- and thermosphere structure up to 180 km
MM-radiometer		5-channel radiometer (90, 50, 30, 20, 10 GHz); scanning antennae	Thermal structure 0-50 km, and H2SO4, SO2 etc. below the clouds
VMC		4 coaxial monitoring cameras: 365, 513, 965, 1000 nm	Dynamics at day side at different altitudes in upper clouds, UV absorber distribution, aerosol, surface emission at 1 μm
LIR *(2)*		Thermal IR camera in 8-12 μm	Thermal structure and dynamics in upper cloud layer
IR2R *(2)*		IR camera in 1.74, 2.02, 2.26 and 2.35 μm	Dynamics and morphologies of middle-to-lower atmosphere, variations of CO
X-range radio occultation		Radio occultation atmospheric experiment	Thermal structure and dynamics of the atmosphere, structure of the ionosphere
Plasma & EM Field complex		7 instruments to analyze plasma spectra and EM field fluctuations	Magnetosphere, ionosphere, escape rate, D/H, lightning
	ARIES-V	Wide angle ion spectrometer 10 eV – 30 k	Composition and intensity of escape ions; ion capture by solar wind; ionospheric clouds; influence of solar activity on Venus plasma; transfer of momentum and energy from solar wind to ionosphere; interplanetary ion influx
	ELSPEC	Electron spectrometer 10 eV – 10 keV	
	NPD	Neutral particles detector 50 eV – 3 keV	
	ASPECT-V	Ion and electron energy spectrometer	Magnetospheric structure; influence of solar activity on magnetosphere
	BMSV-V	Plasma spectrometer 100 eV – 5 keV	Monitoring of solar wind, its interaction with magnetosphere; turbulence of interplanetary medium at high frequencies
	FM-V	Magnetometer ±1000 nT, up to 32 Hz	Interaction of solar wind with magnetosphere; non-thermal atmospheric dissipation; magnetic properties of ionosphere; lightning activity
	GROZA	Radiowave analyzer 15-50 MHz	Detection of radiowave events from lightning activity

Operating orbit of the Venera-D orbiter was designed to satisfy interests and requirements expressed by the atmospheric and plasma science communities. A set of instruments (ARIES-V, ASPECT-V, ELSPEC) for charged particle measurements together with the neutral particle detector (NPD) will be capable to determine the effects of solar activity on Venus' atmosphere and ionosphere, characteristics of the loading of Solar wind plasma stream by planetary ions and parameters of multiscale ionospheric structures. Upstream information on SW parameters will be provided by the BMSV-V instrument and magnetic field variations, produced by various plasma interactions, will be analyzed by the FM-V

Table 6 Table of Venera –D Lander Module (LM) instruments under study. Table of scientific payload (phase A stage). (*): S– instrument requires surface sample; A– instrument requires atmospheric sample; [1]– instrument provisionally provided by Germany

Venera-D Lander Module (LM)				
Instrument		**Description**	**Scientific goals**	**Sample (S = Surface; A = Atm.)**
TVS-VD		Panoramic (5), descent (1) and microscopic (1) cameras	Characterization of local landforms	None
Surface Sampling System		Drill and vacuum pump system to acquire and deliver surface samples to XRD/XRF, MIMOS II, APXS-V,LMS		None
XRD/XRF		X-Ray diffraction and fluorescence spectrometer	Elemental and mineral composition of surface materials; possible detection of bounded water in the surface minerals	S
MIMOS II *(1)*		Moessbauer spectrometer	Surface mineralogical composition, iron phases	S
APXS-V		Analysis of scattering of α-particles from Cm-224 radioisotopic source on atmospheric molecules and surface material	Elemental composition of the atmosphere and surface	S
LMS		Laser mass spectrometer for surface samples	Surface elemental and isotope composition, local geological processes, surface-atmosphere interaction	S
AGNESSA		Active gamma and neutron spectrometer	Radioisotopes (K, U, Th), surface elemental composition to 0.5 m depth (Al, Mg, Fe, O, Na, Si, C)	
VCS		Gas chromatograph & mass spectrometer for atmospheric samples	Vertical profile (70-0 km) of atmospheric composition, trace & noble gasses, aerosol composition	A
ISKRA-V		IR multi-channel tunable laser absorption spectrometer, resolution 10-3 cm-1	Vertical profile (70-0 km) of major atmospheric constituents [SO2 CO CO2 OCS H2O PH3] and their isotopes [C, O, S, D/H]	A
DAVUS		Descent UV spectrometer 250 – 400 nm (Δλ=0.15 nm) for in situ atmosphere analysis	Vertical structure of SO2, SO from 70 to 0 km; unknown UV absorbers; ClO; aerosol extinction in clouds/hazes	None
MTK-V		Suite of sensors for key atmospheric parameters	Vertical profile (70-0 km) of main meteo parameters	None
VERBA		Actinometric spectroradiometer in VIS and IR (0.4-1.1, 1-1.8, 2.4, 3.7, 6.2, 8.7 μm)	Thermal balance below clouds, optical properties of aerosol, profile of H2O	None

magnetometer. Venus is expected to display potential lightning activity (e.g., Lorenz 2018) which will be studied on board by the GROZA radio wave analyzer.

7.3.2 Lander Science

A list of Lander Module science instruments under study is presented in Table 6. The key element of this package is the surface sampling system that will drill the surface to a certain depth and then, using the vacuum pump device, deliver the acquired samples to four analytical instruments:

- X-ray diffraction and fluorescence spectrometer (XRD/XRF) and a Mössbauer spectrometer (MIMOS II) for structural analysis;
- laser mass spectrometer (LMS) and an active APXS-V alpha-particle experiment for elemental analysis.

Gamma and neutron spectrometer with neutron activation AGNESSA will measure the naturally radioactive elements (K, U, Th) and the main rock-forming elements (Al, Mg, Fe, O, Na, Si, Ca) in the activation mode down to ∼0.5 m depth without requiring sampling.

Gas chromatograph (VCS) and Laser absorption spectrometer (ISKRA-V) will study atmospheric samples acquired during the Lander descent (∼50 min) and at the surface, already mentioned in Sect. 7.2.3. These two instruments feature their own sample preparation system and will use the pre-vacuumized Lander as a dump volume. The UV-spectrometer (DAVUS) will continuously study the composition of the atmosphere during the descent down to ∼10 km using an optical cell open to the atmosphere.

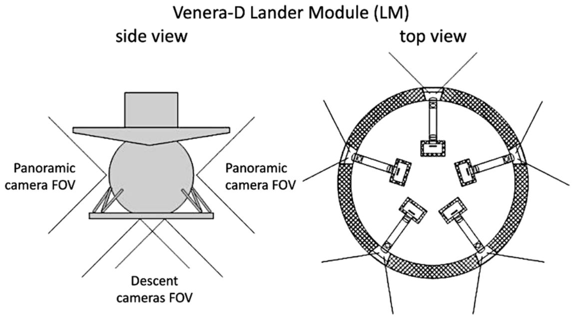


Fig. 24 Concept of the Venera-D Lander Module (LM) imaging system (5 + 2 units): FOV: 90° × 90°, frame size: 2048 × 2048 pix, angular resolution-2.5', Linear resolution @ 2.5 m is 2 mm (see Table 6)

The camera system (TVS-VD) of the Venera-D Lander will provide a series of synoptic images from the descent camera (resolution from a few tens to meters per pixel), complete 360° surface panoramas (Fig. 24). A close-up microscopic camera imaging with resolution of ~100 microns per pixel aims at observing the sampling spot at sub-millimeter scale to characterize its color, texture, grain sizes, traces of weathering, before and after its brushing/sawing/drilling.

7.4 Summary and Conclusions

The Venera-D mission is currently at the Phase A development stage and some mission parameters as well as characteristics of scientific instruments are to be clarified at the subsequent stages. The Aerial Platform will definitely be an important part of the Venera-D mission, currently its scientific payload as well as operation scenarios are being discussed. At the time of publication, the Venera-D launch is planned for the 2029 launch window, although the funding situation may result in a shift to the early part of the next decade.

The Venera-D science team looks forward to productive cooperation (including coordination between the different missions) with its VERITAS, DAVINCI and EnVision colleagues. Certainly, such cooperation could begin even earlier for the Indian Shukrayaan-1 mission to Venus (see Sect. 8), which will carry Russian instruments. The VeSCoor activity in development by ESA, NASA and other international partners could enhance the synergies between Venera-D and the other missions mentioned above.

8 Shukrayaan-1

Capitalizing on the successes of the Moon and Mars missions, with scientific payloads and instruments such as Synthetic Aperture Radar aboard Chandrayaan-1, 2, Mangalyaan-1 and numerous Earth orbiters, ISRO is considering to take a step towards exploring Venus (Antonita et al. 2022). ISRO has been a leader in the development of Synthetic Aperture Radar (SAR) instruments capable of polarimetric measurements. The hybrid-polarization mode in C-band SAR, RISAT-1 and full-polarimetric mode in Dual Frequency SAR in Chandrayaan-2 were implemented for the first time in any mission for observing Earth and Moon respectively.

The main goal of the planned Venus Orbiter Mission or Shukrayaan-1 is to undertake global mapping of the Venusian surface with a polarimetric SAR and to conduct the first penetration radar experiment to access shallow subsurface stratigraphy. The mission also plans to carry multiple instruments targeting the structure, composition, and dynamics of the atmosphere, and for investigating solar-wind interaction with the Venusian ionosphere. The final schedule and the science payload of the mission will be announced following approval by the Union Government of India.

A non-exhaustive list of Shukrayaan-1 contributions to Venus' evolution study includes the global characterization of current geologic activity, insights to the past by assessing vertical structure and stratigraphy of geological units including buried lava flows, global distribution of craters at better spatial resolution and including buried craters. The mission promises long-term monitoring of the atmosphere and clouds, potentially documenting their response to volcanic events, and detailed characterization of the contemporary escape.

8.1 Shukrayaan-1 Science Objectives

8.1.1 Investigation of the Surface Processes and Shallow Subsurface Stratigraphy

The surface and subsurface observations by Shukrayaan-1 will help in understanding geologic and resurfacing history, aeolian features on the surface, impact processes including detection of buried impact craters, vertical structure and stratigraphy of geological units including active volcanic hotspots and lava flows. The proposed VSAR instrument will carry out full polarimetric SAR observations of the surface of Venus which will provide highly accurate estimates of dielectric permittivity (Fung et al. 2010) and surface feature classifications (Ainsworth et al. 2009; Xie et al. 2015).

The first science objective aims to answer several outstanding questions by characterizing the contemporary and past Venus. The global characterization of volcanic and tectonic landforms will help in understanding how active Venus is at present, and assess its current geologic activity. The global mapping at better surface resolution will deliver a refined distribution of impact craters, quantifying their floor, rim morphology, and the parabola deposits. Characterization of prominent features like tessera terrain, unique geologic landforms such as Coronae and anomalous radar-bright regions found from Magellan using polarimetric surface decomposition techniques will be done.

Potentially, active volcanic hotspots and lava flows will be detected via observations of thermal emission in the near-IR atmospheric windows and brightness temperature measurements by SAR instrument in the radiometer mode. Also, variations of emissivity can be used to assess broad-scale surface composition of tessera terrains.

Venus' past will be addressed by stratigraphy of geological units, potential detection of buried impact craters and larger impact basins, particularly within the older tessera terrains. The subsurface observations will allow estimation of buried lava flows thickness and volume at different times.

8.1.2 Studying the Structure, Composition and Dynamics of the Atmosphere

This goal includes cloud dynamics and morphology, variability of SO_2, studying the super-rotation, detection and understanding the role of lightning in the Venusian atmosphere.

By observing the clouds from UV to thermal IR, the mission will address the correlation of the cloud-top altitude with particles' microphysical properties, monitor the spatial and temporal variations of the planet's albedo, particularly in the UV-blue domain, use the cloud opacity to detect changes over various time scales. In the mesosphere, the aerosol will be characterized spectrally, in vertical and horizontal dimensions, including thin clouds and detached layers.

The SO_2 cycle, closely linked to primarily H_2SO_4 clouds and hazes, will be studied via IR occultation spectrometry and the cloud monitoring UV camera. The measurements will provide important insight into the ongoing chemical evolution, atmospheric dynamics, and as an indicator of possible geological activity.

The super-rotation, its long-term trends, the role of wave dynamics, associated planetary-scale cloud structures (the Y-shape) will be studied via the cloud features tracking in the UV, and characterizing the 3D thermal structure and wind field using finely-resolved near-IR CO_2 lines.

Assessing the lightning in Venus' atmosphere is important to understand its rate, strength and spread as well as its possible role in the cloud or atmosphere chemistry. Can lightning be hazardous for atmospheric probes? The detection is planned by analyzing the Hz - kHz electromagnetic spectrum, using the magnetometer and visible imaging data.

8.1.3 Investigation of Solar Wind Interaction with Venusian Ionosphere

This goal includes studying ionospheric dynamics and plasma waves, interaction with the Solar wind, detection of oxygen airglow and understanding its role, to study the upper atmosphere/ionosphere dynamics. Specific questions to address within this goal are: What makes the Venus ionosphere (V-1 and V-3) layers so elusive? What causes ion-holes in the Venus nighttime ionosphere? The measurements are to decipher how the ionospheric parameters depend on the Solar cycle and Solar Zenith Angle (SZA), detect the occasional meteor layer, determine spatio-temporal variation of the neutral composition and density of the upper thermosphere and exosphere, detect the ionosphere plasma waves and characterize escape rates of the Venusian upper atmosphere.

Detecting and observing the oxygen green (557.7 nm) and red (630 nm) lines would help to assess the day-to-night transport in the upper atmosphere, detect signatures of the atmospheric gravity waves. It would probe the atmosphere and ionosphere response to solar disturbances, characterize the sustenance of the nightside ionosphere, and detect large-scale ionospheric structures.

The outstanding questions to address for the Solar wind interaction goal are the loss of the upper atmosphere/ionosphere, the role of different escape mechanisms, characterization of plasma boundaries, assessing the variability of magnetosphere domains and processes responsible for atmospheric sputtering using Energetic Neutral Atom (ENA) measurements.

8.1.4 Astrobiology

The goal of indirect detection of possible bio molecules and life forms in the cloud deck is recognized. The measurement available is the potential PH_3 detection using the IR solar occultation spectrometer.

8.2 Shukrayaan-1 Mission Overview

Shukrayaan-1 is a highly-sophisticated Venus orbiter carrying up to 100 kg of science instruments and delivering up to 500 W of electric power. Shukrayaan-I will be launched on either GSLV Mk II or GSLV Mk III. ISRO has backup launch dates in 2026 and 2028 should it miss the 2024 opportunity. At the time of this publication, ISRO has not yet received approval from the Indian government for the Venus mission and that, as a result, the mission may be delayed until 2031.

Table 7 Key VSAR radar design and performance parameters

Shukrayaan-1 VSAR Parameters	
Instrument Parameters	Value
Platform Altitude Range (km)	200-600
Frequency (GHz)	3.2
Antenna azimuth × elevation dimensions (m)	5.8 × 2
Atmospheric Losses (dB)	−1.6
Polarization modes	Tri-Pol (HH, VV, VH) & Hybrid Pol
Mapping modes RFBW	7.5 MHz, 40 m with 15-20 km swath
Number of looks	6, 13
Radiometric resolution at 10 dB, SNR (dB)	1.2, 1.6
Peak power (W)	300
NES0 (dB)	≤ −25
Swath (km)	15-20

After the Earth-to-Venus cruise and the heliocentric phase, the spacecraft will perform trajectory maneuvers and final braking to reach intermediate Venus 500 × 60,000 km near-polar orbit. A lower orbit, suitable for SAR mapping, with the pericenter at 200 km and the apocenter at 500–600 km, will be achieved by aerobraking. The aerobraking phase will take 6–8 months with controlled pericenter altitude down to 130–140 km in the atmosphere.

For optimized science operations, the spacecraft features 2D orientable (0°–360°; ±90°) solar panels and a 2D gimbal high-gain antenna (Nigar 2022).

8.3 Shukrayaan-1 Science Payload

The Shukrayaan-1 orbiter will carry the VSAR instrument, for mapping the surface. Up to seventeen further potential science instruments have been shortlisted, including a subsurface sounder and a number of instruments targeting the atmosphere, clouds and the plasma environment (Nigar 2019).

8.3.1 VSAR on Shukrayaan-1

Global mapping by Magellan at resolution of 100–200 m was performed in single polarization (HH). Complete polarimetric data of selected sites are only available from earth-based radar experiments. The main instrument onboard, the S-Band Synthetic Aperture Radar (VSAR) targeting high-resolution (40 m), fully-polarimetric global mapping, would provide a major step in Venus surface studies, complementary to the VISAR and VenSAR operations and performance (Table 7). VSAR will be capable of polarimetric decomposition by retrieval of the complete scattering matrix (all four Stokes parameters). It is well known that the cross-pol channels (HV or VH) are more sensitive towards surface roughness and volumetric inhomogeneities within the medium and are not optimally used for dielectric constant estimation (Fung et al. 2010). Thus, co-polarization channels (HH&VV) will estimate surface dielectric properties with the highest accuracy.

Full polarimetric mode is challenging in terms of handling the radar ambiguities, power requirements and has double penalty in terms of radar coverage due to high data rate and reduced PRI. The radar ambiguities are controlled by partially processing azimuth bandwidth against a trade-off of a number of looks (Shah and Seth 2022). The wide antenna area of 5.8 m × 2 m is optimized to reduce the transmit power requirement which aids in reducing the volume and thermal management requirements of the payload. A trade-off of having antenna width of 2 m is that maximum possible swath would be 15-20 km, which either way was restricted due to the doubled PRF in full pol mode. However due to the slow rotation of Venus consecutive orbit passes are 11 km apart at the equator and will ensure continuity in coverage.

The possibility of cycle-to-cycle interferometry is foreseen. In the radiometer mode, SAR will estimate the brightness temperature with an accuracy better than 2 K. The science objectives of Shukrayaan-1 significantly differ and complement those of EnVision and VERITAS, and therefore the overall mission operations and VSAR capabilities, operations and performances are different when compared to VISAR and VenSAR. For each of the three orbiter missions, payload instruments were chosen to meet the broad spectrum of measurement requirements needed to support mission science investigations. Combining the data from all three missions would provide us with deep scientific insights into the geology and evolution of Venus with topographic, polarimetric and global information available at a high resolution.

8.3.2 Subsurface/Surface IR Emissivity

A low frequency (9–30 MHz) radar VARTISS will provide direct measurement of subsurface features. It will provide a vertical resolution of 10–25 m down to a depth of ∼1 km, in a similar technique as the subsurface radar (SRS) currently developed for the EnVision mission (see Sect. 6.3.2 and European Space Agency 2021). VARTISS utilizes three-wire 25-m dipole antennas. VSEAM (Surface Emissivity) instrument to provide planetary temperature and radiation emission data in the 1-μm atmospheric transparency window is also considered.

8.3.3 Atmosphere/Clouds Observations

The atmospheric package includes the Venus Thermal Camera (VTC), UV and visible camera (VCMC) for cloud Monitoring. Together with VSEAM, the imagers will provide cloud tracking at different altitude levels to measure the zonal and meridional wind fields, estimate the horizontal scale of the atmospheric waves.

The near-IR spectro-polarimeter (VASP) aims at cloud microphysics and measuring the cloud-top altitude.

The solar occultation package includes an occultation photometer (SPAV) in the near-IR and visible ranges targeting sub-micron aerosol vertical distribution in the upper clouds. Solar occultation IR spectrometers target detecting trace gasses and studying the mesosphere dynamics through vertical profiling of atmospheric composition and wind speed. Selected as two separate spectrometers, the high-resolution echelle (2.3–4.4 μm) Venus Infrared Atmospheric gas Linker (VIRAL) and a laser heterodyne (1.6 μm) IVOLGA, they are combined into a single two-channel Roscosmos-provided VIRAL. A very high-resolution IR spectrograph ($\lambda/\Delta\lambda > 20{,}000$), VIRAL will measure trace gases at the limb during solar occultations, improving performances of the VEx/SOIR spectrometer by a factor of 10. It will therefore be possible to gain 1 to 2 atmospheric scale heights in depth to explore the upper cloud region and contribute to study the trace species photochemistry at all latitudes at 6 AM and 6 PM local time.

The lightning sensor analyzing the Hz-kHz spectrum (LIVE) will detect lightning activity in coordination with VCMC camera and magnetometer observations.

8.3.4 Measurements Related to Solar Wind/Ionosphere Interactions

The measurements dedicated to Venus' plasma environment will target ionospheric parameters measurements, characterization of neutral and plasma particles, monitoring of radiation environment and solar X-rays. The planned instruments are VEDA (electron density) and RPA (Retarding Potential Analyser), to measure electron and ion density, composition and temperature, VISWAS for mass spectrometry of energetic neutral atoms and ions, VIPER to measure plasma-wave parameters using Langmuir probe, electric field analyzer and magnetometer.

To study the region connecting the neural and ionized atmosphere, a radio-occultation experiment RAVI with German participation and a high-throughput airglow imager NAVA to detect oxygen green and red lines are planned.

To characterize the environment and solar wind, two instruments, VREM to monitor the charged particles (100 keV–100 MeV) and SSXS spectrometer to measure Solar soft X-rays (1–15 keV) are foreseen.

Finally, VODEX, Venus Orbiter Dust EXperiment, to detect interplanetary dust during the cruise phase and at Venus orbits, is being considered.

8.4 Summary and Conclusions

Solar system studies have seen a remarkable growth in the last few decades, due to advances in space technology, observational capabilities and computational technologies. This has enhanced our knowledge and understanding of the diversity of complex processes across the Solar system. It is quite interesting to find clues as to how the planetary systems might have originated and evolved, and how they are different and similar to each other. In this context, the first ever planet explored by humankind for the search of life in the solar system is Venus, our nearest neighbor. Despite many missions including flybys, orbiter and lander, large gaps remain today in our understanding of Venus on its formation, spin, surface evolution, runaway greenhouse phenomenon, super rotation of its atmosphere, its evolution and interaction with solar wind, etc. In this context an orbiter mission to Venus is being considered by ISRO, with the above science objectives, to further improve our understanding of resurfacing processes, neutral atmospheric and ionospheric processes, influence of Sun on Venus atmosphere and ionosphere in particular to produce highest resolution topography, to map sub-surface of Venus, to detect lightning and airglow with better techniques and improved resolutions.

9 Overview of Future Mission Concepts and Science Investigations Addressing Venus Evolution Through Time

In the following Sects. 10-12, we address future mission concepts and measurements that require further technology development beyond the current framework of selected missions, as well as the synergies between these mission concepts, ground-based and space-based observatories and facilities, laboratory measurements, and future algorithmic or modeling activities that pave the way for the development of a Venus program that extends into the 2040s (Wilson et al. 2022; Limaye and Garvin 2023). Continued development of planetary radar technologies, while applicable to many planetary missions, is particularly important for Venus because of the opacity of Venus' cloudy atmosphere to optical imagers. We also discuss complementarities between Venus mission concepts that target specific outcomes that reveal Venus evolution through time, as summarized in Sect. 2, and with non-Venus missions (e.g., exoplanet observatories).

Section 10, Future Mission Concepts and Measurements, addresses key areas and investigations at Venus not covered by the fleet of missions under development described in Sects. 4-8. They include:

Future Surface Investigations. - Since all previous probes have landed in basaltic plains, a new lander in the tesserae highlands, thought to represent the oldest terrains on Venus, is needed to perform a detailed, comprehensive analysis of Venusian surface materials to understand Venus' geologic history, tectonic style, mineralogy, and composition (Sect. 10.1). Meteorology and seismometry, on the other hand, require measurements over months or years. Rather than try to use silicon electronics with associated cooling and power systems, such long-duration lander measurements can be implemented using high- temperature electronics of silicon carbide, gallium nitride or other wide band-gap materials (Wilson et al. 2022). As well as their own scientific investigations, such long-term landers would serve as technology demonstrators developing technology in preparation for mobile surface exploration, which is a post- 2050 Venus exploration goal. Note that the DAVINCI probe will touch-down in tesserae highlands providing ground-truth to enable future landings in complex ridged terrains.

Aerial Platforms; Long-Term Atmospheric* in-situ *Measurements. - Longer duration measurements in the cloud layer could be achieved by using balloons, whether these are constant- or variable-altitude balloons (Sect. 10.2). Balloons offer a lifetime of weeks in arguably the most habitable environment found outside Earth, where temperature is around 20 degrees C, pressure is 0.5 bar, and there is ample sunlight and liquid water in the clouds (albeit mixed with sulfuric acid). Such a mission would explore the coupled chemical, dynamical, and radiative processes at work in this critical part of the long-term evolution of the Venusian atmosphere, as well as further investigations of past and present habitability and astrobiological aspects of the cloud layers. As summarized in Sect. 2 (Gillmann et al. 2022, this collection; Avice et al. 2022, this collection; Westall et al. 2023, this collection) volatile elements have a strong influence on the evolutionary pathways of rocky bodies and are critical for understanding the evolution of the Solar System. Because Venus experienced a different volatile element history than Earth, it provides the only accessible example of an end state for habitable Earth-size planets.

Future Orbital or Suborbital Investigations. - Future orbital investigations include longer-term observations of variable phenomena such as the atmospheric signature of surface events (e.g., large Venusian quakes and their potential airglow signature) and the collection of data on the sources, propagation, and dissipation of gravity waves in the Venusian atmosphere, which will require high-frequency imaging of the entire disk (Sect. 10.3). In addition, various concepts for skimmer probes of the upper atmosphere, diving below the Venusian homopause, and returning samples to Earth have been proposed recently (Shibata et al. 2017; Sotin et al. 2018a). Extremely high RF bandwidth radars operating at S or L-bands, could achieve meter-scale polarimetric SAR imaging of key regions after VERITAS and EnVision, building off of planned L-band systems such as NASA-ISRO's NISAR mission and planned Mars-orbital L-band measurements (JAXA, CSA, ASI, and others).

Sections 11 and 12 address the importance of ground-based, Earth orbit-based, observations and laboratory and modeling activities in support of Venus' evolution through time. They include:

Ground-Based and Space-Based Observatories. - Ground-based observations, or observations from Earth orbit by space-based observatories, complement the space-based instrumentation at Venus by providing long temporal baselines of variable phenomena of interest to the long-term evolution of Venus, such as ground-based radar images of the Venusian surface (Campbell et al. 2017), thermal infrared imaging spectroscopy to monitor SO_2 and H_2O variability possibly related to present-day volcanic activity (Encrenaz et al. 2019), millimeter and submillimeter wave observations, observations of key trace gases, or extended series of ground-based dynamical observations of wind speeds and gravity waves (generated by both convection and topography) that support Venusian general circulation models and present-day dynamical coupling between the lower atmosphere and the surface (Sect. 11.1). Section 11.2 focuses on space-based platforms and the synergies between Venus and exoplanetary observations such as TESS, JWST, CHEOPS, and PLATO, as well as next-generation ground-based facilities such as the ELT (Way et al. 2023, this collection).

Laboratory and Modeling Efforts. - Experimental facilities on Venus are critical to advancing our understanding of this planet in the coming decades (Glaze et al. 2018; Santos et al. 2021, see Sect. 12). Several scientific investigations that address the previously discussed scientific themes and knowledge gaps related to how and when Venus' evolutionary path diverged from Earth are enabled by experimental facilities. Section 12.1 highlights a selection of current facilities and experiments that are particularly relevant to understanding ancient Venus and the long-term evolution of the planet, such as geochemical experiments (Sect. 12.1.1), mission calibration libraries (Sect. 12.1.2), rheology experiments (Sect. 12.1.3). Section 12.2 focuses more on progress and future directions in modeling efforts, particularly in the rapidly expanding capabilities for characterizing the chemical and dynamical interactions between the surface and the atmosphere (which are key to understanding the processes driving the long-term evolution of the spin rate); radiative and radiative-convective models for determining the long-term climate evolution. Newly proposed laboratory capabilities in the USA and Europe (2023 and beyond) could facilitate studies that refine the upcoming observations to improve interpretations.

Finally, Sect. 13, Summary and Conclusions, summarizes the key findings of Sects. 3-12, highlighting which key questions about Venusian evolution through time will be answered convincingly by current and next-generation mission concepts and future investigations; how current limitations in our knowledge of Venus affect current and future exoplanetary science and modeling of the evolution of rocky, Earth-sized exoplanets; and how the study of Venus' evolutionary history informs its habitability history through time.

10 Future Mission Concepts and Measurements

The data acquired with the VERITAS, DAVINCI, and EnVision missions from the end of this decade, in addition to other missions concepts described in Sects. 7-8, will fundamentally improve our understanding of the planet's long term history, current activity and evolutionary path. Yet even with the discoveries that await those missions, compelling science questions will likely remain—such as those regarding the chemical and physical cycles of the atmosphere, the interactions between that atmosphere and the surface, and the make-up and structure of the planet itself. Although new missions may be proposed in the near-term using capabilities currently in development, investments in future technologies and new techniques will enable both long-term surface science and missions that take advantage of mobility in the surface, near-surface, and atmospheric environments (Fig. 25).

10.1 Future Surface Investigations

One of the fundamental measurements that is needed is the bulk elemental composition and mineralogy of the surface from key locations, especially tesserae. Tesserae are thought to be

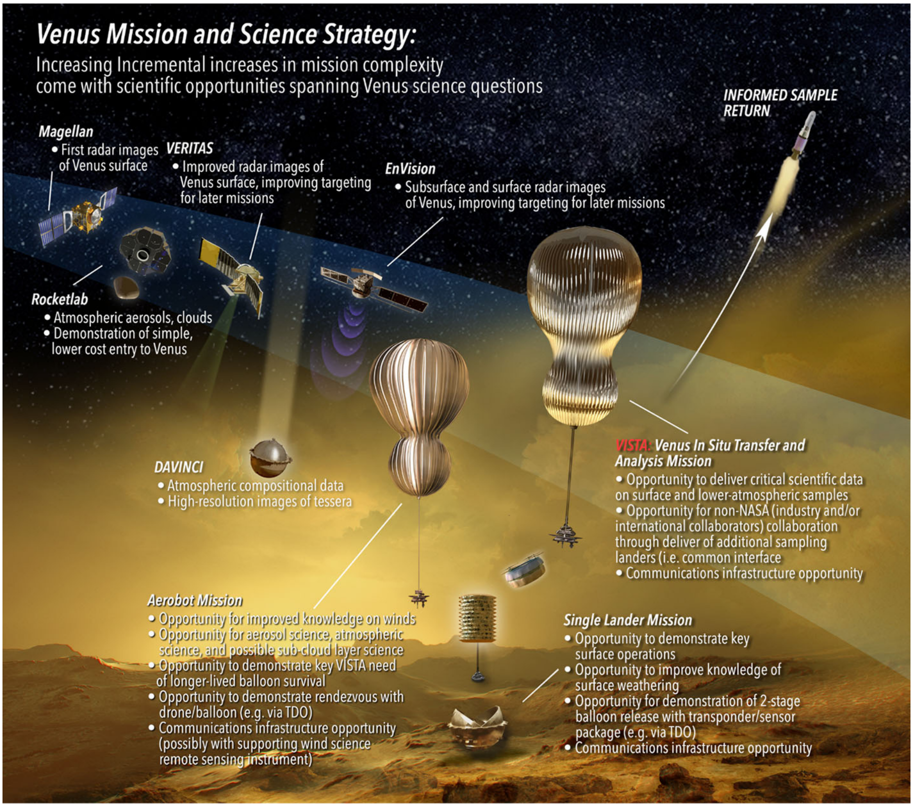


Fig. 25 The Venus *In Situ* Transfer and Analysis mission concept (VISTA) provides an opportunity to obtain measurements that cannot be obtained by a simple, short-term mission to Venus (Izenberg et al. 2023; see also Sect. 10.2.1). This illustration is provided as an example. Data acquired with the VERITAS, DAVINCI, and EnVision missions from the end of this decade will fundamentally improve our understanding of the planet's long-term history, current activity and evolutionary path (top left). Although new missions may be proposed in the near-term using capabilities currently in development, investments in future technologies and new techniques will enable both long-term surface science and missions that take advantage of mobility in the surface, near-surface, and atmospheric environments. Additional future Venus exploration vehicles may include: (1) orbital platforms such as geophysics orbiters for atmospheric remote sensing, and in-situ orbital sensing; aerial or cloud-level platforms; and (3) surface platforms including short-lived landers, long-lived landers, and, ultimately, mobile surface assets. credit: Keck Institute for Space Studies/Noam Izenberg/Chuck Carter

older than the regional plains, and as such may retain evidence of an earlier epoch prior to volcanic resurfacing, including evidence of different climate and weathering (Gilmore et al. 2023, this collection). The ability to perform detailed, comprehensive analysis of Venus surface materials would be game changing. Of course, landers (Fig. 25) must cope with the incredibly harsh conditions of ∼470 °C at the surface of Venus. The Venera landers used only thermal inertia and thermal insulation to keep a central electronics compartment cool that, together with limited radio relay capabilities, only allowed for operation times of order an hour (see e.g., Vorontsov et al. 2011). Modern landers using the same, brute-force thermal approach could last for several hours but certainly not more than, say, one Earth day. Even so, a huge amount of surface mineralogical and petrological science could be achieved in that time.

10.1.1 Surface Images and Mineralogy

The principal science payload of such a lander would include surface imagers and non-contact chemical and mineralogical sensors such as a gamma-ray spectrometer with neutron activation, capable of measuring elemental abundances of U, Th, K, Si, Fe, Al, Ca, Mg, Mn, Cl (Mitrofanov et al. 2010) and/or Raman/LIBS (Clegg et al. 2011). Although the extreme Venus surface temperature (740 K) and atmospheric pressure (93 atm) provide a challenging environment for surface geochemical and mineralogical investigations, laboratory Raman experiments have been conducted under supercritical CO_2 Venus surface conditions, involving single-mineral and mixed-mineral samples (Clegg et al. 2016). The inclusion of surface sample ingestion via a drill/grinder/scoop would enable additional analysis techniques such as mass spectroscopy and X-ray fluorescence (XRF) spectroscopy, but would equally require important, continued technology development and verification.

Gamma- and XRF-based spectroscopic measurements were acquired by the Venera and VeGa landers, but modern equivalents of these instruments would provide much improved measurement accuracy. Moreover, carrying out compositional analyses in a tessera region (none of which has been sampled before) would reveal whether these terrains are chemically distinct from the lava plains where previous analyses have been conducted (e.g., Gilmore et al. 2023, this collection).

Collecting imaging data from the surface is not straightforward (e.g., Garvin et al. 1984), as silicon-based detectors typically used in virtually all modern imagers will not work at Venus surface temperatures. For short-lived landers, one can use silicon imaging chips inside insulated housings (e.g., Kremic et al. 2020). For prolonged operation at the surface, however, imagers capable of sustained operations at high temperatures are needed. Such imaging capability would be essential not only for surface science but for eventual mobile platforms (e.g., rover missions).

10.1.2 Surface Geophysical and Meteorological Data

Long-lived landers would prove valuable in numerous other ways, as well. For instance, long-duration surface operations would allow acquiring essential seismological, heat flow, and meteorological data. But the technological barriers to such long-lived surface missions are twofold, and formidable: (1) the high-temperature environment of the Venus surface, which is too hot for silicon electronics; and (2) the lack of sunlight at the surface, making solar-based power systems difficult of even unviable. As has been discussed by Kremic et al. (2020), Kremic and Hunter (2021), and Wilson et al. (2022), recent advances in high-temperature electronics have made long-duration uncooled landers an exciting possibility that can be explored in the coming decades—but doing so requires continued investment in the development of the electronics, in their packaging, and in their environmental qualification under Venus conditions. Power for long-duration landers on the surface could come from primary molten salt batteries, for at least a first generation of such long-lived landers. Second-generation long-life landers could be powered by RTGs or even wind power—again, both of which would require technology development. Yet, long-lived landers would provide not only essential meteorological and geophysical measurements but also would serve as essential precursors for post-2050 surface missions including more capable seismometry stations but also for eventual surface rovers—a technology that we envisage as being tractable beyond 2050.

Of these measurements, meteorological measurements are the most straightforward to make—indeed, Soviet Venera & VeGa landers made measurements of pressure, temperature, and even wind speed during their brief operation at the surface. However, long-duration operations, i.e., those lasting for at least one Venus solar day (118 Earth days) would be needed in order to understand the temporal evolution of surface winds. Recent modeling suggests that the deep atmosphere of Venus, far from being still like the bottom of a pond, exhibits complex diurnal patterns, mesoscale circulations, and slope winds, all driven by the small day-night temperature difference estimated to be of order 1–2 K (Lebonnois et al. 2018; Lefèvre 2022; Lefèvre et al. 2022). Investigating this deep atmosphere circulation from the surface is important for understanding the evolution of Venus; to give two examples, deep circulation governs the transport of magmatic volatiles (or volcanic ash) into the atmosphere (Wilson et al. 2022, this collection) as well as the aeolian and sedimentation processes that shape the surface of Venus (Carter et al. 2023, this collection).

Long-term meteorological measurements on the surface would require sensors capable of operating at ambient temperatures, such as those proposed by Kremic et al. (2020), Kremic and Hunter (2021). As well as the direct relevance to Venus evolution as described here, such meteorological measurement would provide vital information for the next generation of long-lived surface stations: the viability of wind power for surface stations depends, for example, on knowing the reliability of wind speed and direction. The viability of seismometry at the surface also requires characterization of atmospheric turbulence at the surface so that atmospheric perturbations can be removed from seismic data (Spiga et al. 2018).

10.1.3 Surface Heat Flow Measurements

Surface heat flow—that is, the energy flow from the interior to and across the lithosphere—is an important geophysical parameter that can be used to place constraints on estimates of the chemistry of the interior as well as models of the global tectonics (compare Rolf et al. 2022; Gillmann et al. 2022, this collection; and e.g., Breuer et al. 2022). If we assume that Venus formed with the same concentration of heat producing elements as Earth, and further that it has lost heat at a similar rate, an estimate can be made using the Earth's value which is found to be 45–47 TW (Davies and Davies 2010; Jaupart et al. 2015). Given the mass ratio of Venus and Earth, the corresponding global value range for Venus is 37–38 TW or 82 mW/m^2. However, this scaling argument is overly simplified: numerous estimates of heat flow from surface deformation suggest that the global average is higher than this value; O'Rourke and Smrekar (2018) derived elastic lithosphere thicknesses from Magellan data at coronae to estimate heat flow values of up to 95 mW/m^2 or greater Ruiz (2007); and more recently, Maia and Wieczorek (2022) estimate several 100 mW/m^2 for tessera terrains at the time of formation. New elastic thickness estimates from flexural bending (Smrekar et al. 2022b) correlate well with global elastic thickness estimates from admittance (Anderson and Smrekar 2006). This correlation indicates that $\sim$40% of Venus has high heat flow today, with more low-moderate values elsewhere. Very high values are consistent with active regions (Smrekar et al. 2022b). Since such estimates have significant errors, and require assumed or under-constrained parameters, in-situ heat flow would be a very valuable ground truth.

However, measuring the heat flow *in situ* remains a long-term challenge. On Earth and Mars, daily and seasonal temperature perturbations penetrate for meters into the near-surface and disturb the diurnal / seasonal thermal gradient from which the heat flow is usually calculated (if, in addition, the thermal conductivity is measured, see Grott et al. 2021). On Venus, diurnal temperature variations are expected to be small in amplitude (of order 1 K: Lebonnois et al. 2018) but even this small diurnal temperature difference can lead to heat flow disturbances of the order of 1 W/m^2, an order of magnitude larger than the $\sim$100 mW/m^2 internal heat fluxes when assuming the thermal properties of basalt. The thermal skin depth through which the diurnal perturbation decreases by 1/e can then still be a few meters, depending on the thermal diffusivity. At 60 mW/m^2, the temperature difference per unit value of thermal conductivity (W/m K) per m is 60 mK, and thus within the accessible range of space-qualified temperature sensors, assuming that such technology is otherwise inured to the harsh thermal environment at Venus' surface. Although there is a case for sediments on Venus (Carter et al. 2023, this collection), current radar data indicate rock surfaces over most of the planet.

Heat flow is typically measured in a borehole, as done on Earth; and as was done using holes drilled by Apollo astronauts on the Moon's landing sites. Technologies to install sensors at depth include drilling (e.g., Vago et al. 2017), or penetrators or hammering mechanisms such as on the Rosetta or InSight missions (Spohn et al. 2007, 2018, 2022); or pneumatically, as has been studied for the Moon (Zacny et al. 2013). However, drilling into basalt for constraining the heat flow value at Venus is very challenging. Alternatively, the temperature gradient and thermal conductivity could be measured with the "thermal blanket" technique used for heat flow studies at ocean bottoms (e.g., Johnson et al. 2010), which has been considered for Venus by Smrekar et al. (2014) and Kremic et al. (2020). This technique would see a low-thermal-conductivity blanket or plate, equipped with temperature sensors to measure the warming due to the heat flow from below, placed directly onto the ground. The device would need to be large enough to avoid edge effects from lateral heat conduction, and would be soft or flexible enough to smoothly adapt to uneven ground. On Earth, those blankets typically cover a square meter, and are particularly useful in rocky areas lacking a regolith coverage where a drill or penetrator could not be relied upon to work.

As a further alternative to measuring the thermal conductivity and temperature gradient a miniaturized heat flow probe has recently been proposed (Dominguez et al. 2020). It measures the heat flow across the cm-scale probe after thermal equilibrium is attained. The probe still needs to be emplaced below the thermal skin depth but that might be less demanding than installing a suit of temperature sensors.

10.1.4 Seismic Investigations

Seismology is the preeminent methodology for studying the structure and composition of a planet's interior. The behavior of seismic waves traveling through planetary bodies provides constraints on interior composition, compositional boundaries and transitions, and the state of interior materials (e.g., fluid versus solid, hot versus cold, porous or not). Seismology enables the study of several high-scientific priority questions of Venus. The similar size of Venus and Earth, their similar overall surface ages, and recent evidence of ongoing volcanic activity on Venus (Herrick and Hensley 2023) suggest that it should have a level of seismic activity comparable to Earth's, or at least much higher than the Moon or Mars. The nature of Venusian seismic activity, its level, and where earthquakes are occurring on Venus could enable us to distinguish between big-picture geodynamic hypotheses that predict differing versions of current geological activity. Constraints on models for ancient plate tectonics, which could be derived from future seismic measurements in combination with a more detailed exploration of surface features such as the tesserae and their compositions, would shed light into whether Venus had an early habitable period.

A workshop in 2014 (Stevenson et al. 2015) brought together several seismologists to discuss Venus seismicity. Some participants felt that the overall higher temperatures of the uppermost crust on Venus might make most fault movement aseismic, although the consensus at the workshop was that these elevated surface temperatures probably play a minimal role in affecting overall seismicity. The absence of water in the near surface of Venus could also potentially affect the nature of seismicity, as could the higher surface air pressure, but at present these are mostly unstudied and poorly understand aspect of Venus seismicity.

Because of those high surface temperatures on Venus and the limited solar energy reaching the surface relative to the power needed to transmit data, the option of placing solar-powered seismometers on the surface for an extended period—as has been done on Mars and the Moon—is not currently a viable option for Venus. The longest that a surface lander with conventional electronics has lasted on the Venusian surface is about two hours. However, to accomplish even the most basic goal of determining seismicity levels requires the ability to operate over a period of at least several Earth days. Although nuclear power might be viable for either active cooling or simply as a long-lived power source, regulatory and cost considerations are such that they are not likely to be used for seismology on the Venus surface for the foreseeable future (Venus Exploration Analysis Group/VEXAG 2019).

Over the past several years, research and development of high-temperature electronics has advanced to the point where a seismometer that can operate under Venus ambient conditions using battery power has become technically feasible (Kremic et al. 2020). Even so, the constraints on operation of a first-generation seismometer on Venus will be severe. The battery will likely be capable of enabling the seismometer to operate for a period of a handful of months (Glass et al. 2020; Kremic et al. 2020), but transmission of data from the surface to a orbiting relay spacecraft will be power intensive, such that less than ten hours of data will likely be able to be transmitted from the surface. Because data transmission rate depends in part on transmitter power, it may be the case that the frequency and dynamic range of the instrument will be limited to less than its intrinsic capability. Furthermore, although limited computer memory is being developed for high-temperature devices, power consumption will be high, such that storing even small amounts of data for later transmission may not be possible for such first-generation long-endurance landers. A primary mitigation strategy will involve designing a low-memory algorithm that triggers transmission during earthquakes and avoids transmission during wind and other noise events (Tian et al. 2023).

10.2 Future Aerial Investigations

Venus' clouds represent an important exploration target for understanding Venus evolution, whether for characterizing past and present habitability (Westall et al. 2023, this collection), for placing bounds on tectonic and volcanic activity through infrasound measurements (Ghail et al. 2023, this collection), for searching for atmospheric signs of volcanic activity (Wilson et al. 2023, this collection), for conducting long-duration measurements of noble gas isotopic abundances (Avice et al. 2022, this collection), or for mapping felsic surface composition at higher resolution than is possible from orbit (Gilmore et al. 2023, this collection). Some of these goals can be addressed by descent probe missions: notably, the last three of the above five points will be addressed by DAVINCI (2029 launch) and Venera-D during their descent phases, as has been discussed in Sects. 5 and 7 above. The Venus Life Finder Mission "Morning Star" (Seager et al. 2021) considers a small entry probe that would use an ultraviolet autofluorescence backscatter nephelometer to characterize cloud particles and search for biosignatures as it passes through the clouds.

10.2.1 Aerial Platform Technologies and Operations

Descent probes offer an atmospheric investigation time of, at most, 10-100 of minutes. This short duration can be extended to weeks or months, and to a wide range of latitude, longitudes, altitudes and solar times, by using balloons. The deployment of two small balloons at 55 km altitude, in the heart of the main convective cloud layer, was successfully demonstrated by the Soviet VeGa mission in 1985 (Sagdeev et al. 1986a,b; Linkin et al. 1986; Blamont et al. 1986; Preston et al. 1986). At this altitude, the ambient temperature is a comfortable 20 °C and the pressure is 0.5 atm. The main environmental hazard is the concentrated sulfuric acid that makes up the cloud particles (O'Rourke et al. 2023, this collection; Wilson et al. 2023, this collection); however, this environmental threat can be mitigated by choosing appropriate acid-resistant materials for external surfaces. Balloon-borne platforms at this altitude can take advantage of the fast, super-rotating winds that will carry the spacecraft all the way around the planet in a week or less (depending on latitude and altitude), negating the need for horizontal propulsion with motors. A cloud-level aerobot is an ideal platform for studying interlinked dynamical chemical and radiative cloud-level processes (Fig. 25). It also offers a thermally stable, long-lived platform from which measurements of noble gas abundances and isotopic ratios can be carefully carried out and repeated if necessary—in contrast to a descent probe, which offers one chance for making this measurement, in a rapidly changing thermal environment, at a single location, and at a single time.

By the use of a pumping system to alter a balloon's internal pressure, aerial platforms can explore a range of altitudes: (1) One key altitude range to target is the so-called 'habitable zone' of 54–58 km, corresponding approximately to temperatures of 0–40 °C. This region is not only of greatest astrobiological interest but is also at the heart of the 50–60 km convective cloud zone, and also offers the most benign conditions from the standpoint of safely operating a Venus aerial platform (see Sect. 10.2.2). (2) Operation above 60 km, in the convectively stable upper clouds, would be optimal for photochemical processes and identification of the UV absorber, but the low atmospheric density leads to a relatively small mass fraction for scientific payload. (3) Operation below the main cloud deck has been proposed by Japanese researchers with a primary goal of establishing wind fields below the clouds, but temperatures here exceed 100 °C. But operating an aerial platform between 52 and 62 km would enable detailed investigations of the physical and chemical cycles operating in both the convective cloud and the upper (convectively stable) clouds, as well as how volatiles (and even perhaps ash from volcanic eruptions) are transported to, and through, these parts of the atmosphere.

Balloon-borne aerial platforms could also plausibly be used to image the surface, if they are able to descend—or deploy an imaging system—to below the global cloud layer, at an altitude of about 38 km. This capability would be restricted to near IR imagery, since the atmosphere would be optically thick with respect to Rayleigh scattering at shorter wavelengths. Once again, this environment poses considerable thermal challenges to an aerial platform or instrument, and requires continued work to mature technologies capable of functioning at those sub-cloud altitudes. An intriguing means for revealing winds in the lower atmosphere is to use passive balloons, reflective to radio waves, which could be tracked by radar from orbit. It also bears noting that balloons are not the only type of aerial-based platform that could be utilized at Venus: studies of powered-flight vehicles such as Northrop Grumman's Venus Atmospheric Maneuverable Platform (VAMP) concept is one such example of a non-balloon-based Venus aerial platform (Lee et al. 2015; Warwick et al. 2017).

10.2.2 Aeronomy and Surface-Atmosphere Interactions

By being carried passively along with the prevailing winds at a given altitude, a balloon-borne instrument suite could traverse the entire planet longitudinally in less than one Earth week. There is, at present, no prospect for any remotely comparable level of mobility for a surface-based platform.

As discussed in Sect. 10.2.1, balloons are ideally suited for exploring Venus because they can operate at altitudes where pressures and temperatures are far more benign than at the surface. An airborne instrumental payload operating at ∼55 km can take advantage of the fast super-rotating winds which will carry the balloon all the way around the planet in a week or less, depending on latitude and altitude (Limaye and Garvin 2023). A cloud-level balloon is an ideal platform for studying interlinked dynamical chemical and radiative cloud-level processes. It also offers a thermally stable long-lived platform from which measurements of noble gas abundances and isotopic ratios can be carefully carried out and repeated if necessary.

The mechanical couplings between the solid and atmosphere parts of the planet are sixty times better than on Earth (Garcia et al. 2005), with almost 6% of the energy of a quake radiated in the atmosphere (Lognonné et al. 2015). It has previously been hypothesized that ground motion on Venus could be detected and characterized using infrasonic waves (or infrasound, pressure waves with a frequency less than 20 Hz) generated by quakes and volcanic activity through coupling between the solid planet and the atmosphere. Infrasound is known to travel large distances from the originating event and could be characterized using barometers suspended from balloons at approximately 60-km altitude on Venus, where the temperature and pressure are more Earthlike, and much longer mission lifetimes compared to surface missions can be achieved. Work has already been undertaken to explore the prospect of recording acoustic infrasound with balloons that is generated by ground movements. For example, various low-altitude experiments have been conducted with pressure and accelerometer sensors using active sources (Krishnamoorthy et al. 2018, 2019; Garcia et al. 2021), demonstrating that pressure sensors and accelerometers are capable of detecting the acoustic waves generated by ground movements above the seismic source, but also those generated by seismic surface waves propagating below the balloon.

Further, it was demonstrated recently that pressure records in the Earth's stratosphere can record seismic surface waves from small- and large-magnitude quakes (Brissaud et al. 2021; Garcia et al. 2022). These studies clearly show that the dispersion of seismic surface waves can be observed in pressure records, and that key quake parameters (magnitude, distance, etc.) can be recovered. These data also show that the response of the balloon system to acoustic forcing has an imprint on the pressure records that should be better modeled and understood for application to Venus (Bowman and Krishnamoorthy 2021), as well as Earth and even other atmosphere-bearing worlds such as Mars and Titan. Besides the detection of seismic events, the measurements of acoustic waves in Venus atmosphere can also be used to investigate volcanic eruptions (Byrne and Krishnamoorthy 2020), bolide events, infrasound from interactions between wind and topography (Hupe 2018; Poler et al. 2020), and even potential thunder signals.

The discrete investigations described above could be combined on a single aerial platform, given that the middle atmosphere offers a unique vantage point for exploring both the surface and the upper atmosphere and its interaction with the space environment. Indeed, a combined focus on atmospheric chemistry and physics, aeronomy, and surface–atmosphere interactions forms the basis of Phantom, a mission concept under development for the NASA New Frontiers 5 competition (Byrne 2022).

10.3 Future Orbital or Sub-Orbital Investigations

10.3.1 High-Frequency Imaging of the Atmosphere and Thermosphere

Atmospheric response to geological and atmospheric events (e.g., volcano eruption, quake, storm) can be of short duration and require a large field of view and a high sampling rate to be measured accurately. The VAMOS (Venus Airglow Measurements and Orbiter for Seismicity) mission concept was designed to cover this need (Didion et al. 2018; Sutin et al. 2018). External events created by solar energy injection in the Venus system also have a short duration. A mission capable of performing high-frequency imaging of the thermosphere would allow recovery of these events, which may play an important part in the atmospheric escape of Venus. In addition, the detection of meteor entry tracks from such high rates of imaging would allow us to infer the meteor flux in the inner Solar System, and the seeding of Venus by external sources. Finally, high-frequency imaging of the atmosphere/thermosphere is required to better understand the sources, propagation, and dissipation of gravity waves in the Venus atmosphere. These waves may be key to explaining the long-term evolution of Venus' rotation dynamics by providing a way to transfer mechanical energy from the solid surface to the atmosphere.

All these science objectives require an imaging of the planet full disk with a horizontal resolution on the order of 5–10 km and a sampling rate around 1 second. Due to the large amount of data generated, onboard data processing and selection must be implemented, possibly requiring machine-learning methods trained on the ground but applied onboard. Other orbital observations potentially involving atmospheric lidar remote sensing (e.g., as in CALIPSO/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations in Earth orbit: e.g., Winker et al. 2008, 2010) could add to these measurements with both spectroscopy but also in terms of vertical structure.

10.3.2 Collection and Return to Earth of an Atmospheric Sample

The elemental and isotopic compositions of noble gasses and stable isotopes in the atmosphere of Venus hold clues to the origin and evolution of the entire planet. Past space missions managed to get a first glance of the composition of volatile elements in the atmosphere, and planned investigations (DAVINCI, Venera-D) will greatly improve our knowledge (see this review, Sect. 2, Sect. 2.2.3; Sect. 5, Sect. 5.1; Sect. 7, Sect. 7.1; see also review by Avice et al. 2022, this collection). However, some rare isotopes of noble gasses are important for identifying the source of volatile elements to Venus but are extremely challenging to detect and measure (e.g., ^{78,80}Kr or ^{124,126}Xe). Measurements of other, more abundant isotopes are also greatly complicated by the presence of isobaric interferences (e.g., CO_2^{++} ions interfering with $^{22}Ne^+$ ions). A direct way to draw up the inventory of volatile elements in the atmosphere of Venus would be to send a probe, skimming through the atmosphere of Venus below the homopause $<$ 120 km (Mahieux et al. 2012; Sotin et al. 2018a,b; Rabinovitch et al. 2019) to collect atmospheric samples, before possibly returning them back to Earth (e.g., Shibata et al. 2017). Such samples would be measured with state-of-the-art instruments in laboratories on Earth, enabling us to characterize the composition of the Venus atmosphere to unprecedented accuracy and precision. Although such investigation will likely allow comparative planetology of Earth, Venus, and Mars on a similar basis, sampling and returning to Earth an atmospheric sample of Venus remains challenging. In the configuration of a skimmer probe, gas would be sampled at high velocity ($>$10 km/s), behind a shock wave and the extent of modifications of the molecular, elemental, and isotopic composition of the atmospheric sample remains to be fully studied. After returning the sample to Earth, innovative curating techniques will have to be developed to preserve those invaluable samples for extended periods of time, in the manner of samples from the lunar Apollo program that continue to be assessed to this day.

10.3.3 Venus Lagrange Points Mission

A Venus Lagrange Points (LP) Mission, in which two light spacecraft using heritage, technological readiness & development of Akatsuki, Hayabusa-2 and Destiny+ spacecraft systems are placed in orbit around the Sun-Venus Lagrange points, is under consideration by the Japanese Space Agency's Institute of Space and Astronautical Science (ISAS/JAXA) as one of possible follow-ups of the Akatsuki Mission (Yamashiro et al. 2022). A Venus Lagrange Points Mission, able to continuously and simultaneously monitor the entire planet's atmospheric activity from a distance of about 1 million kilometers, is able to capture phenomena such as atmospheric dissipation and lightning on a global scale and continuous basis.

10.3.4 Cubesat Concepts

Several future projects involve deployment of cubesats in Venus' orbit to monitor atmospheric processes and their evolution: CUVE (CubeSat UV Experiment), a mapping spectrometer concept carrying a multi-spectral UV imager (320-570 nm) complemented by an imaging UV camera (see CUVIS on DAVINCI, Sect. 5.4.2) to study Venus cloud chemical, dynamical properties and radiative balance (Cottini et al. 2018) and TERACUBE, an instrument concept in the Terahertz frequency range. The high spectral resolution (e.g., 100 KHz) and sensitivity of such a heterodyne receiver will allow the spatial and temporal mapping of Doppler lineshifts winds, abundance of minor species (e.g., CO (5-4) at 576 GHz, H_2O 110-101 at 557 GHz) down to a few ppb, and atmospheric temperature, in the altitude range of 70-120 km (Moreno et al. 2020).

10.4 Future Directions

The technology for orbital, aerial, and short-duration surface missions to Venus exists today (Limaye and Garvin 2023). Continued work will naturally lead to ever longer-duration spacecraft, such that—with continued investment in and testing of a variety of technologies from materials to electronics to navigation software—we might reasonably see weeks-long surface operations and perhaps even years-long aerial platform missions in the coming decades.

For the foreseeable future, covering vast distances on Venus will be the exclusive purview of aerial platforms (excluding orbiters, of course); cloud-deck level balloons are to Venus as rovers are to Mars. But the scientific motivation for conducting *in situ*, detailed chemical and geophysical analyses at Venus is at least as compelling as it is at Mars. And so future technology development should take, as its long-term objective, the ability to move along the Venus surface itself (or relocated via hops)—that is, the design and flight of Venus rovers. Leveraging high-temperature electronics designed for long-life landers, rovers (Sect. 10.1.2-10.1.4) could be deployed to numerous terrain types including sites otherwise deemed unsafe for landers such as tesserae. This capability is because of the thick Venus atmosphere: using a delivery system similar in concept to the Skycrane powered descent vehicle that safely placed the Curiosity and Perseverance rovers onto Mars, a Venus rover delivery vehicle could take advantage of the planet's thick atmosphere to target high-standing lower-temperature ($<$715 K) terrains, in contrast to the Red Planet where low elevations and high surface atmospheric pressures are preferred for safe landing, to slow from hypersonic atmospheric entry speeds.

There are likely no technological showstoppers to exploring, at least with robots, the surface of the second planet, such as the Hybrid Automaton Rover-Venus (HAR-V) studied at the Jet Propulsion Laboratory (Sauder et al. 2019, and references therein). But if we are to see rovers traverse Venus' hostile surface later this century, the foundations for that technology must be laid now.

11 Ground-Based and Space-Based Observatories

Ground-based observations of Venus are complementary to spacecraft observations in a number of fields, from geology to atmospheric composition and dynamics. Venus is distant by a fraction of an Astronomical Unit near its inferior conjunction every 584 terrestrial days (synodic period), and periodically very well suited to observation from Earth (or from near-Earth observatories in space).

The highest resolution ground-based radar images of Venus, from the Arecibo observatory, reached spatial resolutions of 1–2 km; while order of magnitude poorer than Magellan radar images (Campbell et al. 2017) the long temporal baseline offered by decades of observation allows a search for temporal changes on these timescales. In addition, ground-based images include polarimetric information not captured by Magellan allowing constraints on surface properties. Earth-based radar can also be used for monitoring of Venus' spin (Margot et al. 2021, Sect. 11.1.1).

Ground-based observatory facilities and their instrumentation may obtain simultaneous measurements sampling a large range of altitudes, using wavelengths and/or spectral resolutions not available among spaceborne / onboard instruments – for studying the atmosphere, ground based telescopes have the advantage that they can be equipped sophisticated spectrometers far too massive and complex to deploy on a spacecraft; they can thus be sensitive to trace constituents, or faint motions of the atmosphere in a way which is complementary to spacecraft observations; and improve the latitude, longitude and local time coverage, and temporal baseline of rapidly variable phenomena. They can also provide monitoring of properties over decade-long periods of time, particularly times when no spacecraft were at Venus, and expand temporal baseline of rapidly variable phenomena (Lellouch et al. 2007; Lellouch and Witasse 2008; Widemann et al. 2008).

Sulfur dioxide and water vapor are key species in the complex photochemical cycles taking place in the troposphere and mesosphere of Venus, and have been extensively observed from Earth in the past decades (Mills et al. 2021, and references therein). They are also the most variable species in the atmosphere of Venus, and can be observed in millimeter wave (Sect. 11.1.2) or in the near-IR and mid-IR (Sect. 11.1.3). Both play a crucial role in determining climate on Venus, as key volatile species to constrain the rate and style of volcanic outgassing in the present era (see Sect. 2.4.3, Sects. 4.1.3-4.1.4, Sects. 5.3.1-5.3.3, Sects. 6.1.4, 6.3.3-6.3.4, and references therein). Amongst all trace constituents, SO_2 exhibits the most dramatic variations at Venus' cloud top, both spatially and temporally (Esposito 1984; Esposito et al. 1988; Marcq et al. 2013, 2020; Vandaele et al. 2017a,b, Encrenaz et al. 2012, 2016, 2019, 2020a, 2023) and so require continuous observations and long temporal baselines to support our understanding of long term climate evolution. Ground-based observations will continue over the decades ahead as newly selected or proposed missions described in Sects. 3-8 prepare a new era of Venus exploration.

The past years have seen an extraordinary growth in our knowledge of planetary systems around other stars, as well as the remarkable diversity and abundance of exoplanets (Sect. 11.2). These advances have been supported by several ground-based and orbital facilities, such as TESS and JWST, and a progression from planet detection to detailed study and characterization of individual planets. The prevalence of Venus analogs will continue to be relevant to Venus. Such observations capable of identifying key atmospheric abundances for terrestrial planets will face the challenge of distinguishing between possible Venus and Earth-like surface conditions.

11.1 Venus Observations from Ground-Based and Earth Orbiting Facilities

11.1.1 Earth-Based Radar Mapping and Speckle Tracking

Geologic mapping of volcanic features, their surface morphology and dielectric permittivity is a cornerstone of Magellan data interpretation (Campbell and Campbell 1992; Campbell 1994). Earth-based radar mapping can achieve 1–2 km spatial resolution and measure echoes in both the opposite-sense (OC) circular polarization and the same-sense circular (SC) mode. The OC echoes are very similar to Magellan measurements and are strongly modulated by slopes that face toward the radar. The SC echoes are much more sensitive to small-scale surface roughness than to topographic slopes. We can also form the circular polarization ratio (CPR = SC/OC), which allows for simple comparisons with rough surfaces on the Earth. The utility of these data was demonstrated in mapping of fine debris in the Venus highlands (Campbell and Rogers 1994; Whitten and Campbell 2016). Earth-based polarimetric mapping using the Arecibo radar shows that information on small-scale roughness correlates Venus lava flows with those in terrestrial settings (Campbell and Campbell 1992), and may reveal deposits formed during recent, volatile-rich eruptions (Campbell et al. 2017).

New methods for combining Earth-based hybrid astronomical radar polarimetry with refined Magellan radar measurements can extend the scientific value of existing datasets while we await the arrival of the next wave of orbital radar mapping missions, VERITAS and EnVision, as well as other radar missions considered for selection described in Sect. 3. Recent work by Garvin et al. (2022b, 2023 in prep.) demonstrated how multiple viewpoint Arecibo polarimetric radar data could be used via Shape-from-Shading together with re-analyzed Magellan radar altimeter radagrams to produce km-scale topography of Alpha Regio as a test-case. Improved methods building on these efforts could map regions on Venus in advance of the upcoming orbiters with advanced computational tools.

Earth-based radar can also be used to monitor Venus' spin state and moment of inertia (Margot et al. 2021). High-precision measurements of the instantaneous spin state of Venus may be obtained with a radar speckle tracking technique that requires two telescopes and does not involve imaging. Margot et al. used the 70 m antenna (DSS-14) at Goldstone, California (35.24°N, 116.89°E) and transmitted a circularly polarized, monochromatic signal at a frequency of 8560 MHz ($\lambda = 3.5$ cm) and power of ∼200-400 kW. Radar echoes were recorded at DSS-14 and also at the 100 m Green Bank Telescope (GBT) in West Virginia (38.24°N, −79.84°E) with fast sampling systems. Despite results not yet sufficient to rule out certain classes of interior models (Dumoulin et al. 2017), the best-fit value of the moment of inertia factor combined with knowledge of the bulk density enable a crude estimate of the size of the core of Venus (Margot et al. 2021). Improved determinations of the spin axis orientation, precession rate, and spin period form the basis of a recommended orientation model for Venus (see also Sects. 4.3.3 and 6.3.4).

11.1.2 Earth-Based Millimeter Wave Observations

Observing Venus at millimeter and submillimeter wavelengths with heterodyne spectroscopy provides unique means to probe the upper mesosphere of Venus (70-120 km). Heterodyne spectroscopy measurements have been performed with single dish antennas for decades in the millimeter range for CO, HDO and H_2O (e.g., Encrenaz et al. 1991, 1995), and in the submillimeter range for CO, SO_2, SO, H_2O and HDO (e.g., Sandor et al. 2010, 2012) using the James Clerk Maxwell Telescope (JCMT) on Maunakea, Hawaii. Altitude resolution is derived from the shape of pressure-broadened spectroscopic lines and the exponential variation of pressure with altitude. This region is dynamically a transition region between the retrograde super-rotation characterizing the lower atmosphere and the day-to-night flow regime prevailing in the thermosphere. Rotational lines of minor species such as carbon monoxide CO and isotopic ^{13}CO are formed at altitudes ranging from 70 km to 110 km, depending upon the strength of the transition used. Millimeter and Submillimeter observations complement the altitudes probed with ground-based IR observations, which investigate atmosphere levels within and below the clouds. in the millimeter-wave range. The Atacama Large Millimeter Array (ALMA) also offered a unique opportunity to probe the upper mesosphere (60–120 km) and monitoring minor species, winds and the thermal structure, targeting CO, SO, HDO and SO_2 transitions in the submillimeter range to derive 3D maps of mesospheric temperatures and minor species in the altitude range 70–105 km (Encrenaz et al. 2015; Piccialli et al. 2017).

11.1.3 Mid-IR, Near-IR and Visible Observations: Chemistry and Dynamics

CO, CO_2, H_2O and SO_2 in the Mid-Infrared 4.3–19 µm Range. - At thermal wavelengths (∼4–50 µm), the spectrum of the planet is close to that of a blackbody at the cloud top temperatures with spectral features mainly belonging to mesospheric CO_2, H_2O, SO_2, and other gasses that absorb at levels within and above the clouds as well as broad signatures of sulfuric acid aerosols. Encrenaz et al. (2012, 2013, 2016, 2019, 2020a, 2023) have performed study of the SO_2 over nearly a decade, using the TEXES high-resolution imaging spectrometer at the NASA InfraRed Telescope Facility (IRTF), also on Maunakea, Hawaii. Maps recorded around 1345 cm^{-1} (7.4 microns, z = 62 km), where SO_2, CO_2 and HDO are observed, and around 530 cm^{-1} (19 µm, z = 57 km) where SO_2 and CO_2 are observed, as well as around 1162 cm^{-1} (8.6 µm, z = 66 km) where CO_2 lines are observed. Mixing ratios are estimated from HDO/CO_2 and SO_2/CO_2 line depth ratios, using weak neighboring transitions of comparable depths. An anti-correlation has been evidenced in the long-term variations of H_2O and SO_2 at the cloud top, a long-term decrease of H_2O associated with a long-term increase of SO_2, as well as a planetocentric distribution of the SO_2 volume mixing ratio enhancement between 120 and 200 East longitude at Venus (Encrenaz et al. 2020a). High-resolution spectroscopic observations of both day and night sides of Venus were also acquired using the CSHELL spectrometer at NASA IRTF between 4.53 and 4.54 µm, to investigate the effect of the decrease of SO_2 (from 2007 onward) at the cloud top level on the spatial distribution of CO, since both species are involved in the mesospheric photochemical cycles (Marcq et al. 2015).

Near-Infrared Windows: H_2O, HCl, CO, OCS, SO_2 in the 1.18, 1.74, 2.32 and 2.46 µm Windows. - Infrared windows at shorter wavelengths in the near-IR probe deeper regions in the atmosphere (Allen and Crawford 1984). Several key gasses can be mapped below the cloud deck, at 0-50 km altitude: water vapor (H_2O and HDO) (Bézard et al. 2009; Arney et al. 2014), sulfur compounds (SO_2, OCS) and carbon monoxide (CO) (Marcq et al. 2006, 2021; Iwagami et al. 2010; Arney et al. 2014) - all potential volcanic volatile gasses or involved in long-term surface-atmosphere exchanges. In particular, discovering spatial variability of the D/H ratio – whether associated with volcanic plumes or other fractionating processes – would be fundamental for understanding the history of the water on Venus. The atmosphere is known to be variable on a range of time scales from minutes to years, so measurements over a wide range of timescales are still required. A plan to monitor Venus' atmosphere using an Earth-orbiting cubesat, CLOVE (Chasing the Long-term Variability of Our Nearest Neighbor Planet Venus), is currently under study by the Institute for Basic Science (IBS) of South Korea to perform observations from Earth's orbit between 320 nm and the near-infrared (Lee et al. 2022).

Atmospheric Circulation in the Visible and Near-IR. - The measurement of wind regimes in support of Venus General Circulation Models is achieved by two means: (1) directly, by Doppler or image correlation velocimetry using cloud features at different altitudes within the cloud layer, and (2) indirectly, using thermal and cyclostrophic wind balance relations to calculate equilibrium wind fields from measured temperature and pressure fields. In complement to cloud tracking in images taken at different wavelengths, which has proved an invaluable tool for extracting wind speeds at distinct vertical levels in the cloud region (Sánchez-Lavega et al. 2008, 2016; Hueso et al. 2012, 2015; Khatuntsev et al. 2013; Titov et al. 2018; Horinouchi et al. 2018; Fujisawa et al. 2022), wind speeds measured using Doppler-shifted spectroscopy, provided signal-to-noise limited precision of ∼5 m/s using scattered solar Fraunhofer and CO_2 lines in the visible (dayside), sounding cloud tops (70 km) and a few kilometers above, using ESPaDOnS high-resolution spectrograph at Canada-France-Hawaii telescope (Widemann et al. 2007, 2008; Machado et al. 2012, 2014, 2017, 2021). Cloud-tracked winds may also be observed in the near-IR 2.26 μm window (Peralta et al. 2016, and references therein).

Solar Transits of Venus in 2004 and 2012. - A rare 2004 Venus transit imaging observing campaign with NASA's Transition Region and Coronal Explorer (TRACE) demonstrated the ability of Earth-orbiting observatories to constrain the properties of the upper atmosphere of Venus as a model for a transiting exoplanetary atmosphere (Ehrenreich et al. 2011; Pasachoff et al. 2011; Tanga et al. 2012). A follow-up ground-based campaign was organized in 2012 in coordination with Venus Express/SOIR and the HMI instrument aboard the Solar Dynamic Observatory (SDO) at the time of the 2012 transit to observe the refracted sunlight light curve as a probe of the thermal structure and composition of the upper atmosphere near the terminator (Widemann et al. 2012; Pere et al. 2016; Machado et al. 2023).

11.1.4 Ultraviolet Observations: Albedo Variations

Hubble Space Telescope Imaging Spectrograph (HST/STIS) UV observations of Venus' upper cloud tops have been used in coordination with VMC on board ESA's Venus Express, JAXA's Akatsuki UVI images, and NASA MESSENGER/MASCS UV spectral data to monitor the sulfur cycle and long-term UV albedo variations (Jessup et al. 2015; Lee et al. 2019). Lee et al. discuss the decadal variation of Venus's 365 nm albedo between 2006 and 2017; Solar EUV radiation might affect photochemical reactions involving SO_2 that are necessary for aerosol formation on Venus (Mills et al. 2007; Parkinson et al. 2015). Further studies are required to explore the role of the solar activity cycle on the Venusian upper atmosphere, as many intervening factors that may act in combination to produce the observed albedo variations: the chemical composition and reaction rate of the unknown absorber, its interaction with or dependency on the chemical state of other atmospheric constituents, such as sulfur species SO and SO_2, and the variability of the cloud and haze structure as a function of time (Lee et al. 2019).

11.2 Exoplanets Detection and Characterization

The planetary systems that have been discovered - as exemplified by the 7-planet system around TRAPPIST-1 (Gillon et al. 2016, 2017) only about 12 pc away - are extremely diverse, and study of the demographics of large numbers of exoplanets has led to several advances in understanding, including the recognition that many small-mass planets possess hydrogen atmospheres. Progress in observational technology will enable discovery of an even greater number of systems, and much expanded characterization of individual exoplanets by, e.g., the James Webb Space Telescope. Overall, the ability to image exoplanets both when they are forming and in their mature stage, the ability to characterize these exoplanets and their atmospheres, is providing us with new opportunities to understand planetary systems in the universe and to compare them with the long-term evolution of solar system planets.

Before the discovery of exoplanets, planet formation theories were limited to explaining the Solar system and thus, were unintentionally biased (e.g., Scora et al. 2020). Now, with thousands of extrasolar planetary systems, there is a diverse set of data to test against formation theories. Since planets at the inner edge of can sustain several very different possible atmospheres, depending on the initial water inventory and the water loss time-scales (see e.g., Turbet et al. 2020; Fauchez et al. 2022; Kaltenegger et al. 2023; Barrientos et al. 2023), exoplanetary observations of young planets around G-stars in the Venus Zone will be critical to understanding Venus' long term evolution through time. Determining that a planet resides in the Venus Zone provides a first-order estimate about the potential environment on that planet and criteria for its long term evolution.

Three next generation ground-based (>20 m in diameter) observatories are currently under construction or likely to be built in the near future: the European led Extremely Large Telescope (ELT), the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). The former two are currently under construction in Chile while the TMT is proposed for the northern hemisphere, although the exact location remains uncertain. With increasing advances in adaptive optics, they will afford new opportunities to explore the atmospheres of nearby exo-Venuses, as they are discovered by space observatories devoted to detecting such systems via the transit method (e.g., Kepler, TESS, CHEOPS, PLATO).

In space, JWST has already demonstrated how it can detect atmospheres around a few nearby terrestrial planets in systems such as Trappist-1 (Fig. 26), although such observations continue to be challenging, as discussed by (Way et al. 2023, this collection and references therein). The ARIEL mission (Tinetti et al. 2021), led by ESA, is also scheduled to be launched by the end of the decade with the ambition to measure the chemical fingerprints of $\sim$1000 exoplanetary atmospheres.

12 Laboratory and Modeling Efforts

12.1 Laboratory Experiments and Measurements

There are many areas where new laboratory work is needed to support our understanding of the Venus system. Experimental facilities can replicate the pressure, temperature, and chemical conditions of various layers of the planet and their interfaces; they also can be used to develop, test, and prove technologies to explore Venus. Thus, Venus experimental facilities are critical to moving forward our understanding of this planet in the next decades (Glaze et al. 2018; Santos et al. 2021). In this section we highlight a small selection of current facilities and experiments which the authors consider particularly relevant to the theme of understanding ancient Venus and the long-term evolution of the planet.

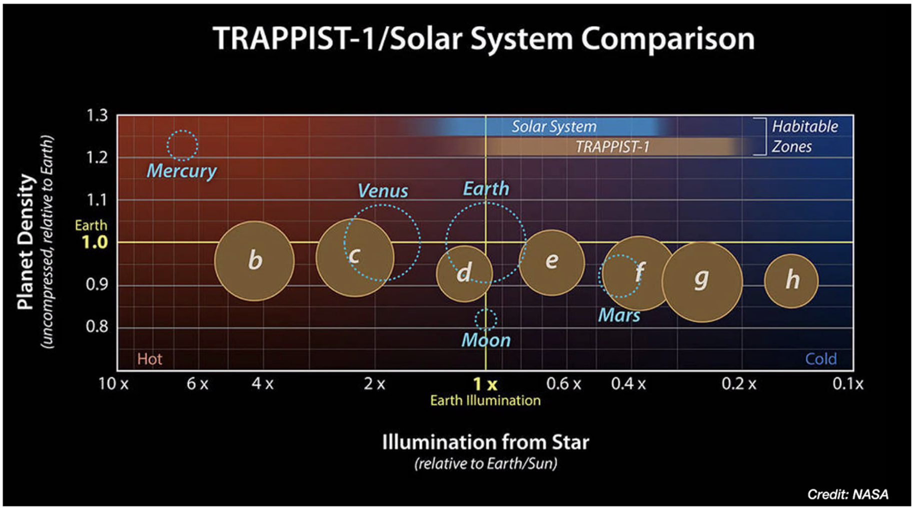


Fig. 26 The Trappist-1 system planets (Gillon et al. 2016, 2017) are among an abundance of Venus Zone planets which are promising candidates for follow-up ground- and space-based observatories, such as JWST and the TESS missions. Of these candidates, the TRAPPIST-1 planets in the Venus Zone are especially intriguing, and observational constraints on their atmospheres will provide an opportunity to compare the differences between Earth and Venus to planets receiving similar insolation flux (Way et al. 2023, this collection)

12.1.1 Geochemical Experiments

Geochemical experiments focus on the stability of minerals in the Venus surface environment and the transfer of elements or isotopes that take place during mineral-mineral or mineral-gas chemical reactions. These studies are important to ancient Venus and long-term planetary evolution because the preservation of mineralogical evidence of ancient planetary processes depends on mineral stability/weathering over geologic time. Additionally, secondary minerals produced by reactions of the atmosphere with the surface of a planet are a major sink of atmospheric gasses and can therefore strongly impact its long-term climate. Many aspects of mineral stability can be assessed using thermodynamic calculations, however major outstanding questions remain in the field of reaction kinetics and mechanisms that are crucial to resolve to understand how mineral-gas reactions unfold over time. Experimental studies that provide relevant reaction kinetic information will also aid in constructing models of surface weathering that include factors such as weathering rates (Gilmore et al. 2017; Santos et al. 2021; Reid 2021; Gilmore et al. 2023, this collection). There are many experimental approaches that can be taken to address these questions, several of them available in typical high temperature lab setups, but here we will highlight one facility that can accommodate both geochemical experiments and exploration technology testing. The reader is referred to many of the other current Venus weathering studies, and references therein, to understand the breadth of approaches in this field (e.g., Berger et al. 2019; Port et al. 2020; Port and Chevrier 2020; Radoman-Shaw 2019; Reid 2021; Teffeteller 2020).

The Glenn Extreme Environments Rig (GEER), located at NASA's Glenn Research Center, is capable of reproducing Venusian temperature, pressure, and complex atmospheric chemistry (CO_2, N_2, traces of SO_2, H_2O, CO, OCS, HCl, HF, and H_2S) for long durations (see experiment description in Radoman-Shaw 2019). The GEER pressure vessel is an

~800 L cylinder made of 304 stainless steel, and this volume allows the accommodation of mission hardware for development and testing. Along with its size, one of the key capabilities of this facility is its precision gas mixing and control system that is capable of making compositional corrections at high pressure and temperature. The gas composition is monitored using an external gas chromatograph. The gas boosting capability is useful for mineral reaction experiments because it can keep the gas composition within a specified range, as opposed to a typical batch reactor where the gas composition is permanently changed by reaction with the samples. This facility has been used for mission and technology development (e.g., Neudeck et al. 2018), materials science investigations (e.g., Costa et al. 2018; Lukco et al. 2018, 2020), and mineral weathering experiments (Radoman-Shaw 2019; Santos et al. 2023).

12.1.2 Mission Calibration Libraries: Planetary Spectroscopy Laboratory (PSL)

The unique environmental conditions on Venus can interfere with some of our traditional remote sensing techniques, for example, the thick atmosphere prevents visible light imaging or mapping of the planet's surface from orbit. Venus-specific exploration methodologies have to be developed and tested as a result. It was determined from data returned by the Galileo mission that there are windows in the CO_2 spectrum around 1 µm that allow us to see surface near-IR emissivity (Carlson et al. 1991), however spectral libraries built from analyses of a large number of geologic materials need to be developed to maximize the return on this type of data (Hashimoto et al. 2008; Mueller et al. 2008). In response to this challenge, the Planetary Spectroscopy Laboratory (PSL) at the German Aerospace Center (DLR) has designed a chamber to demonstrate and calibrate near-IR spectroscopy for Venus (Helbert et al. 2016, 2018). This data can be used as a reference to compare with surface emissivity spectra obtained by a future Venus orbiter. Furthermore, the emissivity chamber has an near-IR transparent window allowing mounting of near-IR spectrometers built for future Venus orbiter missions to take measurements at Venus conditions, for instrument calibration and performance study. A number of sample preparation and analysis tools and experiment sub-systems are available to the facility: a collection of hundreds of rocks and minerals, synthetic minerals, an Apollo 16 lunar sample, several meteorites, set of sample holders for reflectance (plastic, aluminum or stainless steel), various sets of sieves, grinders, mortars, saw, scales, microscope, an oven (20° to 300 °C), ultra-pure water, wet chemistry materials, a second ovens (30° to 3000 °C) for sample treatments, a press to produce pellets (10-mm or 20-mm diameter), purge gas generator for water and CO_2 free air, liquid-nitrogen tank, an ultrasonic cleaning unit and 2 microscopes. When enough sample material is available, the typical grain size separates that are produced for spectral measurements are <25 µm, 25-63 µm, 63-125 µm, 125-250 µm. Larger separates as well as slabs are also routinely measured. Models of anhydrite and hematite coatings on basalt mixtures suggest that changes in emissivity spectra due to chemical weathering can result in shifts in total emissivity, usefully constrain rock types and surface composition based on transition metal contents, but also provide local scale assessments of fresh versus mature lava flows (Dyar et al. 2021).

New High-temperature Dielectric Permittivity Laboratory Measurements relevant to future Venus radar mapping are underway at NASA's JPL (Barmatz et al. 2022) to further extend the value of SAR-based observations and enhance retrievals of surface electrical properties for the upcoming era of Venus radar mapping by VERITAS and EnVision. Measuring the complex dielectric permittivity of Venus analogue rocks and fines, as well as their intrinsic dielectric anisotropy, is important as new radars and radar sounders measure Venus from orbit, and eventually from cloud-deck altitudes (e.g., with balloon-born micro-SAR instruments).

12.1.3 Rheology Experiments: Plume-Induced Subduction on Venus

Venus relatively young surface points towards either a quite recent catastrophic renewal of the whole planet surface, or the continuous renewal of small areas. Geophysical observations suggest that the large coronae are due to the impact of hot plumes rising in the Venusian mantle. Sandwell and Schubert (1992a) had proposed that these plumes could induce subduction, but this hypothesis had remained in the schematic state since then. One challenge for evaluating the plume-induced subduction mechanism is the difficulty of simulating the brittle viscosity, and history-dependent lithospheric rheology in three-dimensional (3D) numerical models, which still cannot fully model deformation on a wide range of scales. Laboratory experiments using complex rheology fluids such as colloidal dispersions provide a means to bridge this gap (Davaille et al. 2017).

A more detailed analysis of Magellan data (radar, topography and gravimetry), where the resolution is sufficient, confirms the existence of the plume-subduction association on the largest corona, Artemis (2300 km diameter), and on Quetzalpetlatl (800 km diameter). In both cases, the proven subduction does not describe a complete circle but only an arc. Furthermore, high emissivities have been measured on Quetzalpetlatl (Smrekar et al. 2010a), and interpreted as a signature of recent volcanism. This suggests that the plume beneath Quetzalpetlatl is still hot and active, which implies that the subduction around it must also be currently active. Larger and probably at a later stage of its evolution, Artemis also shows a large oceanic ridge-like structure inside the corona, where new plate is created by upwelling of hot magma. Different corona structures may represent not only different styles of plume–lithosphere interactions but also different stages in evolution (Smrekar and Stofan 1997; O'Rourke and Smrekar 2018; Smrekar et al. 2018; Gülcher et al. 2020).

Laboratory experiment mechanisms predict the asymmetric, arcuate trenches, and the extensional fractures that radiate outward from the trench, observed at Artemis and Quetzalpetlatl coronae, as well as at other coronae on Venus. Davaille et al. (2017) compare laboratory experiments of plume-induced subduction in a colloidal solution of nanoparticles to observations of proposed subduction sites on Venus. The experimental fluids are heated from below to produce upwelling plumes, which in turn produce tensile fractures in the lithosphere-like skin that forms on the upper surface. Plume material upwells through the fractures and spreads above the skin, analogous to volcanic flooding, and leads to bending and eventual subduction of the skin along arcuate segments. In this unique experiment, the tank is dried from above and uniformly heated from below, allowing for the development of both a gravitationally unstable skin, the experimental 'lithosphere', and several hot upwelling plumes below this skin (Fig. 27). Both processes are due to convection, either solutal or thermal, respectively. In both cases, the intensity of convection is in the range of a planetary mantle. The laboratory experiment mechanisms predict the asymmetric, arcuate trenches, and the extensional fractures that radiate outward from the trench, observed at Artemis and Quetzalpetlatl coronae, as well as at other coronae on Venus. The gravity data are also consistent with the thickness, lengths and dips of those observed in experiments.

Further laboratory experiments are needed to bridge the gap between interior evolution models and surface observations of deformation structures, topography, and volcanism.

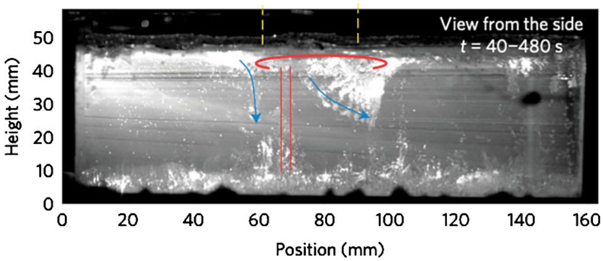


Fig. 27 Experimental facilities can replicate the pressure, temperature, and chemical conditions of different layers of the planet and their interfaces. Here, a laboratory experiment uses an aqueous colloidal dispersion dried from above and heated from below to simulate the plume-induced subduction mechanism in the Venusian mantle (Davaille et al. 2017; see Sect. 12.1.3)

12.2 Numerical Modeling

Modeling studies strongly suggest that the evolution of the atmosphere and interior of Venus are coupled (Way and Del Genio 2020; Weller and Kiefer 2020), emphasizing the need to study the atmosphere, surface, and interior of Venus as a system.

The interaction between the surface and the atmosphere is a key to understanding the processes driving the dynamics of both the atmosphere and the solid planet. The exchanges of heat and angular momentum drive the temperature and wind structure in the deepest layers of Venus's atmosphere. Chemical and dynamical modeling of interactions between the lower atmosphere and the surface, at the inner edge of the habitable zone, must take into account the variety of properties, trace atmospheric compounds and their reaction rates, local circulation and energy balance at the surface (e.g., Leconte et al. 2013; Lebonnois et al. 2018).

1-D radiative and radiative-convective models for the determination of climate are suddenly widespread as researchers worldwide attempt to determine the likely climate of exoplanets (Turbet et al. 2019, 2020; Fauchez et al. 2019, 2022; Way and Del Genio 2020; Bower et al. 2022; Wolf et al. 2019, 2022;Kaltenegger et al. 2023; Barrientos et al. 2023; Way et al. 2023, this collection, and references therein). Venus offers a proving ground for these models much closer to home, one where the conditions are much better known than on exoplanets. Radiative transfer calculations on Venus are difficult: uncertainties in the radiative transfer properties of carbon dioxide at high temperatures and pressures are the main unknown, particularly in the middle- and far- infrared where there are no spectral window regions to allow empirical correction. As on Earth, clouds play an important role, reflecting away sunlight but also trapping upwelling infrared radiation. The state-of-the art Venus radiative balance are still mainly 1-D models representing an average over the whole planet. However, we now know that the clouds are very variable; the vertically integrated optical thickness (as measured at 0.63 μm) can vary by up to 100% (Barstow et al. 2012) and the vertical structure of clouds varies strongly with latitude. In-situ measurements of cloud properties with co-located radiative flux measurements are also needed to determine the diversity of cloud effects on the global radiative balance.

12.3 Summary / Outcomes Revealing Venus Evolution

Future geochemical modeling and experiments will greatly benefit from better constraints on near-surface atmospheric composition and the composition and mineralogy of the solid surface. In fact, the composition of the solid planet (in terms of chemistry, mineralogy, and isotopic values) is a major knowledge gap that is relevant to almost all areas of Venus science. Obtaining better data in this area will also enable other kinds of experiments to be conducted, such as those in the field of experimental petrology, which have provided significant insight into the evolution of other planetary bodies, but cannot be as rigorously applied to Venus due to the current state of our petrologic data from the planet.

13 Summary and Conclusions

The discoveries of many exoplanets, including terrestrial exoplanets perhaps similar to Venus, due to increasingly sensitive methods of discovery and characterization, make exchange between exoplanetary and planetary scientific communities increasingly necessary. The search for exoplanets is largely motivated by the answers to the questions: Is our solar system common and is there life outside our solar system? Answering these questions requires also understanding the habitability of a planet, i.e., the potential of a planet to develop and maintain a living environment. Venus and Earth formed under very similar conditions and were probably supplied with water in the same way. At some point in their history, the evolution of their surfaces and atmospheres diverged dramatically. Venus could be the type of planet that has changed from a habitable and Earth-like state to an uninhabitable one (Way and Del Genio 2020).

Thus, Venus is particularly important to our understanding of terrestrial planets' habitability, providing a natural laboratory to understand its evolution in time. Venus exploration offers therefore unique opportunities to answer fundamental questions about the evolution of terrestrial planets and the habitability within our own solar system. Venus' enhanced D/H ratio suggests that it has lost large amounts (possibly several terrestrial oceans) of water, but it is not clear whether it condensed (as happened on Earth) or whether this water was lost in the steam atmosphere phase; if it had a liquid water ocean phase, Venus may have been habitable for billions of years. There is no consensus on how much water there is in Venus' interior, and how much of this water has been outgassed, a question which has important implications for Venus' atmospheric water and in turn for its habitability through time. Exoplanet transit detection surveys have a bias to detecting exoplanets close to their parent stars: the growing number of such Venus-like exoplanets discoveries emphasizes the relevance of Venus in the search for habitable exoplanets.

Venus has been an object of fascination throughout the space age. It was the site of the first planetary flyby in 1962 (Mariner-2), first entry probe in 1967 (Venera-4), first soft landing in Dec. 1970 (Venera-7), first image from the surface of another planet in 1975 (Venera-9), first orbiter and radar in 1978 (Pioneer). The Soviet series of Venera & VeGa missions were phenomenally successful, not only in their technologically advanced landers which returned colour pictures from Venus and analyzed drill samples despite 450 °C heat, but also successfully deployed balloons in the atmosphere in 1985 (Sagdeev et al. 1986a, 1986b; Linkin et al. 1986; Blamont et al. 1986; Pieters et al. 1986).

Now is a pivotal time in Venus exploration. Since NASA-JPL's Magellan orbiter provided initial global radar imaging and altimetry (1989–1994), and USSR's Venera landers measured major and heat- producing elements in several locations (1975–1985), there have been considerable advances relevant to understanding Venus' evolution. ESA's Venus Express (2006-2014) and JAXA's Akatsuki (2010-present) orbiters focused primarily on atmospheric science. Both revealed many secrets of Venus' atmosphere, but have also left many questions unanswered. There have been new ground-based observations of surface and atmospheric properties e.g., from Arecibo and NASA's Infrared Telescope Facility; new analyses of existing data, in particular surface emissivity from Venus Express; new hypotheses for the origin of plate tectonics; advances in the numerical tools and laboratory simulation of interior convection; and new modeling of the evolution of rocky earth-sized exoplanets, in need of observational constraint using Venus as a reference point. The difficulties in modeling the atmospheric superrotation of Venus meet new developments as the atmospheres of typical tidally locked terrestrial exoplanets are expected to superrotate (Imamura et al. 2020, and references therein).

Many important questions about the current state of Venus remain unanswered, suggesting that there are major gaps in our understanding of how and when Venus's evolutionary pathway diverged from Earth's (Morrison and Hinners 1983). As we developed in this final review, a new fleet of Venus missions is currently in development. These include radar-equipped orbiters (such as the ESA-led EnVision M5 orbiter and NASA-JPL's VERITAS orbiter missions), entry probes / landers/flybys (such as NASA GSFC's DAVINCI mission). Further Venus missions are also considered with Russia's Venera-D orbiter, aerial platform and lander mission and India's ISRO/Shukrayaan-1 orbiter mission. Japan and China have also announced a likely orbiter proposed for launch before the end of this decade. Furthermore, various concepts to detect seismic activity, whether from landers, from balloons or from orbit are also under study (Limaye and Garvin 2023).

The science strategy for all of these missions is in development now and in the coming few years; therefore, now is an ideal time to collate knowledge of Venus evolution scenarios and the observations needed to distinguish between them. Sects. 4-6 captured the considerable advances that the three newly selected missions VERITAS (Sect. 4), DAVINCI (Sect. 5) and EnVision (Sect. 6) will bring to these science goals. These rich, highly synergistic datasets will provide an invaluable resource to assess the long-term history, stability of water reservoirs in the mantle and atmosphere, current levels of activity, divergent pathways and evolution toward habitability. Together they will reveal whether Venus-like and Earth-like planets can potentially transition into one another over time, which would imply that Earth-like exoplanets may be common among Earth-sized exoplanets.

List of Acronyms and Glossary

ABX	Aerobraking Exit Maneuver
ADC	Analog to Digital Converter
AFN	Autofluorescing Nephelometer (Venus Life Finder Science Payload)
AP	Aerial Platform (Venera-D mission)
AU	Astronomical Unit
CC	Carbonaceous
CLOVE	Chasing the Long-term Variability of Our Nearest Neighbor Planet Venus, an Institute for Basic Science (IBS, South Korea) cubesat project to perform observations from 320 nm to the near-infrared
CNES	Centre National d'Études Spatiales
CPR	Circular Polarization Ratio
CRIS	Carrier Relay Imaging Spacecraft (DAVINCI mission)
CUVIS	Compact Ultraviolet Imaging System (DAVINCI science payload)
D/H	Deuterium to Hydrogen isotopic ratio
DAVINCI	Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging

DM	Descent Module (Venera-D mission)
DS	Descent sphere (DAVINCI mission)
DSN	Deep Space Network
DV	Delta Velocity
ECM	Eccentricity Control Maneuver
EDL	Entry, Descent and Landing
ELT	39-m Extremely Large Telescope, European Southern Observatory
EM	Electromagnetic
ENA	Energetic Neutral Atom
Eotvos	A non-SI unit of acceleration divied by distance; 1 Eotvos (E) $= 10^{-9}$ galileos cm^{-1}; in SI, 1 E $= 10^{-9}$ s^{-2}; after Loránd Eötvös (1848-1919)
ESA	European Space Agency
ESI	Engineering Science Investigation (DAVINCI)
Ga	Gigayear, one billion years
GBT	Green Bank Telescope, West Virginia
GCM	General Circulation Model
GMT	Greenwich Mean Time
GMT	25-m Giant Magellan Telescope, Las Campanas Observatory, Chile
GRAIL	Gravity Recovery and Interior Laboratory
GROZA	Radio Wave Analyzer 15-50 Mhz (Venera-D Science Payload)
GSFC	Goddard Space Flight Center
GSLV	Geosynchronous Satellite Launch Vehicle
Hadean	Geologic eon extending -4.6 to -4 Ga preceding earliest known minerals on Earth
HF	High Frequency, a range of radio frequencies extending from 3 MHz to 30 MHz i.e., from 10 to 100 m in wavelength.
HGA	High Gain Antenna
HH and HV	Horizontal and Vertical Polarization (conventional imaging radar systems)
HZ	Habitable Zone, a range of distances around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure, and thus provide conditions for the emergence of life, or its precursors. By extension, range of altitudes within the atmosphere or the liquid layers of a planetary or natural satellite interior with similar properties.
InSAR	Interferometric Synthetic Aperture Radar
ISRO	Indian Space Reseach Organisation
IVOLGA	Infrared Heterodyne Fiber Analyzer/Spectrometer (Venera-D Science Payload)
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope, Maunakea, Hawaii, a ground-based millimeter- submillimeter wave telescope facility
JPL	Jet Propulsion Laboratory
JSDT	Venera-D Joint Science Definition Team
k_2	Tidal Love number, gravitational potential modification due to the tidal deformation of a planet. After Augustus E. H. Love (1863-1840)

Ka-band	a nominal frequency range, from 26 to 40 GHz (0.8-1.1 cm in wavelength) within the microwave portion of the electromagnetic spectrum
LGA	Low Gain Antenna
LIDAR	LIght Detection And Ranging
LIR	Longwave Infrared Camera (Venera-D Science Payload)
LIVE	Lightning Sensor (Shukrayaan-1 Science Payload)
LM	Lander Module (Venera-D mission)
LOD	Lengh of Day
LOS	Line of Sight
LT	Local (solar) time, hour angle of the Sun as observed from a given point on Venus
LWIR (or Thermal IR)	Long Wavelength Infrared radiation, 8 – 15 μm in wavelength, within the infrared portion of the electromagnetic spectrum
Magellan	NASA Venus Orbiter Mission 1990-1994
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MAVEN	Mars Atmosphere and Volatile EvolutioN
Meridian	Any great circle joining the North and South poles of a planet
MERTIS	Mercury Radiometer and Thermal Infrared Spectrometer (BepiColombo science payload)
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
Mid IR or MWIR	Mid Infrared (Wavelength) radiation, 3 – 8 μm in wavelength, within the infrared portion of the electromagnetic spectrum
Millimeter wave	Range of electromagnetic spectrum between 10 millimeters (30 GHz) and 1 millimeter (300 GHz), also known as the extremely high frequency (EHF) band.
(volume) Mixing ratio	Amount of an atmospheric constituent (in moles) divided by the total (in moles) of all other atmospheric constituents. For minor species, it is usually expressed in parts per million (ppm) or parts per billion (ppb)
MGS	Mars Global Surveyor
MM-R	Millimeter Wave Radiometer
MO	Magma Ocean
MoI	Moment of Inertia
MOIF	Moment of Inertia Factor
MOLA	Mars Orbiter Laser Altimeter (MGS science payload)
MSL	Mars Science Laboratory / Curiosity
MWRS	Microwave Radiometric Sounder (VOICE Science Payload)
Myr	Megayear = Million years
N/A	Not applicable
Nadir	Direction pointing directly below a particular location. The radar nadir refers to the downward-facing viewing geometry of an orbiting radar.
NASA	National Aeronautics and Space Agency
NASEM	National Academies of Sciences and Engineering
NC	Non-carbonaceous
Near IR or nIR	Near Infrared radiation, 0.75 – 1.4 μm in wavelength, within the infrared portion of the electromagnetic spectrum (from the approximate end of the response of the human eye to that of silicon)

NES0	Noise Equivalent Sigma Zero, a measure of SAR sensitivity, usually expressed in dB
OBP	On-board Processing
OC	Opposite Sense, circular polarization
SC	Same Sense, circular polarization
OM	Orbiter Module (Venera-D mission)
p, T	Pressure, temperature
PFS	Probe Flight System (DAVINCI mission)
Polarization	orientation of the electric field vector in an electromagnetic wave, “horizontal” (H) or “vertical” (V) in conventional imaging radar systems.
PolSAR	Polarimetric Synthetic Aperture Radar (VOICE Science Payload)
QMS	Quadrupole Mass Spectrometer
Radar	RAdio Detection And Ranging
R-LIBS	Raman-Laser Induced Breakdown Spectroscopy
RAVI	(Shukrayaan-1 Science Payload)
RPI	Repeat-Pass Interferometry
RTM	Radiative transfer model
S-band	a nominal frequency range, from 2 to 4 GHz (7.5-15 cm in wavelength) within the microwave portion of the electromagnetic spectrum
S/C	Spacecraft
SAM	Sample Analysis at Mars suite (MSL science payload)
SAM	Sample Analysis at Mars
SEP	Solar Electric Propulsion
SfM	Structure-from-Motion processing of descent images (DAVINCI, Sect. 5.3.4)
SHARAD	Mars SHAllow RADar sounder (Mars Reconnaissance Orbiter Payload)
SNR	Signal-to-noise ratio
SP1	Science Phase 1 (VERITAS mission)
SP2	Science Phase 2 (VERITAS mission)
SPICAV	Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus (Venus Express Science Payload)
SRS	Subsurface Radar Sounder (EnVision science payload)
SRTM	Shuttle Radar Topography Mission
SSAS or SS-AS	Subsolar to antisolar (wind circulation)
SSPA	Solid State Power Amplifier
SVET	Fourier Infrared Thermal Spectrometer (Venera-D Science Payload)
SWIR	Short Wavelength Infrared radiation, 1.4 – 3 μm in wavelength, within the infrared portion of the electromagnetic spectrum
SZA	Solar zenith angle, the angular distance between the vertical direction and the direction of the Sun from a specific location
TanDEM-X	TerraSAR-X satellite add-on for Digital Elevation Measurement
Tb	1 Tb = 1 terabit = 10^{12} bits; 1 terabyte = 1 TB = 8 Tb
TB	1 TB = 1 terabyte = 10^{12} bytes
TDI	Time delay and Integration
TESS	Transiting Exoplanets Survey Satellite

Thermal IR (or LWIR)	Long Wavelength Infrared radiation, 8 – 15 μm in wavelength, within the infrared portion of the electromagnetic spectrum
TMT	30-m Thirty-Meter Telescope, TMT International Observatory
TRAPPIST	TRAnsiting Planets and Planetesimals Small Telescope, a ground-based observatory on two sites: TRAPPIST-S in La Silla Observatory, Chile; TRAPPIST-N in Oukaïmeden Observatory, Morocco.
TRAPPIST-1	A cold dwarf star in Aquarius constellation, 40.55 ± 0.04 light-years away from Earth, with a planetary system of seven known exoplanets TRAPPIST-1b/h
TT&C	Telemetry, Tracking and Command
TW	1 TW = 1 terawatt = 10^{12} watts
TWTA	Travel Waveguide Tube Amplifier
USO	Ultra-Stable Oscillator
UVN-MSI	Ultraviolet-Visible-Near Infrared Multi-Spectral Imager (VOICE Science Payload)
VARTISS	(Shukrayaan-1 Science Payload)
VASI	Venus Atmospheric Structure Investigation (DAVINCI Science Payload)
VCMC	Visible Camera for Cloud Monitoring (Shukrayaan-1 Science Payload)
VEDA	Electron Density (Shukrayaan-1 Science Payload)
VEM	Venus Emissivity Mapper (VERITAS science payload)
VenDI	Venus Descent Imager (DAVINCI Science Payload)
VENIS	IR grating spectrometer and imager, 2-5 μm (Venera-D Science Payload)
VenSpec	Venus Spectroscopy suite (EnVision science payload)
VenSpec-H	Venus Spectroscopy High Resolution (EnVision science payload)
VenSpec-M	Venus Spectroscopy Mapper (EnVision science payload)
VenSpec-U	Venus Spectroscopy Ultraviolet (EnVision science payload)
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VEx	ESA Venus Express orbiter mission 2007-2014
VfOx	Venus Oxygen Fugacity Experiment (DAVINCI Student Collaboration Experiment)
VIKA	near-IR spectrometer suite 1.05 – 1.65 μm (Venera-D Science Payload)
VIRAL	Venus Infrared Atmospheric gas Linker, a high-resolution echelle spectrograph 2.3–4.4 μm (Shukrayaan-1 Science Payload)
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer (Venus Express science payload)
VIRTIS-H	The high spectral resolution channel of the Venus Express VIRTIS IR spectrometer, aboard Venus Express
VIS	Visible spectral range (0.38 – 0.75 μm, or 380 – 750 nm)
VISAR	Venus Interferometric Synthetic Aperture Radar (VERITAS science payload)
VISOR	Venus Imaging System for Orbital Reconnaissance (DAVINCI Science Payload)
VISWAS	(Shukrayaan-1 Science Payload)

VMC	Venus Monitoring Camera (Venus Express Science Payload)
VMS	Venus Mass Spectrometer (DAVINCI science payload)
VODEX	Venus Orbiter Dust EXperiment (Shukrayaan-1 Science Payload)
VOI	Venus Orbit Insertion
VOLNA	(Venera-D Science Payload)
VSAR	(Shukrayaan-1 Science Payload)
VSEAM	(Shukrayaan-1 Science Payload)
VTC	Venus Thermal Camera (Shukrayaan-1 Science Payload)
VTLS	Venus Tunable Laser Spectrometer (DAVINCI Science Payload)
VZ	Venus Zone, defined by Kane et al. (2014) as part of the habitable zone (HZ) in which an Earth-sized planet is more likely to be a Venus analog than an Earth analog
X-band	a nominal frequency range, from 8 to 12 GHz (2.5-3.8 cm in wavelength) within the microwave portion of the electromagnetic spectrum
XRF	X-ray fluorescence

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Declarations

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