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Exploring Venus: next generation missions beyond those currently planned

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As of mid-2023 at least ten missions are in development or being planned to explore Venus in the next 2 decades. Most of these emphasize atmospheric chemistry and surface/interior scientific objectives and only a few directly address past and present habitability of Venus as a primary science goal. All of the missions employ previously flight-tested platforms—Orbiters and general atmospheric probes, yet none (as of yet) plan to utilize longer-lived atmospheric platforms (e.g., balloons or airships) or landers. Thus several key questions about Venus will necessarily remain unanswered after the current wave of missions in development which will explore Venus starting in 2029 and continuing throughout the 2030s. This future-oriented perspective outlines the major scientific questions that the next-generation of missions to Venus should address for a better understanding of the planet as a system and provide a reliable comparative basis for the Venus-analogue exoplanets which can be investigated only by means of remote observations such as from the James Webb Space Telescope (JWST). This next generation of Venus missions may require long lived atmospheric platforms that either float or which "fly" at different altitudes, longer lived surface stations, and eventually samples of the atmosphere/cloud particles (aerosols) and surface returned to Earth laboratories. Although ideas for aerial platforms, long-lived landers, and missions to return atmospheric and surface samples are being conceptualized at present to be ready for upcoming international competed opportunities (e.g., NASA, ESA, ISRO, JAXA), they await further investment in technologies to provide the combination of scientific measurement capabilities and flight-system performance to make the breakthroughs that the community will expect, guided by longstanding science priorities.

KEYWORDS

Venus missions, atmosphere escape, Venus, search for life, atmosphere, surface, missions, future

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Abbreviations: AFN, Auto fluorescence nephelometer; DAVINCI, Deep Atmosphere Venus Investigation of Noble gases, Chemistry and Imaging; ESA, European Space Agency; InSAR, Interferometric Synthetic Aperture Radar; ISRO, Indian Space Research Organisation; JAXA, Japan Aerospace Agency; JWST, James Webb Space Telescope; MAVEN, Mars Atmosphere and Volatile Evolution; NASA, National Aeronautics and Space Administration; NIR, Near infrared; PVO, Pioneer Venus Orbiter; VERITAS, Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy.

1 Introduction

Despite decades of exploring Venus with space missions, there remains a great deal to be learned about the planet and its evolutionary history, from its massive atmosphere to surface and interior. The possible existence of liquid water on the planet in the past remains a key topic, along with it the possibility of some form of biological activity and new considerations of the prospects of extant microbiology in the acidic clouds, even today. With the recent interest in habitable exoplanets and the origin of life, Venus continues to represent a high priority target on the basis of its past and present habitability possibilities [Origins, Worlds, and Life, PAS-DS, 2022].

A number of orbiter and deep atmosphere probe missions are poised to investigate Venus atmosphere and its surface with far more advanced instruments than those carried by the initial wave of missions in the 1970s and 1980s. Four missions are under development for launch in the upcoming –10 years. At least two others are being seriously planned with likely funding commitments (Table 1). These upcoming orbiter and deep atmosphere probe missions to Venus will address questions about Venus surface and its atmospheric chemistry, yet there will always be some questions that require follow on missions which will also respond to the discoveries of those that will explore Venus by 2035 (e.g., DAVINCI, VERITAS, EnVision). Such lingering questions include atmosphere-surface interactions which can potentially provide additional clues about the rotation state and deep interior processes and even the possibility of microbial life in the habitable zone that may or may not exist within the mid-deck clouds. Both of these compelling objectives require sustained measurements (as time-resolved samples) over a period perhaps as long as one Venus solar day (116 Earth days) in the atmosphere/clouds and on the surface at multiple locations. None of the forthcoming missions (e.g., DAVINCI, VERITAS, EnVision, ISRO Venus Orbiter, Russia's Venera-D) offer such capability.

The privately-funded *Rocket Lab* mission to Venus (French et al., 2022) consists of a single instrument, short-lived mini cloud-deck probe and is based on the preliminary concept of a Venus Life Finder mission sequence (Seager et al., 2022) and includes plans for two follow on missions. It is the only mission

TABLE 1 Planned/funded missions to Venus in the next decade.

Mission	Agency (Planned Launch)	Mission Architecture	Primary science objectives	Reference
Venus Life Finder Mini-Probe "*Morning Star*"	Rocket Lab (January 2025?)	Short-lived Entry probe into the Venus middle clouds with single instrument	Sample the cloud layer of Venus with a single AFN sensor	French et al. (2022)
DAVINCI	NASA (2029)	Deep Atmospheric probe (5 instruments) and carrier remote sensing spacecraft (3 instruments)	Measure detailed atmospheric properties and chemistry to inform Venus evolution and role of oceans with first-descent imaging for surface composition plus fO_2	Garvin et al. (2022)
VERITAS	NASA (*no earlier than* 2031)	InSAR Orbiter with NIR emissivity mapper	Venus geophysics (topography and gravity) and regional NIR emissivity (composition)	Smrekar et al. (2022)
Venera-D	Roscosmos (no earlier than 2030?)	Orbiter and Lander	Venus atmosphere and surface science	Zasova et al. (2019)
EnVision	ESA/NASA (2031 or 2032)	Multi-instrument Orbiter with polarimetric SAR, radar sounder, and UV, VIS, IR spectrometers	Venus surface and atmosphere evolution, including shallow subsurface and upper clouds	Voirin et al. (2021) Ghail et al., 2018
In planning stage				
VOICE	China Space Agency (2026 or 2028?)	Multi-instrument Orbiter	Polarimetric SAR and UV, IR remote sensing	Xiaolong et al. (2022)
Venus Orbiter	ISRO (2031)	Radar Orbiter	Venus atmosphere and surface properties via polarimetric SAR mapping	https://www.isro.gov.in/PLANETVENUS.html
Akatsuki 2	JAXA (>2031)	Sun-Venus Lagrange Point Orbiters	Solar wind interaction, cloud cover monitoring	Yamashiro (2022)
CLOVE	Institute for Basic Science/S. Korea	Earth orbiting CubeSats	Venus climate by monitoring global cloud cover, SO2, haze and cloud altitude variations	Lee et al. (2022)
Venus Life Finder Habitability Mission (private mission)	TBD (>2027?)	Instrumented 52 km fixed-altitude balloon with four mini-probes, or two large probes	"support or refute evidence for signs of extant life in the Venus cloud layers; ascertain the habitability of the Venusian clouds or lack thereof"	Seager et al. (2022)
Venus Life Finder Sample Return Mission	TBD (>2030?)	Return up to 1 L of atmosphere and few grams of cloud aerosol particles to Earth	"Is there life in Venus' clouds?"	Seager et al. (2022)

with the singular, specific goal of "Search for habitable conditions and signs of life in Venus's cloud layer", although NASA's DAVINCI deep atmosphere probe (2029 launch) will provide the detailed chemical context to support interpretation of the data acquired by the initial *Rocket Lab* mission (i.e., as per National Academies of sciences Astrobiology 2018 report recommendations). An autofluorescence nephelometer (Baumgardner et al., 2022) is the only instrument on the "Morning star" cloud-deck probe which will seek evidence of fluorescing organic molecules in the Venus clouds during the 3 min that it will spend traversing the altitudes of interest. Considering the probability of this mini-probe's short-lived science-based descent in the mid-deck Venus clouds at a velocity of tens of meters every second and identifying a scientifically sufficient number of fluorescent organic molecules, any detection of fluorescence could be revolutionary in the context of upcoming measurements by DAVINCI and EnVision. Non-detection of such organic molecules would not rule out their complete absence on the basis of an extremely short-duration sampling of the very dynamic Venus cloud-deck atmosphere at a single location with only one instrument. Sustained sampling for detailed measurement (especially of aerosols) by multiple approaches would be required to resolve at least some details absence or presence of trace organic chemistry in the Venus clouds.

Other inferences about the past presence of liquid water on Venus are anticipated via more detailed investigation of the unique tesserae highland formations first discovered from Venera 15/16 SAR imaging (C-band) and subsequent global Magellan radar mapping (S-band). Vastly Improved mapping of the Venus surface including global topography is expected from the VERITAS and EnVision orbiter missions in 2030s, and locally via the DAVINCI descent imaging of Alpha Regio (Tesserae) (Garvin et al., 2022), and perhaps earlier if the ISRO Venus orbiter mission is launched in 2028. These new observations may reveal refined details of the tesserae (8% of Venus surface) which are believed to be ancient and may provide evidence of the role of liquid water in the past (i.e., compositionally or via signs of hydrological processes). Recent analysis of Venus tesserae via Earth-based Arecibo, USSR Venera 15/16, and Magellan SAR data (Byrne et al., 2020; Gilmore et al., 2015; Whitten et al., 2021) have proposed evidence of fluvial erosion and various tectonic processes (Khawja et al., 2020). Discrimination of felsic rocks within the tesserae may confirm the critical role of crustal water in the formation of highlands on Venus.

2 What questions about Venus will likely remain after these missions

Capable as they are, the planned (in development) missions (Table 1) will not directly address several key questions about Venus, including some aspects of its origins and evolution on a completely different path from Earth. Some of the broad questions are described below beginning with the first one to be addressed via the Rocket Lab "Morning Star" mission. The Venus Exploration and Analysis Group (VEXAG) chartered by NASA and open to the global scientific community periodically updates the documents describing the goals and objectives for future Venus exploration (available at: www.usra.edu/vexag). The most recent updates were issued before the Discovery mission selections in June 2021 and hopefully will be updated in the future. The extant National Academies of Sciences Planetary-Astrobiology sciences Decadal Survey (Origins, Worlds, and Life, 2022) includes science measurement priorities with key questions for the 2023 to 2032 time frame, with others (some of which are below) that must await for the critical context to be provided by some of the missions in development (Table 1).

2.1 Is there life in the clouds today?

A primary motivation for the search for any extant life on Venus comes from the theoretical possibility that microorganisms within the cloud layer could contribute to the absorption of incident solar radiation and the associated inability to determine the nature and identity of the absorbers that give Venus its unique appearance at shorter than blue wavelengths (Morowitz and Sagan, 1967; Grinspoon, 1997; Schulze-Makuch et al., 2004; Limaye et al., 2018). Seager et al. (2020) proposed a conceptual life cycle for the putative microorganisms and Bains et al. (2021) suggested that sulfuric acid could play the role of water as a solvent for some bio molecules. This compelling but extremely challenging question requires knowledge of the possible organic chemical context of the cloud deck beyond current knowledge and new information to be acquired upcoming missions including DAVINCI and EnVision will provide some of the key information that inhibits progress in this thematic area at present.

2.2 Did life exist in the past on Venus?

The possibility of life in the early history of Venus hinges in part on whether it had liquid water, which is an open question for now. First suggestions for the past presence of liquid water came from the discovery that the deuterium/hydrogen (D/H) ratio (in water) in the Venus atmosphere is ~150 times greater than in Earth's ocean (Donahue et al., 1982; Donahue and Hodges, 1993) on the basis of 1978 Pioneer Venus Large Probe data. Other indirect indications came from near infrared data regarding felsic composition of Venus highlands (Hashimoto et al., 2008). Lacking sufficient information and chemical data, climatological and geophysical modeling approaches have been used to investigate the past presence of water in any potential state. If there was a time period when liquid water persisted the Venus' surface, Way et al. (2016) found from modeling the climate history that it could have survived for >2 billion years or until as recently as about a billion years ago. Way and Del Genio (2020) followed up to investigate the fate of the oxygen left behind after the dissociation of water and escape of hydrogen and found that long term persistence of liquid water was possible rather than a steam atmosphere. Höning et al. (2021) followed up by assuming specific physical conditions concerning ~50 million years after formation of Earth and Venus and modeling the climate evolution. Turbet et al. (2021) found that water vapor could never have condensed onto the surface as an "ocean" as the environment was too warm under some specific initial conditions. Weller and Kiefer (2020) investigated the transition from stable mobile lid convection to stagnant lid convection by geodynamic modeling, and found that Venus may have lost its crustal water in the last 1.4 billion years.

Accurate measurements of the noble gas isotopic composition can help address the question of past presence of liquid water in the context of atmospheric evolution, and the 2029 DAVINCI mission will obtain these measurements at an order of magnitude higher precision than before and including the heavier nobles gases including Xe and Kr (Garvin et al., 2022). Additionally, the investigation of tesserae as possible exposed ancient crustal materials (Gilmore et al., 2019) from emissivity-based compositional mapping from EnVision and VERITAS missions will promote future *in-situ* measurements of the surface to confirm the presence of rocks formed in association with water. DAVINCI's near-infrared descent imaging will further constrain the role of water in local-scale rock compositions in one tesserae (Alpha Regio) at spatial scales not accessible from orbit together with detailed near-surface trace gas chemistry and direct measurements of fO_2. Although it would of high scientific interest to search for fossil signatures (Kohler et al., 2021) in case liquid water did persist on Venus surface in the past, it may be feasible only within the rugged tesserae provided they have not been overplated by post-formational basaltic volcanism. Data from DAVINCI, VERITAS, and EnVision (as well as the planned ISRO radar mapper) will help resolve this question and extend consideration to other surface units where the role of hydrological processes may have been active and preserved.

2.3 Surface atmosphere interaction: angular momentum and volatile exchange

2.3.1 Angular momentum exchange

It is generally accepted that Venus and Earth were similar when they formed at the beginning of solar system history (Correia and Laskar, 2001; Lammer et al., 2020). This includes comparable inventories of volatiles, surface temperature profiles, and rotation rates. At present, the surface environmental conditions are different on the two planets in spite of their similarities in physical size and bulk density. With a massive 93 bar (CO_2) atmospheric pressure, Venus surface experiences much greater surface drag which may affect its rotation period, determined on the basis of 29 years of radar observations to be about 243.0212 ± 0.0006 days (Campbell et al., 2019) but backwards (relative to Earth and Mars). Margot et al. (2021) found from speckle radar measurements during 2006–2020 that the rotation rate displays measurable variations of ~20 min indicating that the angular momentum exchange between the atmosphere and the solid planet is ~4%, but no resolvable trend is detectable from the short period over which the measurements are available.

Without a natural satellite, how and when did the rotation rate of Venus decrease from perhaps a few hours to longer than its orbital period and how did the planet's the spin orientation change? Large body collisions in the formative stages of Venus (post accretion) could have played a role in altering the inclination of the spin axis and the rotation rate, but so could the impact of atmospheric drag. The evolution of the rotation rate has been investigated through analytical studies (Ingersoll and Dobrovolskis, 1978; Dobrovolskis, 1980; Correia and Laskar, 2001; Auclair-Desrotour et al., 2016) and numerical models (Correia et al., 2003; Correia and Laskar, 2003). The numerical studies by Correia and Laskar (2003) showed that regardless of the initial spin state, Venus would end up in its current slow rotation state due to the effect of the atmospheric tides once the atmosphere developed (to its present massive state) to exert significant stress. Although monitoring the spin rate of Venus routinely would be ideal, it has not been possible as the large radio telescopes needed to transmit a powerful signal and detect the reflected signal some minutes later are few (e.g., Arecibo, Goldstone) and in great demand to track and receive data from the many planetary spacecraft as well as to conduct other planetary radar observations. The recent demise of Arecibo is a huge loss for this line of investigation.

To corroborate the frictional stress regime, near surface wind speed and direction at a few locations (at least 3) on Venus are needed. To date, only measurements of wind speed are available without critical directional information (Avduevskij et al., 1976) from cup anemometers at the Venera 9 and Venera 10 locations (i.e., near Beta Regio) as well as an acoustic measurement approach at Venera 13 and Venera 14 landing sites in Venusian rolling plains (Ksanfomaliti et al., 1983). It would be highly desirable to obtain more extensive measurements of near-surface or surface wind velocities with directions for at least one Venus day at a few locations in the future. Note that the DAVINCI probe will enable improved wind speed assessment in the deep atmosphere over a tesserae including limited but new information on magnitude and direction as a function of altitude with very high sampling rates, all in the context of pressure and Temperature (Garvin et al., 2022).

2.3.2 Injection of volatiles into the atmosphere

A number of recent studies suggest that Venus may be geologically active today based on Magellan and Venus Express data (Bondarenko et al., 2010; D'Incecco et al., 2021; Gülcher et al., 2020; Herrick and Hensley, 2023; Shalygin et al., 2015). Volcanic emissions of gases and dust affect the deep atmospheric composition and may provide connections to the possibility of microbial life in the middle cloud layer. No direct measurements of the volcanic input into the atmosphere are available, but the upcoming missions (Table 1) will provide a multi-mission observational framework to assess present-day volcanic activity and its change over time.

2.3.3 Absorption of volatiles by the surface

There are suggestions that volatile species could be dynamically exchanging with the surface materials (rocks, sediments, etc.), but these hypotheses are as yet unproven. Long-duration measurement of such chemical exchanges will require a capability that may be achievable in the middle-late 2030's with the recent progress in prolonged battery life and electronics. Kremic et al. (2020) describe a long-lived lander design (LLISSE) for operations on the Venus surface for about a solar day.

2.4 What is the escape rate of the atmosphere?

Without an intrinsic magnetic field, Venus has managed to retain its atmosphere due to an induced magnetosphere (Futaana et al., 2017). However, there is detectable atmospheric loss from the few measurements available (Masunaga et al., 2019; Persson et al., 2020). Such measurements are available only from two spacecraft, Pioneer Venus Orbiter (PVO) and Venus Express, both of which were in near polar, elongated orbits around Venus with apoapsis about 10 x Venus surface radius and thus the measurements do not provide a complete accounting of the atmospheric loss.

2.5 Seismic activity

Does Venus quake? Although the Magellan radar imaging did not reveal any direct indication of terrestrial-style plate tectonics on Venus, vertical tectonics as evidenced by faults, rift valleys, and volcanic centers have been documented. Thus, like Mars, Venus should have measurable Venus-quakes. The characteristics of the quakes have revealed much about Earth's interior and the same may be expected for Venus since it is impractical or impossible to explore its deeper interior directly.

Venus quake activity can be detected from the surface from a long lived platform (Kremic et al., 2017). On Earth, quakes can also be detected from stratospheric balloons by detecting the small pressure perturbations by acoustic and gravity waves triggered by quakes (Garcia et al., 2022). Similar approach is being investigated for the Venus atmosphere from long lived balloons or other atmospheric platforms (Krishnamoorthy and Bowman, 2023).

2.6 Remnant magnetism

No magnetic field around Venus has been directly detected by orbiting spacecraft. Did Venus ever have a magnetic field that disappeared when the internal dynamo became ineffective or inactive? If there was an early intrinsic magnetic field, is it possible that a relict signature has been left in the crust via magnetized rocks and perhaps detectable in exposed ancient rocks? A planet's magnetic field plays an important role in the evolution of its atmosphere (Gillmann et al., 2022) through loss of ions to space and Venus has escaped the fate of Mars which lost its atmosphere due to a weak magnetic field when the dynamo shut down (Sakata et al., 2020), as measured extensively by MAVEN.

2.7 Deep atmosphere superrotation

The maintenance of the superrotation of the Venus atmosphere is still not understood. Some clues about the origins of the superrotation near the cloud tops have been recently obtained (Horinouchi et al., 2020), but a full understanding await pertinent data. Among the unknnowns is accurate knowledge of the level of the cloud motions which are used to infer the ambient winds. Another challenge is understanding the discrepancy between Döppler spectroscopic wind estimates at the cloud tops (Gonçalves et al., 2020) and and cloud motions. Similarly, the cyclostrophic wind estimates of balanced flow suggest different altitudes for the cloud motions than expected (Limaye, 1985; Piccialli et al., 2012) the bias that exists (at least for Earth observations) in the estimates of angular momentum transport determined solely from cloud motions (Virji, 1981). The cloud motion measurements provide a good temporal and spatial coverage from Venus images, but the day and night side measurements are not on the same level. This complicates the calculation of the angular momentum transport estimates (Limaye, 2007). In the deep atmosphere the measurements of three wind components have been provided by tracking of the four Pioneer Venus descending probes to the surface, (Counselman et al., 1980), and only line of sight Döppler speeds (close to the zonal direction) from several Venera probes (Kerzhanovich, 1972; Kerzhanovich and Marov, 1977; Kerzhanovich et al., 1982). These are too few to understand momentum transports in the deep atmosphere and many more measurements are needed. Future Venus exploration missions needed to address remaining questions.

New or improved versions of different observing/measurement platforms will be needed for critical future measurements. Some of the key future Mission goals include:

- Long duration measurements on the surface including meteorological, volatile fluxes, winds, and others (see VEXAG documents and 2021 goals)
- Vertical measurements of the upper meter of mantling "fines" (as soils or regolith) with depth-resolution (active sedimentary layer)
- Long duration *in situ* and remote observations of clouds with attention to aerosol chemistry and kinetics over one Venus day
- Improved measurements of atmospheric escape
- Atmosphere (gas and aerosol) and surface sample return missions
- Sun-Venus connection in short (~solar cycle) and long term global cloud cover/climate changes

Some exciting mission concepts have been explored recently which can achieve some of these objectives, while others await to be investigated. These include long-lived surface stations (about one solar day) for chemical, seismic, and meteorological measurements (Kremic et al., 2020). Human enabled exploration of Venus has also been considered as a means of bringing crew-tended sensors and deployed systems to the Venus system (Izenberg and Lefland, 2022). Flying or floating aerial platforms of 1 week or longer durations have been conceptualized (Polidan et al., 2015; Agrawal et al., 2022; Arredondo et al., 2022; Buchanan et al., 2022; Bugga et al., 2022). The role of aerial platforms in sample capture and analysis has been presented[1] in the context of analysis of *in-situ* samples from the Venus surface transferred by an ascent craft to an aerial laboratory (Venus *In-Situ* Sample Capture Mission concept, 2002). Long term monitoring of Venus cloud cover and upper atmosphere from Lagrange Point orbiters which can also provide continuous data relay capability (from surface stations) has been suggested via recent mission studies (Kovalenko et al., 2019; Kovalenko et al., 2020).

As an example the NASA NIAC-funded LEAVES is an innovative concept currently funded for design maturation of "Lofted Environmental Atmospheric Venus Sensors" for

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[1] Cutts, J.A., Venus *In Situ* Sample Capture and Analysis: Role of Aerial Platforms, KISS Workshop, 2021, https://kiss.caltech.edu/workshops/VenusInSitu/lectures/Cutts.pdf.

measuring the atmospheric conditions at a number of locations from the clouds towards the surface (Balcerski et al., 2021). Krishnamoorthy and Bowman (2023) describe a number of airborne sensors for detecting possible seismic events on Venus.

The privately-funded Venus Life Finder multi-mission concept is series of progressively complex designs to investigate habitability indicators within the clouds, search for signs of extant life chemical signatures in the middle clouds, and an atmospheric sample return mission (Seager et al., 2022). Such approaches await initial implementation in the 2020's via Rocket Lab and associates.

3 Ground based observations of Venus

Planetary exploration began with telescopic observations of Venus more nearly a century ago. With newer and more capable telescopes and instruments operating at a wide range of wavelengths from near UV to meters, ground based observations will continue to provide crucial data about Venus. Space based telescopes such as Hubble Space Telescope (HST) and James Webb Space Telescope (JWST) are very constrained in observing Venus due to its proximity to the Sun.

The unfolding program of flyby, orbital, probe, and landed observations planned for Venus within the next 10–12 years will necessitate continuity and extension of ground-based observations, especially of the upper atmosphere. Future high spectral and spatial resolution measurements of the cloud top Döppler winds will be valuable. Existing and planned ground-based observatories including ALMA and new VLT capabilities will add important scientific context to the planned observations from DAVINCI (i.e., hyperspectral UV imaging spectroscopy at 0.2 nm spectral resolution) and EnVision (integrated UV spectroscopy from orbit) as well as other international orbiters from India, China, and Russia. Improvements in Earth-based radar astronomy may also come to fruition even after the end of the Arecibo radio-telescope in Puerto Rico. As new measurements from the armada of planned and funded missions are implemented over the next 7 years, the advancement of synergistic ground-based observations will provide critical context for the more local observations, and connect to exo-planetary observations as well of exo-Venus analogues by the James Webb Space Telescope and other astrophysical observatories. Furthermore, laboratory based measurements and simulations of the Venus atmosphere (including aerosols in the clouds) and surface-atmospheric interactions will further improve interpretations from orbital and probe/lander based missions, setting up for an era of sustained exploration of Venus, including the advent of balloon-based measurement systems and long-lived surface stations.

4 Future steps

To address the questions about Venus that will remain after the currently planned missions (Table 1), a set of advanced technology/capability demonstration missions may be required. The global Venus science community will need to come together to prioritize and collaborate on required technology development pathways to develop implementation concepts that are affordable. The data communication from atmospheric and surface platforms is one key area where cooperation will be very useful as has been demonstrated for international Mars exploration. Prioritizing the science goals and a progressive approach to technology demonstration missions or experiments should be discussed by the wider Venus community. Finally, investment in technology development is needed within industry and international space agency programs in direct support of future missions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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